Towards a Quantum-Safe Central Bank Digital Currency

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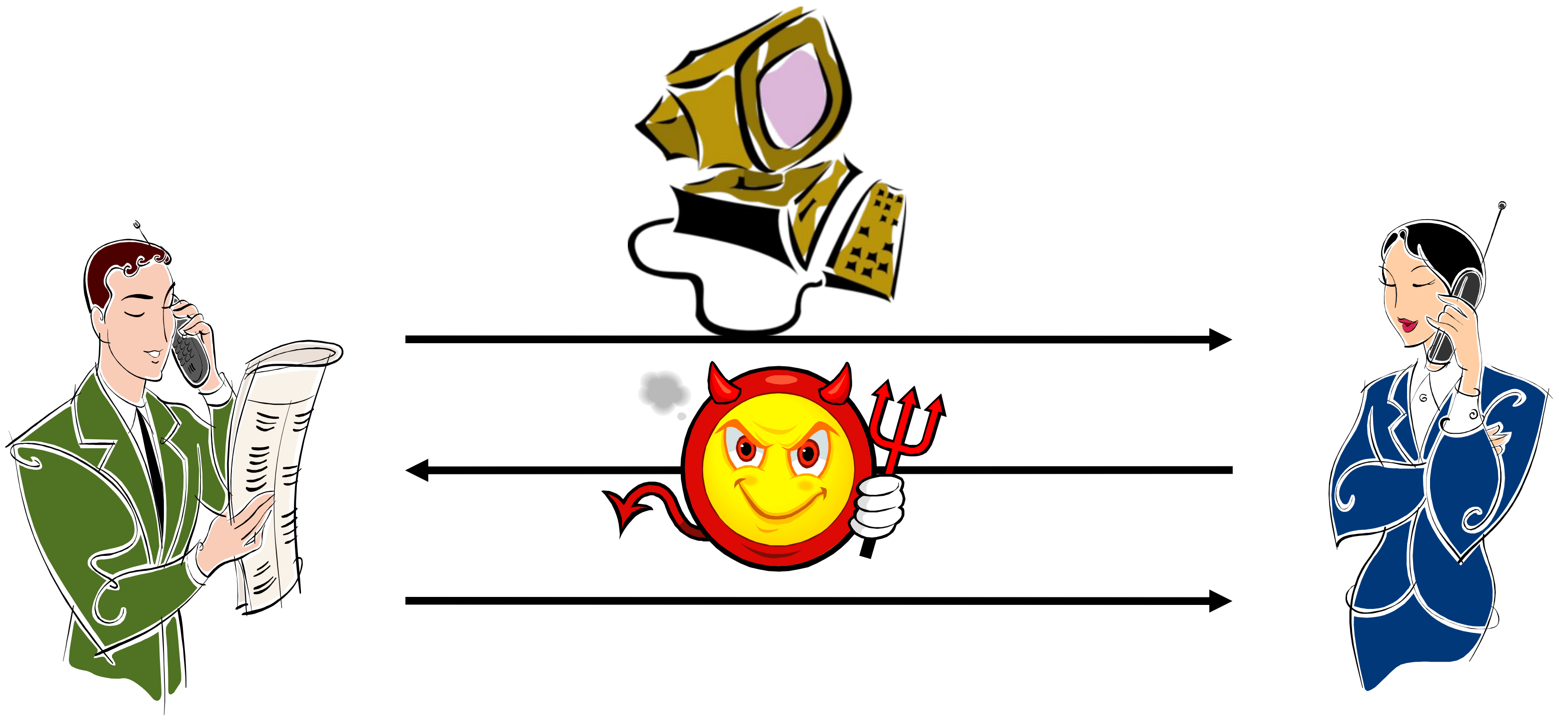
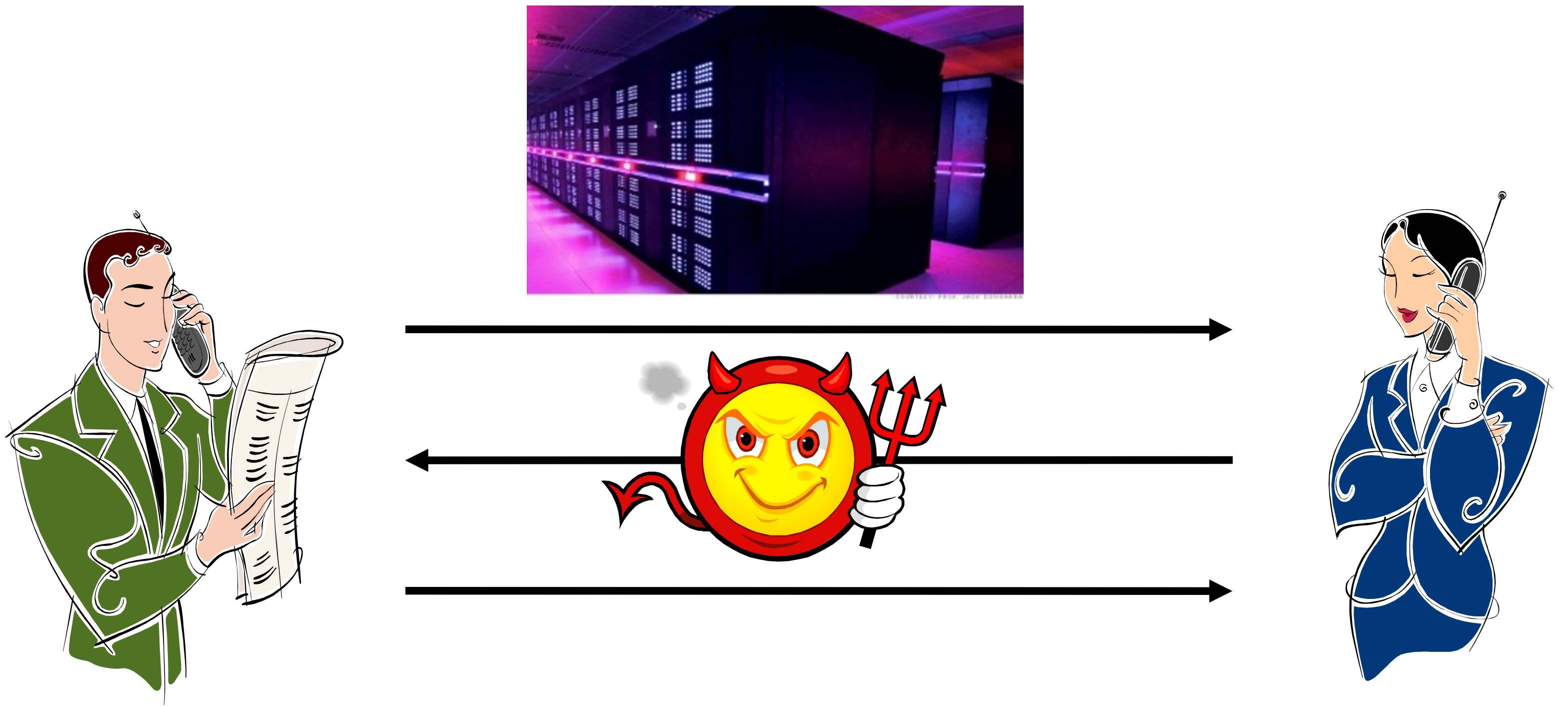
Cryptography

Allows for secure communication in the presence of malicious parties



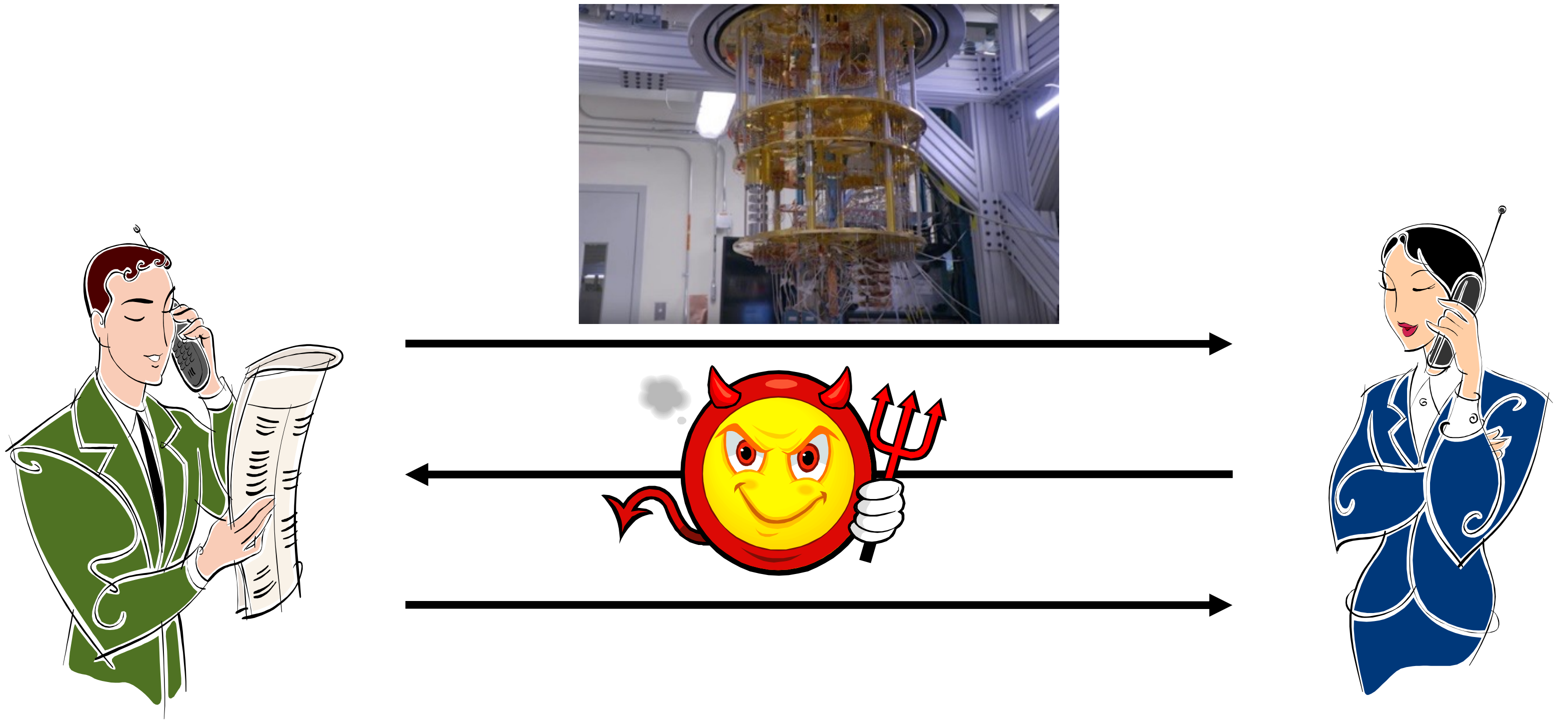
Cryptography

Large increase in the adversary's computing power requires only a small increase in the key size



Cryptography

A quantum computer is outside the classical model of computation for efficiency purposes



Symmetric-Key Cryptography

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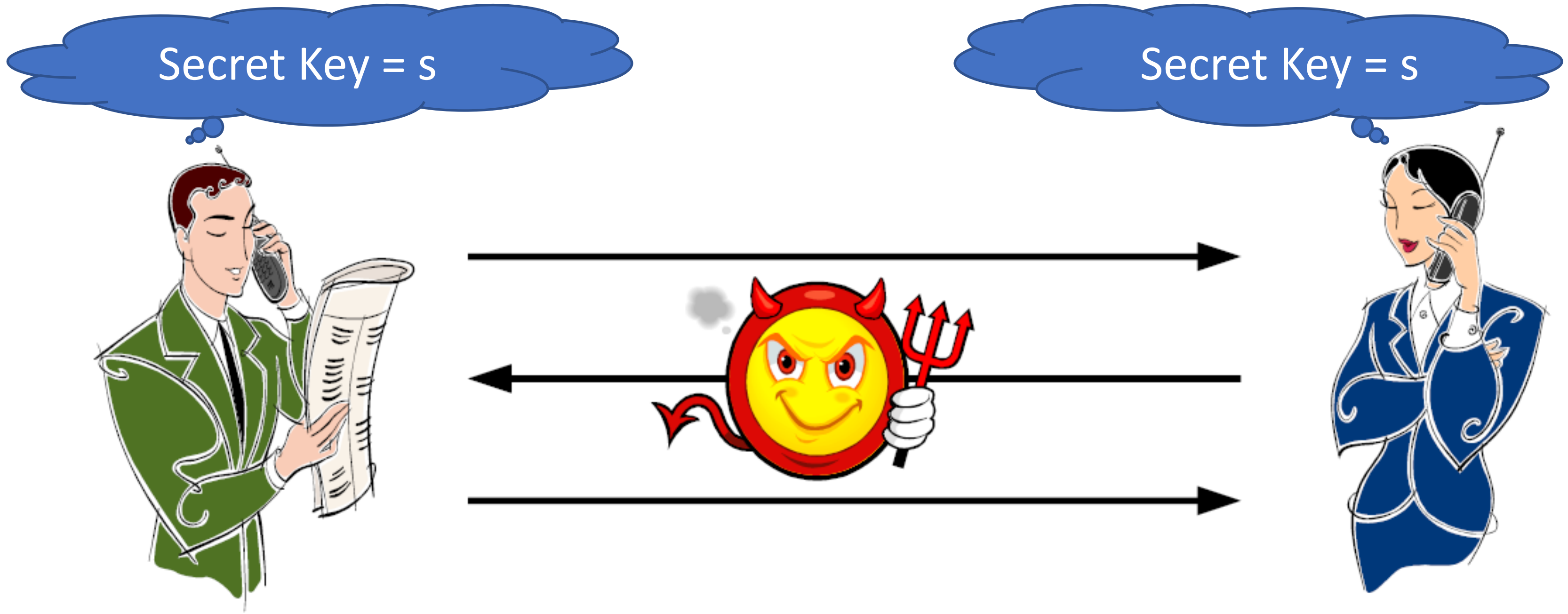
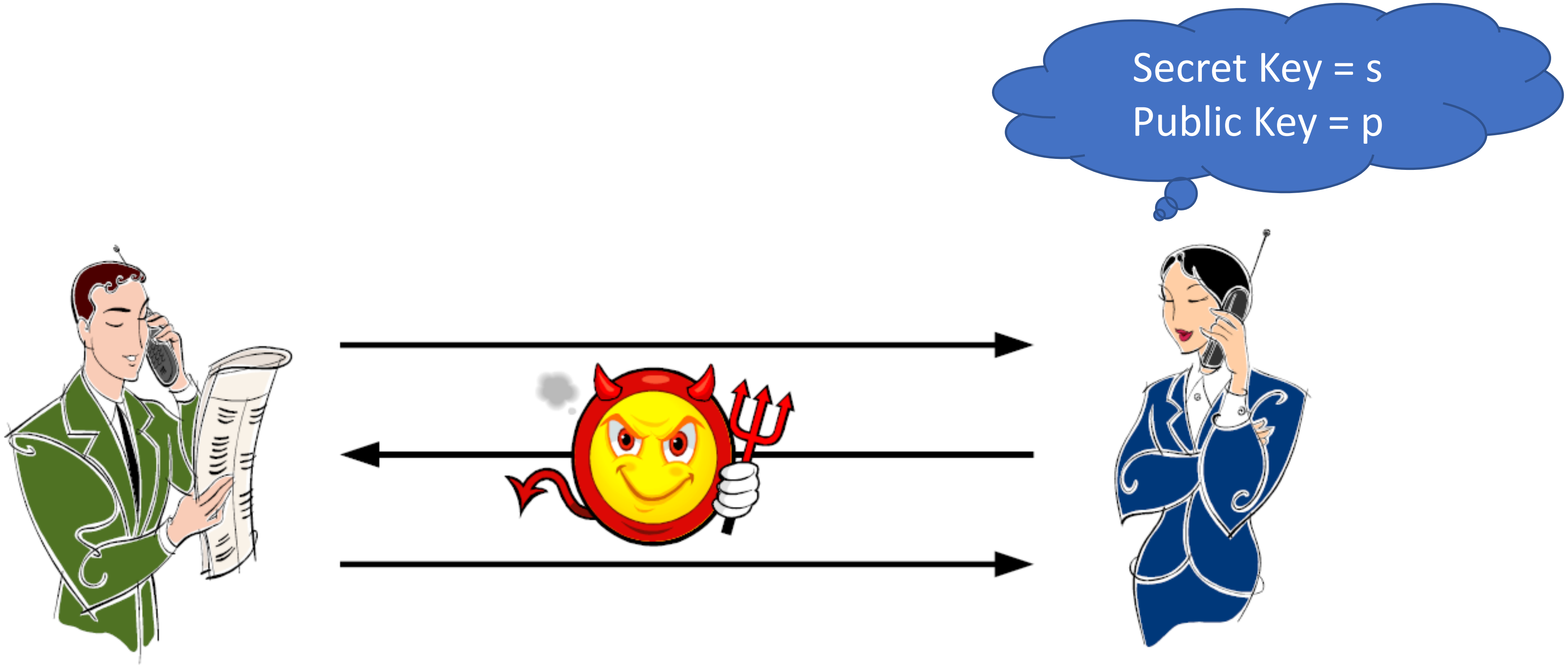
Will still exist if quantum computers are built



Public-Key Cryptography



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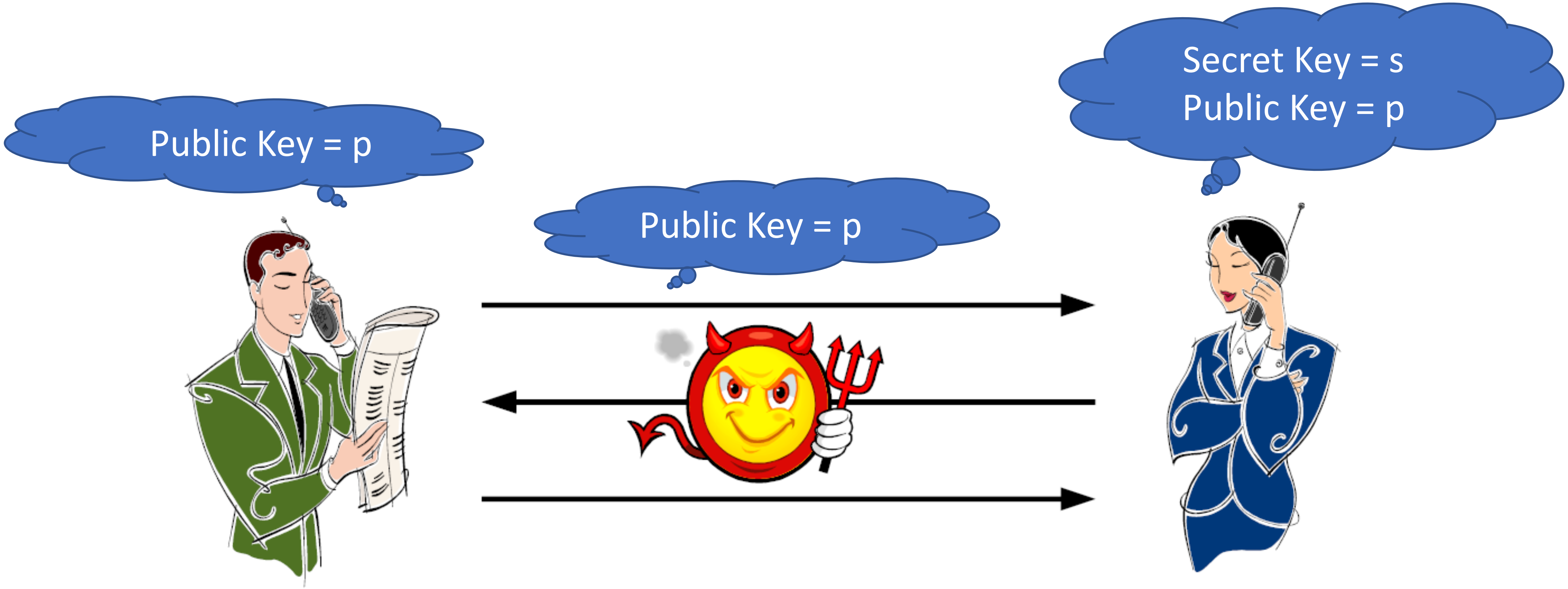


Mathematical Assumptions for Public-Key Cryptography

Factoring is hard

$N=pq$

Computing discrete logs is hard

$g^x=y \bmod p$

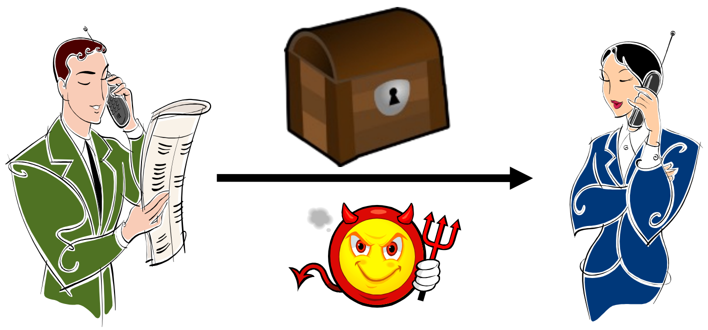
Mostly problems from number theory

All broken once a quantum computer is built

Consequence of quantum computing

Current public key schemes will be broken

Quantum computers will recover all of **today's** secrets



Do not need quantum to defend against quantum

Quantum computers are not all-powerful.

They simply solve some problems faster.

Base cryptography on problems they don’t solve.

How do we know that (quantum) computers don’t solve a problem?

We don’t … all we can say is that researchers tried to solve the problem for X decades and failed.

Categories of Quantum-Safe Crypto

No Changes Necessary

Symmetric Cryptography:

- AES
- SHA-256 / SHA-3
- HMAC
- etc.

Done.

Almost Drop-in Replacements

NIST standardizations:

- Public Key Encryption
- Key Exchange
- Digital Signatures

A few other things:

- Identity-Based Encryption

Almost standards. Ready for deployment.

Serious Alterations of Protocols Required

Advanced Primitives:

- Zero-Knowledge Proofs
- Distributed Privacy
- Many blockchain privacy applications

Lots of recent progress on design. Near-optimality has just been achieved for certain primitives. Implementation starting at ZRL.

Can Only Be Done with Lattice Cryptography

- Fully-Homomorphic Encryption (FHE) - computation over encrypted data
- Some Obfuscation (still unclear if it can be efficient or have any useful applications)

Implementation / deployment of FHE at Haifa.

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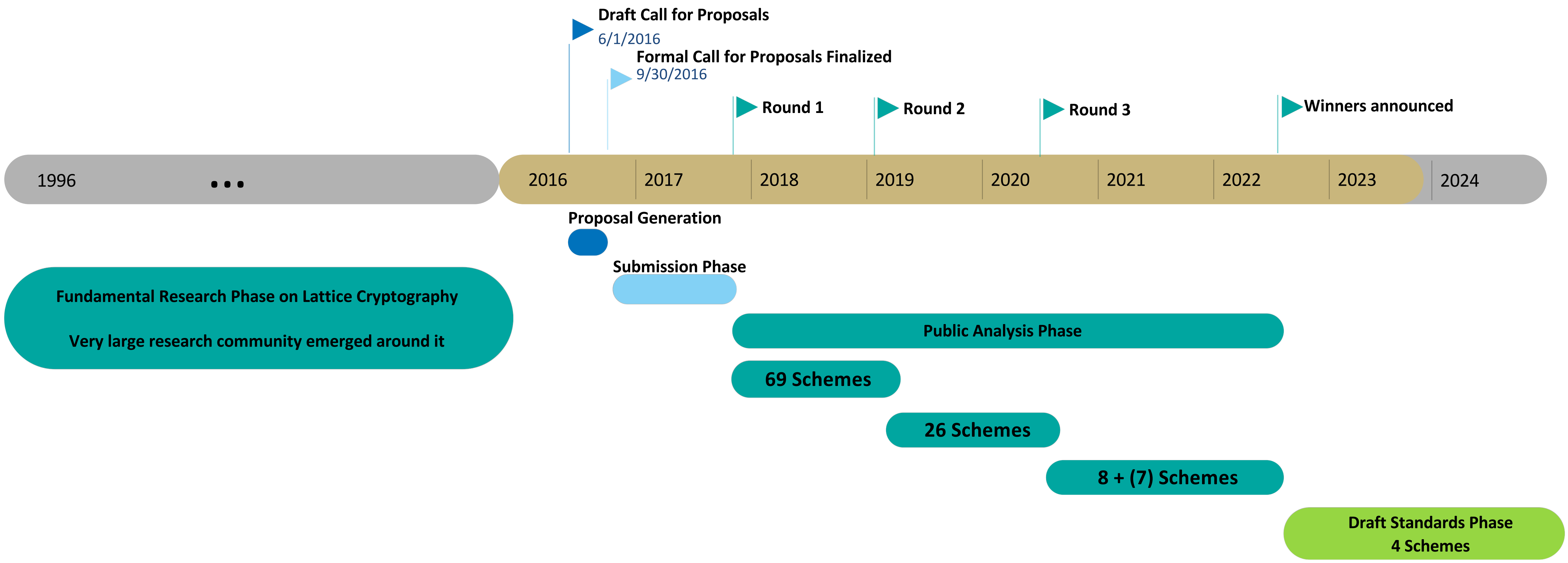
NIST Quantum Safe Standardization



NIST Selection (July 2022)

KEM (Encryption Scheme)

- CRYSTALS-Kyber — Primary

Digital Signature

- CRYSTALS-Dilithium — Primary
- FALCON — Specialized
- SPHINCS+ — Specialized

NSA Selection for CNSA 2.0 (September 2022)

KEM (Encryption Scheme)

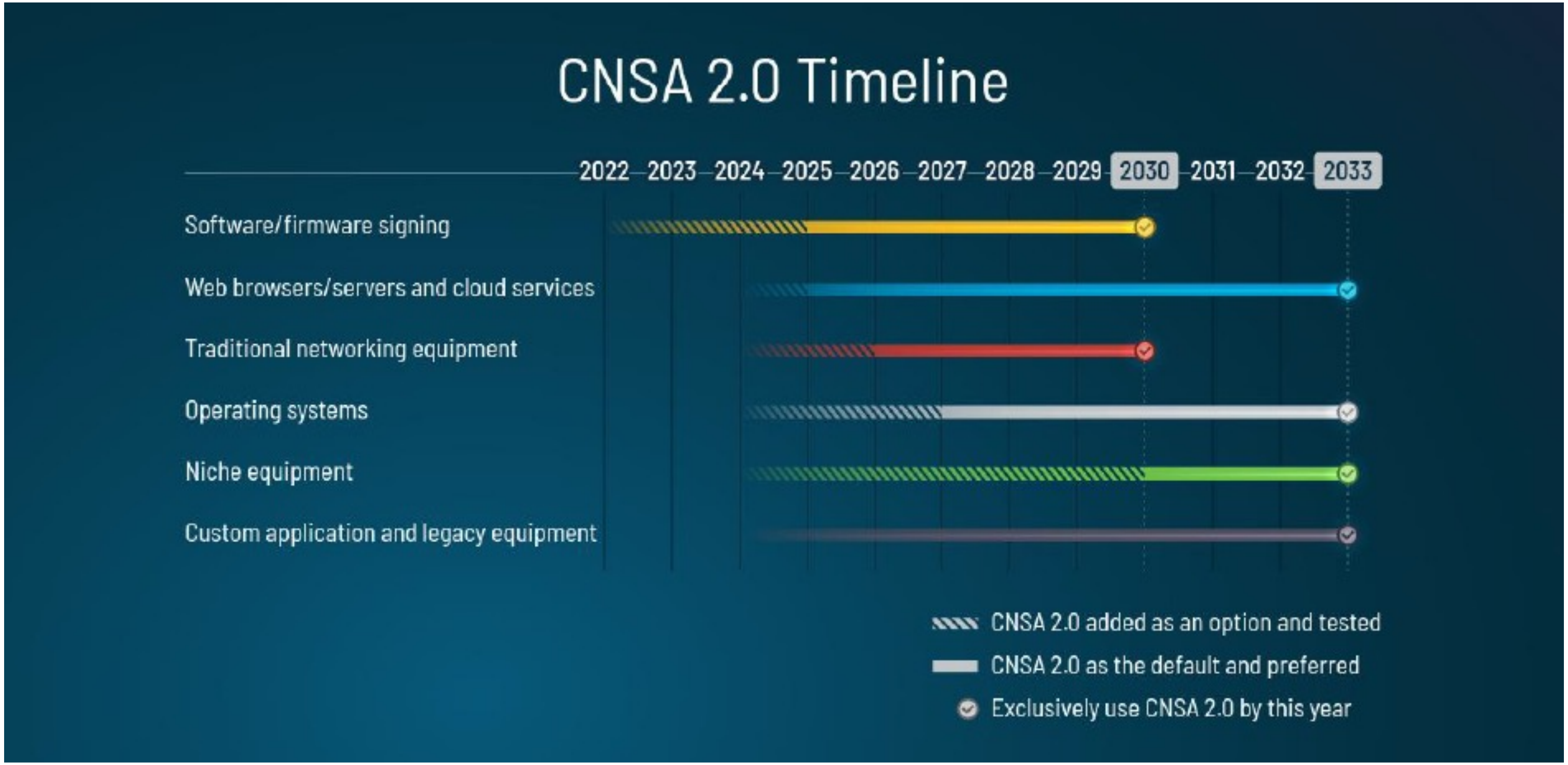
- CRYSTALS-Kyber (Security Level 5: 256-bit security target)

Digital Signature

- CRYSTALS-Dilithium (Security Level 5: 256-bit security target)
- LMS For firmware and software signing only
- XMSS For firmware and software signing only

LMS and XMSS are the **stateful** versions of SPHINCS+

Time for Transition



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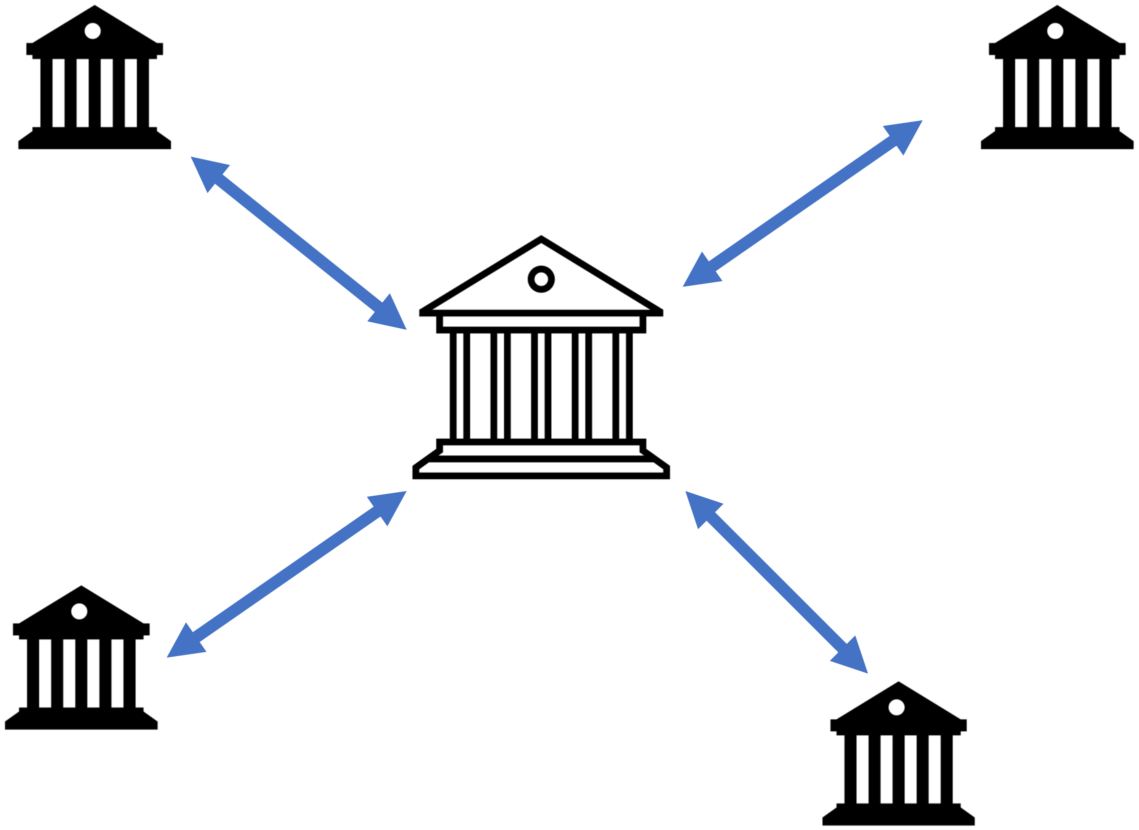
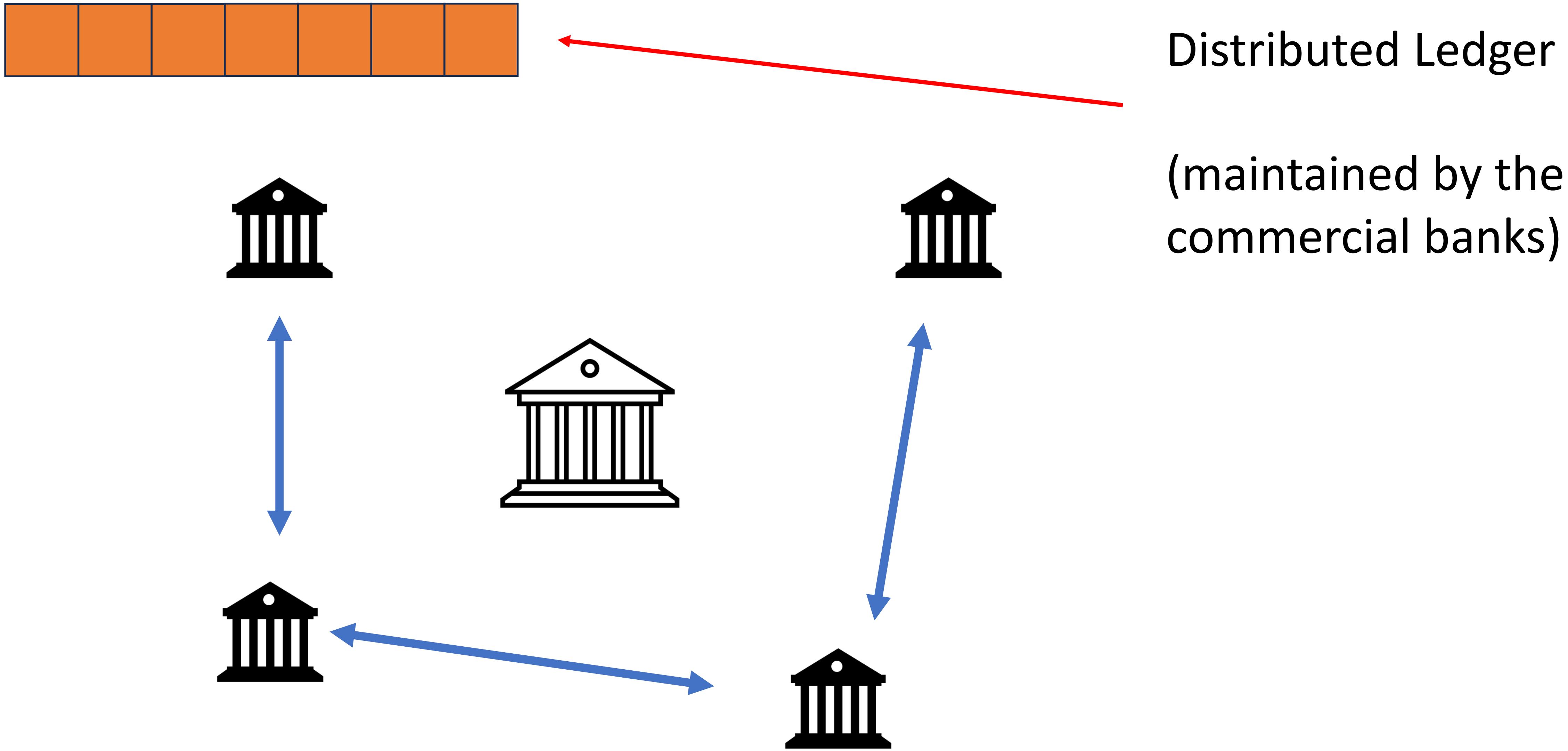
Central Bank Digital Currency

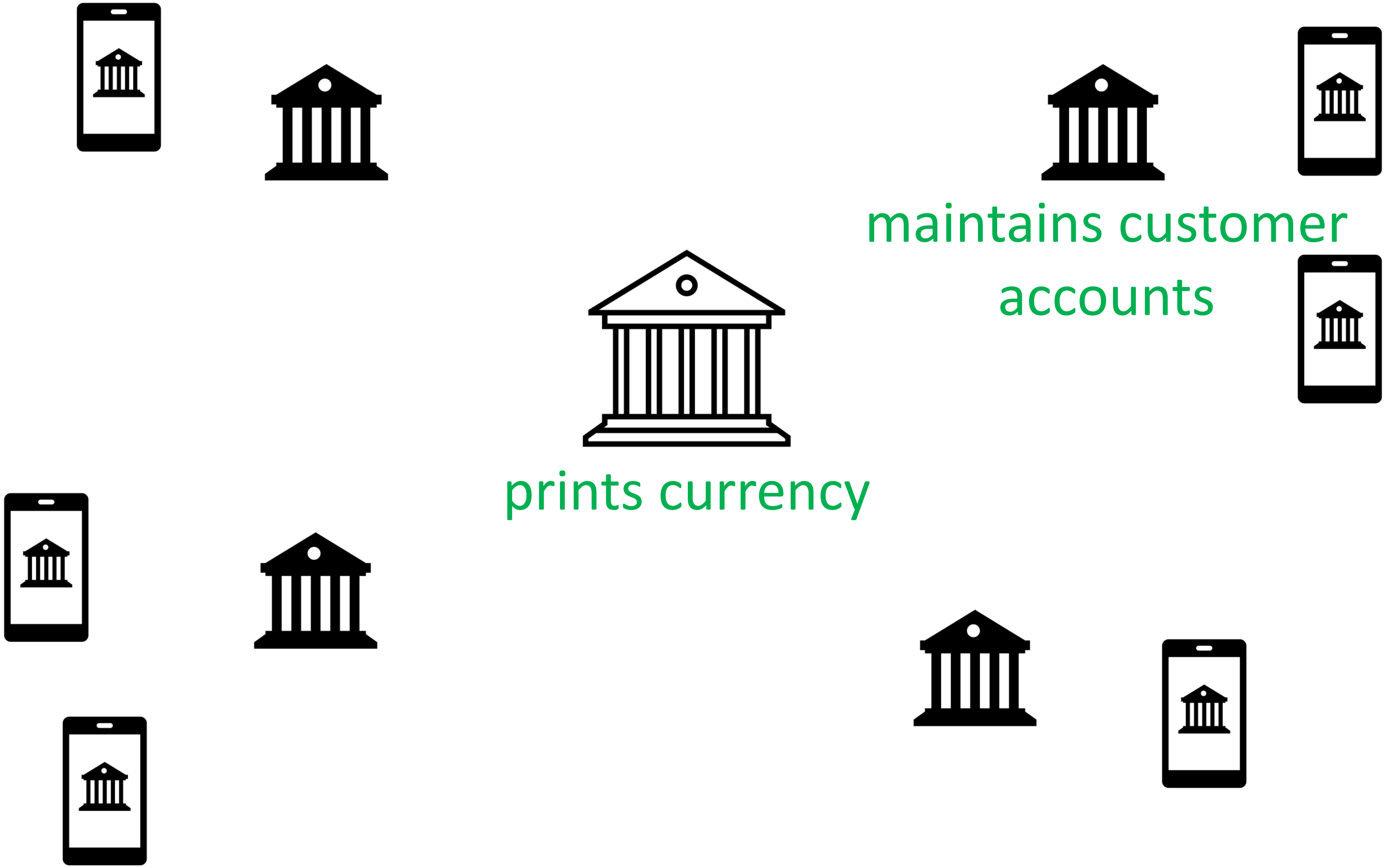
Wholesale CBDC



Wholesale CBDC



Retail CBDC – should have the privacy of cash



(Naïve) Digital Cash

My account is 12345.
Give me $1.

Signature(x)

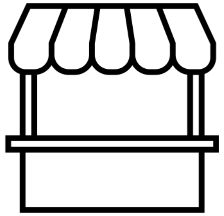
pick random x

Spent list

x

No privacy!

x, Signature(x)



check that x is not on the “spent list”

By seeing the x, the bank traces the purchase to the customer

The Blind Signature Approach

Blind Signature [Cha '82]

pick random x

My account is 12345.
Give me $1.
f(x)

BlindSignature(f(x))

Use a "blind signature" to sign f(x)

derive signature of x

Spent list

x

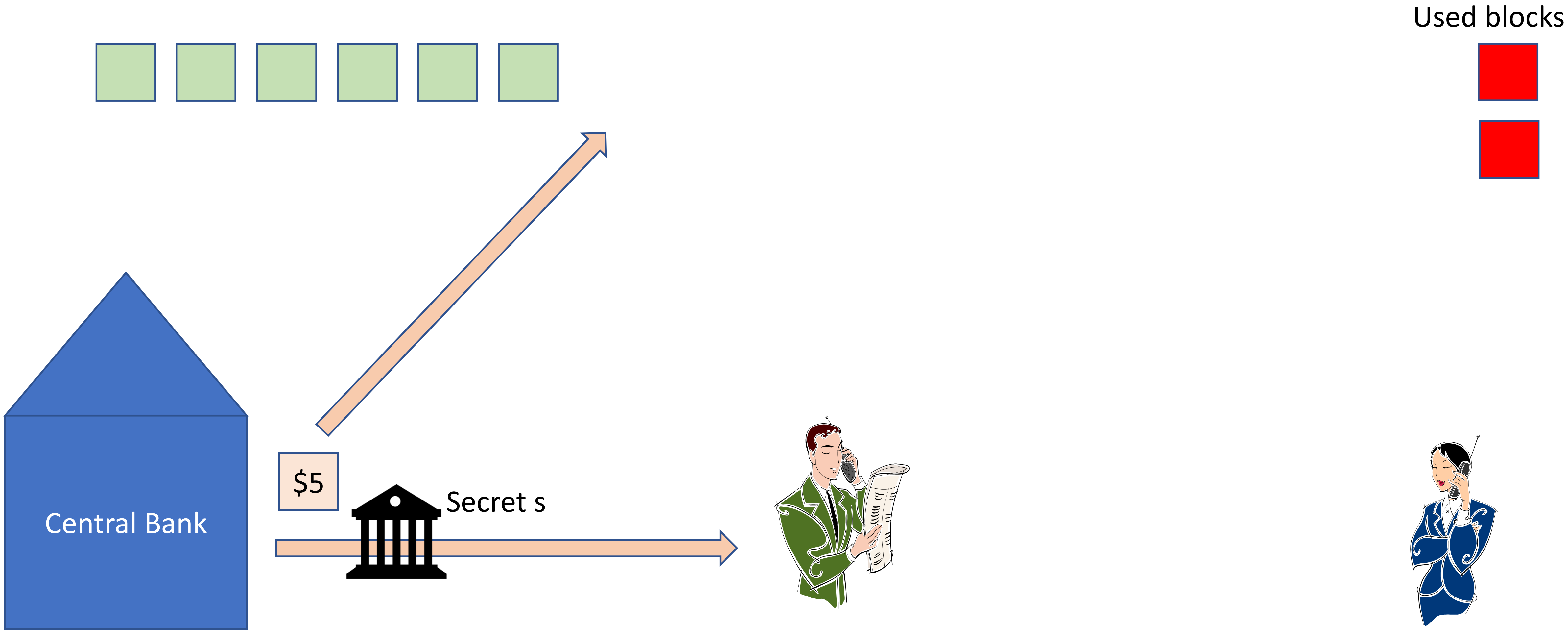
Perfect privacy! Bank cannot trace f(x) to x

x, Signature(x)

check that x is not on the "spent list"

The Zero-Knowledge Approach

Zero-Knowledge (ZK) and Central Bank Digital Currency (CBDC)



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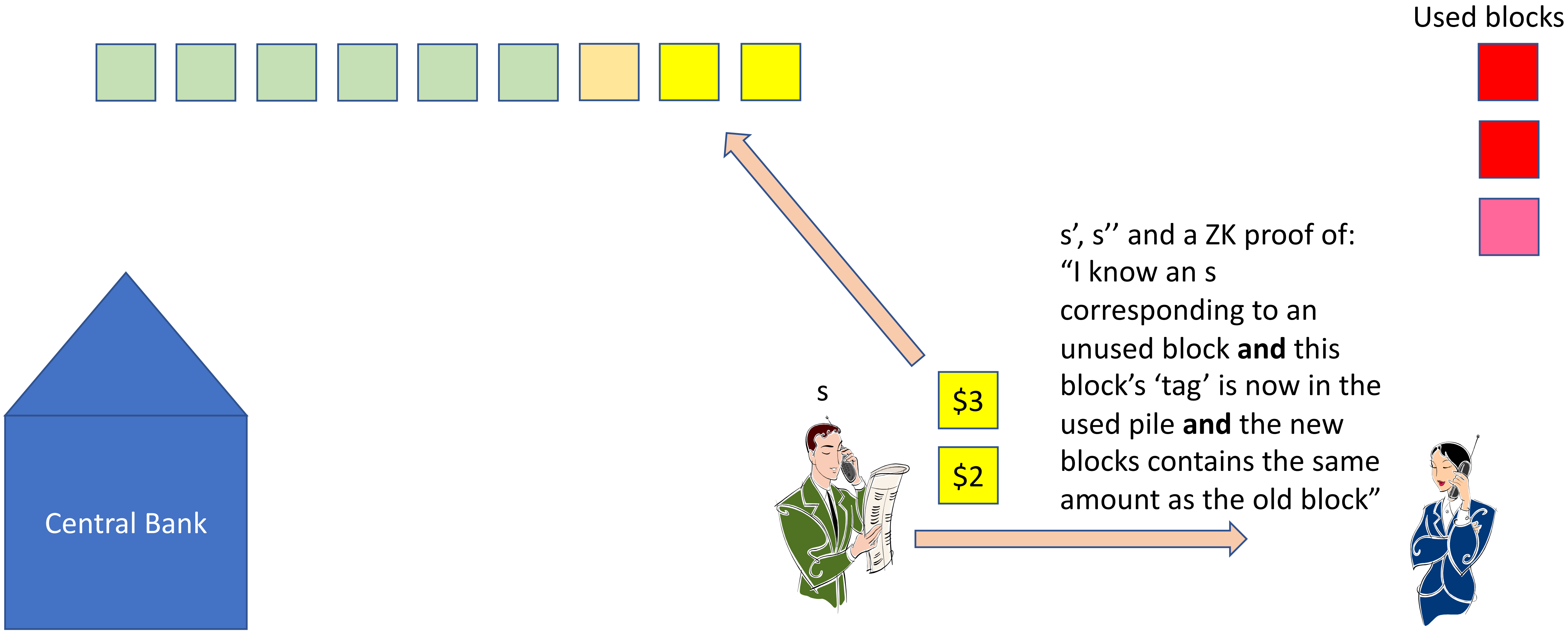

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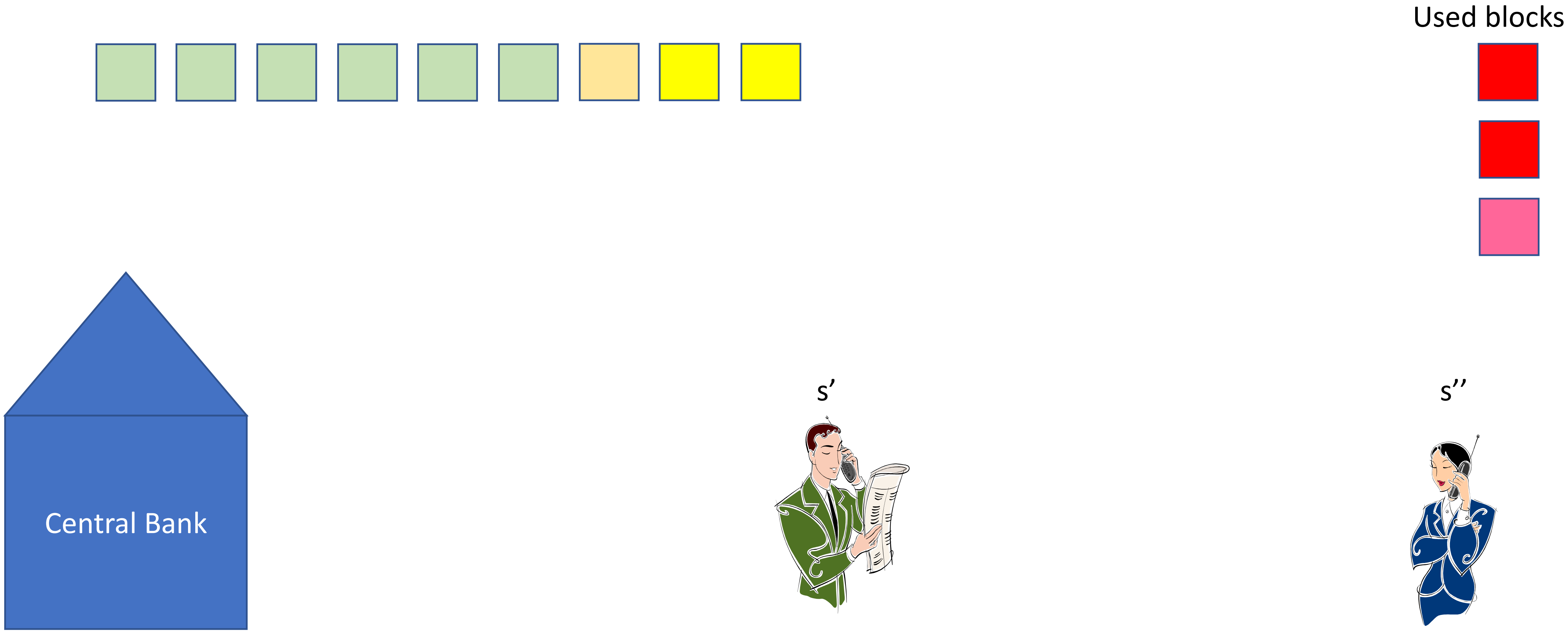

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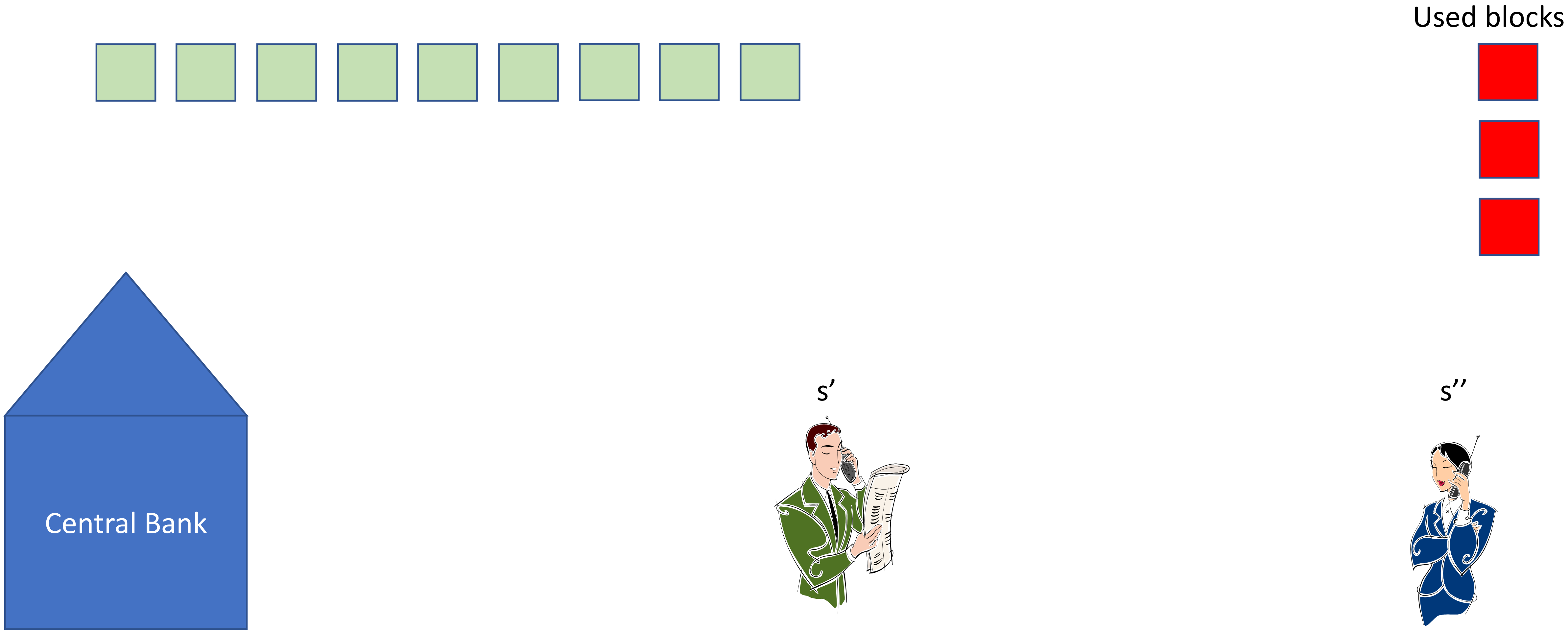


ZK Proofs Past and Present

- The most efficient ZK proofs now are **not** quantum-safe
- CBDC will need to have a clear road map to quantum-safe
- The most efficient quantum-safe proofs seem to be based on lattices

Work of the Quantum-Safe group at ZRL

2018 → 2022

Linear-Size ZK Proofs

3MB → 12KB

Sub-Linear ZK Proofs

?? → 60KB

Lattices and Some Building Blocks

Hard Problem Intuition

$$\begin{pmatrix} & & \\ & \mathbf{A} & \\ & & \end{pmatrix} \begin{bmatrix} \\ \mathbf{y} \\ \\ \end{bmatrix} = \begin{bmatrix} \mathbf{z} \\ \\ \\ \end{bmatrix} \mod p$$

Given (**A**,**z**), find **y**

Easy! Use Gaussian elimination.

Hard Problem Intuition

$$\mathbf{A}\,\mathbf{y} + \mathbf{e} = \mathbf{z} \mod p$$

$\underbrace{\mathbf{y}, \mathbf{e}}$ Small coefficients

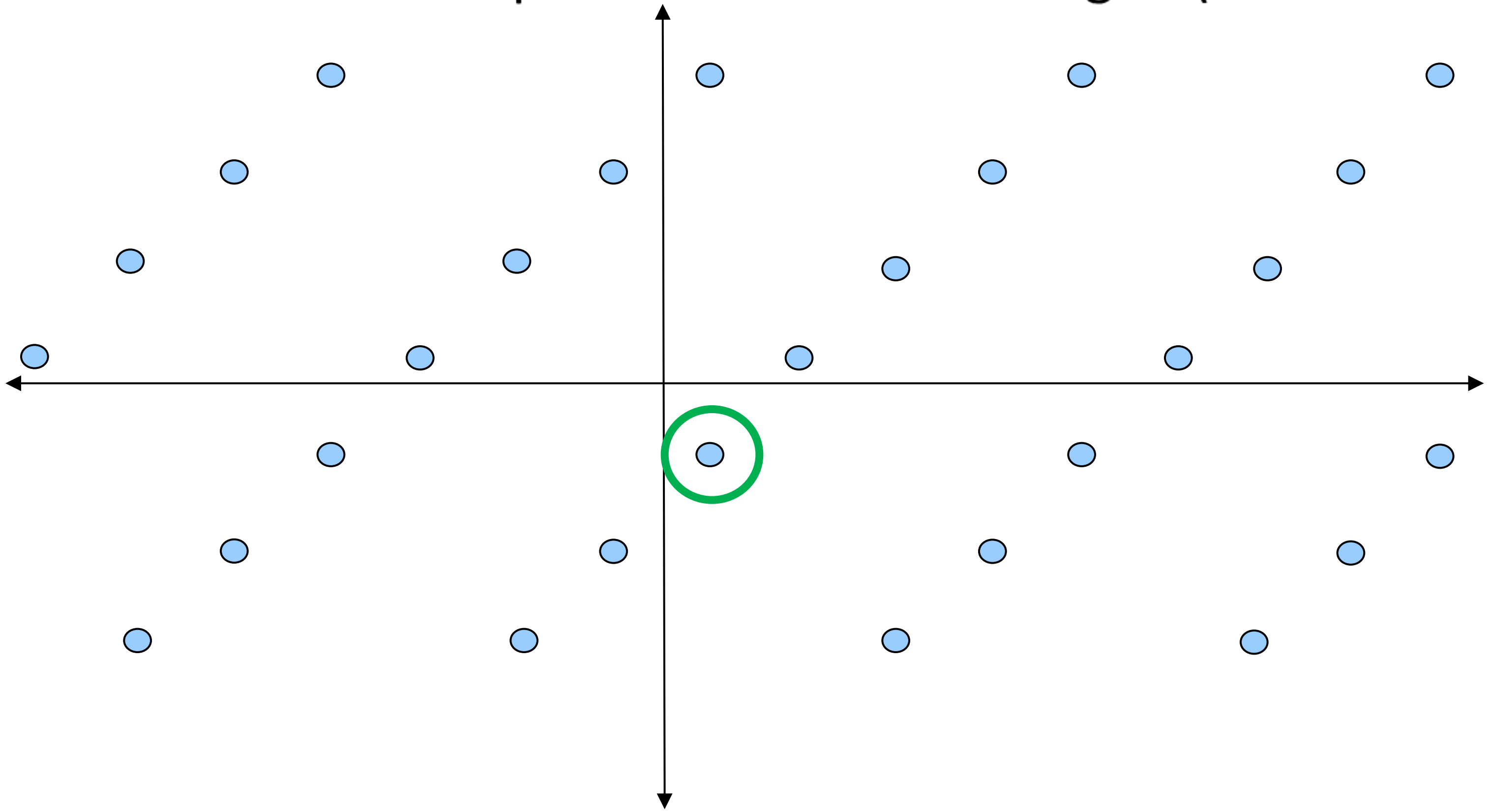
Given (**A**,**z**), find (**y**,**e**)

Seems hard.

Why is this "Lattice" Crypto?

All solutions $\binom{y}{e}$ to **Ay**+**e**=**z** mod p form a "shifted" lattice.

We want to find the point closest to the origin (BDD Problem).



Lattice (Assumption) Basics

Discrete log

- Public element g
- Secret integer s
- One-way function f: Z → Z_q

f(s) = g^s mod q

(g,g^s mod q) is random

Lattices

- Public random matrix A in $Z_q^{n \times m}$
- Secret integer vector s with ||s|| << q
- One-way function f : Z^m → Z_q^n

f(s) = As mod q

(A,As mod q) is pseudorandom

Can create A with a trapdoor that allows inversion of f

Lattice Blind Signatures from ZK Proofs

On the security of giving out pre-images

Random matrix A

An oracle that:

1. Generates a random **y**
2. Generates a small **s** from distribution D such that **As** = **y** mod p

is useless because the same distribution (**s**,**y**) can be generated by

1. Generate a small **s** from distribution D
2. Compute **As** = **y** mod p

The GPV signature scheme

Random matrix A

An oracle that:

1. When given any x
2. Generates a small **s** from distribution D such that **As** = **H(x)** mod p

is useless because the same distribution (**s**,**H(x)**) can be generated by

1. Generate a small **s** from distribution D
2. Compute **As** = **y** mod p
3. Program H(x)=y

Lattice-Based Blind Signature

Public key: A
Secret Key: Trapdoor for A
Public Randomness: B

Message m
Choose vector r with small norm

$t=Br + H(m,H(r))$
ZKPoK π_1 of r,m satisfying above

→

- Check π_1
- Use the trapdoor to compute s with small norm such that $As = t$

s

←

Signature is:

- m
- H(r)
- ZKPoK π_2 of r,s satisfying $As=Br+H(m,H(r))$