P79: Cryptography and Protocol Engineering

University of Cambridge
MPhil in Advanced Computer Science / Computer Science Tripos, Part III
Lent term 2025/26
https://www.cl.cam.ac.uk/teaching/2526/P79/

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Motivation

- The Internet (and hence, the modern world) would not function without cryptography
- Cryptography has a reputation of being somehow magic
- Not magic! But complex and easy to get wrong
- This module aims to demystify modern cryptography

About this module

- Ran first time in 2024/25
- Practical orientation: focus on you writing code
  - Theory (e.g. security proofs) is very important too
  - Implementation + formalisation would be too much for one module
  - Plenty of engineering challenges in implementation
- Assessed by lab reports + code submissions
  - Don't just write the code, also reflect on it critically
  - Code need not be production-quality, but you should explain what would be required to make it so

“Don’t roll your own crypto!”

- Cryptography implementations are very prone to subtle flaws that **completely break** the intended security properties
- Production software (where harm could result if it’s broken) should use **expert-audited**, preferably **formally verified** code
  - And those expert audits are not cheap
- But if you want to become one of those experts yourself, reading and writing crypto code is a part of the journey
- If you put your code on GitHub, please add a big **warning label**!

Module objectives

By the end of this module, you should hopefully...

- appreciate real-world cryptography
- know the mathematical notation and concepts used in crypto protocols
- be able to understand and implement research papers and crypto standards
- use crypto libraries correctly
- have tried some attacks on crypto protocols
- got a glimpse into recent research
- got better at technical writing (through lab reports)

Assessment

- Four assignments, deadlines two weeks apart:
  1. Elliptic curve Diffie-Hellman (X25519): 3 Feb 2026
  2. Elliptic curve signatures (Ed25519): 17 Feb 2026
  3. Authenticated key exchange (SIGMA): 3 Mar 2026
  4. Private information retrieval: 17 Mar 2026
- For each assignment you need to submit a **lab report** and **code**
- Equal weighting: each assignment counts 25% towards final mark
- Discussions with others are allowed, but code and lab report must be your individual work
- We're happy to answer your questions – please ask!
- We aim to get you feedback on one report before the next is due, so you can take it on board

Code: what you will implement

We will focus on implementing asymmetric cryptography:

- For hash functions (e.g. SHA-3) and symmetric ciphers (e.g. AES), just use a library
- For big integer arithmetic, use Python's built-in integers
  - NOTE: this is not constant-time
- Everything else (e.g. elliptic curves) you will implement from scratch
- Write suitable tests to catch bugs
- Tolerate maliciously generated input from the network
- No need for real networking, but do encode/decode to bytes
- Don't bother building user interfaces

Code: how to submit

- We provide you with a template for Python
- You can use another language (e.g. Rust), but we won't be able to help you with it
- If using Python, use type annotations and a static type-checker (we suggest `ty`)
- Submit as a `.zip` archive that includes at least:
  - Your code
  - A `Dockerfile` that typechecks/compiles and runs your code and tests
  - A `run.sh` that builds and starts your Dockerfile
  - Your lab report
- At the end of today's lecture, we will set up a sample project together.

Code: what we look for

- **Correctness** $\gg$ **robustness** $\gg$ performance
- **Simplicity and clarity** are good, complexity is bad
- **Tests** covering both common and edge cases
- **Design of your API:** type checking, error handling, misuse resistance, naming, consistency
- **Documentation:** high-level picture, do not comment every line, make meaningful comments, API language should be self-documenting
- **Well-motivated extensions and comparisons:** benchmarking, interesting testing approaches, compatibility with other libraries, extra hardening, side-channel resistance, ...
  - More features $\neq$ better! More features $=$ more bugs

Lab reports

> *Remember, kids: the only difference between screwing around and science is writing it down.*
> – *Adam Savage*

Up to 1,000 words, explaining key aspects of your code:

- How it works
- Why it's correct
- Any findings from your work (e.g. limitations or trade-offs you found)
- What you'd need to change to make it production-quality
- Other insights, e.g. how it compares with other implementations (performance or otherwise)

Opportunity for your critical insights and creativity!

Lab report requirements

PDF written in LaTeX (or comparable tool such as Typst)

No fixed structure, but should contain:

- Explanation of core ideas behind your code
- How do you know that it is correct?
  - Minimum acceptable: "I copied it from the RFC"
  - Better: tests, types, derived formulas yourself
  - Ideal (but not required for this module): formal proof
- References to relevant literature (do not count towards word limit)

Assessment criteria:

- Correctness and clarity of explanations
- Critical reflection
- High marks require significant creative insight

Lab report style tips

- No need to repeat anything from the lecture notes
  - Write for a reader who has read the lecture notes
  - Different from a dissertation or research paper!
- No need for lengthy introduction, motivation, background
- Use the first person ("I designed...")
- Give evidence for your claims when possible
- Critical reflection, subjective opinions, experience reports, trade-off discussions are welcome
- Thought process is welcome, e.g. alternatives considered
- It's fine if you're not sure about something; best to call out doubts explicitly
- Don't give pseudocode; if you want to include code snippets, take them from your actual implementation
  - No need for lengthy code quotations
  - Code and lab report can reference each other

Recommended reading

We don't know of a textbook that covers the material in this module.

No required reading, but if you want a bit more background (earlier editions are fine too; check the library):

- **More practical:** Jean-Philippe Aumasson. Serious Cryptography, 2nd Edition. No Starch Press, 2024.
- **More formal:** Jonathan Katz and Yehuda Lindell. Introduction to Modern Cryptography, 3rd edition. CRC Press, 2020.
- **On elliptic curves:** Darrel Hankerson, Alfred Menezes, and Scott Vanstone. Guide to Elliptic Curve Cryptography. Springer, 2004.
- References in the lecture notes

Basic cryptography recap

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Basic cryptography recap

Hope you already know (roughly) what SHA-256, AES-GCM, and Diffie-Hellman are...

- Let's quickly recap the core primitives and their security properties.
- Let's also get you writing code that uses those primitives (provided by crypto libraries).
- We will use PyNaCl (Python wrapper for libsodium).
- PyCryptodome is also popular

Setup for the code examples:

```
brew install uv # or equivalent on your OS
uv run --with pynacl python
```

Hash functions

$H(x)$ takes an arbitrary-length bit string x and returns a fixed-length bit string

- e.g. SHA-256, SHA-3, BLAKE2/3
- **Preimage resistance**: given $H(x)$ you can only find x by trying all possible values of x
- **Collision resistance**: computationally infeasible to find $x \neq y$ such that $H(x) = H(y)$
- **Birthday paradox**: need $O(\sqrt{2^n}) = O(2^{n/2})$ computation to find a collision in an n-bit hash function

```
from hashlib import sha256 # Python standard library
in_bytes = 'Hello'.encode('utf-8')
print(sha256(in_bytes).hexdigest())
# 185f8db32271fe25f561a6fc938b2e...
```

Symmetric encryption

- $key \leftarrow \mathrm{Gen}()$ generates a key
- $c \leftarrow \mathrm{Enc}(key, msg)$ returns ciphertext c
- $msg \leftarrow \mathrm{Dec}(key, c)$ decrypts c, returns msg or error
- Generally want **authenticated encryption**: ensures that if c is manipulated, Dec returns error
- Block/stream cipher + Msg Authentication Code (MAC)
- **AEAD**: Authenticated Encryption with Associated Data (AD is unencrypted but authenticated)
- e.g. AES-GCM, ChaCha20-Poly1305, XSalsa20-Poly1305

```
from nacl.secret import SecretBox
from nacl.utils import random
key = random(SecretBox.KEY_SIZE)
ciphertext = SecretBox(key).encrypt(b'Hello')
print(SecretBox(key).decrypt(ciphertext))
```

Security definition for encryption

We normally require authenticated encryption to provide **indistinguishability under adaptive chosen ciphertext attack** (IND-CCA2)

A game between **challenger** and **adversary**:

- Challenger generates secret key
- Adversary may ask challenger to encrypt/decrypt any number of messages ("oracle")
- Adversary chooses two plaintexts m_0, m_1 of equal length
- Challenger encrypts one of them, chosen randomly, and returns ciphertext c to adversary
- Adversary may continue to request any number of encryptions/decryptions (but not decryption of c)
- Adversary guesses which one of m_0, m_1 was encrypted
- Adversary can't do better than random guess (50/50)

Message Authentication Code (MAC)

$\mathrm{MAC}(key, msg)$ takes a symmetric key key and byte string msg, returns a fixed-length **authentication tag**

- Security definition: existential unforgeability against chosen-message attack (EUF-CMA). Cannot forge a tag on some message without knowing key, even knowing tags for other messages
- Proof that a message was constructed by someone who knows key, and that the message was not altered
- To check, recompute $\mathrm{MAC}(key, msg)$ and check whether you get the same result
- Use a constant-time comparison, otherwise timing allows adversary to guess the right tag!
- Implementations based on hash (HMAC), block cipher (CBC-MAC), or polynomial (Carter-Wegman, GCM)

Hash-based MAC (HMAC) – RFC 2104

- $H(key \parallel msg)$ is not a secure MAC when H is SHA-256: length extension attacks!
- $\mathrm{HMAC}(key, msg) =$
  $H((key \oplus outerPad) \parallel H((key \oplus innerPad) \parallel msg))$
  where $\parallel$ is concatenation, $\oplus$ is bit-wise XOR
- Some hash functions (e.g. BLAKE2/3) have a **keyed mode**, which can be used as a MAC directly

```
import hmac
import secrets
key, msg = secrets.token_bytes(16), b'hello'
tag1 = hmac.new(key, msg, 'sha256').digest()
tag2 = hmac.new(key, msg, 'sha256').digest()
print(hmac.compare_digest(tag1, tag2))
```

Asymmetric (public key) cryptography

Hash functions, symmetric ciphers

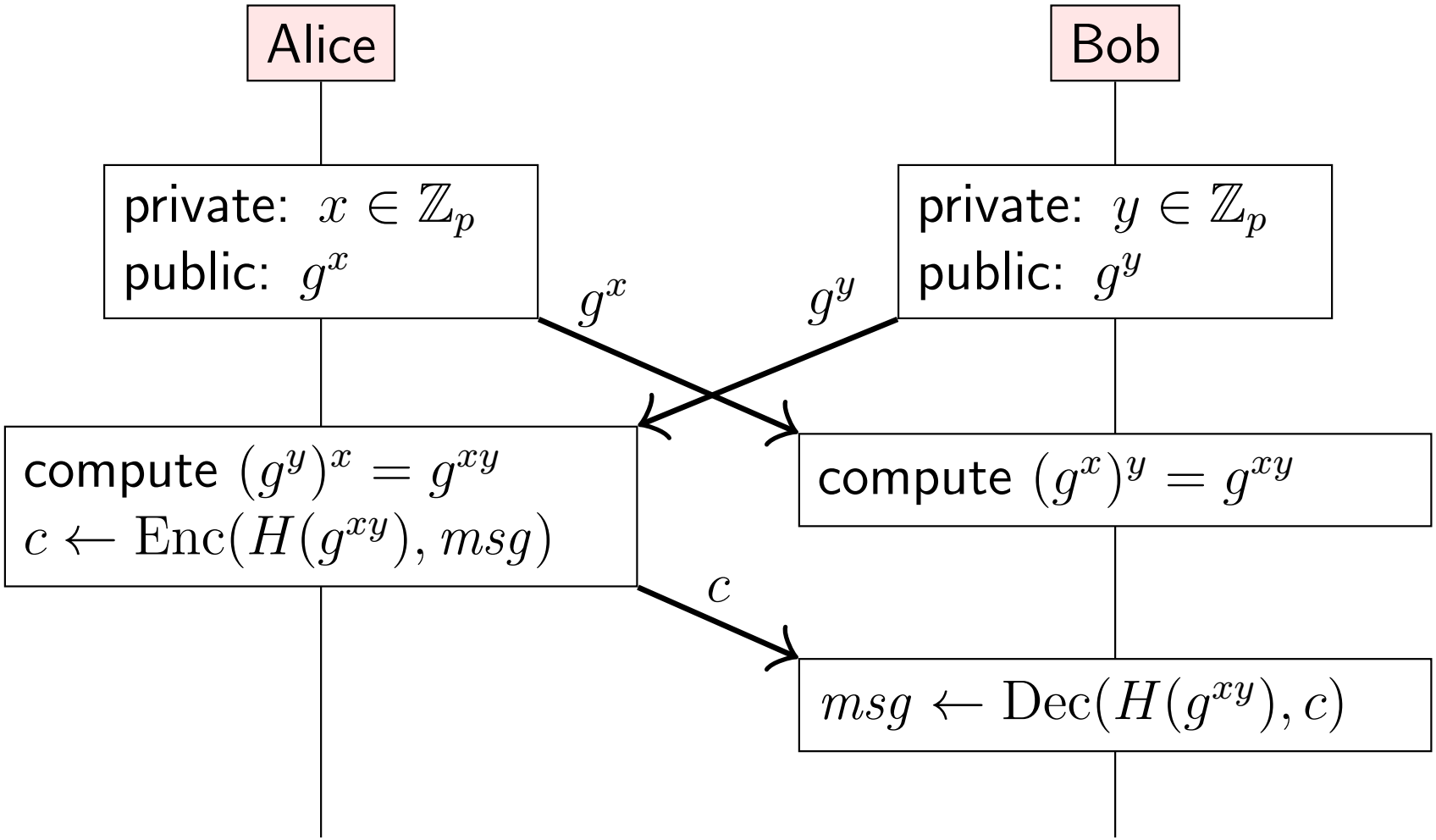
- Lots of bit shifts, XORs, lookup tables
- Not much underlying mathematical structure

Asymmetric cryptography:

- Number theory, algebraic objects (groups, finite fields...)
- Based on computational hardness assumptions
  - Multiplying numbers vs. factoring
  - Computing exponentials vs. discrete logarithms
  - Vector/matrix arithmetic vs. solving linear equations with random noise
- Many protocols rely on using asymmetric crypto in creative ways
- Focus of this module

Diffie-Hellman

Let g be a generator of a group of order p in which discrete logarithms are hard (we'll explain this later).



Diffie-Hellman

- sk = private (secret) key, pk = public key
- $\mathrm{DH}(sk_A, pk_B) = \mathrm{DH}(sk_B, pk_A)$
- Constructed as $\mathrm{DH}(sk, pk) = pk^{sk}$, $pk = g^{sk} \pmod p$
- Use hash of $\mathrm{DH}()$ output as key for symmetric encryption
- Discrete log: given g and g^{sk}, hard to compute sk
- **Not authenticated**: network adversary could swap your public key for their own

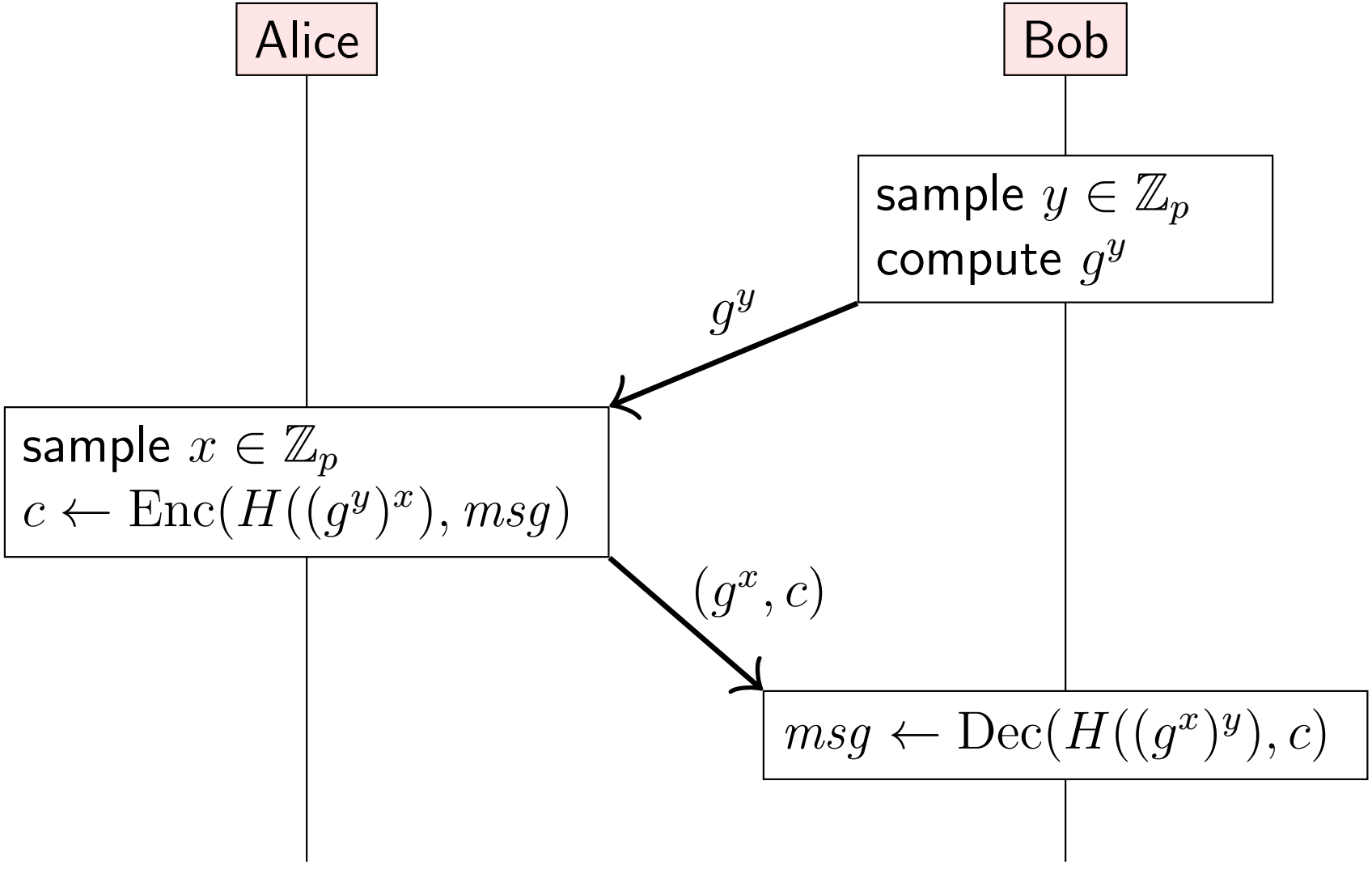
```
from nacl.public import PrivateKey, Box
alice_sk = PrivateKey.generate()
bob_sk   = PrivateKey.generate()
alice_pk = alice_sk.public_key
bob_pk   = bob_sk.public_key
print(Box(bob_sk, alice_pk).shared_key().hex())
print(Box(alice_sk, bob_pk).shared_key().hex())
```

Asymmetric (public key) encryption

- $(pk, sk) \leftarrow \mathrm{Gen}()$ generates keypair (pk public, sk secret)
- $c \leftarrow \mathrm{Enc}(pk, msg)$ returns ciphertext c
- $msg \leftarrow \mathrm{Dec}(sk, c)$ decrypts c, returns msg or error
- Unauthenticated: anyone who knows pk can encrypt
- e.g. RSAES-OAEP, Hybrid Public Key Encryption
- Often use Diffie-Hellman to compute shared key, then use authenticated encryption for the actual message
- IND-CCA2 like symmetric case, but adversary is given pk

```
from nacl.public import PrivateKey, SealedBox
private = PrivateKey.generate()
public = private.public_key
ciphertext = SealedBox(public).encrypt(b'Hello')
print(SealedBox(private).decrypt(ciphertext))
```

Public key encryption from Diffie-Hellman



Digital signatures

- $(pk, sk) \leftarrow \mathrm{Gen}()$ generates keypair (pk public, sk secret)
- $sig \leftarrow \mathrm{Sign}(sk, msg)$ returns signature
- $ok \leftarrow \mathrm{Verify}(pk, msg, sig)$ returns true or false
- e.g. DSA, ECDSA, EdDSA
- $\approx$ a MAC, but asymmetric
- Security definition: existential unforgeability against chosen-message attack (EUF-CMA). Cannot forge a signature on a message that the key owner didn't sign

```
from nacl.signing import SigningKey, VerifyKey
private = SigningKey.generate()
public = VerifyKey(private.verify_key.encode())
message = 'Hello'.encode('utf-8')
signed_msg = private.sign(message)
print(public.verify(signed_msg)) # b'Hello'
```

Security parameter

Most cryptography is breakable, given sufficient resources!

Want brute-force to be sufficiently hard that breaking it on a human timescale would be cost-prohibitive.

Generally we aim for **128-bit security**:

- On the order of 2^{128} computational steps required
- Finding the key for a 128-bit symmetric cipher
- Finding a collision in a 256-bit hash function
- Factoring a 3,072-bit RSA modulus
- Computing discrete log on an 256-bit elliptic curve

Sufficiently large quantum computers could efficiently factorise (break RSA) and compute discrete logs (break elliptic curves).

Can make symmetric ciphers quantum-safe by doubling key length (256 bits); quantum-safe hash is 384 bits

Lab time

- Clone the sample code: `git clone https://github.com/lambdapioneer/p79-sample.git`
- Install `uv` and Docker
- Run everything: `./run.sh`
- Fix the tests
- ...
- Critique!

Elliptic Curve Diffie-Hellman

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Introducing Elliptic Curve Cryptography (ECC)

- Very widely used – protects majority of Internet traffic
- Key agreement: Elliptic Curve Diffie Hellman (ECDH)
- Digital signatures: Elliptic Curve Digital Signature Algorithm (ECDSA) or Edwards Curve Digital Signature Algorithm (EdDSA)
- Lots of funky advanced stuff also possible
- Faster than RSA, DSA; smaller keys and signatures (at same security level)

In this module:

- We will use ECC for the first three assignments
- You need to implement it from scratch, using only Python's built-in primitives
- Suggested reading: Martin's Curve25519 tutorial

(Abelian) Groups

A set E and an operation $\bullet$ such that:

	additive	**multiplicative**
closed: $\forall a, b \in E.\ a \bullet b \in E$	$a + b \in E$	$ab \in E$
commutative: $\forall a, b \in E.\ a \bullet b = b \bullet a$	$a + b = b + a$	$ab = ba$
associative: $\forall a, b, c \in E.$ $(a \bullet b) \bullet c = a \bullet (b \bullet c)$	$(a + b) + c = a + (b + c)$	$(ab)c = a(bc)$
identity exists: $\exists id \in E.\ \forall a \in E.\ a \bullet id = a$	$a + 0 = a$	$a \cdot 1 = a$
inverse exists: $\forall a \in E.\ \exists b \in E.\ a \bullet b = id$	$a + (-a) = 0$	$a \cdot a^{-1} = 1$

Groups of integers modulo n

$\mathbb{Z}_n$: Additive group of integers modulo n

- $\mathbb{Z}_n = \{0, 1, \ldots, n-1\}$
- Operator is addition mod n. Python: `(a + b) % n`
- Inverse is $-a = n - a$

$\mathbb{Z}_n^*$: Multiplicative group of integers modulo n

- When n is prime, $\mathbb{Z}_n^* = \{1, 2, \ldots, n-1\}$
- Operator is multiplication mod n. Python: `(a * b) % n`
- Inverse of a exists when $\gcd(a, n) = 1$
- For prime n, compute inverse by Fermat's little theorem:

  $a^{n-1} = a \cdot a^{n-2} \equiv 1 \pmod{n}$

  so $a^{n-2} \pmod{n}$ is the multiplicative inverse of a

```
p = 2**255 - 19; a = 42 # p is prime
a_inv = pow(a, p - 2, p)
print((a * a_inv) % p) # 1
```

Fields

A set E and two operations $+$, $\cdot$ such that:

- $(E, +)$ is an abelian group with identity 0
- $(E \setminus \{0\}, \cdot)$ is an abelian group with identity 1
- Distributive: $a \cdot (b + c) = ab + ac$

For convenience we will write:

- $a - b = a + (-b)$ where $-b$ is the additive inverse
- $\frac{a}{b} = a \cdot b^{-1}$ where b^{-1} is the multiplicative inverse

Arithmetic works like what you learnt in secondary school.

Finite field (Galois field) uses a finite set:

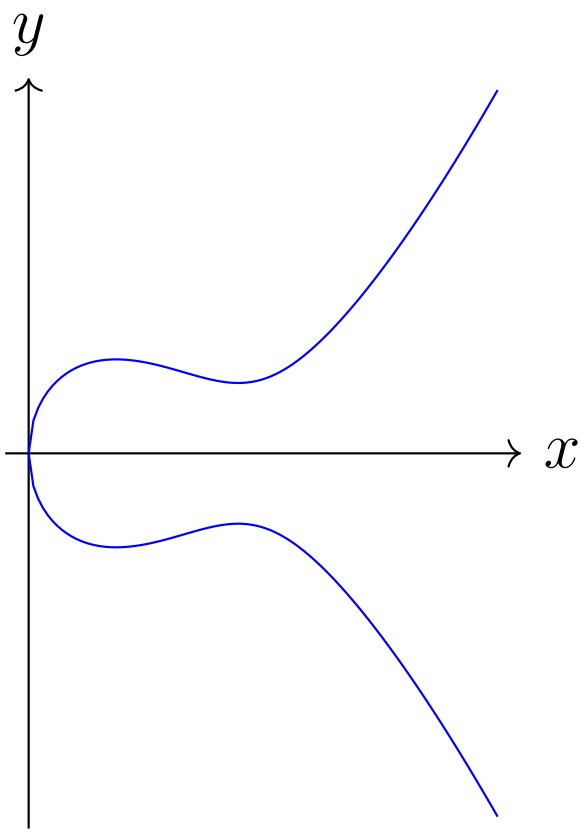
- We'll use $\mathbb{F}_p$: integers modulo p where **order** p is prime
- Also written $GF(p)$
- Fields $\mathbb{F}_n$ also exist when $n = p^k$, p prime, $k > 1$

Implementing finite fields

For elliptic curves we will use the field $\mathbb{F}_p$ for a large prime p

- In particular, $p = 2^{255} - 19 =$ `0x7fffffffffffffffffffffffffffffff` `ffffffffffffffffffffffffffffffed` (255 bits long)
- Python integers have no fixed size: 255-bit (or bigger) ints are no problem
  - Addition `(a + b) % p` is fine
  - Subtraction `(a - b) % p` is fine
  - Multiplication `(a * b) % p` is fine
- Most CPUs natively have max. 64-bit arithmetic $\Longrightarrow$ need to break down big ints into several smaller ones
- ⚠ Python int arithmetic and most bignum libraries are **not constant-time** (not suitable for production code)
- ⚠ Python division operators `a / b` and `a // b` **do not work** for finite fields – need to use multiplicative inverse

Montgomery curves (a family of elliptic curves)



For now we will use **Curve25519**, the elliptic curve

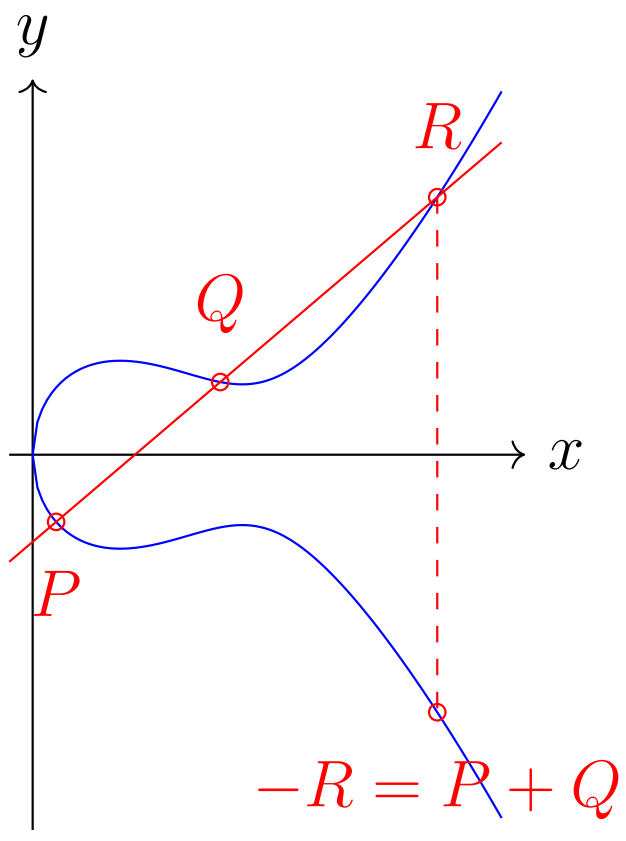
$$y^2 = x^3 + ax^2 + x$$

over the field $\mathbb{F}_p$ where $p = 2^{255} - 19$ and $a = 486662$ (params chosen to make the curve cryptographically useful).

A point (x, y) is *on the curve* if it satisfies the curve equation.

Plot shows what it would look like over $\mathbb{R}$ with $a = -1.9$.

Constructing a group from a curve



We will now define a **group** whose elements E are **points on the curve** (plus one special element ∞ called "point at infinity").

$$E = \{(x, y) \mid y^2 = x^3 + ax^2 + x\} \cup \{\infty\}$$

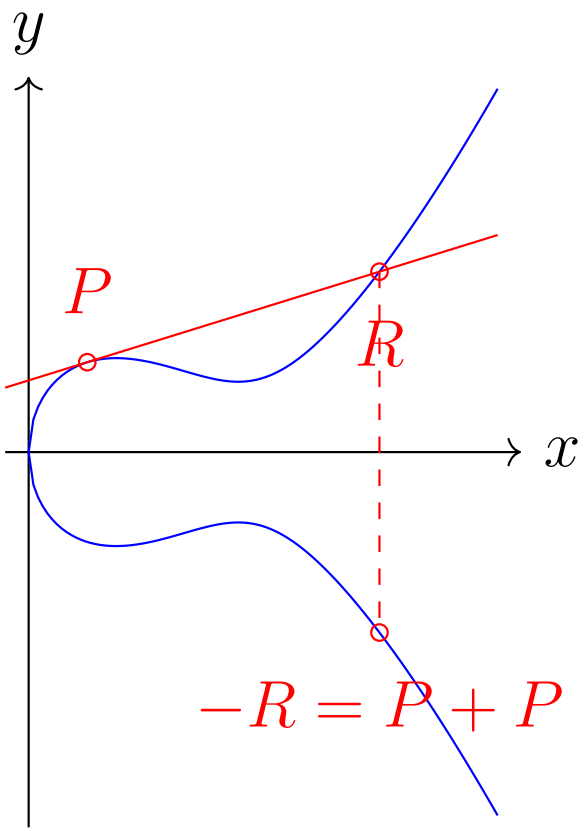
Define identity element as ∞

Define inverse as: $-(x, y) = (x, -y)$

The $+$ operator combines two points $P, Q \in E$ to produce a new point:

- Draw straight line through P and Q
- It intersects the curve at R
- Mirror R by x axis to get $P + Q$

Adding a point to itself (doubling)

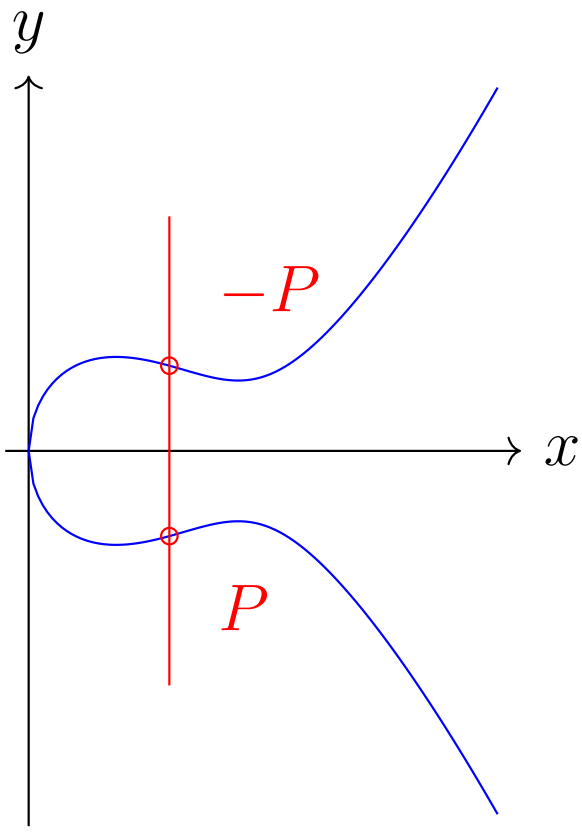


The definition on the last slide works when $P \neq Q$ and $P \neq -Q$.

To add $P \in E$ to itself ($P + P = 2P$):

- Draw a tangent to the curve at P
- It intersects the curve at R
- Mirror R by x axis to get $P + P$

Handling vertical lines



The final case we need to handle is $P + Q$ where $Q = -P$ (i.e. P and Q have the same x coordinate, but different y coordinates).

In this case the line through P and Q is vertical, and there is no (finite) third intersection point.

Define $P + Q = \infty$ if $P = -Q$.

Fits with definition of $-P$ as inverse of P, and ∞ as identity element.

(By definition, $\forall P \in E.\ P + \infty = P$)

Constructing a group from a curve

Amazingly, that definition results in an abelian group $(E, +)$

(Closed, identity exists, and inverse exists by definition; easy to see that it's commutative. Proving associativity is harder.)

Group law for Montgomery curves ($y^2 = x^3 + ax^2 + x$):

Point addition: $P + Q = (x_1, y_1) + (x_2, y_2) = (x_3, y_3)$ where

$$x_3 = \left(\frac{y_2 - y_1}{x_2 - x_1}\right)^2 - a - x_1 - x_2$$

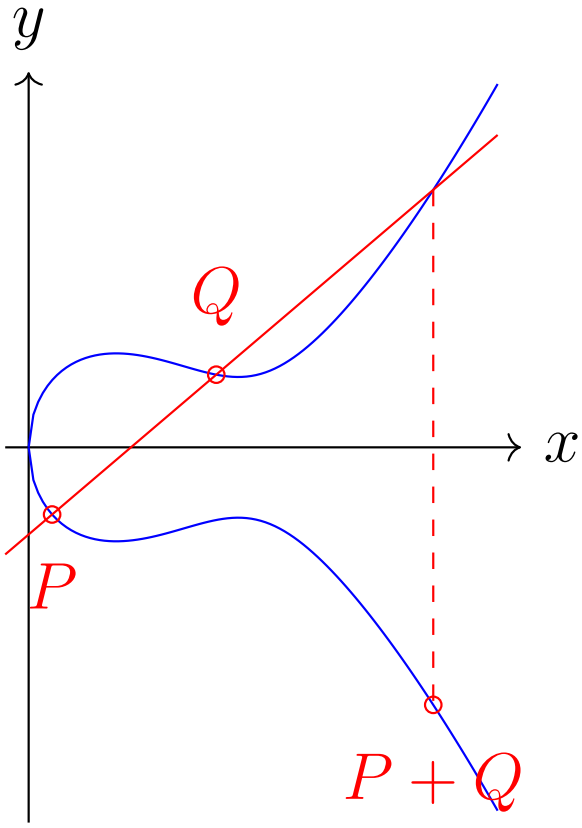
$$y_3 = \frac{(2x_1 + x_2 + a)(y_2 - y_1)}{x_2 - x_1} - \left(\frac{y_2 - y_1}{x_2 - x_1}\right)^3 - y_1$$

Point doubling: $2P = (x_1, y_1) + (x_1, y_1) = (x_3, y_3)$ where

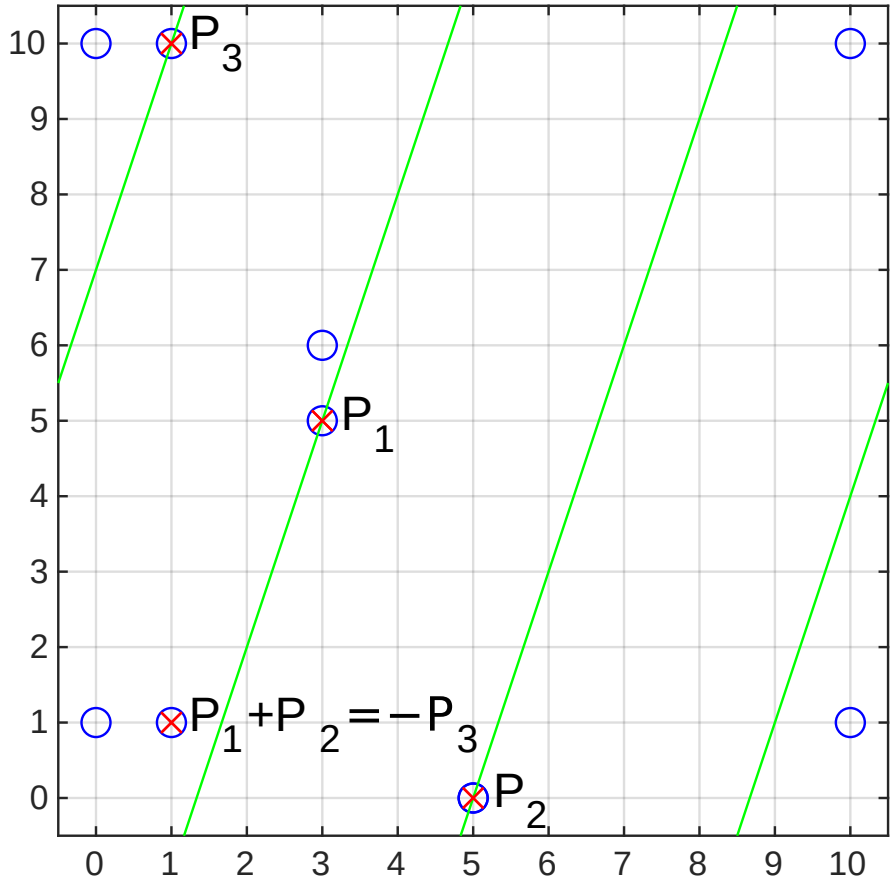
$$x_3 = \left(\frac{3x_1^2 + 2ax_1 + 1}{2y_1}\right)^2 - a - 2x_1$$

$$y_3 = \frac{(3x_1 + a)(3x_1^2 + 2ax_1 + 1)}{2y_1} - \left(\frac{3x_1^2 + 2ax_1 + 1}{2y_1}\right)^3 - y_1$$

Elliptic curve over a finite field



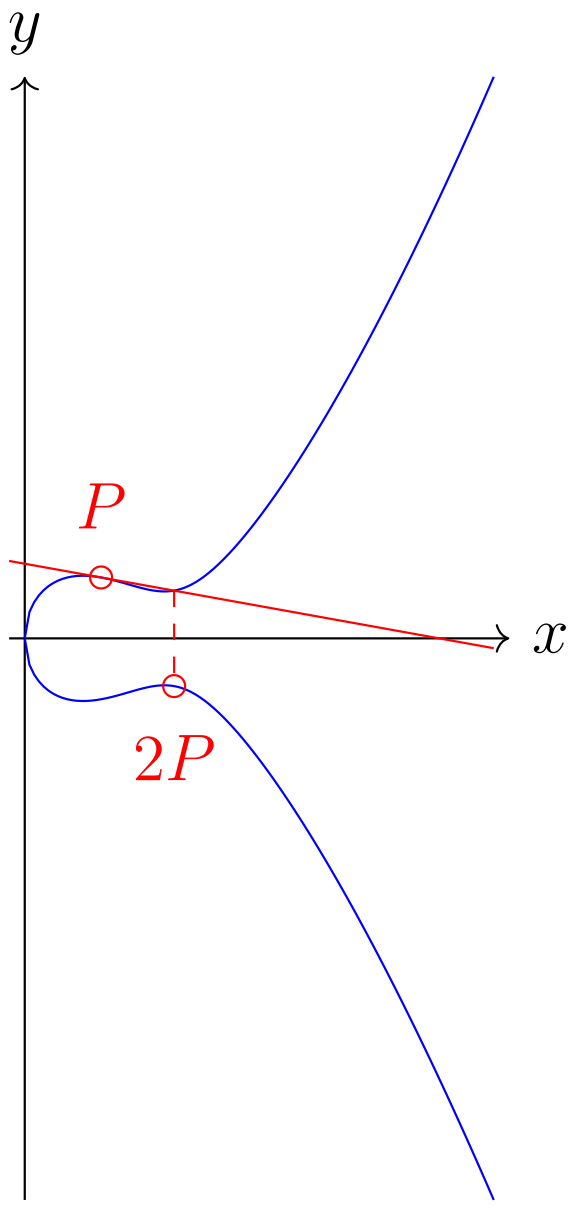
Curve over $\mathbb{R}$



Curve over $\mathbb{F}_{11}$

Image by Markus Kuhn

Repeated addition of a point to itself



Define **scalar multiplication** of a point $P \in E$ as:

$$kP = \underbrace{P + P + \cdots + P}_{k \text{ times}}$$

If you look at the sequence of points P, $2P$, $3P$, ..., it "jumps around" all over the curve.

For a suitably chosen P, this sequence repeats only for very large k.

Given P and kP, it's **hard** to determine k (try all possible values!)

Multiplying a point by a number

Because the group operator $+$ is associative we have:

$$j(kP) = \underbrace{(\underbrace{P + \cdots + P}_{k \text{ times}}) + \cdots + (\underbrace{P + \cdots + P}_{k \text{ times}})}_{j \text{ times}}$$
$$= \underbrace{P + \cdots + P}_{j \cdot k \text{ times}} = (jk)P$$

Double-and-add algorithm to compute the scalar product:

$$kP = \begin{cases} P & \text{if } k = 1 \\ 2(\frac{k}{2}P) & \text{if } k \text{ is even} \\ 2(\frac{k-1}{2}P) + P & \text{if } k \text{ is odd and } k > 1 \end{cases}$$

Computes kP with $O(\log k)$ point additions/doublings

Generator of a group

$|E|$ (the number of elements in the group) is its **order**.

Curve parameters determine $|E|$; prime if possible.

In Curve25519 ($p = 2^{255} - 19$, $a = 486662$), we have $|E| = 8q$ where q is a large (252-bit) prime.

Given $P \in E$, consider the series P, $2P$, $3P$, ...

If it repeats after m steps, we say $|P| = m$ is the **order** of P.

$\langle P \rangle = \{iP \mid i \in \mathbb{N}\}$ is the set **generated** by P. $|\langle P \rangle| = |P|$

If $\langle P \rangle = E$, then P is a **generator** of E with $|E| = |\langle P \rangle|$.

If $\langle P \rangle \subset E$, then $\langle P \rangle$ is a **subgroup** of E.

We choose a **base point** P for which $|P|$ is a large prime (q).

Additive vs. multiplicative group notation

Crypto literature has two ways of writing the same thing:

	additive (used in ECC papers)	**multiplicative** (used in protocols)
generator	base point B	generator g
group operator	$P + Q$	$a \cdot b$ or ab
scalar multiplication	kB	g^k (exponentiation)
inverse	$-P$	a^{-1}

The problem

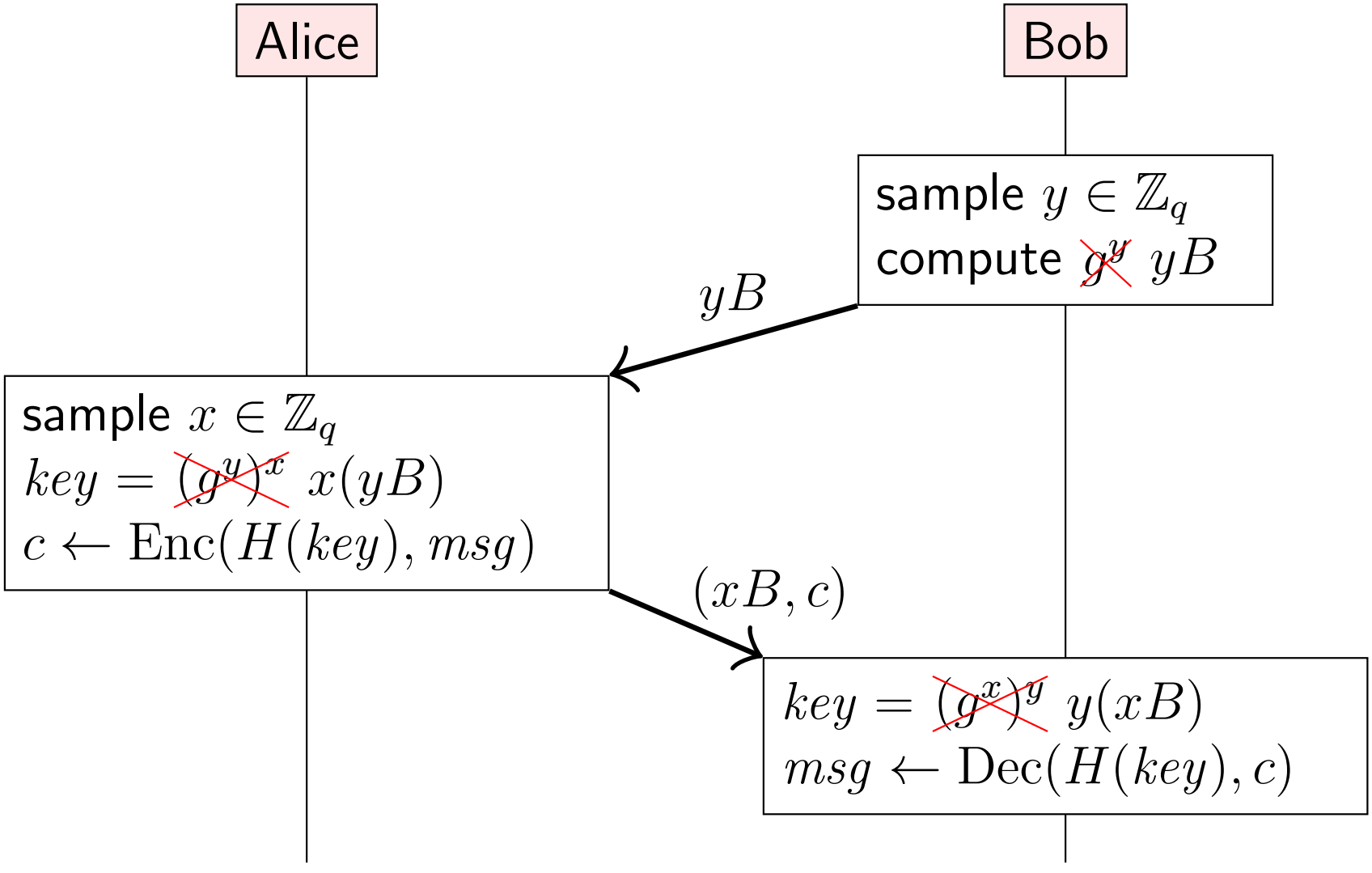
- compute k given kB and B
- compute k given g^k and g

is called **discrete logarithm**, even in additive notation

Discrete log on (selected) EC groups **believed to be hard**

Elliptic Curve Diffie-Hellman (ECDH)

Public parameter: base point $B \in E$ with order q



X25519: Diffie-Hellman using Curve25519

One of the supported EC groups in TLS 1.3.

- $\mathrm{X25519}(sk_A, base) = pk_A$
- $\mathrm{X25519}(sk_A, pk_B) = \mathrm{X25519}(sk_B, pk_A)$
- Private keys are 32 bytes, public keys also 32 bytes
- Designed to have simple constant-time implementation
- Fast: only computes x coordinate, not y coordinate
- Allows use of *Montgomery ladder* instead of group law
- No need to validate whether byte string is a valid curve point (which other protocols require)
- Secure even though underlying curve is not prime-order

X25519 algorithm

- **Private key**: start with 32 random bytes
  - interpret bytes as little-endian integer, then do clamping:
  - set 3 least-significant bits to 0 (make it a multiple of 8)
  - set most significant bit to 0 (make it $< 2^{255}$)
  - set second-most significant bit to 1 (make it $\geq 2^{254}$)
- **Public key**: 32 bytes received from the network
  - interpret bytes as little-endian integer
  - set most significant bit to 0, then reduce mod p
  - result is the coordinate $x \in \mathbb{F}_p$ of a curve point
- **Base point**: $x = 9$, $y = \sqrt{x^3 + 486662x^2 + x}$
- **X25519 function**:
  - Input private and public key (or private key and base)
  - Compute scalar product of private key (scalar) and the public key (group element)
  - Output x coordinate of the resulting group element
- Hash the result before using it as symmetric key

Assignment 1

Implement X25519 from scratch, relying only on bignums for field arithmetic.

Do it two ways and check they agree:

- Using the Montgomery curve group law and a double-and-add algorithm for scalar multiplication
- Using the Montgomery ladder. See Bernstein's paper; RFC 7748 (Python code); Martin's ECC tutorial (C code)

You can find test vectors in RFC 7748.
See lecture notes for hints on interpreting RFC 7748.

Due date for code and lab report: 3 Feb 2026.

Hope you have fun!

Software Engineering for Cryptography

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Part III/MPhil in Advanced Computer Science

Why Do We Have Standards?

- Standards are important for interoperability
  - Different implementations need to work together
  - Writing it in text requires that everything is specified
- Standards are important for security
  - Well-reviewed specifications
  - Clear security requirements and properties

Major Standardization Bodies

IETF typically protocols

- TLS 1.3 (RFC 8446)
- COSE (RFC 8152)

NIST typically algorithms

- AES (FIPS 197)
- SHA-3 (FIPS 202)

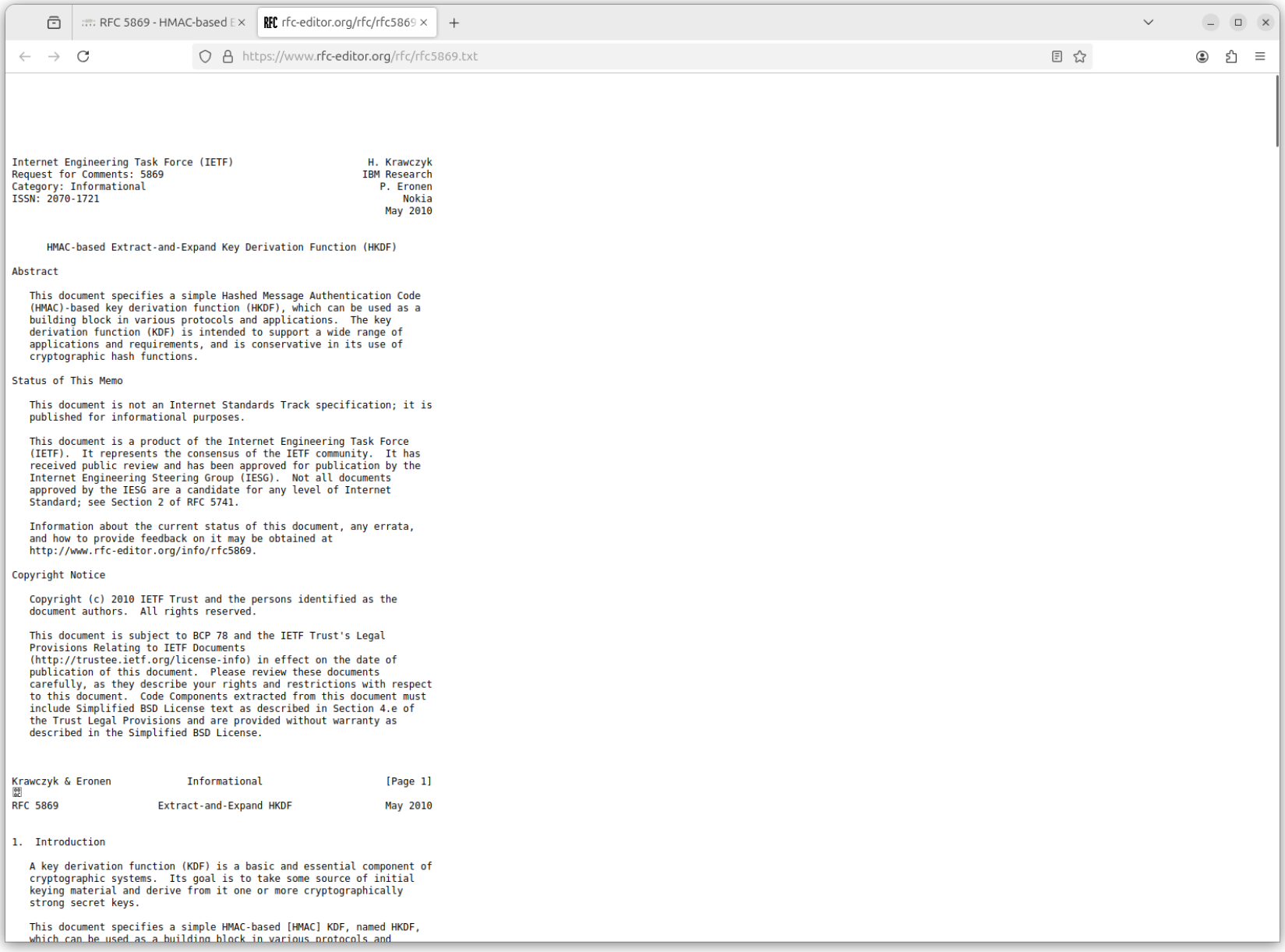
IEEE typically hardware/protocols

- IEEE 802.11i (WPA2/WPA3)

Reading RFCs

- Example: RFC 5869 - HMAC-based Extract-and-Expand Key Derivation Function (HKDF)
- Let's walk through how to read and understand an RFC
- They are available at https://datatracker.ietf.org/doc/html/rfc5869

RFC Formats - Text



Internet Engineering Task Force (IETF) H. Krawczyk
Request for Comments: 5869 IBM Research
Category: Informational P. Eronen
ISSN: 2070-1721 Nokia
May 2010

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Information about the current status of this document, any errata, and how to provide feedback on it may be obtained at http://www.rfc-editor.org/info/rfc5869.

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Krawczyk & Eronen Informational [Page 1]
RFC 5869 Extract-and-Expand HKDF May 2010

1. Introduction

A key derivation function (KDF) is a basic and essential component of cryptographic systems. Its goal is to take some source of initial keying material and derive from it one or more cryptographically strong secret keys.

This document specifies a simple HMAC-based [HMAC] KDF, named HKDF, which can be used as a building block in various protocols and

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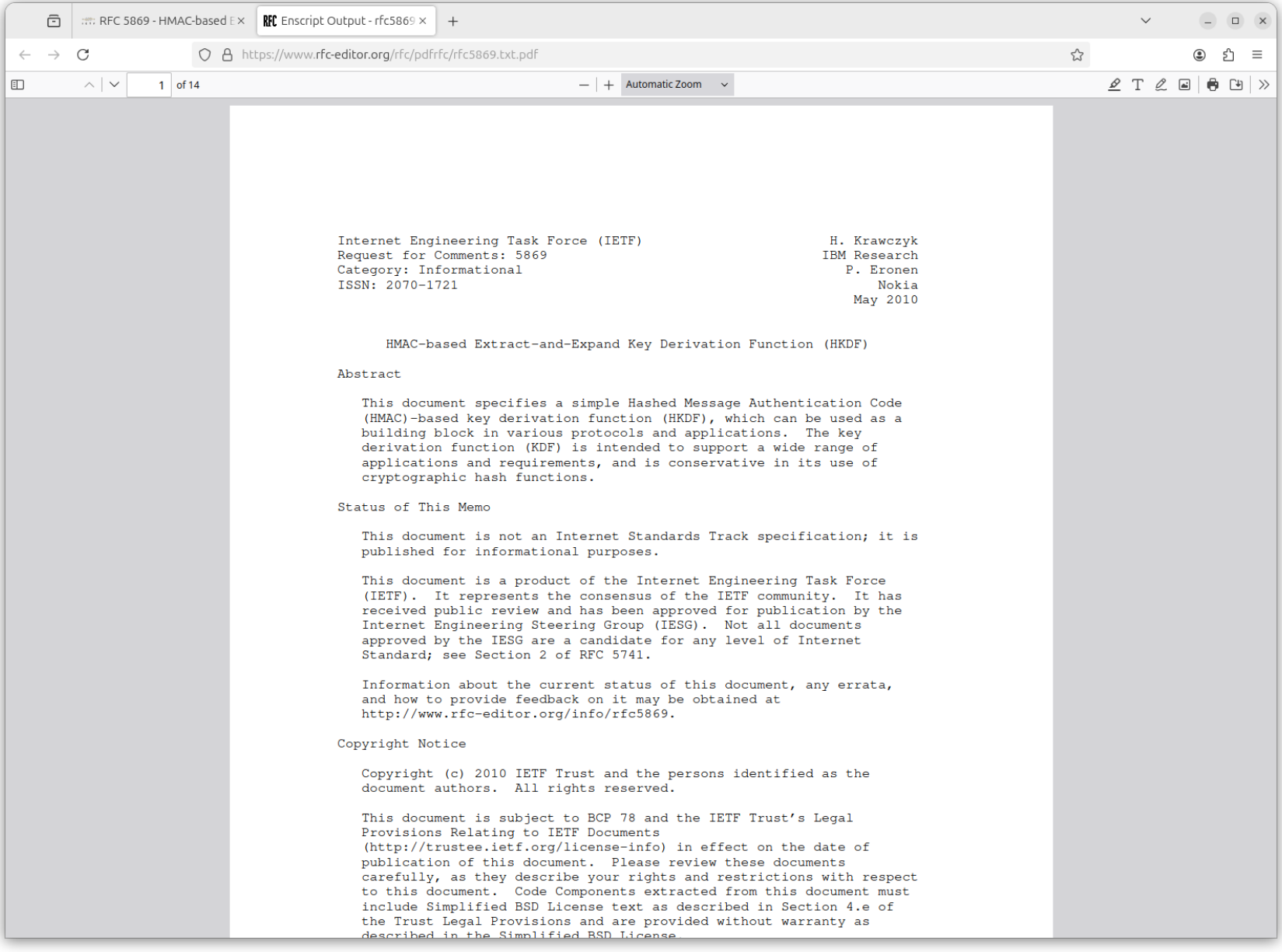

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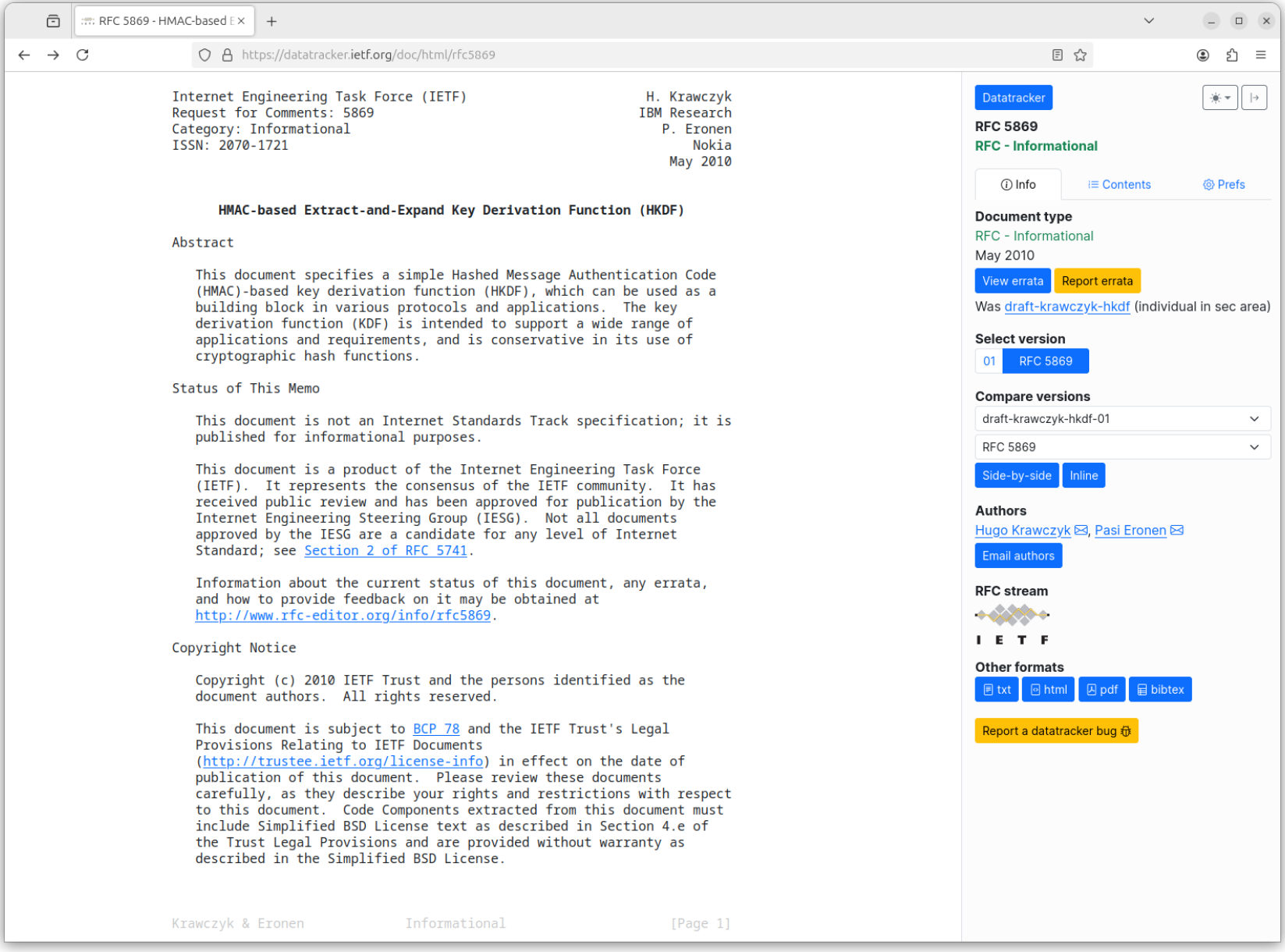

RFC Header (RFC 5869)

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RFC Categories

- Standards Track
  - Proposed Standard: Initial standardization
  - Internet Standard: Proven, stable standard
- Informational: Background information, guidelines
- Experimental: Experimental protocols

Introduction (RFC 5869)

1. Introduction

A key derivation function (KDF) is a basic and essential component of cryptographic systems. Its goal is to take some source of initial keying material and derive from it one or more cryptographically strong secret keys.

This document specifies a simple HMAC-based [HMAC] KDF, named HKDF, which can be used as a building block in various protocols and applications, and is already used in several IETF protocols, including [IKEv2], [PANA], and [EAP-AKA]. The purpose is to document this KDF in a general way to facilitate adoption in future protocols and applications, and to discourage the proliferation of multiple KDF mechanisms. It is not intended as a call to change existing protocols and does not change or update existing specifications using this KDF.

Notation (RFC 5869)

2.1. Notation

HMAC-Hash denotes the HMAC function [HMAC] instantiated with hash function 'Hash'. HMAC always has two arguments: the first is a key and the second an input (or message). (Note that in the extract step, 'IKM' is used as the HMAC input, not as the HMAC key.)

When the message is composed of several elements we use concatenation (denoted |) in the second argument; for example, HMAC(K, elem1 | elem2 | elem3).

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [KEYWORDS].

Notation

Key words (defined in RFC 2119):

- **MUST=SHALL** (= is required to)
- **SHOULD** (= strongly recommended)
- **MAY** (= optional)
- **SHOULD NOT** (= not recommended)
- **MUST NOT=SHALL NOT** (= prohibited)

> *"MUST This word, or the terms REQUIRED or SHALL, mean that the definition is an absolute requirement of the specification."*

Notation

Key words (defined in RFC 2119):

- **MUST=SHALL** (= is required to)
- **SHOULD** (= strongly recommended)
- **MAY** (= optional)
- **SHOULD NOT** (= not recommended)
- **MUST NOT=SHALL NOT** (= prohibited)

> *"SHOULD This word, or the adjective RECOMMENDED, mean that there may exist valid reasons in particular circumstances to ignore a particular item, but the full implications must be understood and carefully weighed before choosing a different course."*

Algorithm (RFC 5869)

```
Inputs:
   PRK       a pseudorandom key of at least HashLen octets
             (usually, the output from the extract step)
   info      optional context and application specific information
             (can be a zero-length string)
   L         length of output keying material in octets
             (<= 255*HashLen)

Output:
   OKM       output keying material (of L octets)

The output OKM is calculated as follows:

N = ceil(L/HashLen)
T = T(1) | T(2) | T(3) | ... | T(N)
OKM = first L octets of T

where:
T(0) = empty string (zero length)
T(1) = HMAC-Hash(PRK, T(0) | info | 0x01)
T(2) = HMAC-Hash(PRK, T(1) | info | 0x02)
T(3) = HMAC-Hash(PRK, T(2) | info | 0x03)
...

(where the constant concatenated to the end of each T(n) is a
single octet.)
```

Algorithm Section (RFC 5869)

- Contains detailed technical specification
- Describes the protocol/algorithm step by step
- Often includes:
  - Input/output parameters
  - Processing steps
  - Implementation requirements
  - Pay attention to the allowed parameter ranges
- Typically does *not* include error handling
- May contain pseudocode or formal specifications

Test Vectors

Appendix A. Test Vectors

This appendix provides test vectors for SHA-256 and SHA-1 hash functions [SHS].

A.1. Test Case 1

Basic test case with SHA-256

```
Hash = SHA-256
IKM  = 0x0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b (22 octets)
salt = 0x000102030405060708090a0b0c (13 octets)
info = 0xf0f1f2f3f4f5f6f7f8f9 (10 octets)
L    = 42

PRK  = 0x077709362c2e32df0ddc3f0dc47bba63
       90b6c73bb50f9c3122ec844ad7c2b3e5 (32 octets)
OKM  = 0x3cb25f25faacd57a90434f64d0362f2a
       2d2d0a90cf1a5a4c5db02d56ecc4c5bf
       34007208d5b887185865 (42 octets)
```

References

7. References

7.1. Normative References

[HMAC] Krawczyk, H., Bellare, M., and R. Canetti, "HMAC: Keyed-Hashing for Message Authentication", RFC 2104, February 1997.

[KEYWORDS] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, March 1997.

[SHS] National Institute of Standards and Technology, "Secure Hash Standard", FIPS PUB 180-3, October 2008.

7.2. Informative References

[1363a] Institute of Electrical and Electronics Engineers, "IEEE Standard Specifications for Public-Key Cryptography - Amendment 1: Additional Techniques", IEEE Std 1363a-2004, 2004.

[800-108] National Institute of Standards and Technology, "Recommendation for Key Derivation Using Pseudorandom Functions", NIST Special Publication 800-108, November 2008.

Errata

Status: Reported (1)

RFC 5869, "HMAC-based Extract-and-Expand Key Derivation Function (HKDF)", May 2010

Source of RFC: IETF - NON WORKING GROUP

Area Assignment: sec

Errata ID: 5161

Status: Reported

Type: Editorial

Publication Format(s) : TEXT

Reported By: Dale R. Worley

Date Reported: 2017-10-20

Section 2.3 says:

```
(where the constant concatenated to the end of each T(n) is a
single octet.)
```

It should say:

```
(where the constant concatenated to the end of each T(n) is a
single octet with value mod(n, 256).)
```

Notes:

It's clear what the values of the octets are supposed to be, but the text doesn't actually say what they are.

How NIST Competitions Work

- Open call for submissions from the cryptographic community
- Multiple rounds of evaluation:
  - Security analysis by cryptographers worldwide
  - Performance benchmarking across platforms
  - Implementation characteristics and complexity
  - Public feedback and discussion
- Candidates may be eliminated due to:
  - Security vulnerabilities discovered
  - Poor performance characteristics
  - Implementation difficulties
- Final selection based on balance of security, performance, and practicality

NIST Post-Quantum Cryptography Standardization

- Started in 2016 to standardize quantum-resistant cryptographic algorithms
- Goal: Protect against both classical and quantum computer attacks
- Focus on:
  - Key-establishment mechanisms
  - Digital signatures

Selection Process Timeline

- **Round 1 (2017)**: 69 candidates accepted
  - 14 published attacks
  - 9 submissions withdrawn
- **Round 2 (2019)**: 26 candidates selected
- **Round 3 (2020)**: 7 finalists + 8 alternates
- **Round 4 (2022-2023)**:
  - Selected CRYSTALS-Kyber for key encapsulation
  - Selected CRYSTALS-Dilithium, FALCON, and SPHINCS+ for digital signatures

Case Study: Dual_EC_DRBG

- NIST SP 800-90A standardized Dual_EC_DRBG in 2006
- Concerns raised about potential backdoor:
  - Outputs "too many" bits
  - Unclear choice of parameters P and Q
  - Observer might learn internal state of RNG
- Snowden leaks in 2013 suggested NSA involvement
- NIST withdrew the standard in 2014

Case Study: Choice of p in X25519

> *"I chose my prime* $2^{255} - 19$ *according to the following criteria: primes as close as possible to a power of 2 save time in field operations (as in, e.g, [9]), with no effect on (conjectured) security level; primes slightly below* $32k$ *bits, for some* k*, allow public keys to be easily transmitted in 32-bit words, with no serious concerns regarding wasted space;* $k = 8$ *provides a comfortable security level. I considered the primes* $2^{255} + 95$*,* $2^{255} - 19$*,* $2^{255} - 31$*,* $2^{254} + 79$*,* $2^{253} + 51$*, and* $2^{253} + 39$*, and selected* $2^{255} - 19$ *because 19 is smaller than 31, 39, 51, 79, 95"*

Bernstein 2006, p. 13

Case Study: Choice of A in X25519

> *"To protect against various attacks discussed in Section 3, I rejected choices of A whose curve and twist orders were not $\{4 \cdot \text{prime}, 8 \cdot \text{prime}\}$; here 4, 8 are minimal since $p \in 1 + 4\mathbb{Z}$. The smallest positive choices for A are 358990, 464586, and 486662. I rejected $A = 358990$ because one of its primes is slightly smaller than 2^{252}, raising the question of how standards and implementations should handle the theoretical possibility of a user's secret key matching the prime; discussing this question is more difficult than switching to another A. I rejected 464586 for the same reason. So I ended up with $A = 486662$."*

Bernstein 2006, p. 14f

Error handling

- Error handling is crucial for production software
- Still, development is often focussed on the happy path
- In cryptographic software, we need to handle errors carefully
  - Indicate benign failures (e.g. out-of-memory)
  - Indicate malicious interference (e.g. invalid signature)

Approaches to error handling

I introduce three main paradigms for error handling that you will encounter in different languages:

- Return values (C, C++, ...)
- Exceptions (Java, Python, ...)
- Result types (Rust, Go, ...)

These interact a lot with the language's type system as well. And we will discuss these aspects in more detail later.

C-style error handling

Declared as such:

```
int decrypt_aes_gcm(
    uint8_t* key,
    uint8_t* ciphertext, size_t ciphertext_len,
    uint8_t* plaintext, size_t plaintext_len
);
```

Used as such:

```
plaintext = malloc(...)
if (decrypt_aes_gcm(&key, &ciphertext, &plaintext)) {
    // do something here
}
```

C-style error handling

However, it's error prone:

```
plaintext = malloc(...)
decrypt_aes_gcm(&key, &ciphertext, &plaintext)
// do something here
```

C-style error handling

```
int random_key(uint8_t* key)

uint8_t* key;
random_key(&key)
// ....
uint8_t* ciphertext = malloc(...);
if(aes_gcm_encrypt(&key, &plaintext, &ciphertext)) {
    // send ciphertext over the internet
}
```

C-style error handling

```
int random_key(uint8_t* key)

uint8_t* key;
if (!random_key(&key)) {
    // handle error
    return
}
// ....
uint8_t* ciphertext = malloc(...);
if(aes_gcm_encrypt(&key, &plaintext, &ciphertext)) {
    // send ciphertext over the internet
}
```

C-style error handling: lessons learned

- Making error checking optional is dangerous
- Relying on humans to follow patterns is infeasible
- We need help from our tools!
  - Static analysis (e.g. `-Wunused-result`)
  - Linting (e.g. `clang-tidy`)
  - Or, maybe using better paradigms...

Before we look at modern paradigms, let's see how we can deal with this in C in our call sites.

C-style error handling: writing better call sites

```
int decryptProtocolMessage(...) {
    if (checkSignature(&otherPublicKey, &ciphertext)) {
        uint8_t key = malloc(16);
        if (dh(&privateKey, &otherPublicKey, &key)) {
            if (decrypt(&key, &ciphertext, &plaintext)) {
                free(key)
                return OK
            } else {
                free(key)
                return ERR_DECRYPTION_FAILED
            }
        } else {
            free(key)
            return ERR_DH_FAILED
        }
    } else {
        return ERR_SIGNATURE_CHECK_FAILED
    }
}
```

C-style error handling: writing better call sites

```
int decryptProtocolMessage(...) {
    if (!checkSignature(&otherPublicKey, &ciphertext)) {
        return ERR_SIGNATURE_CHECK_FAILED
    }

    byte[] key = malloc(16);
    if (!dh(&privateKey, &otherPublicKey, &key)) {
        free(key)
        return ERR_DH_FAILED
    }

    if (!decrypt(&key, &ciphertext, &plaintext)) {
        free(key)
        return ERR_DECRYPTION_FAILED
    }

    free(key)
    result = &plaintext
    return OK
}
```

C-style error handling: writing better call sites

```
int decryptProtocolMessage(...) {
    int err = -1
    byte* key = NULL
    byte* plaintext = NULL

    if ((err = checkSignature(&otherPublicKey, &ciphertext)) != 0)
        goto fail;

    key = malloc(16);
    if ((err = dh(&privateKey, &otherPublicKey, &key)) != 0)
        goto fail;

    if ((err = decrypt(&key, &ciphertext, &plaintext)) != 0)
        goto fail;

    fail:
        if (key) free(key)
    done:
        return err
}
```

Case study: goto fail (CVE-2014-1266)

```
static OSStatus
SSLVerifySignedServerKeyExchange(/* ...*/)
{
        OSStatus        err;
        /* ... */
        if ((err = SSLHashSHA1.update(&hashCtx, &serverRandom)) != 0)
                goto fail;
        if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
                goto fail;
                goto fail;
        if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
                goto fail;
        /* ... */
fail:
        SSLFreeBuffer(&signedHashes);
        SSLFreeBuffer(&hashCtx);
        return err;
}
```

Exception-based error handling

Declared as such:

```
byte[] decrypt(byte[] key, byte[] ciphertext)
throws DecryptionFailedException {
    // ...
}
```

Used as such:

```
int doSomething() {
    try {
        plaintext = AesGcm.decrypt(key, ciphertext)
        // do something
    } catch (DecryptionFailedException e) {
        // handle error
    }
}
```

Exception-based error handling

```
int doSomething() {
    try {
        plaintext = AesGcm.decrypt(key, ciphertext)
        doSomethingWithPlaintext(plaintext)
        andSomeOtherThings(plaintext)
    } catch (DecryptionFailedException e) {
        // handle error
    } catch (OtherException e) {
        // handle error
    } catch (AndAnotherException e) {
        // handle error
    }
}
```

Exception-based error handling

```
int doSomething() {
    try {
        plaintext = AesGcm.decrypt(key, ciphertext)
        doSomethingWithPlaintext(plaintext)
        andSomeOtherThings(plaintext)
    } catch (Exception e) {
        // super defensive!!11
    }
}
```

Exception-based error handling

```
int doSomething() throws Exception {
    plaintext = AesGcm.decrypt(key, ciphertext)
    doSomethingWithPlaintext(plaintext)
}


int main() throws Exception {
    try {
        doSomething();
    } catch (Exception e) {
        // handle error
        // - but what exactly should we do?
        // - benign or malicious error?
    }
}
```

Result types for error handling

Declared as such:

```
fn decrypt_aes_gcm(key: &[u8], ciphertext: &[u8])
    -> Result<Vec<u8>, DecryptionError>
```

Used as such:

```
fn do_something(&self) -> Result<(), Error> {
    let maybe_text = decrypt_aes_gcm(&key, &ciphertext);
    match maybe_text {
        Ok(text) => { /* do something */; Ok(()) },
        Err(err) => Err(Error::from(err, "aes gcm failed"))
    }
}
```

Result types for error handling (ergonomics)

Using `let-else` for error handling:

```
fn do_something(&self) -> Result<(), Error> {
    let Ok(text) = decrypt_aes_gcm(&key, &ciphertext) else {
        return Err(MyDecryptionError::DecryptionFailed);
    };
    /* do something with text */;
    Ok(())
}
```

Using anyhow for error handling:

```
fn do_something(&self) -> anyhow::Result<()> {
    let text = decrypt_aes_gcm(&key, &ciphertext)?;
    /* do something */;
    Ok(()) // No need for return keyword
}
```

Error messages

Consider the following code:

```
cipher = AesGcm.create(key)
plaintext = cipher.decrypt(ciphertext)
# do something with the plaintext
```

Let's assume the library is generally following a exception-based error handling approach. What behaviors would be good? Helpful? Unhelpful? Dangerous?

Error messages: be helpful

- `decryption failed`
  - No information about what went wrong
  - No guidance on how to fix it
- `decryption failed: bad key length`
  - Indicates the specific issue
  - Still lacks guidance on how to fix it
- `decryption failed: key must be 16 or 32 bytes, but was 128 bytes`
  - Clearly states what went wrong
  - Provides exact requirements
  - Shows the actual problematic value

Error messages: but not too helpful

```
decryption failed:  key must be 16 or 32 bytes,
got value "secretkey" which is 9 bytes long
```

- This leads us to our next topic: **leaky implementations**

Leaky implementations

Idealised formal world:

- Operations are solely defined by their mathematical properties
- Perfect black boxes
- Often assuming infinite resources

Real world:

- Implementations are not perfect
- Adversary can learn exact hardware/software steps
- Work against a finite set of resources

Side-channels

- Timing side-channels
- Error messages
- Memory access patterns
- Energy consumption
- Electromagnetic emissions
- ...

Every bit of information can be used by an adversary.
Especially if accessible in a repeated manner with adversary-controlled input.

Timing side-channels

- If the execution time of an algorithm depends on a secret value, measuring the time may leak that value, e.g. private key (**timing side-channel**)
- Memory access patterns can be revealed by timing (cache hits/misses)

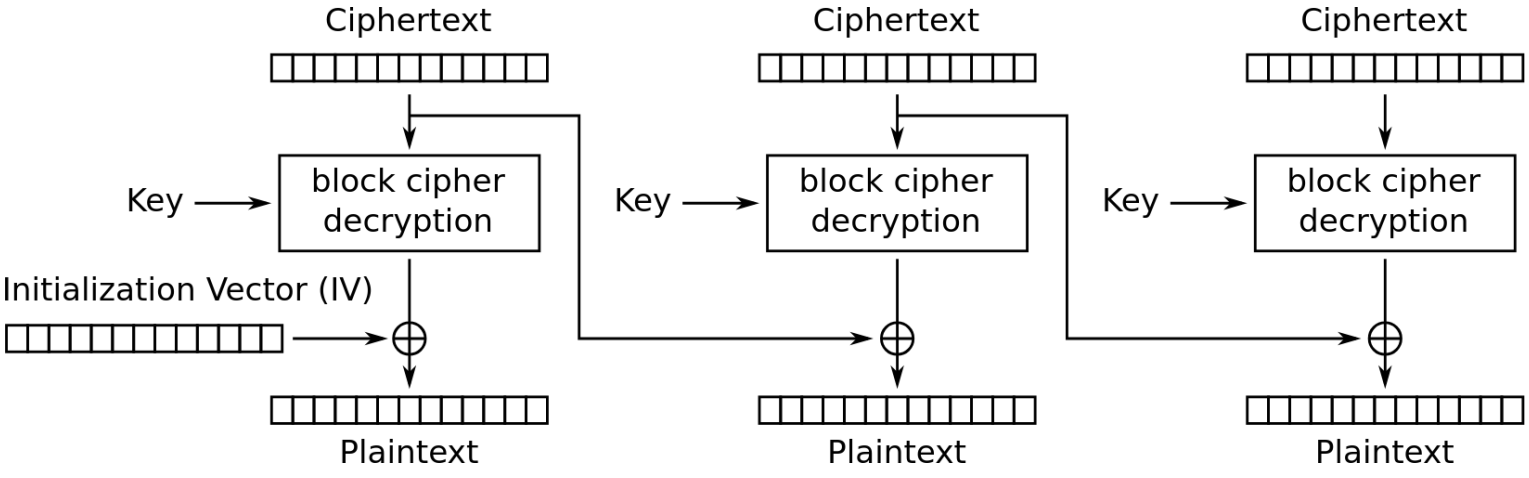
Implementations should be **constant-time** to avoid this:

- No branches (if/else, break, ...) conditional on a secret
- No memory access (array lookups) dependent on a secret
- Individual CPU instructions (e.g. multiplying two 32-bit numbers) typically assumed to be constant-time

Code you write in this module **need not** be constant-time. However, your lab report should discuss how you could make it constant-time.

Padding oracle attack

- Assume AES-CBC with PKCS#7 padding
  - Padding pattern: `??  ??  ??  ??  04 04 04 04`
  - Decryption: $P_i = D_K(C_i) \oplus C_{i-1}$ and $C_0 = IV$



- Server returns either *nothing* or `PADDING_ERR`

Figure: Wikipedia, public domain.

Padding oracle attacks in the real-world

- Initial attack in 1998 by Bleichenbacher against RSA $\rightarrow$ fixed
- More efficient attack against CBC-mode AES in 2002 by Vaudenay $\rightarrow$ fixed
- Lucky Thirteen attack against TLS in 2013 (AlFardan and Paterson) by using the same technique but with a timing side-channel $\rightarrow$ fixed
- This introduced another timing side-channel CVE-2016-2107 $\rightarrow$ fixed
- to be continued...

Not leaking information in Internet-connected services really is a **hard problem**!

What is a secret key actually?

Let's return to our X25519 secret key: $x \in \mathbb{F}_p$. But what exactly *is* x in the real world?

- A number in the set $\mathbb{F}_p$?
- The binary representation of that number?
- A Python object?
- The serialized bytes?
- Also the logic to interpret the bytes?
- ...

Example: X25519 key

```
x: int
```

- Simple
- Confusion possible with different keys
- Unclear how to turn into/from bytes
  - This process is often called serializing or marshalling

Example: X25519 key

```
x: bytes
```

- Relatively simple
- Still able to confuse with different keys
- Might be too short/long

Slightly better in languages, e.g. Rust, with fixed-sized arrays:

```
x: [u8; 32]
```

Example: X25519 key

```
@dataclass
class X25519SecretKey:
    x: int
```

- Strong type avoids mixing up different keys
- Can have extra functionality, e.g. comparison
- Can have extra checks, e.g. avoid uninitialized value

Going past one type

This sounds great at first. However, it becomes tricky when integrating multiple components, e.g. asymmetric key agreement and symmetric encryption.

```
def enc(
    x: X25519SecretKey, gy: X25519PublicKey,
    message: bytes,
) -> bytes:
    shared = x.dh(gy)  # probably just bytes
    aes_key = CipherLib.AESKey(shared)
    # encrypt message and return
```

Going past one type

We might want to use more types to describe these boundaries. For example:

- `DerivedSecret`: result from a DH operation
- `SecureRandom`: anything that gives us high-entropy random numbers

```
KeyMaterial = DerivedSecret | SecureRandom
class AesKey:
    def __init__(self, key: KeyMaterial):
        self.key = key
```

Going past one type

This comes with challenges:

- Cross-library interfaces require widely accepted types/patterns.
- Imperfect representations of all cryptographic properties.
- At some point, types become too bothersome
  - Developers go back to raw `byte[]` arrays

It's not an exact science.
Don't be too clever.
Empathy and pragmatism win.

More complex types

Consider an encrypted AEAD message. It typically contains:

- A nonce or IV
- Associated data
- Encrypted data
- A tag

Strong types help here, as they ensure elements are not accidentally mixed up. But does the callee actually need to know about this? High-level API $\leftrightarrow$ low-level API

Static Type Checking with ty

- `ty` is a static type checker for Python
- Helps catch type errors before runtime
- Popular alternatives:
  - mypy
  - Pyright (from Microsoft)
  - Pyre (from Meta/Facebook)
  - Pytype (from Google)
- Easy to install and configure:

```
# Install ty:
uv add --dev ty

# Run ty:
uv run ty check your_file.py
uv run ty check .
```

Basic Type Annotations

- Start with built-in types
- Use generic types from the typing module
- Type checking works with nested types

```python
from typing import List

def sum_numbers(numbers: List[int]) -> int:
    total: int = 0
    for num in numbers:
        total += num
    return total

# OK
result = sum_numbers([1, 2, 3])

# type error: List[str] not assignable to List[int]
bad_result = sum_numbers(["1", "2", "3"])
```

Runtime Type Checking

- Type hints are not automatically checked at runtime
- Use assertions for runtime checks

```
from typing import List
import typing

def sum_numbers(numbers: List[int]) -> int:
    assert isinstance(numbers, list),\
        "numbers must be a list"
    assert all(isinstance(x, int) for x in numbers),\
        "all elements must be integers"

    total: int = 0
    for num in numbers:
        total += num
    return total
```

Advanced Type Features

- TypeAlias: Create aliases for complex types
- Union: Allow multiple types
- Modern Python also supports | syntax for unions

```python
from typing import TypeAlias, Union, List

Matrix: TypeAlias = List[List[float]]
Number: TypeAlias = Union[int, float]

def add_constant(matrix: Matrix, c: Number) -> Matrix:
    return [[x + c for x in row] for row in matrix]

# Both valid
result1 = add_constant([[1.0, 2.0]], 1)    # [[2.0, 3.0]]
result2 = add_constant([[1.0, 2.0]], 0.5)  # [[1.5, 2.5]]
```

Self-referential Types

- `Self` type for methods returning instances
- Useful for creation methods and operations

```
from typing import Self

class Matrix:
    def add(self, other: Self) -> Self:
        return Matrix([
            [self.data[i][j] + other.data[i][j]
            for j in range(self.cols)]
            for i in range(self.rows)
        ])

    @classmethod
    def zeros(cls, rows: int, cols: int) -> Self:
        return cls([[0.0] * cols for _ in range(rows)])

m1 = Matrix.zeros(2, 2)
m2 = m1.add(m1)
```

Pattern: type state (1, motivating example)

```
struct AkeClient {
    x: Secret,
    k: Option<DerivedKey>,
    has_verified_server: bool,
}

impl AkeClient {
    fn handle_server_response(
        &mut self,
        response: ServerHelloResponse,
    ) -> Result<()> {
        if self.has_verified_server {
            bail!("already verified server");
        }
        // verify server response ...
        self.has_verified_server = true;
        self.k = Some(derive_key(&self.x, response));
        Ok(())
    }
}
```

Pattern: type state (2)

```
struct AkeClientInitialized {x: Secret}
struct AkeClientWaiting {x: Secret}
struct AkeClientVerified {k: DerivedKey}

impl AkeClientWaiting {
    fn handle_server_response(
        self, response: ServerHelloResponse
    ) -> Result<AkeClientVerified> {
        // verify server response ...
        // derive key ...
        let k = derive_key(&self.x, response);
        Ok(AkeClientVerified {k})
    }
}
```

Pattern: type state (3)

```
struct AkeClient<S> { state: S }

trait AkeClientState {}
impl AkeClientState for AkeClientInitialized {}
impl AkeClientState for AkeClientWaiting {}
impl AkeClientState for AkeClientVerified {}

impl AkeClient<AkeClientWaiting> {
    fn handle_server_response(
        self, response: ServerHelloResponse
    ) -> Result<AkeClient<AkeClientVerified>> {
        // verify server response ...
        // derive key ...
        let k = derive_key(&self.state.x, response);
        Ok(AkeClient {state: AkeClientVerified {k}})
    }
}
```

Pattern: type state (4)

```
struct SharedState {debug_log: Vec<ProtocolLogEntry>}
struct AkeClient<S> {
    state: S,
    shared: Box<SharedState>,
}

impl<S> AkeClient<S> where S: AkeClientState {
    fn log(&mut self, entry: ProtocolLogEntry) {
        self.shared.debug_log.push(entry);
    }
}
```

Pattern: type state (5)

Benefits:

- Move important logic to compile time (or type checker)
- Improves IDE ergonomics
- Easier reasoning about state

For cryptography in particular:

- Clear management of secret life times
- Protections against accidental secret reuse

More examples for constraints that can be modelled:

- We can only access API methods after authentication
- Once a connection has been terminated, we cannot call any send/receive methods
- After A, both B and C have been called (in any order), before D can be called

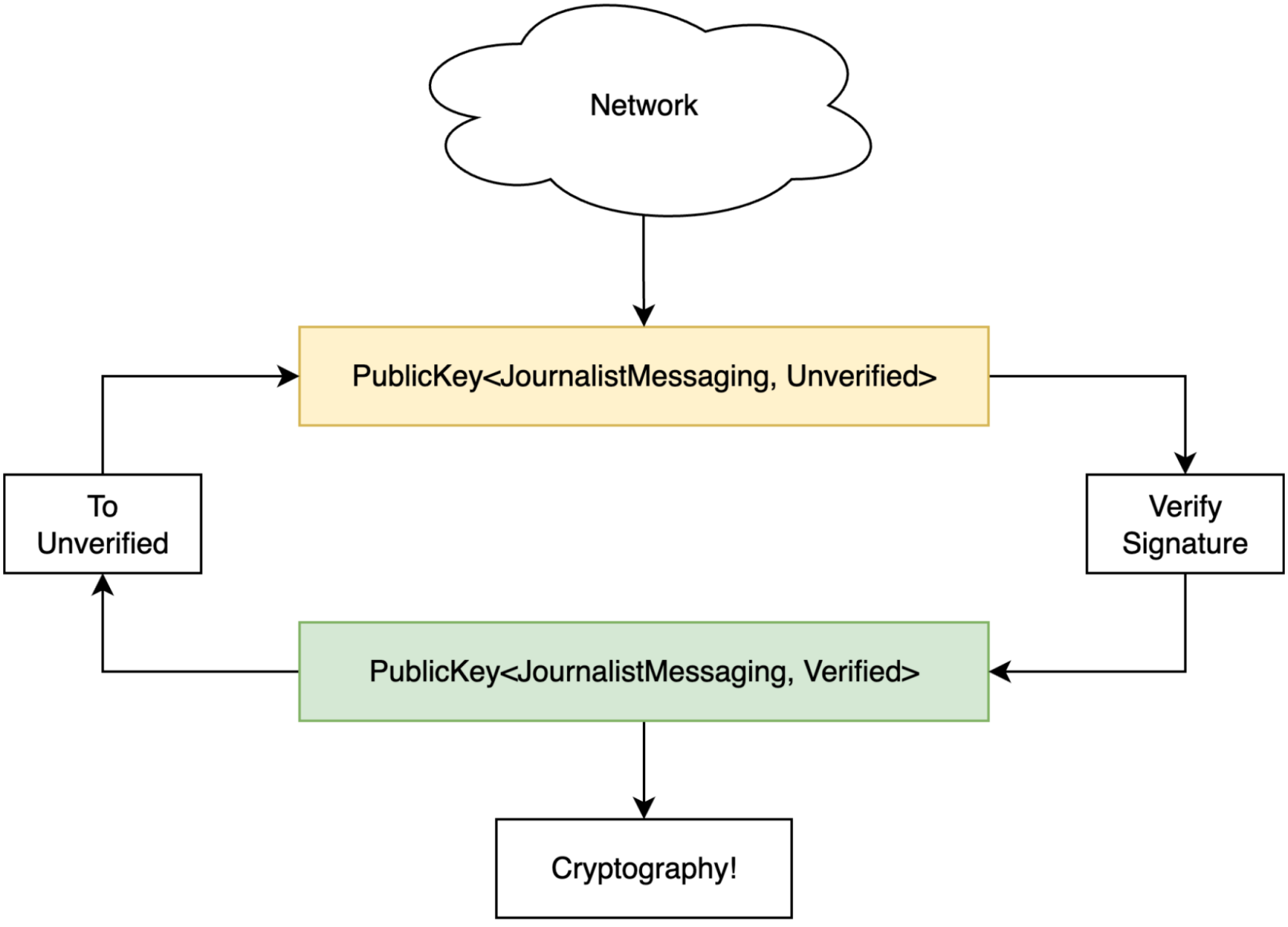
Pattern: type promotions

```
struct UnverifiedKey { bytes: [u8; 16]}
struct VerifiedKey { bytes: [u8; 16]}

fn load_root_of_trust(
    path_buf: &PathBuf,
    trusted_digests: &[u8]
) -> RootOfTrust {
    // check: date constraints && matches trusted digests
    return ...
}

fn verify_key(
     key: UnverifiedKey,
     certificate: &Certificate,
     root_of_trust: &RootOfTrust
) -> Result<VerifiedKey> {
    // check: date constraints && chained signature
    return ...
}
```

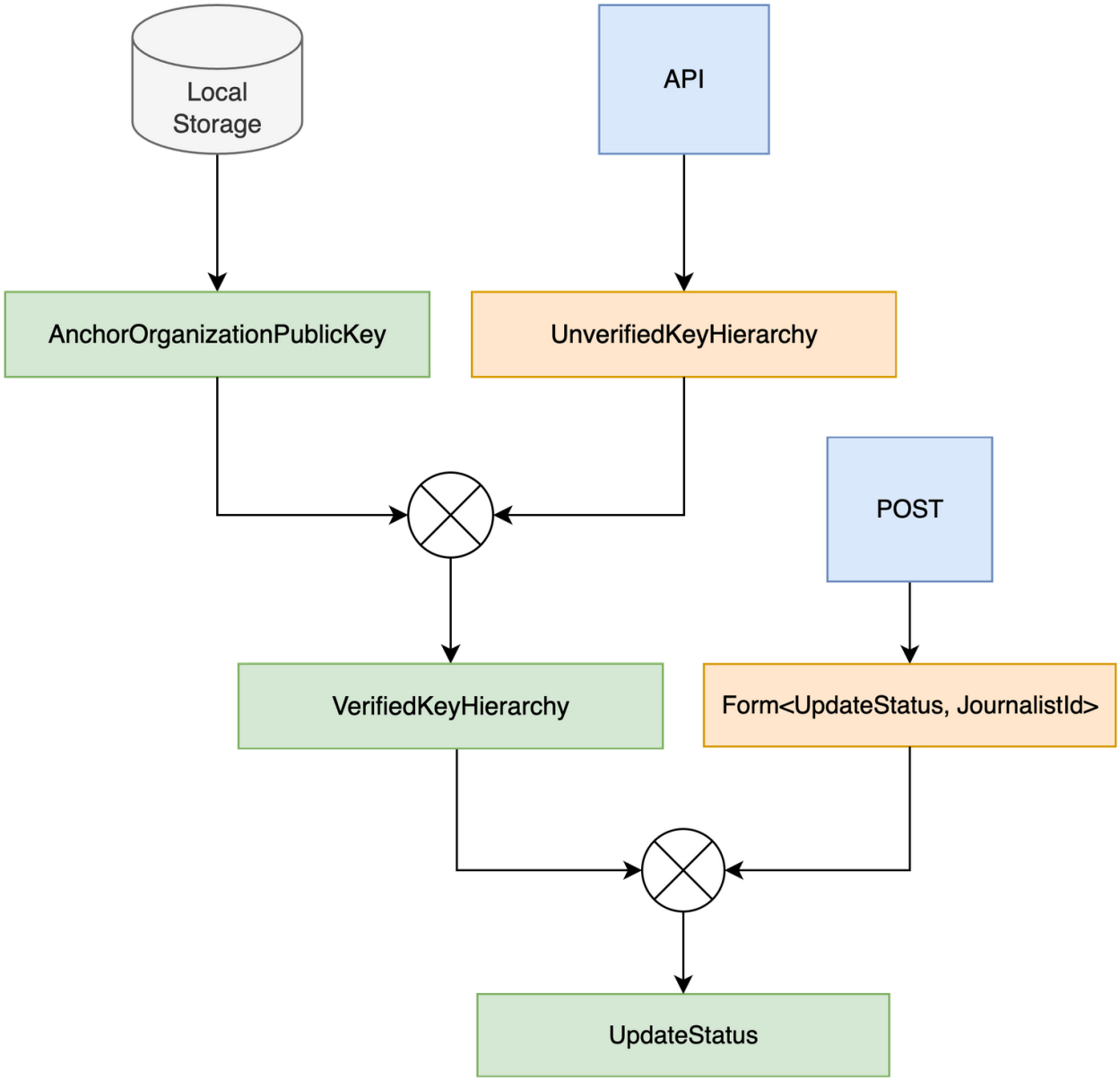
Pattern: scoped secrets

```
struct ScopedUnverifiedKey<Role>
    { bytes: [u8; 16], _role: PhantomData<Role> }
struct ScopedVerifiedKey<Role>
    { bytes: [u8; 16], _role: PhantomData<Role> }

fn verify_key_for_role<S>(
    root_of_trust: &RootOfTrust,
    certificate: &ScopedCertificate<S>,
    key: &ScopedUnverifiedKey<S>
) -> Result<ScopedVerifiedKey<S>> where S:Role {
    // ...
}

fn sign_message_to_server(
    key: &ScopedVerifiedKey<Client>, msg: &[u8]
) -> Vec<u8> {
    // ...
}
```

Example: CoverDrop's use of types



Example: CoverDrop's use of types



Elliptic Curve Signatures

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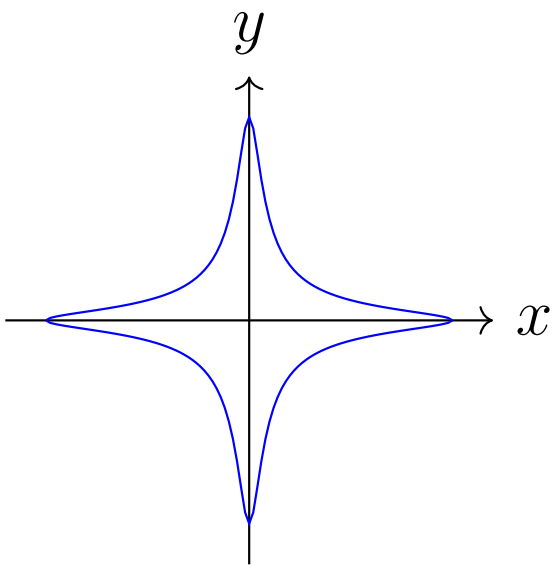
Twisted Edwards Curves



$x^2 + y^2 = 1 - 300x^2y^2$
plotted over $\mathbb{R}$

Edwards25519 is the twisted Edwards curve

$$-x^2 + y^2 = 1 + dx^2y^2$$

with $x, y \in \mathbb{F}_p$, $p = 2^{255} - 19$, and $d = -\frac{121665}{121666}$.

There is a 1:1 mapping ("birational equivalence") between points on this curve and Curve25519.

Advantage over elliptic curve: the group law is simpler $\Rightarrow$ faster to compute (with same security properties).

Group law on twisted Edwards curve

Point addition for curve $-x^2 + y^2 = 1 + dx^2y^2$:

$$(x_1, y_1) + (x_2, y_2) = \left(\frac{x_1y_2 + x_2y_1}{1 + dx_1x_2y_1y_2}, \frac{x_1x_2 + y_1y_2}{1 - dx_1x_2y_1y_2} \right)$$

Complete: no need for seperate doubling formulas since the denominators are always non-zero. (Helps with constant-time)

Define **scalar multiplication** like on elliptic curve, using double-and-add.

Faster scalar product by working in **extended homogeneous (projective) coordinates**: instead of (x, y) use (X, Y, Z, T) where $x = X/Z$, $y = Y/Z$, $xy = T/Z$. See RFC 8032.

Compute the inverse of Z only at the end of scalar product, not for every point addition.

Point compression

For X25519, we could get away with only using x coordinates.

For signatures, we need the y coordinate as well. But: sending both x and y coordinates doubles data size ($32 \to 64$ bytes).

For a given x coordinate there are at most two possible values $\pm y$ such that (x, y) lies on the curve.

Point compression: encode the x coordinate along with one bit to say which y value is used ("sign bit").

When $x \in \mathbb{F}_p$ for $p = 2^{255} - 19$, x fits in 255 bits $\Rightarrow$ use the 256th bit for the sign of y, still fits in 32 bytes.

(Actually Ed25519 encodes y coordinate and the sign of x.)

Define y to be **positive if even, negative if odd**.
Note $-y \equiv p - y \pmod{p}$, so y is even iff $-y$ is odd.

Then the "sign bit" is simply the least significant bit of y.

Point decompression

Point decompression: take the low 255 bits (little-endian) as x, error if it's $\geq p$. Then

$$y = \pm\sqrt{\frac{1+x^2}{1-dx^2}} \quad \text{using } + \text{ or } - \text{ according to sign bit.}$$

How to compute **square root** modulo $p = 2^{255} - 19$:

$$\sqrt{a} = \begin{cases} a^{(p+3)/8} & \text{if } (a^{(p+3)/8})^2 = a \\ a^{(p+3)/8}\sqrt{-1} & \text{if } (a^{(p+3)/8})^2 = -a \text{ where } \sqrt{-1} = 2^{(p-1)/4} \\ \text{error} & \text{otherwise} \end{cases}$$

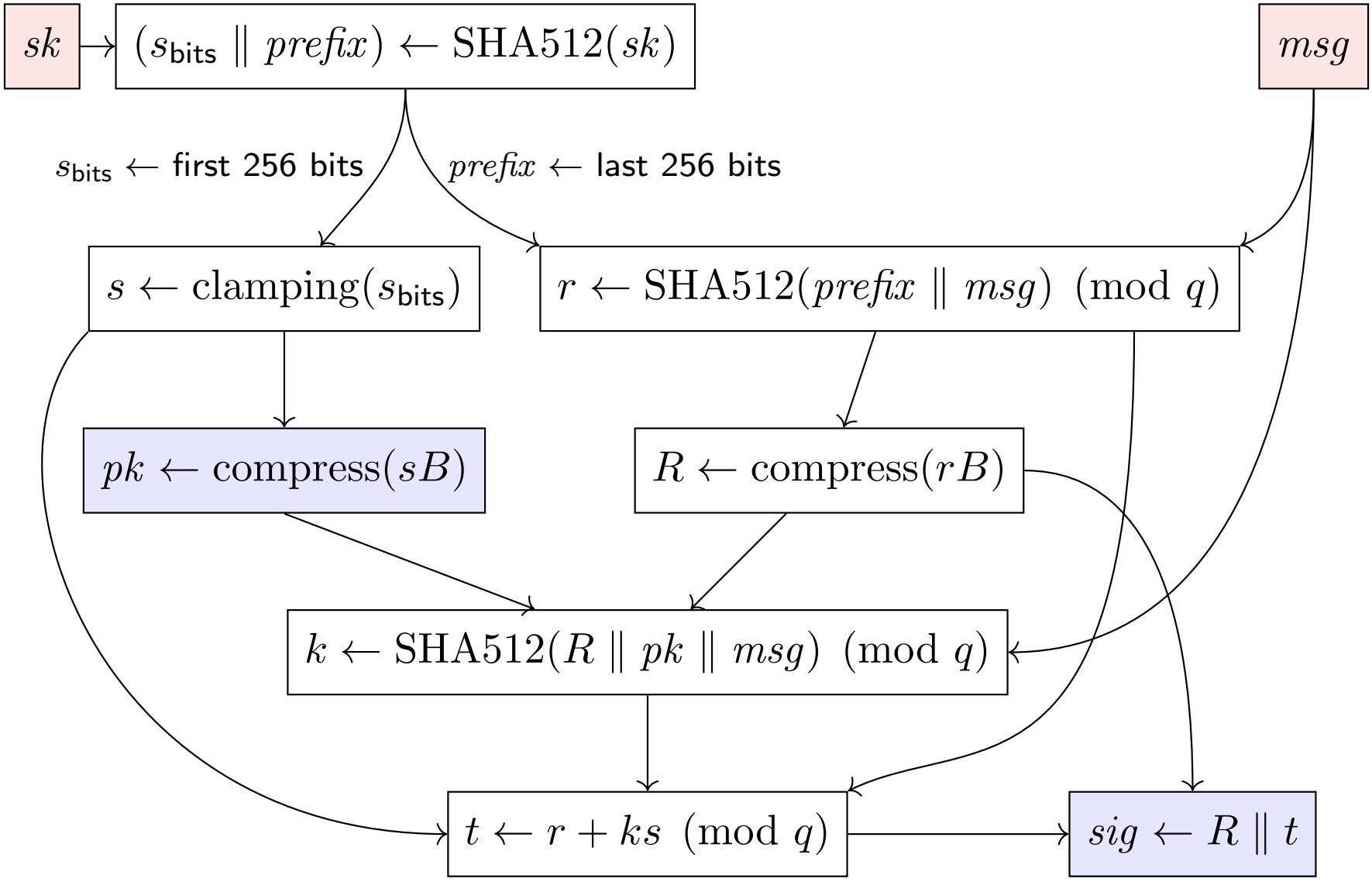
See RFC 8032, Tonelli–Shanks algorithm.

This also ensures that (x, y) is a valid point on the curve.

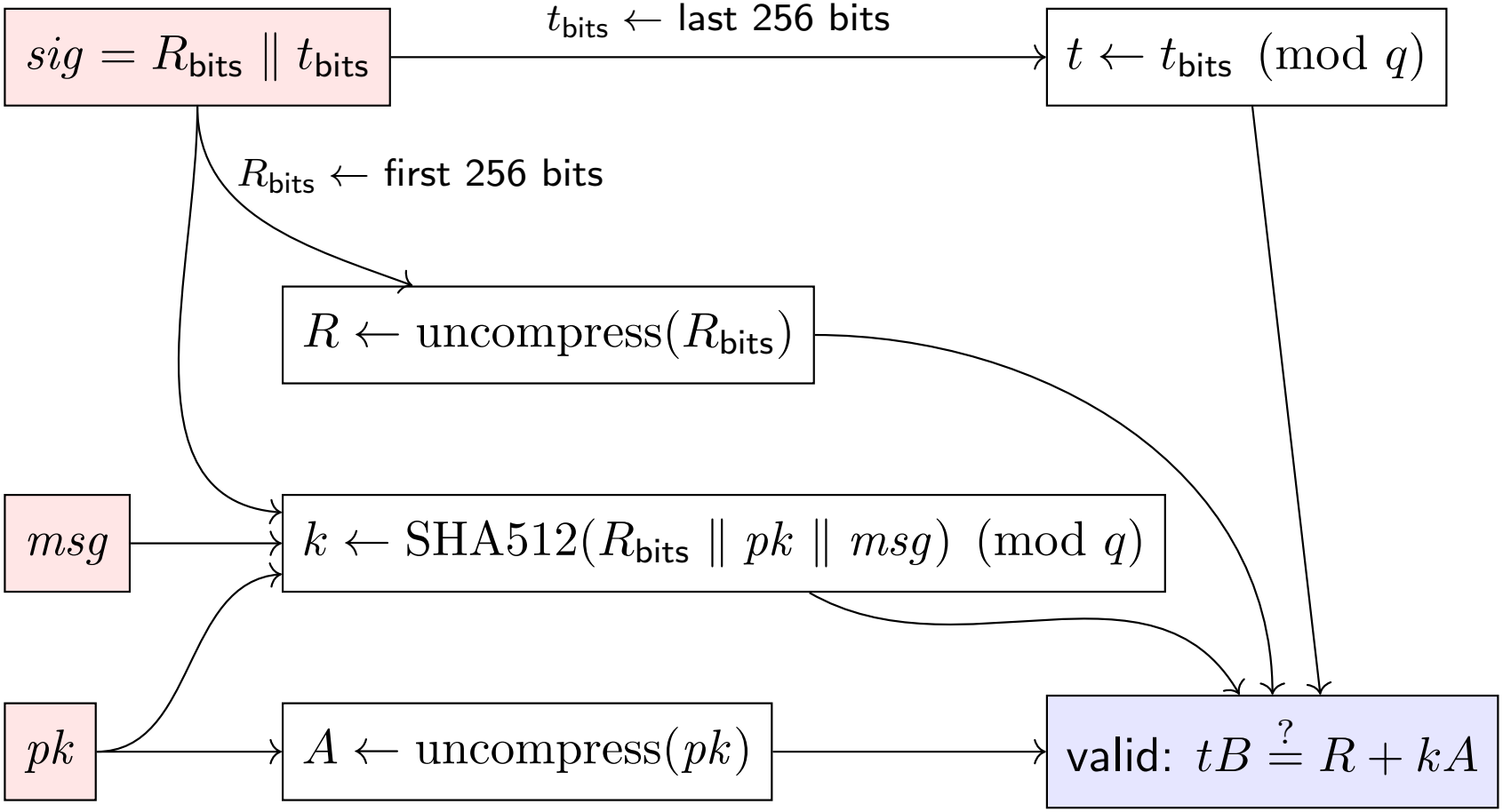
The Ed25519 signature scheme

- EdDSA: general algorithm;
  Ed25519: EdDSA over Edwards25519 curve
- Very widely used, e.g. TLS 1.3, SSH, Signal
- sk 32 bytes, pk 32 bytes, signature 64 bytes
- Deterministic: signing requires no randomness, no nonce
  - Whereas ECDSA requires nonce per signature
  - Nonce reuse in ECDSA is catastrophic
  - Ed25519 computes r from hash of private key and message $\Rightarrow$ safer to use
- Variant of Schnorr signatures
- B is base point with order q, where $|E| = 8q$ is group order (different from field order p)

Ed25519 signing



Ed25519 signature verification



Assignment 2

Implement Ed25519 from scratch, relying only on bignums for field arithmetic.

You can find example code and test vectors in RFC 8032.

Due date for code and lab report: 17 Feb 2026

Authenticated key exchange

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Cryptographic protocols

We've seen **cryptographic primitives**: symmetric encryption, hashes, Diffie-Hellman, signatures.

Now let's look at **protocols**: interactive communication between two or more parties, sending messages over a network.

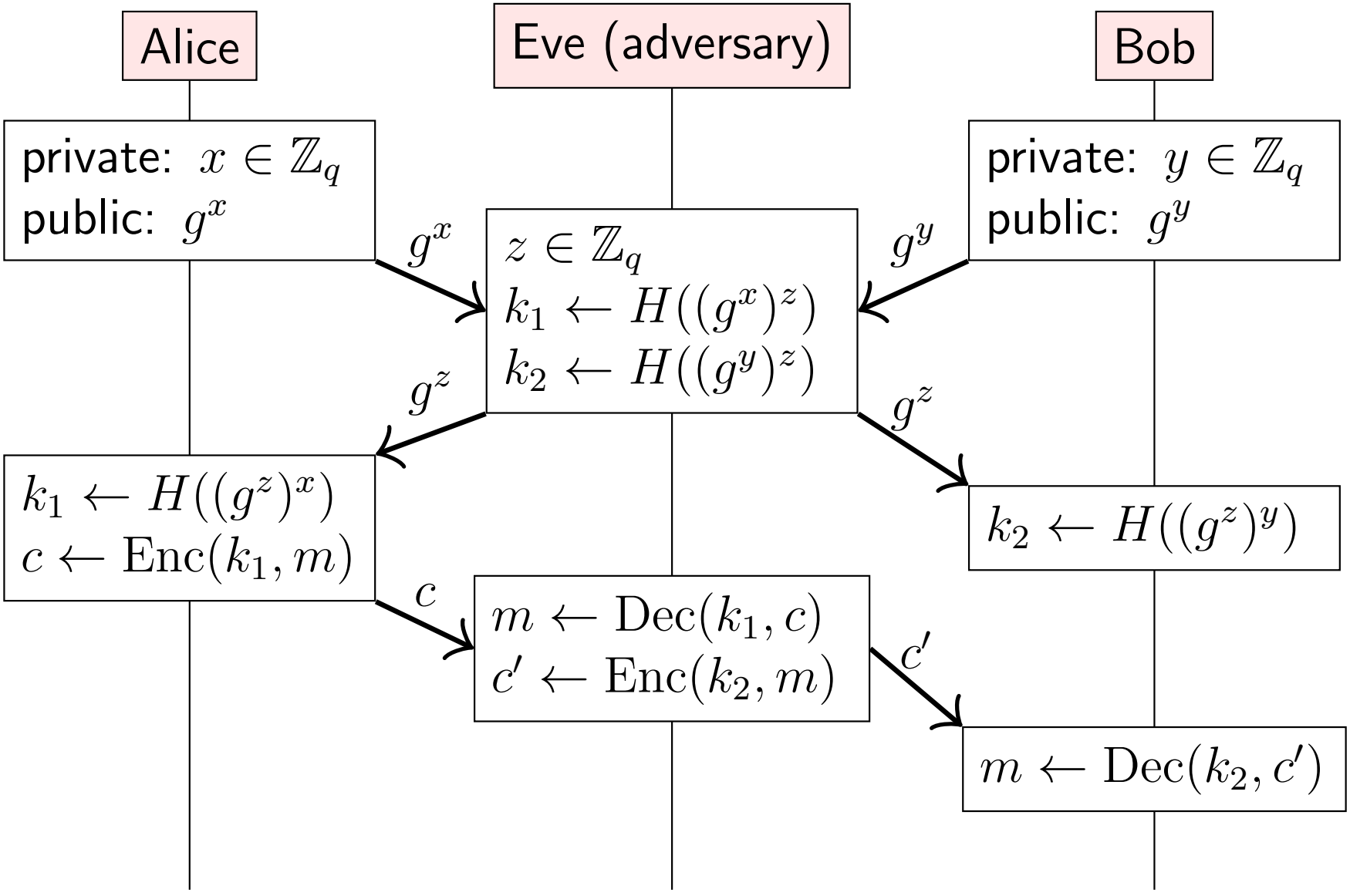
Threat model: assume what each party may do / not do, and what the network may do / not do

Common assumption: **Dolev–Yao model**. The adversary...

- sees everything sent over the network (eavesdropping)
- chooses if and when messages are delivered
- can inject fake messages, replay old messages (active)
- sees multiple protocol runs between different parties

Reasonable model if you're on a coffee shop wifi!

Unauthenticated Diffie-Hellman



Mutual authentication in protocols

How do two communicating parties convince each other that they are genuine?

Two usual forms of mutual authentication:

- **Authenticated Key Exchange** (AKE):
  each party has a private key; other party knows the corresponding public key
- **Password-Authenticated Key Exchange** (PAKE):
  the two parties share a (low-entropy) password; prove they know it without revealing it (e.g. wifi password)

On the web it's usually asymmetric:

1. **Server authenticates itself to client** using public key
2. **Client authenticates itself to server** by sending password over encrypted+authenticated connection

Public Key Infrastructure (PKI)

But how does each party find out the other party's public key?

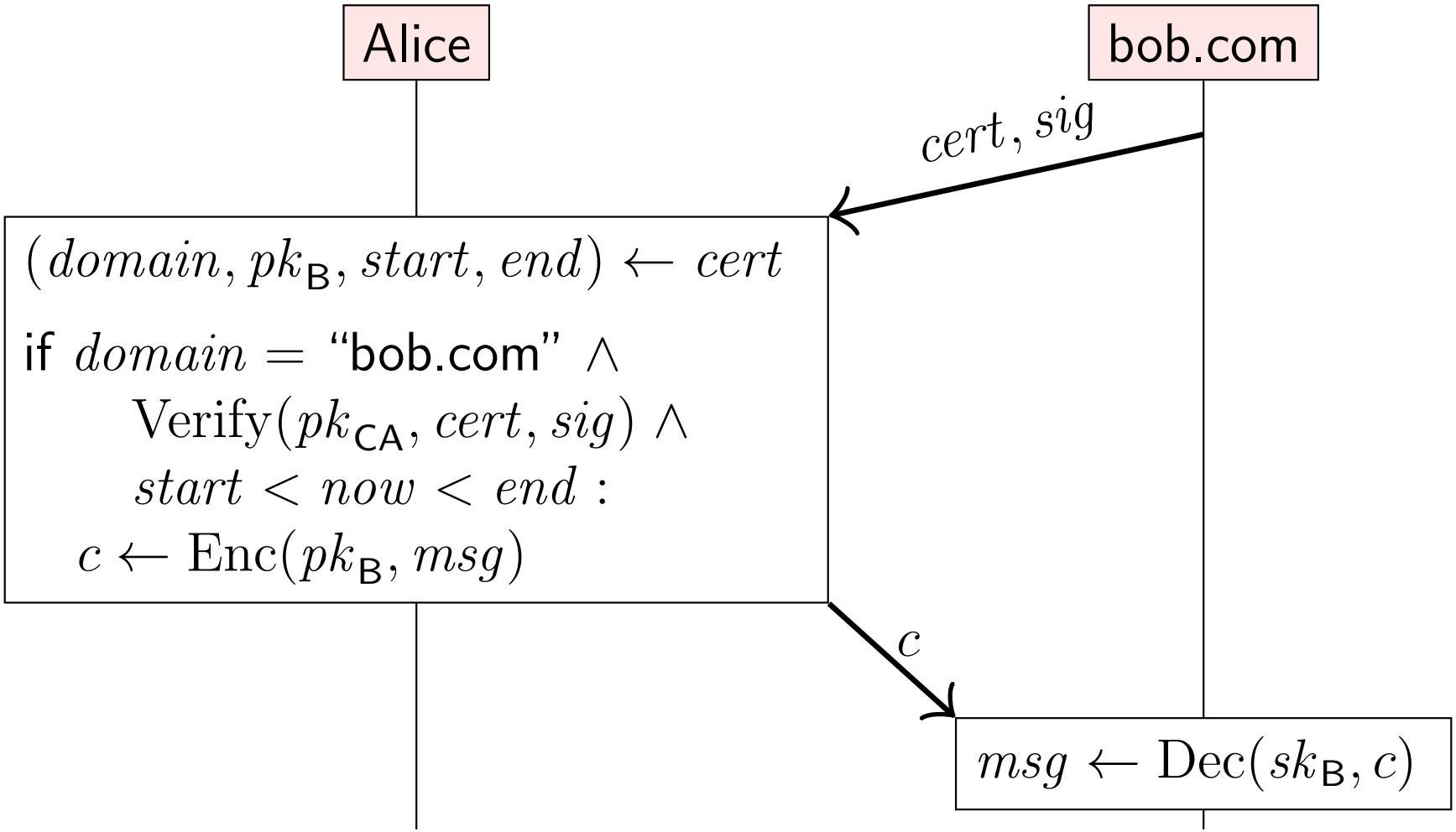
- **Web** (WebPKI):
  - Certificate is (domain name, pubkey, validity dates)
  - Certificate is signed by a **certificate authority** (CA)
  - Several CAs' public keys are built into the web browser
  - New website: CA checks via HTTP request or DNS whether you own the domain
- **Secure messaging** (Signal, WhatsApp, iMessage, . . .)
  - **Key directory**: database of phone number $\rightarrow$ pubkey
  - Identity of key directory is built into messaging app
  - User registration: directory sends SMS to phone number

Can check whether CA/directory is honest using **certificate transparency** (and other transparency logs)

Simple server authentication

Let $cert = (\text{“bob.com”}, pk_{\mathsf{B}}, startDate, endDate)$

Let $sig = \mathrm{Sign}(sk_{\mathsf{CA}}, cert)$ and assume Alice knows pk_{CA}



Including key compromise in the threat model

A simple scheme:

- Server sends its certificate to client, client checks it
- Client samples a random session key, encrypts it under server's public key (using a public key encryption scheme)
- Server decrypts session key
- Encrypt+authenticate communication using session key

If the server's private key is ever compromised, **all communication ever** with that server can be decrypted!

Adversary could record all ciphertexts now and hope to compromise key in the future ("store now, decrypt later")

We should try to handle key compromise as well as possible

Forward secrecy

Forward secrecy (aka *perfect forward secrecy*):
If adversary learns private keys, they cannot decrypt any communication prior to compromise

Considered essential in many modern protocols
TLS since 1.3 always offers forward secrecy

- Use ephemeral keys (i.e. new keys for every connection)
- Keep generating new keys from old ones (ratchet)
- Diffie-Hellman with ephemeral keys is forward secure...
- ...if we can authenticate it correctly!

What about communication after compromise?

- Can still offer **post-compromise security** against passive eavesdropping
- Refresh keys from time to time, e.g. with new DH
- Can't prevent active impersonation by adversary

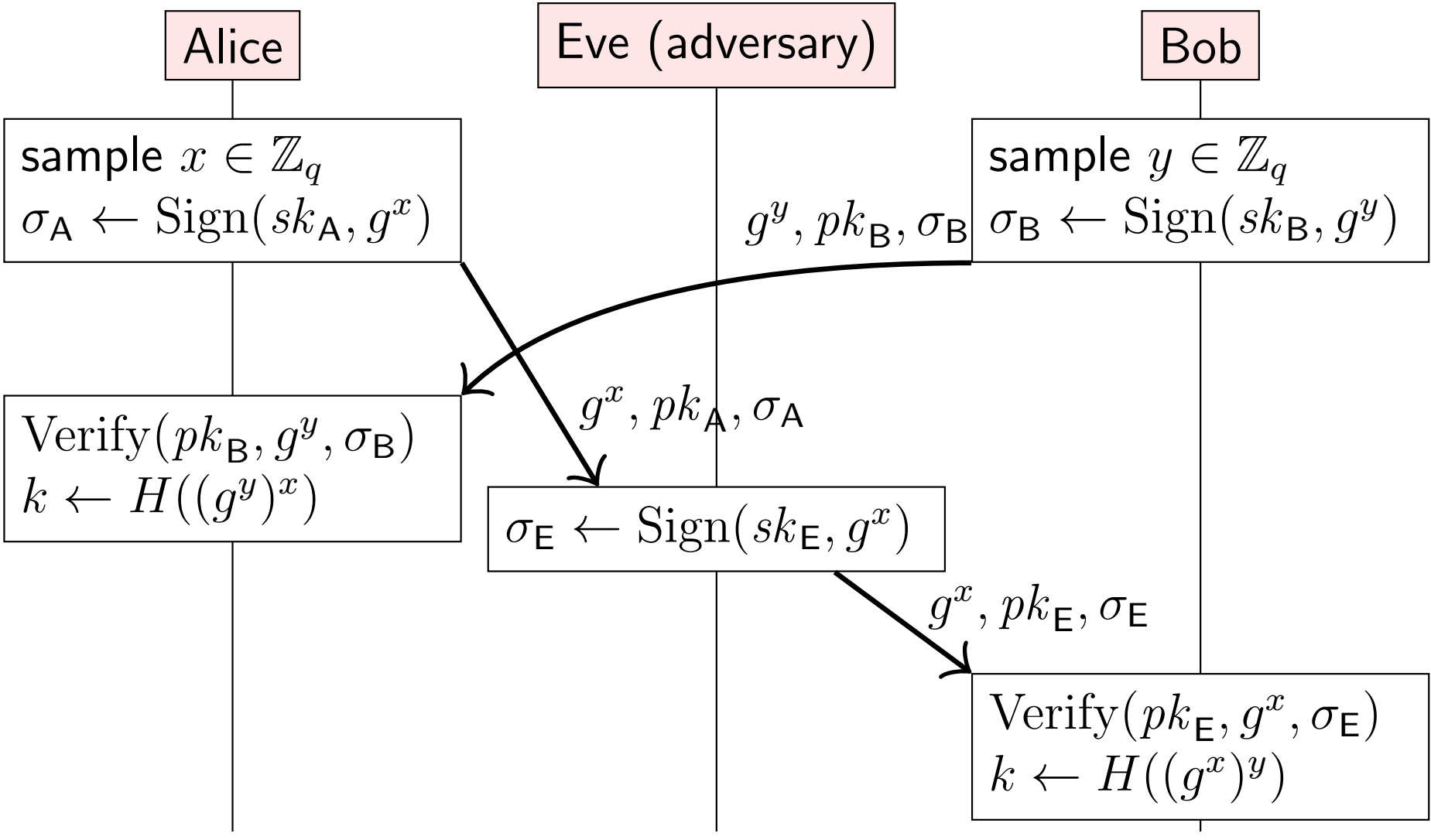
Requirements for authenticated key exchange

For secure two-party communication, establish a **session key** for use with an authenticated symmetric encryption scheme with the following properties:

- **Confidentiality**: when two honest parties communicate, the adversary learns nothing about the session key
- **Authentication**: each party can verify the identity of the other party; adversary cannot impersonate
- **Consistency**: if A thinks it's communicating with B, then B thinks it's communicating with A
  - Violation is called **identity misbinding attack**
- **Forward secrecy**: if adversary compromises a party's private state, past session keys remain confidential

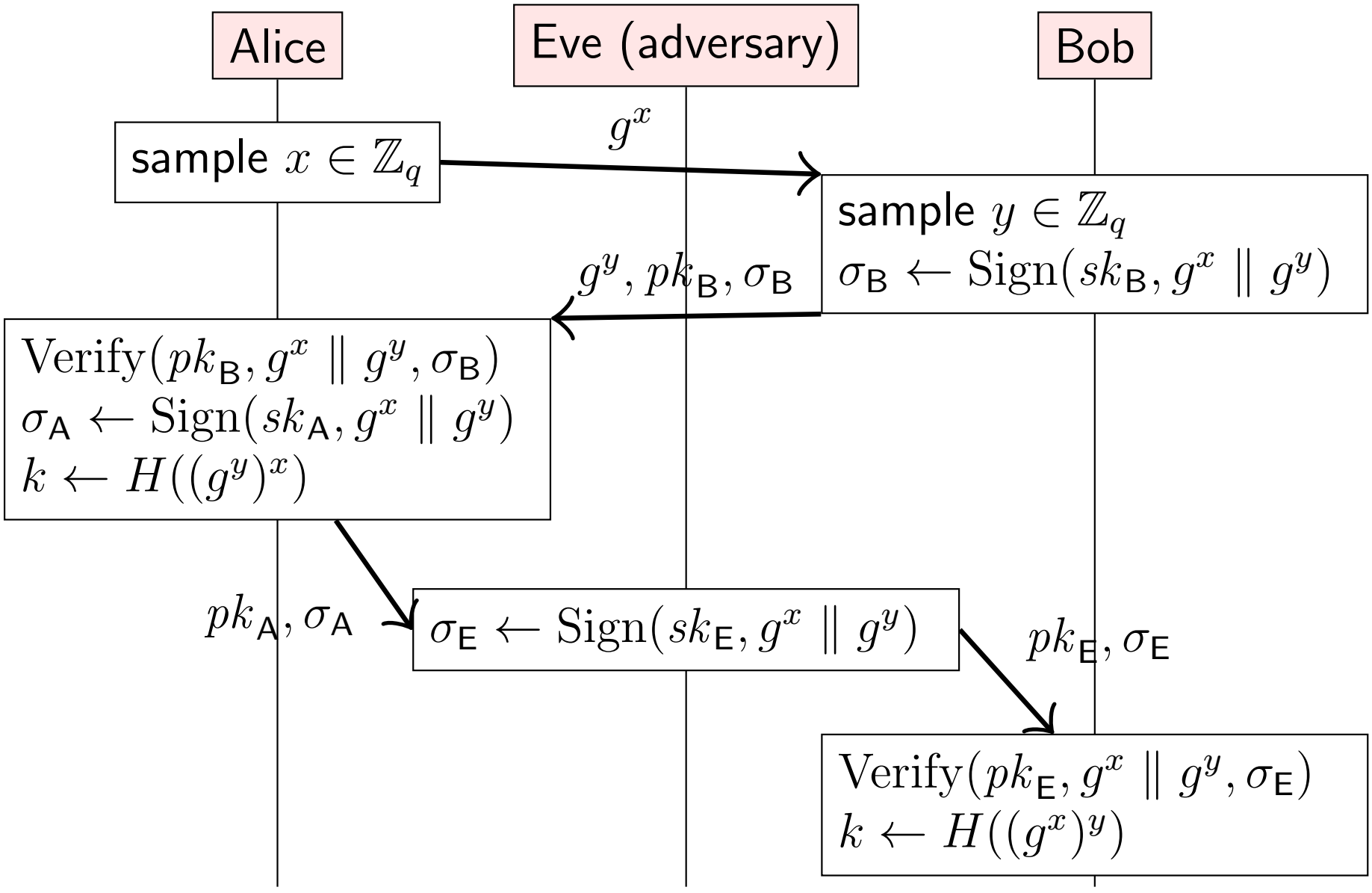
There are also **group key exchange** protocols for more than two parties (beyond scope of this module)

Badly Authenticated Diffie-Hellman (1)



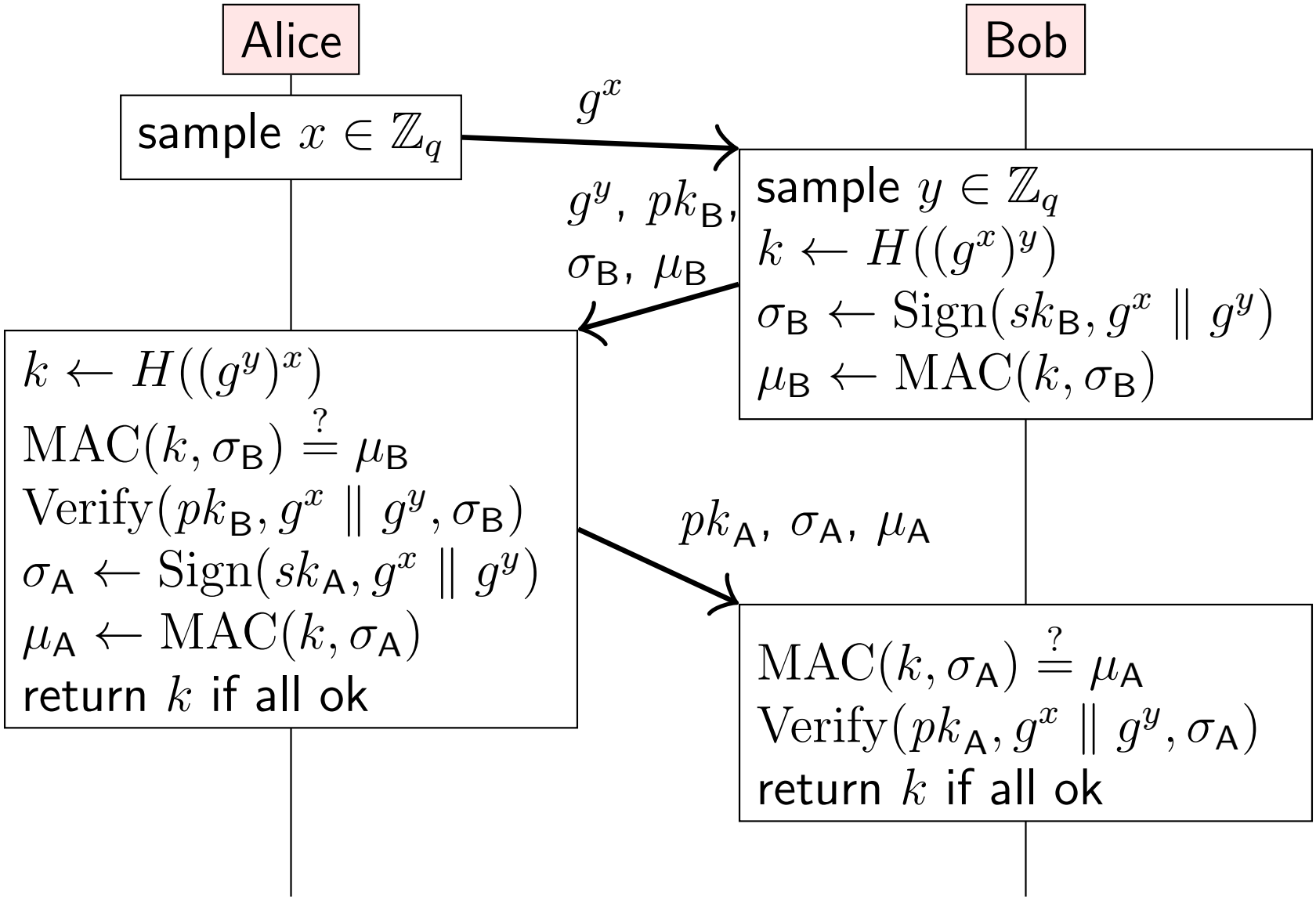
Alice is talking to Bob, but Bob thinks he's talking to Eve

Badly Authenticated Diffie-Hellman (2)



Again Bob thinks he's talking to Eve

MAC variant of STS protocol

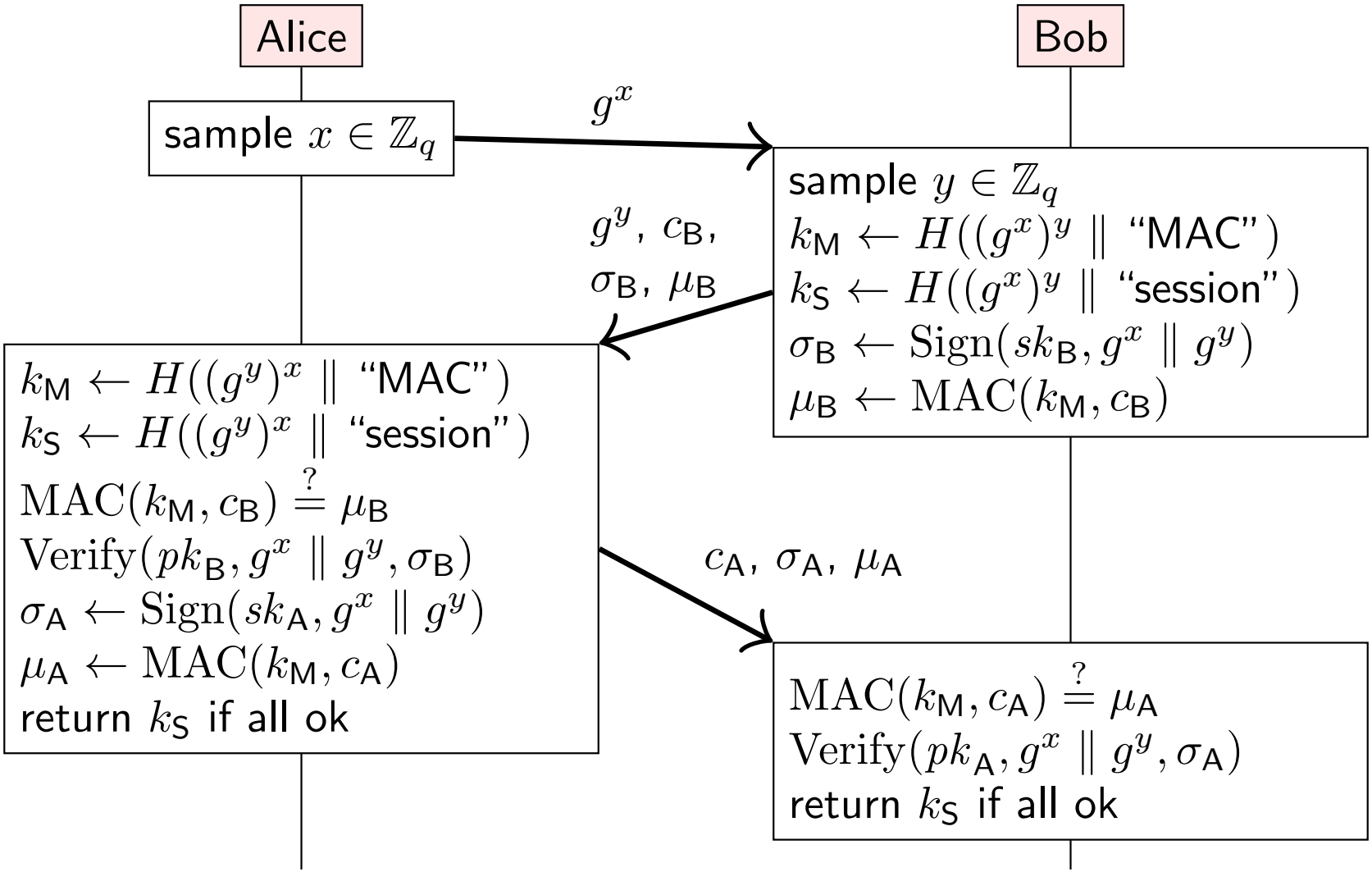


Weaknesses in the STS protocol

1. The same k is used as MAC and as session key
   - Violates single-purpose principle
2. Identifies the public key of the other side, but not the human-readable name
   - Could Eve take Alice's public key pk_{A} and register ("Eve", pk_{A}) with the PKI?
   - If so, we have an identity misbinding attack again
   - To prevent, PKI must check whether Eve knows sk_{A}
3. Adversary might be able to create a new keypair $(sk_{\mathsf{new}}, pk_{\mathsf{new}})$ such that signature $\sigma_{\mathsf{A}} = \mathrm{Sign}(sk_{\mathsf{A}}, m)$ validates with pk_{new}, i.e. $\mathrm{Verify}(pk_{\mathsf{new}}, m, \sigma_{\mathsf{A}}) = \mathsf{true}$
   - Then Eve registers pk_{new} with PKI and replaces pk_{A} with pk_{new} in last message
   - Depends on signature scheme
   - Existential unforgeability says you can't make a new valid signature for a given key; it doesn't say you can't make a new key that validates an existing signature!

SIGMA protocol

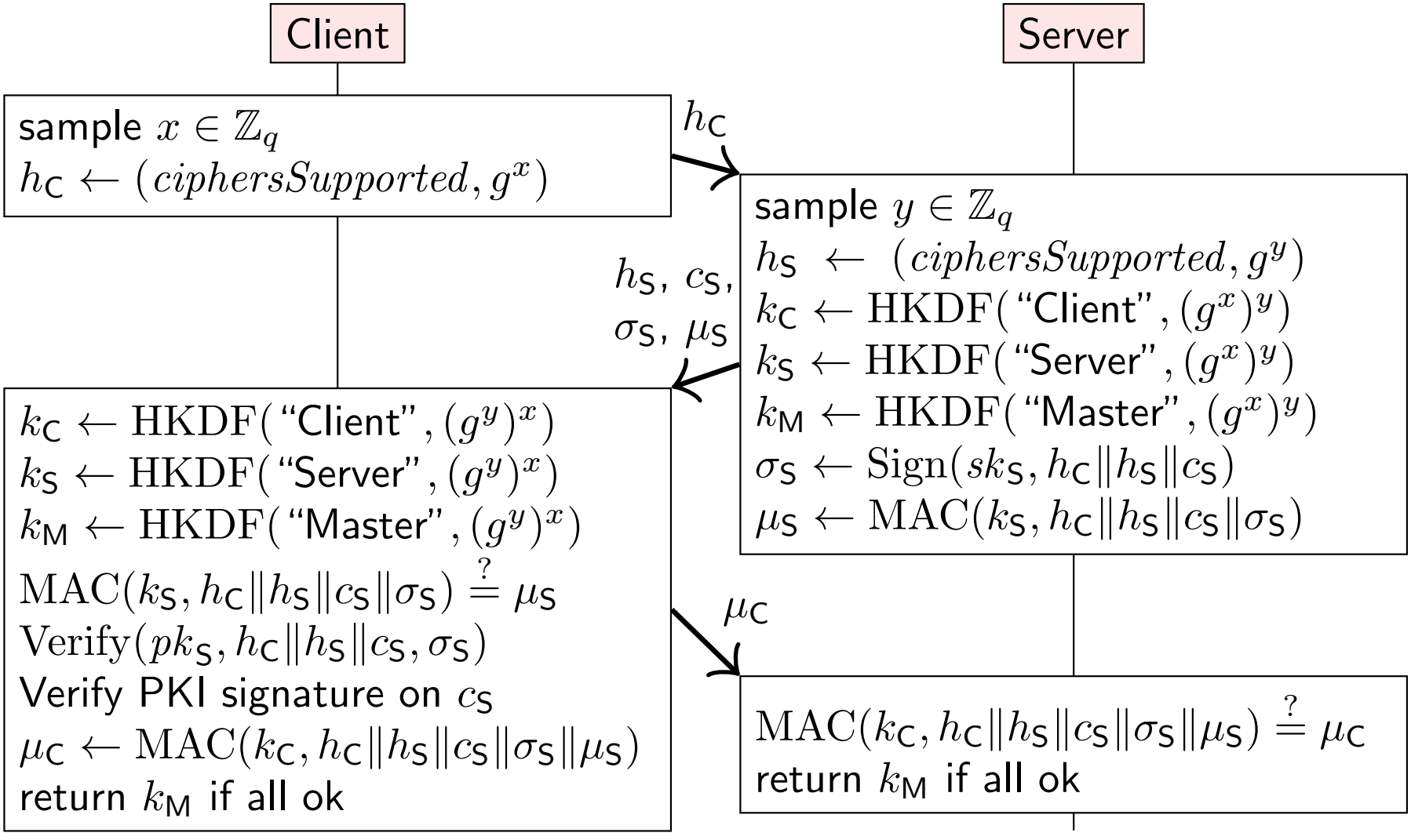
Let $c_\mathsf{A} = (\text{“Alice”}, pk_\mathsf{B}, start, end)$ + PKI signature; c_B similar.
Let g be a generator of a group with prime order $|g| = q$.



Finally secure?!

TLS handshake, simplified

Let $c_S = (\text{“example.com”}, pk_S, start, end)$ + PKI signature



More on authenticated key exchange

Now just use the session key with an authenticated symmetric encryption scheme, and that's the core that makes most secure communications (TLS, secure messaging, VPNs, ...) work!

Lots of extensions to that core:

- Identity protection: encrypt public keys + identifiers so that eavesdropper can't see who is communicating
  - e.g. Great Firewall of China blocks websites based on hostname in TLS handshake
- Ratchet: for long-running sessions, periodically refresh keys (for forward secrecy + post-compromise security)
- From two-party to group communication
  - including adding and removing group members
- Managing trust in the PKI (transparency logs, ...)
- Some protocols (e.g. OTR, Signal's X3DH) offer deniability (no cryptographic proof of communication)

Assignment 2, Task 1

Implement the SIGMA protocol using X25519, Ed25519, and HMAC.

- There's no RFC, so you need to define the format of the messages yourself (and justify it in your lab report)
- Use it to build a basic **two-party secure messaging protocol** (use a library for hashes and symmetric crypto)
- As PKI, implement a basic CA that issues certificates (signed using Ed25519), and include certificate validation in your protocol implementation
  - X.509 certificates are complicated; make your own simple format
  - Omit check whether user controls the phone number/email address/domain name
- Identity protection, ratcheting, etc. are not required
- Simulate the network in a single process

Password-Authenticated Key Exchange (PAKE)

Authenticated Key Exchange requires knowing the other party's public key. In most cases that means trusting a PKI (CA or key directory) for global name $\rightarrow$ pubkey mapping.

Can we manage **without a PKI**?

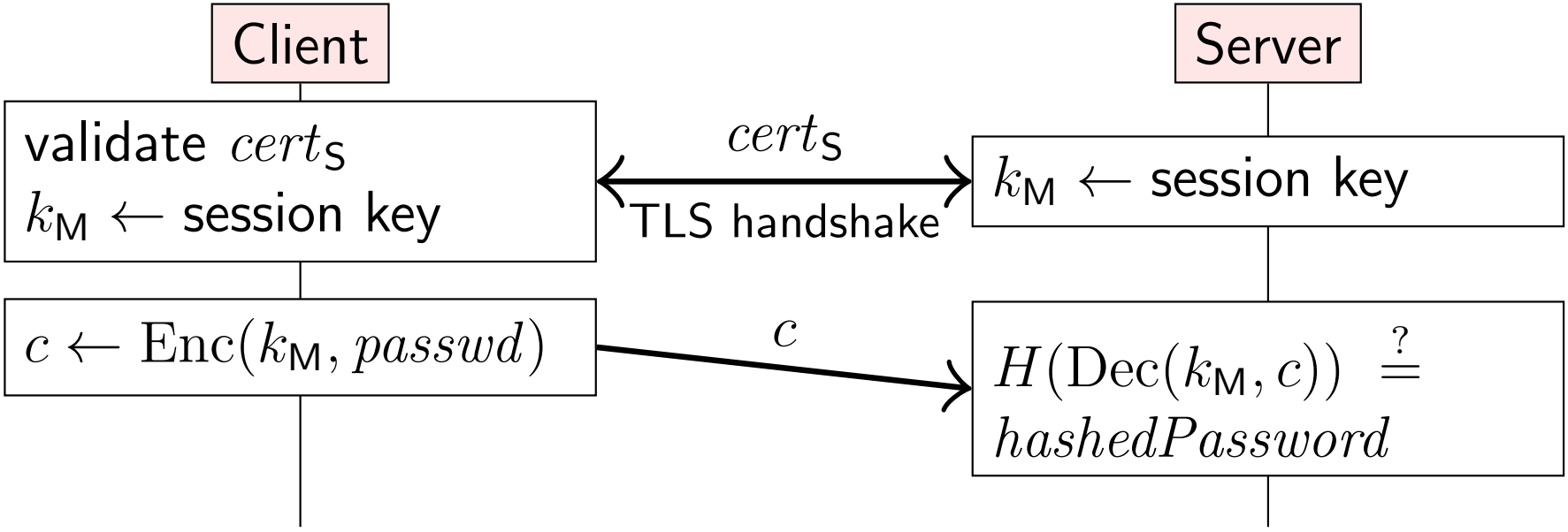
PAKE: no global names, no pubkeys, just a shared password

- e.g. wifi router: password is printed on the box
- e.g. device pairing: one device displays a code, type it into the other (or scan a QR code)
- e.g. link shared via secure messaging/video call/email

Password should be short enough that you can sensibly type it (i.e. much less than 128 bits entropy), and PAKE should upgrade this to a strong shared secret

Passwords on the web: Not a PAKE

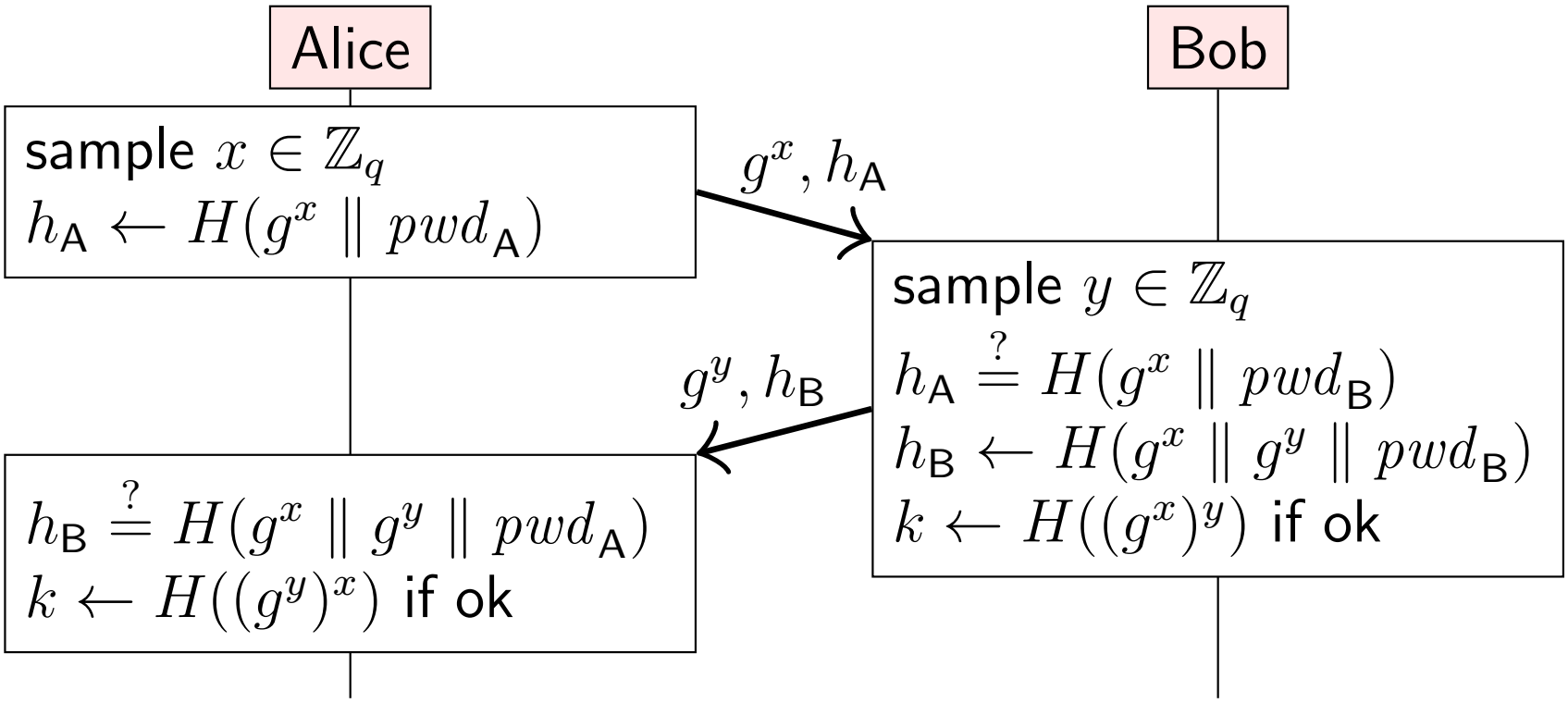
Let $cert_{\mathsf{S}} = (\text{“example.com”}, pk_{\mathsf{S}}, start, end)$ + PKI signature



Doesn't work without a PKI: client wouldn't know who it's sending the password to

An insecure PAKE

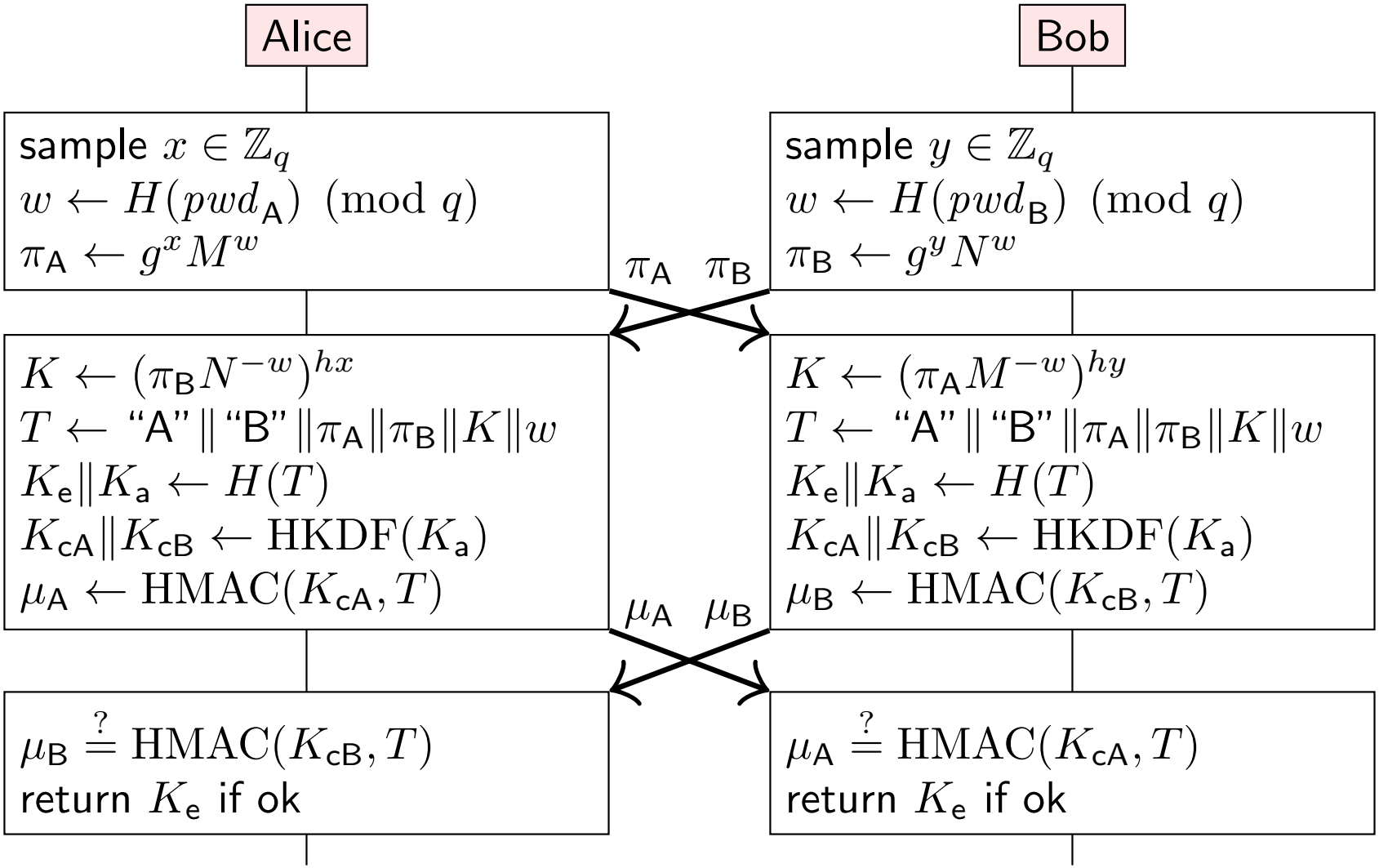
Say Alice knows a password pwd_{A} and Bob knows pwd_{B}. We want them to agree on a shared secret k if $pwd_{\mathsf{A}} = pwd_{\mathsf{B}}$.



Problem: adversary who has intercepted g^x and h_{A} can run an offline brute-force search, trying many passwords p until they find one such that $H(g^x \parallel p) = h_{\mathsf{A}}$

The SPAKE2 protocol

Let E be a group of order $|E| = hq$. Let $g \in E$ be a generator of prime order $|g| = q$. Let $M, N \in E$ be elements whose discrete log is unknown.



SPAKE2: Why it works

- $\pi_A = g^x M^w \implies (\pi_A M^{-w})^{hy} = (g^x M^w M^{-w})^{hy} = g^{hxy}$
- π_A and π_B are uniform random group elements $\implies$ leak no information about password
  - $g^x M^{H(pwd)}$ essentially encrypts g^x with the password
  - Intentionally unauthenticated! Authentication would enable offline brute-force
- The MAC μ_A allows the party that generated π_B to verify whether the passwords were equal (similarly with μ_B and π_A), but not an eavesdropper
- In any run of the protocol, adversary can talk to Alice, pretend to be Bob, and guess some password pwd_B.
  - If it succeeds (MAC is correct), guess was correct
  - If it fails, adversary only learns that password was wrong
  - $\implies$ adversary gets one password guess per protocol run
  - $\implies$ limit protocol retries based on password entropy

SPAKE2: Trusted setup

If adversary knows discrete log n such that $N = g^n$:

- Adversary pretends to be Bob, sets $\pi_{\mathsf{B}} = g^y$, receives $\pi_{\mathsf{A}} = g^x M^w$ and μ_{A} from Alice
- Alice computes $K = (\pi_{\mathsf{B}} N^{-w})^{hx} = (g^y g^{-nw})^{hx} = (g^x)^{(y-nw)h} = (\pi_{\mathsf{A}} M^{-w})^{(y-nw)h}$
- Adversary knows π_{A}, M, y, n, h; just not w
- Adversary can now guess $w = H(pwd) \pmod q$, compute K, hence compute K_{cA} and the MAC
- If the MAC matches μ_{A} from Alice, pwd guess is correct
- Adversary can now run offline brute-force search

Attack is prevented if nobody knows n.

Requires **trusted setup**: whoever generates M and N must convince others that their discrete log is unknown.

Assignment 2, Task 2

Implement the SPAKE2 protocol using Edwards25519.

- Same curve as for Ed25519 – you can use your implementation from assignment 1 (but don't have to)
- RFC 9382 contains M and N values you can use (given using compressed point encoding)
- The RFC contains some ambiguities; you'll need to decide on some details yourself
- Deadline: 3 Mar 2026

Software Engineering for Cryptography – Part II

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Part III/MPhil in Advanced Computer Science

Randomness

- Cryptography requires random inputs
  - Key generation
  - Nonce generation
  - Tokens
  - ...
- Building strong random number generators is not trivial

LAB: build your own PRNG (10 min)

Hidden from the published slides.

LAB: collect (5 min)

Hidden from the published slides.

Real-world entropy

Instead of relying on deterministic algorithms, we can use real-world entropy sources.

- Interrupts (e.g. from user input)
- Hardware sources (e.g. electrical noise, nuclear decay, ...)
- Observation of physical phenomena
- Lava lamps
- ...

Lava lamps

Image from Wikipedia (CC-BY 2.0 Dean Hochman)

Real-world entropy

Instead of relying on deterministic algorithms, we can use real-world entropy sources.

- Interrupts (e.g. from user input)
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- Observation of physical phenomena
- Lava lamps
- ...

Problem:

- Not uniformly distributed
- Slow entropy sources
- Might be temporarily unavailable

Cryptographically secure PRNGs (CSPRNGs)

PRNGs are not suitable for cryptographic applications. We need a CSPRNG with strong guarantees:

- **Next-bit test**: given all previous i output bits, predicting the next bit is computationally infeasible
- **Forward security:** if an adversary learns the state of the PRNG, they cannot use it to predict previous outputs
- **Recovery:** after compromise of the state, new entropy can be added

Measuring entropy

Entropy is the amount of uncertainty in a source, i.e. "how surprising is the next event?".

The entropy H of a discrete random variable X with possible values $\{x_1, \ldots, x_n\}$ and probability mass function $P(X)$ is defined as:

$$H(X) = -\sum_{i=1}^{n} P(x_i) \log_2 P(x_i)$$

Example: A fair coin has an entropy of 1 bit per toss (we assume it will not land on its edge). A sequence of four fair coin tosses has an entropy of 4 bits.

LAB: compare (10 min)

Hidden from the published slides.

Randomness tests

The NIST Statistical Test Suite is a collection of tests that can be used to evaluate the quality of a random number generator.

- Frequency test
- Block frequency test
- Runs test
- Compression tests
- ...

The Linux CSPRNG design

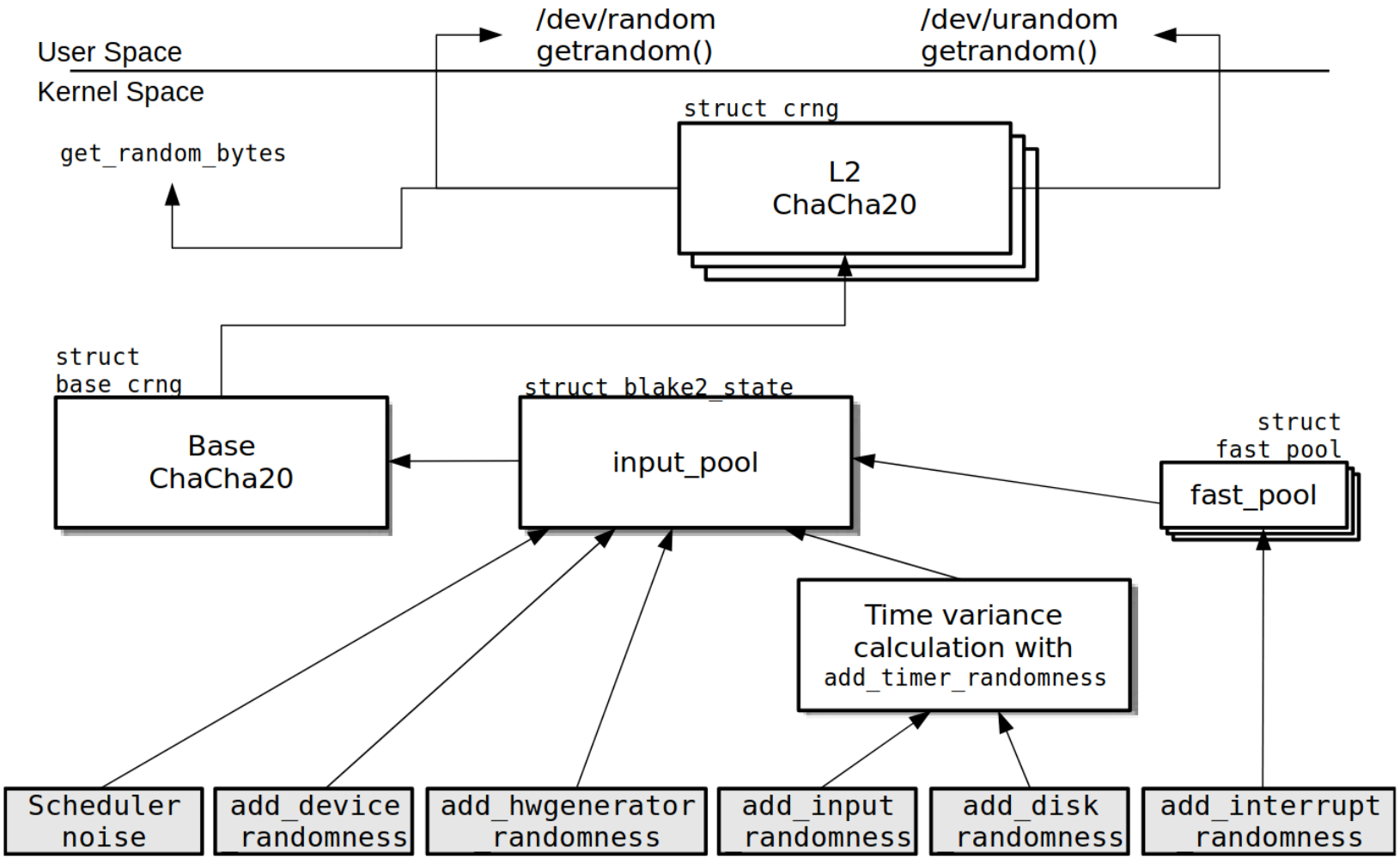


Image from [BSI, 2022].

CSPRNGs in practice

Linux:

- Read from `/dev/urandom` or `/dev/random`[1]
- `getrandom()` system call

Python:

- Preferred method: `secrets` module
- Still common: `os.urandom(...)`

[1] The only difference is that `/dev/random` blocks if the entropy pool is empty, e.g. early during boot. You can read the available entropy from `/proc/sys/kernel/random/entropy_avail`.

Case study: Debian OpenSSL Predictable PRNG (CVE-2008-0166)

- OpenSSL collects entropy from many different sources (`/dev/urandom`, time, ...)
- Read method tried to be clever and includes also uninitialized parts of a buffer

```
int RAND_load_file(const char *file, long bytes) {
    /* ... */
    i=fread(buf, 1, n, in);
    if (i <= 0) break;
    /* even if n != i, use the full array */
    RAND_add(buf, n, double(i));
    /* ... */
}
```

Case study: Debian OpenSSL Predictable PRNG (CVE-2008-0166)

- Down-stream developers (Debian) saw Valgrind warnings
- Remove two lines that adds these uninitialized buffers
- The only remaining source of entropy was the PID...
- Keyspace $|K| = 32\,768$

Take-aways:

- Low entropy can be more dangerous than no entropy at all
- Avoid user-level CSPRNGs. Use the kernel-level CSPRNG instead.

Dealing with imperfect randomness

Often we deal with randomness that is not perfect, e.g. biased and not uniformly distributed. We can capture these conditions with the following definition:

A probability distribution $\mathcal{X}$ has **min-entropy** (at least) m if for all a in the support of $\mathcal{X}$ and for random variable X drawn according to $\mathcal{X}$:

$$\text{Prob}(X = a) \leq 2^{-m}$$

We cannot use these sources directly as input for our cryptographic primitives that require uniform randomness. This includes pseudo-random functions (PRFs) that are the basis of many constructions.

Key derivation functions (KDFs)

We can use a **KDF** to generate cryptographically strong keys from a source with min-entropy m:

- The initial extraction step also relies on a secret salt
- HKDF [Krawczyk, 2010] is a popular KDF with an HMAC-based extract-and-expand construction

As such we can expand a short random seed into a larger number of pseudorandom bytes. In addition, extra *info* parameters enable domain separation for keys.

Indistinguishability

Two probability ensembles $\mathcal{X} = \{X_n\}_{n\in\mathbb{N}}$ and $\mathcal{Y} = \{Y_n\}_{n\in\mathbb{N}}$ are **computationally indistinguishable** if for every probabilistic polynomial-time distinguisher D there exists a negligible function negl such that:

$$|\Pr_{x\xleftarrow{\$}X_n}[D(x) = 1] - \Pr_{y\xleftarrow{\$}Y_n}[D(y) = 1]| \leq \mathsf{negl}(n)$$

The distinguisher D would output 0 if it thinks its input is sampled from $X \in \mathcal{X}$ and 1 if it thinks its input is sampled from $Y \in \mathcal{Y}$.

Testing and correctness

"Testing security is pretty much impossible. It's hard to know if you're ever done."

– Daniel Rohrer, VP of Software Security at NVIDIA

Approaching correctness

- It is really really hard to convince ourselves that our code is always, always correct and secure
- In fact, it is already hard to precisely define what this means
  - Edge cases and error handling
  - Side-channels
  - Abstraction: source code, binary file, execution, ...
  - Assumptions about the compiler, hardware model, ...

Testing strategies

- Bottom-up: testing individual operation thoroughly across their specification range
- Top-down: economic testing of overall functionality and compatibility
- Edge cases and error handling
- Randomized tests
  - Against another implementation
  - Fuzzing (later slides)

Formal approaches

For serious real-world implementations, it is helpful to ground the *implementation strategy* in a formal approach.

- Derive implementation step-by-step from specification
  - That is most-likely the best approach for your lab reports
  - Scope: a few days
- Prove all implementation steps
  - Requires model of the underlying system (compiler, hardware, ...)
  - Scope: an MPhil thesis
- Derive implementation from formal description & hardware model
  - Requires detailed model of hardware
  - Scope: a PhD thesis or research group

Test-driven development (TDD)

- Popularized by Kent Beck
- Write test first, then write code
- Some advantages
  - Understanding of edge cases
  - View point of the callsite
  - Motivates testable APIs (mocking)
  - Psychological: gamification, avoiding write-then-challenge

Test vectors

- The bread and butter of testing cryptographic implementations
- As a very basic minimum requirement, each library should pass the test vectors provided in the specification
- Good tests:
  - check intermediate values
  - generate additional test vectors for edge cases
  - strategically build coverage
- Project Wycheproof collects “tricky” test vectors

Advanced test vector patterns

Test vectors are also a great way to test compatibility of different implementations.

Example: server written in Go and an Android app in Kotlin

- Server adds new test vectors as part of CI
- Android app tested in CI against vectors
- **ensures spatial compatibility**

Can be extended with persisted vectors

- continuously add test vectors from committed versions
- test new versions against existing vectors
- **ensures temporal/backwards compatibility**

Case study: Wycheproof finds bugs in `elliptic` (2024)

The JavaScript `elliptic` library is downloaded over 10 million times weekly.

- Trail of Bits ran Wycheproof test vectors against the library
- **CVE-2024-48949** (EdDSA signature malleability):
  - Missing check that $s < n$ (FIPS 186-5, section 7.8.2)
  - Allows forging new valid signatures from existing ones
- **CVE-2024-48948** (ECDSA verification failure):
  - Leading zeros stripped from hash before truncation
  - Valid signatures rejected with probability 2^{-32}

Fuzzing

Automated testing of programs using randomized input.

Initial population:

- Test vectors
- State from previous runs
- Samples from production code

Classic fuzzing loop:

- Add new candidates (bit flips, dictionaries, . . .)
- Measure “coverage” (basic blocks, edges, . . .)
- Trim population

Fuzzing

- Traditionally focused on C-style bugs
  - but can be applied to logic bugs itself given reference
- Particularly valuable for anything that parses adversary-controlled input
  - Deserialization code
  - File formats
  - Network protocols
  - ...
- Continuous fuzzing as part of CI/CD strategy (e.g. OSS Fuzz)

Fuzzing road-blocks

Some code is easier to fuzz than other. Tricky conditions that are unlikely to pass with random guessing are often referred to as “road blocks”.

```
def handle_packet(pkt: Packet):
    tag = pkt[32:40]
    if hash(pkt[:32]) == tag:
        parse_packet(pkt[:32])
```

Countermeasures:

- Allow fuzzer to disable/skip checks
- Symbolic execution, back-propagation
- Additional entry points

Performance optimizations

- Write a **correct** (naïve) implementation first. Celebrate.
- Make all tests pass
- Add benchmarks and ensure they are solid
- Do small step-by-step improvements
  - The tests give you confidence
  - Benchmarks help you to evaluate changes as you go

Benchmarking with `timeit`

```
import timeit
x = setup(...)
ts = timeit.repeat(
    'your_function(x)',
    globals=globals(),
    repeat=5, number=5
)
```

- Minimize the lines under test
- Consider mean, media, p_{90}, p_{99}, ...
- Reduce noise (GC, dynamic frequency, ...)
- "Warm-up" the code

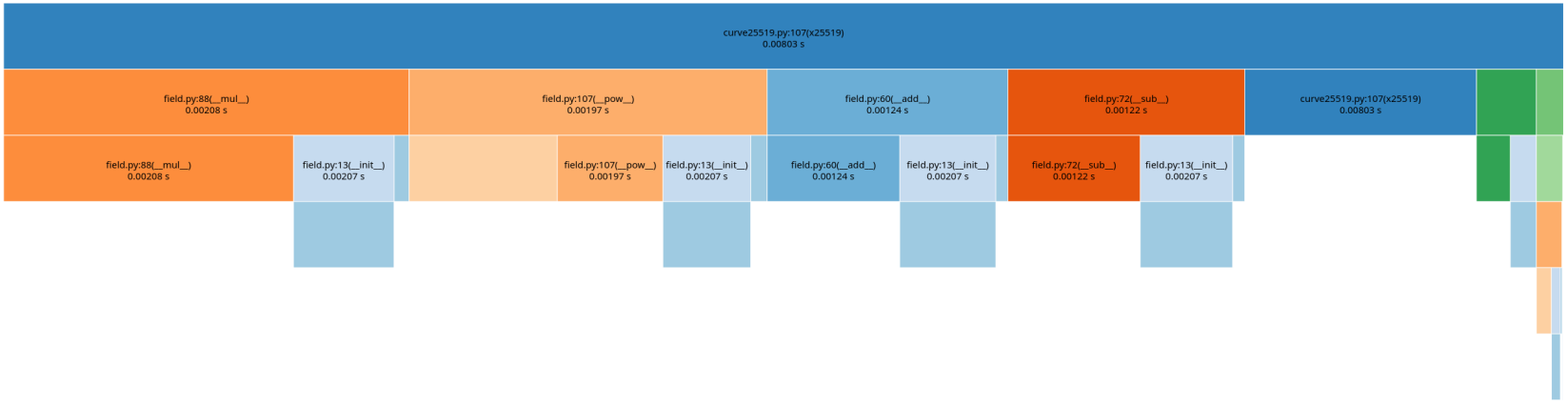
Profiling with cProfile

```
import cProfile, pstats
with cProfile.Profile() as pr:
    x25519(alice_sk, bob_pk)
    pr.disable()
    pstats.Stats(pr) \
        .strip_dirs() \
        .sort_stats('cumulative') \
        .print_stats(5)
```

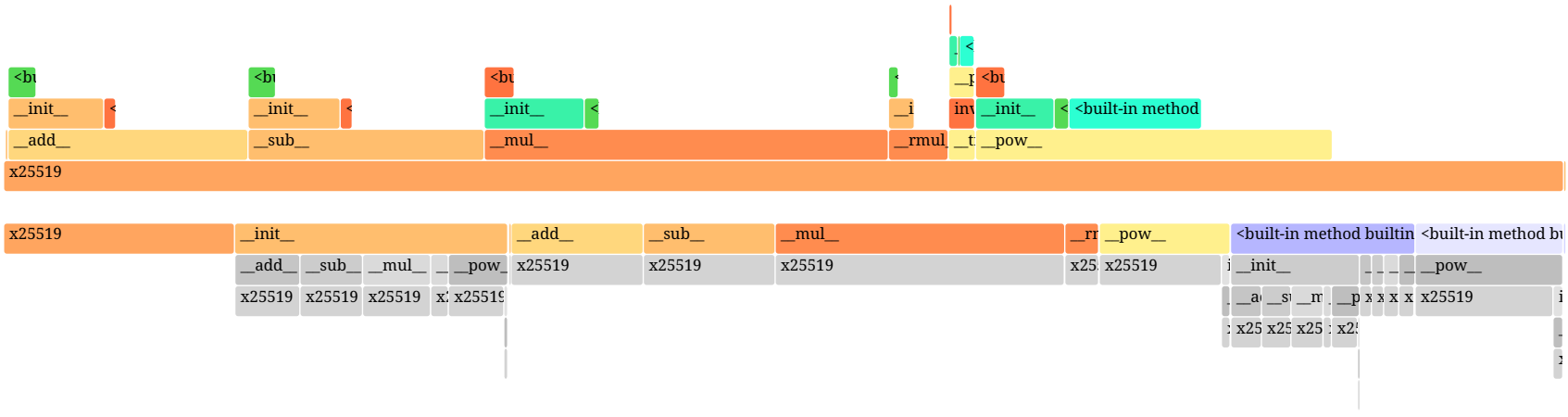
```
ncalls  tottime  percall  cumtime  percall filename:lineno(function)
     1    0.001    0.001    0.007    0.007 curve25519.py:102(x25519)
  1276    0.001    0.000    0.002    0.000 field.py:77(__mul__)
  1021    0.001    0.000    0.002    0.000 field.py:96(__pow__)
  4596    0.001    0.000    0.002    0.000 field.py:8(__init__)
  1020    0.001    0.000    0.001    0.000 field.py:49(__add__)
```

Profiling with cProfile (Flamegraph)

```
import cProfile, pstats
with cProfile.Profile() as pr:
    x25519(alice_sk, bob_pk)
    pr.disable()
    pr.dump_stats('x25519.prof')
```



Profiling with `cProfile` (Flamegraph)



Serialization/marshaling/...

- We already translated the ideal mathematical objects into some representation in our programming language
- Representing them as byte streams
  - Storage on disk
  - Transport over network
  - ...
- In both cases, there will be two parties: the writer and the reader
  - Could be temporally separate (store now, load later)
  - Could be spatially separate (send over network)

Python's pickle is not great

- A very simple mechanism
- Requires both parties to have (roughly) the same class definitions
- Allows to customize the serialization/deserialization process
  - Making sure to only store what's needed
  - A wide attack surface

Pickle example (1)

```
import pickle

class Foo:
    def __init__(self, name):
        self.name = name

foo = Foo('good')
with open('foo.pkl', 'wb') as f:
    pickle.dump(foo, f)
```

Pickle example (2)

```
import pickle

class Foo: pass

with open('foo.pkl', 'rb') as f:
    foo = pickle.load(f)
```

Pickle example (3)

```
import pickle

class EvilFoo:
    def __reduce__(self):
        return (
            exec,
            ('import os; os.system("uname -r")',)
        )

with open('evil.pkl', 'wb') as f:
    pickle.dump(EvilFoo(), f)
```

Pickle example (4)

```
$ xxd -c8 evil.pkl
00000000: 8004 9538 0000 0000  ...8....
00000008: 0000 008c 0862 7569  .....bui
00000010: 6c74 696e 7394 8c04  ltins...
00000018: 6578 6563 9493 948c  exec....
00000020: 1c69 6d70 6f72 7420  .import
00000028: 6f73 3b20 6f73 2e73  os; os.s
00000030: 7973 7465 6d28 2268  ystem("h
00000038: 746f 7022 2994 8594  top")...
00000040: 5294 2e              R..
```

Pickle example (5)

```
import pickle

class Foo: pass

with open('evil.pkl', 'rb') as f:
    foo = pickle.load(f) # Boom
```

Do not use Python's pickle!

Warning: The `pickle` module **is not secure**. Only unpickle data you trust.

It is possible to construct malicious pickle data which will **execute arbitrary code during unpickling**. Never unpickle data that could have come from an untrusted source, or that could have been tampered with.

Consider signing data with `hmac` if you need to ensure that it has not been tampered with.

Safer serialization formats such as `json` may be more appropriate if you are processing untrusted data. See Comparison with json.

- If you have to, make sure that nobody can tamper with the files (using a MAC, . . .)
- The AI/ML community is rediscovering this
  - `model = torch.load(PATH, weights_only=False)`
  - Still an on-going issue

Case study: Log4J

- Log4Shell (CVE-2021-44228) is considered one of the most serious vulnerabilities of the last years
- Messages could contain special tags `${type:arg}` to enhance the message
- Log4J allowed plugin-like behaviour with `${jndi:url}`

- Faults
  - Trusting untrusted user-controlled input
  - Message parsing leads to code loading and execution
  - JRE allows downloading code during runtime by default

Better choices: length-encoding, protobuf, JSON

- Protobuf:
  - Describe types and messages
  - Compiler generates language bindings
- JSON
  - Simple and human readable
  - Type differences between languages (date format, ...)
- Custom formats (e.g. length encoded)

Serde example (1)

```
use serde::{Deserialize, Serialize};

#[derive(Serialize, Deserialize)]
enum Message {
    Ok,
    Text{msg: String},
}
```

Serde example (2)

```
serde_json::to_string(&msg)?;
// json: {"Text":{"msg":"Hello world!"}}
```

Serde example (3)

```
rmp_serde::to_vec(&msg)?;
// msgp: 81A45465787491AC
//       48656C6C6F20776F
//       726C6421
```

Serde example (4)

```
#[derive(Serialize, Deserialize)]
#[serde(tag = "type")]
enum Message {
    Ok,
    Text{msg: String},
}

// json: {"type":"Text","msg":"Hello world!"}
// msgp: 92A4546578 74AC48
//       656C6C6F20776F72
//       6C6421
```

Serde example (5)

```
#[derive(Serialize, Deserialize)]
#[serde(untagged)]
enum Message {
    Ok,
    Text{msg: String},
}

// json: {"msg":"Hello world!"}
// msgp: 91AC48656C6C6F20
//       776F726C6421
```

What we want from serialization tools

- Simple (complexity is danger)
- Expressive (avoids writing custom sub-parsers)
- Cross-platform and cross-language type agreement
- Backwards compatibility (new code)
- Streamable parsing
- Pluggable

Postel's law

> *"2.10 Robustness principle: [. . .] be conservative in what you do, be liberal in what you accept from others."*
>
> — *RFC 761, Transmission Control Protocol*

- Great idea for making systems work together
- Often bad for cryptographic systems
- Example: YAML v1.1
  - `name: peter` is a string
  - `name: yes` is a boolean
  - Requires very careful parsing and generating

YAML's country surprise

```
countries-iso:
- SE
- NO
- FI
```

ASN.1

- Abstract Syntax Notation One (ASN.1) is an interface description language
  - Independent of used computer architecture and language
- Used in many specifications such as X.509, LDAP, ...
- Many features handy for cryptography such as constraints on values and arbitrary-precision integers
- Supports different encodings
  - Basic Encoding Rules (BER)
  - Distinguished Encoding Rules (DER, subset of BER)
  - XML Encoding Rules

ASN.1 example (1)

```
MyModule DEFINITIONS ::= BEGIN
    Message ::= CHOICE {
        ok OKMessage,
        text TextMessage
    }

    OKMessage ::= NULL

    TextMessage ::= SEQUENCE {
        message UTF8String (SIZE(0..1024))
    }
END
```

ASN.1 example (2)

```
import asn1tools

for codec in ('der', 'xer', 'jer'):
    mod = asn1tools.compile_files('module.asn', codec)
    msg = mod.encode(
        'Message',
        ('text', {'message': 'Hello'})
    )

    with open(f"message.{codec}", 'wb') as f:
        f.write(msg)
```

ASN.1 example (3)

```
$ xxd -c9 message.der
00000000: 3007 0c05 4865 6c6c 6f  0...Hello
```

```
<Message>
    <text><message>Hello</message></text>
</Message>
```

```
{"text": {"message": "Hello"}}
```

Popular serialization formats

JSON	▶ Human readable and flexible ▶ Few built-in types (no support for, e.g. dates)
MessagePack	▶ "Binary JSON encoding" (concise and fast) ▶ Compact encoding and less ambigious encoding
protobuf	▶ Efficient binary format by Google ▶ Schema required (compiled)
ASN.1	▶ Complex standard for telecom/crypto ▶ Multiple encodings (BER, DER, etc.) ▶ Platform independent
CBOR	▶ Concise and fast ▶ Extensible without schema

Other deserialization challenges

- Protection against resource exhaustion and Denial of Service (DoS) attacks
- Defense against ZIP bombs (e.g. compressed long, repetitive strings or recursive archives)
  - Limit expansion and deny nested compression
  - Less of a problem with streaming processing
- Handling recursive encodings and references
  - Avoid formats that allow clever references
  - Detect cycles and/or limit stack size

PSA: Universally Unique Identifier (UUID)

`d37b6a75-0419-11f0-9ba1-f875a40a2c42`

- Created to uniquely identify objects (128 bits) and designed to avoid conflicts.
- Different versions exist:
  - V1: 48-bit MAC address + 60-bit timestamp
  - V4: 6-bit version + 122-bit random number
  - V7: 6-bit version + 48-bit timestamp + 74-bit counter/random
- Do not assume that a UUID is a valid cryptographic secret! For instance, it is not uniformly random and subsequent UUIDs can be predicted.

Password-based key derivation functions

- We cannot use the passphrase directly as a key, as it is not uniformly random. However, we can fix that using a KDF.
- Problem: the min-entropy is low and hence passwords are vulnerable to brute-force attacks
- Solutions:
  - Generate high-entropy passphrases for the user
  - Making the password derivation step intentionally expensive

Generating high-entropy passphrases (EFF)

- EFF word list: $|L| = 6^5 = 7776$ words
  - Also called "dice list"
  - Chosen to avoid pairs of words that are similar (e.g. "build" and "built")
- Single word provides: $\log_2(6^5) = 12.92$ bits
- For 128-bit security we need 10 words:

"snowfield enamel subtext awkward viscous yippee hardly clamshell deploy anew"

Generating high-entropy passphrases (BIP 39)

- BIP 39 word list: $|L| = 2048$ words
  - Each word uniquely identified by its first 4 letters
- Single word provides: $\log_2(2048) = 11$ bits
- For 128-bit security we need 12 words:

"wild artefact gossip float pelican novel toddler salute dish agent actor figure"

"wild arte goss floa peli nove todd salu dish agen acto figu"

Let us make things slower

- Hash function $H(pw)$: 10,000s of millions per second
- PBKDF1: $H(H(...H(pw)))$
- PBKDF2: combine intermediate results using XOR and allow for variable output length
  - Single guess cannot be parallelized
  - However, multiple guesses can be parallelized using GPUs / ASICs
- Adversary scales with computation speed

Adversary with compute power (cloud GPU)

Assume:

- GPU computes 100 GHash/s (NVidia H100)
- Adversary rents 1,000 GPUs

In one day the adversary can make:

- $\approx$ 8.6 quintillion guesses ($\approx$ 63 bits)

LAB: Design a memory hard function

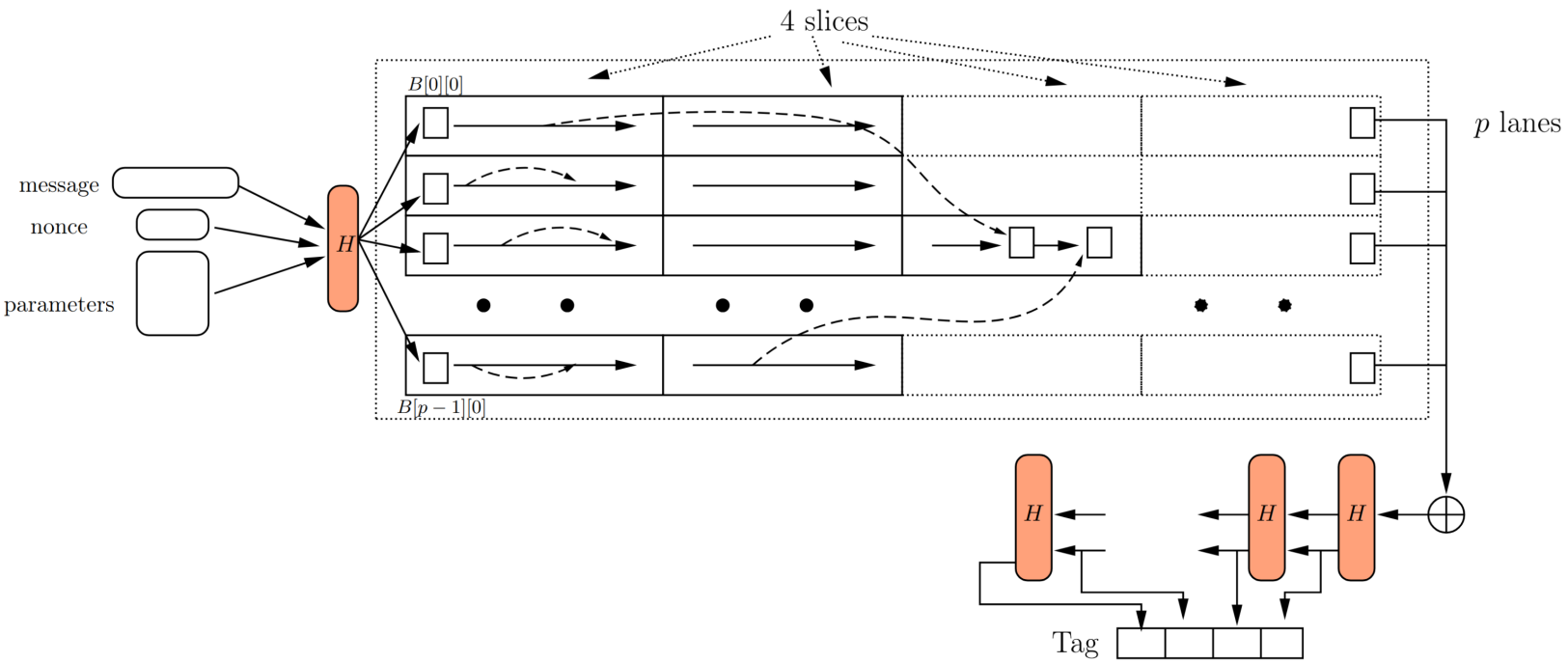
Challenge: design a function that is memory hard! It should take a password and have the following requirements:

- Easy to compute if you have 100 MiB space
- Hard to compute if you have much less than that

5 min to think about it and then we'll gather and discuss solutions

Argon2 (RFC 9106)

- Parameters: memory, number of iterations, parallelization
- 2+1 version: Argon2d, Argon2i, Argon2id
- Optimized for multi-core and assembly



Graphic from https://www.password-hashing.net/argon2-specs.pdf

Why optimize an intentionally slow step?

- Hardness relies on difficulty of the underlying problem. Not our implementation!
- Making it faster allows us to choose harder parameter within our acceptable bounds

$\rightarrow$ We work against an adversary which has the fastest possible computation

Cambridge HPC

Assume:

- Cambridge HPC: $\sim$500 PiB memory
- 10ms per guess, limited only by memory
- Set Argon2 memory parameter: 256 MiB

In one day the adversary can make:

- $\approx$ 104 billion guesses ($\approx$ 36 bits)

Using generated passphrases

- Adversary makes can guess up to 2^{36} passphrases per day
- We want to protect for at least 1,000 years
- Hence, we need $\log_2(2^{36} \cdot 1000 \cdot 365) \geq 55$ bit
- BIP 39 word list $\rightarrow$ 5 words

"primary boil army core robust"

Forcing strict rate limits

- Using a third-party for evaluation of the hash (e.g. OPAQUE)
  - Not suitable for local encryption (e.g. full disk encryption)
  - Or where the scheme needs to work offline
- Alternative: use a "built-in third party"
  - Secure Element part of most modern devices (especially smartphones)
  - Resist local attacks

Modern hash functions (SHA-3)

- Part of Keccak, published by NIST, 2015
- Based on a sponge construction
  - Different to Merkle–Damgård in SHA-1 and SHA-2
- Large (hidden) internal state prevents length extension

Modern hash functions (BLAKE2)

- Faster than SHA-3, based on ChaCha
- Prevents length-extension attacks by compressing the last block differently
- Argon2 uses the variant BLAKE2b

Nonces and IVs

- IVs generally assumed to be unpredictable (though not secret)
- Nonce only need to be unique, e.g. $0, 1, 2, \ldots$
- Nonce re-use is typically "catastrophic", i.e. allows an attacker to break the encryption

Example: if nonces are random, for AES-GCM (96-bit nonce) and $m = 2^{32}$ messages the chance of collision is:

$$p \approx \frac{m^2}{2 \cdot n} = \frac{2^{2 \cdot 32}}{2 \cdot 2^{96}} = 2^{-33}$$

Approach 1: counting per direction

- Party A counts 0, 2, 4, ... and party B counts 1, 3, 5, ...
- Choose A to be the one with the lexicographical lower DH input

- Simple and collision free
- Difficult to use with $n > 2$ parties and in decentralized settings
- Storage and retry mechanism go into security scope!

The Noise protocol uses 64-bit nonces (to differentiate from random and for compatibility with some ciphers)

Approach 2: nonce-reuse resistant modes

- Using a synthetic initialization vector (SIV) which depends on the nonce and the message
- Example: AES-GCM-SIV (RFC 8452)
- In case of nonce reuse, it is only revealed whether two messages are the same or not.
- Needs two passes over text (no streaming)
- "Collisions" after 2^{32} messages

Approach 3: extended nonces

- Make the nonce space very large so that collisions are unlikely
- Typically 192-bit, e.g. XChaCha20-Poly1305, XAES-256-GCM
- Increasingly popular, especially when trying to make misuse-safe APIs

Example: for XAES-256-GCM (192-bit nonce) and 2^{64} messages the chance of collision is:

$$p \approx \frac{2^{2 \cdot 64}}{2 \cdot 2^{192}} = 2^{-64}$$

LAB: Library design reflections

Topic: What third-party cryptography libraries have you worked with?

- Good aspects?
- "Interesting" aspects?
- Dangerous patterns or APIs?

Collect your thoughts for a few minutes and then we'll discuss!

Cryptographic agility

- Idea: allow upgrading the underlying cipher suites
  - Phase out old algorithms
  - Upgrade to new algorithms (e.g. PQC)

- Challenges:
  - Backwards compatibility prevents us from removing old algorithms, see e.g. SHA-1 in TLS
  - Negotiation happens early, i.e. before we establish authenticity.
  - New schemes might require larger underlying changes, e.g. allowed message size
  - Complexity! Specification, implementation, proofs, ...

Case study: JSON Web Token (RFC 7519)

- Given out to clients after authentication
- JOSE Header {"typ":"JWT", "alg":"HS256"} + claim
- HS256: HMAC using SHA-256

  "To support use cases in which the JWT content is secured by a means [...] using the "alg" Header Parameter value "none" and with the empty string for its JWS Signature value" – RFC7519

- In 2020 researchers found that many libraries "correctly" accepted `none` in production systems...

Authoritative versioning

- Idea: Each API/protocol endpoint only supports one version
- Advantages:
  - Reduces complexity by having separate endpoints $\rightarrow$ we can actually delete code!
  - No negotiation required
- Migration strategies:
  - Shadow traffic
  - Brown-outs

Opinionated libraries

- Avoid user misconfiguration and wrong usage
  - Limited choice
  - Secure defaults
  - High-level abstractions
- You have seen a few:
  - LibNacl, LibSodium, LibHydrogen
  - Noise protocol
  - Many Rust libraries
  - ...

Case study: Low-level APIs in libsodium (2025)

- Originally designed for high-level operations only
  - Users shouldn't need to know internal algorithms
- Over time, low-level functions were exposed for protocol designers
  - "a lot of code to maintain"
  - Only `--enable-minimal` builds API that is fully supported
  - Allows library consumers to avoid adding additional dependencies
- 2025: Bug in low-level point validation function.
  - High-level APIs (`crypto_sign_*`) unaffected
  - Custom protocol implementations potentially vulnerable

Pure functions

- All information and state are explicitly passed
  - Input/output parameters
  - Environment: file system, time, ...
- On embedded systems this might include
  - Memory allocation
  - Secure random generator
- Added benefit: drastically simplifies testing!

Managing secret life times

- We want to minimize the lifetime of secrets in memory
  - Quickly transform into derived secrets
  - "Erase" memory
- Have the language help us with this
  - Rust: `Drop` handler
  - C++: RAII pattern
  - Java: `AutoCloseable`, `finalize`
  - ...
- Difficult in user interfaces which are often not under our control
  - Also, side-channels such as keyboard predictions

Rust

- `Drop` handler can automatically erase memory
- Non trivial: making sure the compiler does not optimize this step away

```
use zeroize::{Zeroize, ZeroizeOnDrop};

#[derive(ZeroizeOnDrop)]
struct SessionKey { bytes: [u8; 16] }
```

This is harder in non-native languages

- Java/... do not provide direct access to memory
- The GC might inadvertely copy our secrets

```
pw = byte[16];
read_pw(pw);

// do work

Arrays.fill(pw, 0);
```

This is harder in non-native languages

- Use `ByteBuffer` or equivalent to manage directly allocated memory

```
pw = ByteBuffer.allocateDirect(16);
read_pw(pw);

// do work

pw.rewind();
pw.put(new byte[16]);
```

This is harder in non-native languages

Add safety by using `finalize` method which is (supposed to be) called just before an object is garbage collected.

- Variant A: perform the operation for the user (might be delayed or unreliable)
- Variant B: cause crashes in debug builds (see e.g. Android's strict mode)

Locking memory

- Prevent swapping out to disk
  - Extra motivation why swap should always be encrypted
- On Linux we have to simple call `mlock` and `munlock`

```
int mlock(const void *addr, size_t len);
int munlock(const void *addr, size_t len);
```

Case study: crash dump leak (MS STORM-0558)

- Microsoft has an isolated production environment for signing final artifacts
- A crash dump from this environment was exported for investigation
  - Usually, secrets are filtered out from crash dumps (this was broken)
  - Usually, secrets would be detected and revoked by other systems (this was broken)
- Attackers had access to the investigation machine which was outside the isolated environment
- Libraries did not automatically validate the key scope
- Result: attackers were able to access enterprise emails using forged tokens.