Introduction to cryptology (GBIN8U16)

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Public-Key Cryptography: Discrete logarithm-based schemes

Pierre Karpman
pierre.karpman@univ-grenoble-alpes.fr
https://www-ljk.imag.fr/membres/Pierre.Karpman/tea.html

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How to get a key

So far we assumed the presence of a shared secret between participants, but how do you get there?

Some possibilities

- Meet in person (impractical)
- Use secure message transmission (not so practical (but very nice!))
- Use asymmetric “public-key” schemes (quite practical) $\leftsquigarrow$ our focus now!

Public-key algorithms

Some major examples:

- Asymmetric encryption (one key to encrypt, another to decrypt), e.g. RSA (+ some randomized padding)
- Digital signature (one key to sign, another to verify), e.g. DSA
- Public-key key exchange, e.g. Diffie-Hellman

Note: RSA can be used to implement both a key-exchange and a signature

Group definitions

Finite cyclic group (*multiplicative notation*)

A finite group $\mathbb{G}$ of *order* (or cardinality) N is *cyclic* if $\exists\, g \in \mathbb{G}$ s.t. $\forall\, x \in \mathbb{G}, \exists\, i \in [\![0, N-1]\!]$ s.t. $x = g^i$. Such an element g is called a *generator* (or primitive element) of the group.

Properties

- Any element h of $\mathbb{G}$ generates a subgroup $\mathbb{H} := \langle h \rangle$. The order $\mathrm{ord}(h)$ of h is defined as the order (or cardinality) of $\mathbb{H}$. If $\mathbb{H} = \mathbb{G}$, h is a generator of the full group $\mathbb{G}$.
- A group may have several generators.
- (Lagrange Theorem) If $\mathbb{H}$ is a subgroup of $\mathbb{G}$, $\#\mathbb{H} \mid \#\mathbb{G}$ (Corollary: if $\#\mathbb{G}$ is prime, all elements except 1 are primitive)

Group examples

An additive group:

- $(\mathbb{Z}/512\mathbb{Z}, +)$, $g = 1$, $\mathrm{ord}(g) = 512$

Any multiplicative group of a finite field (and more):

- $\mathbb{F}_{257}^{\times}$, $g = 3$, $\mathrm{ord}(g) = 256$
- $(\mathbb{F}_2[X]/X^8 + X^4 + X^3 + X^2 + 1)^{\times}$, $g = X$, $\mathrm{ord}(g) = 255$
- $(\mathbb{Z}/n\mathbb{Z})^{\times}$, of order $\varphi(n)$ (= n – 1 when n is prime)
  - Cf. the extended Euclid algorithm... later!

Today's focus: Diffie-Hellman

A simple protocol:

- Let $\mathbb{G} = \langle g \rangle$ be a cyclic finite group with a generator g
- A picks $a \xleftarrow{\$} [\![0, \mathrm{ord}(g) - 1]\!]$, sends g^a to B
- B picks $b \xleftarrow{\$} [\![0, \mathrm{ord}(g) - 1]\!]$, sends g^b to A
- A computes $(g^b)^a = g^{ba} = g^{ab}$, sets $k = \mathrm{KDF}(g^{ab})$
- B computes $(g^a)^b = g^{ab}$, sets $k = \mathrm{KDF}(g^{ab})$

With KDF some *key derivation function* (e.g. a $\sim$ hash function)

Why this works?

Functionality

- A and B only need public information to perform the exchange
- They get the same k

$\Rightarrow$ Public-key key exchange

Security: necessary conditions

- Given g, g^a, g^b, it must be hard to compute g^{ab}
- $k = \mathrm{KDF}(g^{ab})$ must be "random-looking" when a, b are random
- (Related: there must be many possible values for k)

Security focus

A necessary condition: computing *discrete logarithms* in $\mathbb{G}$ must be "hard"

Discrete logarithm

Let $\mathbb{G} = \langle g \rangle$ be a finite group of order N, the *discrete logarithm in base g* of $h = g^a$, $a \in [\![0, N-1]\!]$ is defined as a

How hard is the "discrete logarithm problem" (DLP) for various groups?

DLP hardness

Proposition

It is always possible to compute the discrete logarithm in a group of order N in time $O(\sqrt{N})$

So one must *at least* pick N s.t. $2^{\log(N)/2}$ is large. But:

- $(\mathbb{Z}/n\mathbb{Z}, +)$: DLP always easy (logarithm $\equiv$ division)
- $\mathbb{F}_q^\times$: usually hard, not *maximally* hard (needs much less work than $\sqrt{N}$)
- $E(\mathbb{F}_q)$: usually maximally hard (needs about $\sqrt{N}$)

A simple generic algorithm

Idea: use *collisions* to reveal the solution. One way to do this: baby-step/giant-step

- Let $\mathbb{G}$ be of order N, $h = g^a$ for some $a \in [\![0, N-1]\!]$
- Let $r = \lceil \sqrt{N} \rceil$, then $a = ra_1 - a_0$, with a_0, a_1 less than r
- We have $h = g^{ra_1 - a_0}$, so $hg^{a_0} = g^{ra_1}$

$\Rightarrow$

1. Compute $L_0 = [hg^x, x < r]$, $L_1 = [g^{ry}, y < r]$
2. Find i, j s.t. $L_0[i] = L_1[j]$
3. Return $a = rj - i$

Baby-step/giant-step: Comments

- The baby-step/giant-step algorithm works *with any* group
- It has time and memory complexity equal to $\sqrt{\mathrm{ord}(\mathbb{G})} \Rightarrow$ generically optimal!
- It can easily be parallelised
- It can easily be adapted when the logarithm is know to lie in a "small" interval
- Other collision-based algorithms exist with constant or small memory complexity (such as Pollard's ρ (also parallelisable) or kangaroos)!
- Depending on $\mathbb{G}$, better algorithms may be available (we've seen some examples)

More on how to pick a group

If the order N of $\mathbb{G}$ is not prime, $\mathbb{G}$ has *subgroups*

- Let $N = pN'$, then g^p generates a group of order N'

Proposition (Pohlig-Hellman)

It is possible to solve the DLP in $\mathbb{G}$ subgroup-by-subgroup

$\Rightarrow$ For the DLP to be hard, $\mathbb{G}$ must be of order N s.t. DLP is hard in a subgroup of order p, the largest prime factor of N (But no details for now)

Are we done? Not quite

- Hardness of the DLP cannot be “proven”, but a reasonable assumption for some groups
- We also need g^x to be random-looking (ditto)

But regardless, Diffie-Hellman as presented only protects againts *passive* adversaries

⇒ Not very useful in practice

Diffie-Hellman with a man in the middle

- A sends g^a to B
  - C intercepts the message, sends g^c to B
- B sends g^b to A
  - C intercepts the message, sends g^c to A
- A and C share a key $k_a = \mathrm{KDF}(g^{ac})$
- B and C share a key $k_b = \mathrm{KDF}(g^{bc})$
- Anytime A sends a message to B with key k_a, C decrypts and re-encrypts with k_b (and vice-versa)

One way to solve this: signatures

A wants to be sure it is talking to *B*

- Find *B*'s public verification key for a *signature* algorithm
- Ask *B* to sign g^b
- Only accept it if the signature is valid

Works well, but A needs to know B's public key *beforehand*

⇒ We again have a bootstrapping issue

So are we back to square one?

Public-key infrastructures can help

Public keys still help compared to private ones:

- Possibly long term (v. have to be changed after a while (although not a real limitation))
- Scales linearly w/ the number of participants (v. quadratically)
- Trusting only one key is enough, if it signs all the ones you need!

Example: TLS certificates

The simple picture:

- Web browsers are pre-loaded with "certificates" ($\sim$ public keys) of certification authorities (CAs)
- CAs sign the certificates of websites using secure connections (possibly using intermediaries)
- When connecting to a website, check the entire chain of certificates
- If everything's fine, use the website's public key to authenticate the exchange

So how do we sign?

Signature possibilities

- Use a discrete logarithm based protocol
- Or RSA
- But in both cases, also need a hash function!

Signatures: what?

Objectives of a signature algorithm:

- Given $(\mathrm{sk}, \mathrm{pk})$ a key pair
- message m + secret key $\mathrm{sk} \rightsquigarrow$ signature $s = \mathrm{S}_{\mathrm{sk}}(m)$
- message m + signature s + public key $\mathrm{pk} \rightsquigarrow$ verified message $\mathrm{V}_{\mathrm{pk}}(m, s)$

Informal security objectives

- Given pk, it should be hard to find sk
- Given pk, it should be hard to forge signatures
- (Variant: given access to a signing oracle $\mathbb{O}_{(\mathrm{sk},\mathrm{pk})}$, it should be hard to forge signatures)
- Formalised as *Existential unforgeability under chosen-message attacks* (EUF-CMA)

EUF-CMA for Public-Key signatures

EUF-CMA for (S, V): An adversary cannot forge a valid signature σ for a message m such that $\mathrm{V}(pk_C, \sigma, m)$ succeeds, when given (restricted) oracle access to $\mathrm{S}(sk_C, \cdot)$:

1. The Challenger chooses a pair (pk_C, sk_C) and sends pk_C to the Adversary
2. The Adversary may repeatedly submit queries m_i to the Challenger
3. The Challenger answers a query with $\sigma_i = \mathrm{S}(sk_C, m_i)$
4. The Adversary tries to forge a signature σ_f for a message $m_f \neq_i m_i$, s.t. $\mathrm{V}(pk_C, \sigma_f, m_f) = \top$

Related: interactive proof of identity

Objective of a proof of ID scheme:

- Publish public identification data α
- When challenged, prove knowledge of a secret related to α

Example of a one-time scheme:

1. Let $\mathcal{H}$ be a preimage-resistant hash function, $\mathcal{R}$ a large set
2. The prover draws $x \xleftarrow{\$} \mathcal{R}$, computes and publishes $X = \mathcal{H}(x)$
3. When challenged, reveals x

Many-time variant:

1. Draw $x \xleftarrow{\$} \mathcal{R}$, compute and publish $X = \mathcal{H}^N(x)$
2. When challenged, reveal $\mathcal{H}^{N-1}(x)$, reset $X = \mathcal{H}^{N-1}(x)$

A discrete-log based PoID scheme

1. Let $\mathbb{G} = \langle g \rangle$ be a group with a hard DLP
2. The prover draws $x \xleftarrow{\$} \mathcal{R}$, computes and publishes $X = g^x$
3. When challenged; draws r, sends $R = g^r$
4. The verifier picks c and sends it
5. The prover computes $a = r + cx$ and sends it
6. The verifier checks that $RX^c = g^a$

This can be run many times, BUT r's should be *uniformly* random and never repeat!

From PoID to signature

Differences between PoID and signatures:

- PoIDs are interactive (in the verification), signatures are not
- Signatures also involve a message

One major observation:

- If the prover can guarantee that it doesn't control *both* R and c, interaction is unnecessary
- (Otherwise, nothing is proved)

$\Rightarrow$ Fiat-Shamir transformation: generate c from R with a hash function

Schnorr signatures

To sign a message m with the key pair $(\mathrm{sk}, \mathrm{pk})$ $(x, X = g^x)$

1. Pick $r \xleftarrow{\$} \mathcal{R}$ and compute $R = g^r$
2. Compute $c = \mathcal{H}(R, m)$
3. Compute $a = r + cx$ and output (c, a) as the signature of m

To verify a signature:

1. Compute $\hat{R} = g^a / X^c = g^a / g^{cx}$
2. Check that $c = \mathcal{H}(\hat{R}, m)$

Important: r must (again) be ***uniformly*** random and not repeat! (Why?)

Remember randomness (always)!

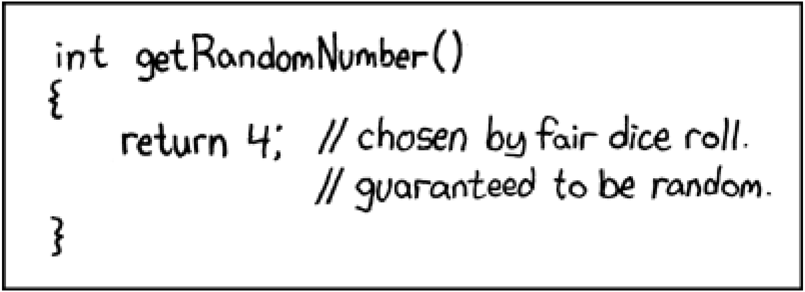

Figure: Not good for Schnorr signatures

Where are we with dlog?

If $\mathbb{G} = \langle g \rangle$ is a prime-order group where the DLP is hard (on average $\equiv$ in the worst case), then:

- Can do asymmetric key exchange
- Can do public-key signatures

For signatures we also need

- Good hash functions
- Good pseudorandom number generation (for “classical” signature algorithms)

What if I don't trust my PRNG?

- Typical dlog-based signatures break easily if r is not random enough
  - Vulnerable to bad implementations or government backdoors
- But one can tweak them to generate r from the message and the private key using a VIL/VOL-PRF (either completely deterministically or not)
  - Example: RFC6979
- N.B. It is indeed fine for a signature algorithm to be deterministic (cf. also later RSA examples)
- ... But in the case of dlog-based schemes, determinism may help physical attacks

Some comments on dlog attacks

When $\mathbb{G} \approx \mathbb{F}_p^\times$, the current dlog records are:

- $|p| \approx 795$ bits (Boudot et al., 2019), using a *Number Field Sieve* (NFS) algorithm
  - Took about 3100 core years
- $|p| \approx 1024$ bits for a *trapdoored* prime (Fried et al., 2017), using a *Special NFS* (SNFS) algorithm
  - Took about 385 core years

Note: it may be hard to decide if a prime is trapdoored

One nice (for an attacker) feature of (S)NFS:

- The largest part of the cost is a *precomputation*, then computing *individual dlogs* is *very fast*

Some more comments on dlog: small subgroup attack

Consider a *semi-static* key exchange,

- Where one of g^a or g^b (say g^b) is fixed

using $\langle g \rangle \subset \mathbb{F}_p^\times$ where $\mathbb{F}_p^\times$ has many small subgroups

- Then B must check that "$\hat{g}$" sent by A is in the correct group
- Otherwise, if $\hat{g}^b$ is in a small group of order N, a malicious A can learn $b \mod N$
- ... Then $b \mod N'$, etc.

One way to easily prevent this: use $p = 2q + 1$, q a Sophie Germain prime
$\Rightarrow$ Only a small subgroup of order 2 to check for in $\mathbb{F}_p^\times$

What about implementation, though?

- We need to compute g^x, for a large x (e.g. 256 bits)
- Cannot just do $g \times g \times g \times \ldots \times g \approx 2^{256}$ times!
- Notice that $g \times g = g^2$, $g^2 \times g^2 = g^4$, $g^4 \times g^4 = g^{16}$, etc.
- Also: $g \times g^2 = g^3$, $g^2 \times g^{16} = g^{18}$, etc.

$\rightsquigarrow$ "Square & multiply" algorithm

Square & multiply

Square & multiply

Input x, g
Output g^x

1. $h = 1$
2. While $x \neq 0$
3.   if $(x \& 1)$
4. $h \leftarrow h \times g$
5. $g \leftarrow g \times g$
6. $x \leftarrow x \gg 1$
7. Return h

$\Rightarrow$ Only $\log(x)$ iterations needed!
(Problem here, runtime also depends on $\mathrm{wt}(x)$)

Implementation: what else?

- We also need multiplication, addition in $\mathbb{G}$
- If $\mathbb{G} \subseteq \mathbb{F}_p^\times \Rightarrow$ modular arithmetic
- Require big number multiplication, (integer) division, remainders, addition
- $\Rightarrow$ split f as e.g. $f_0 + 2^{64} f_1 + 2^{128} f_2 + \dots$
- Can use dedicated arithmetic for "efficient" primes (e.g. efficient Barrett reduction)