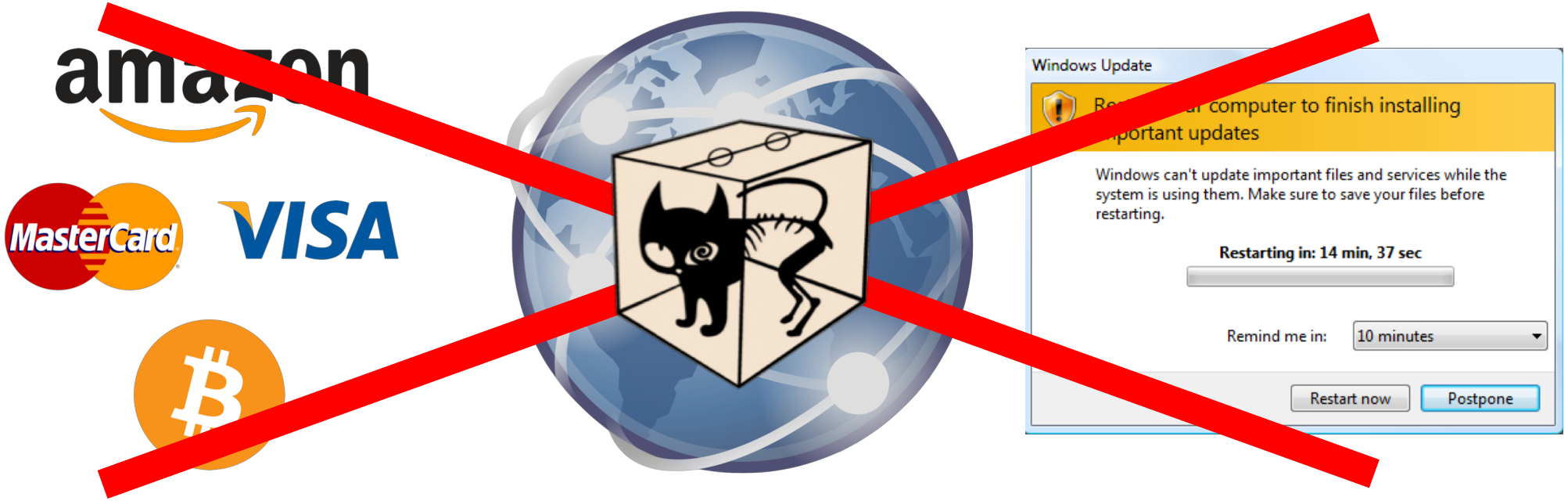
Quantum-safe cryptography & more

Fang Song

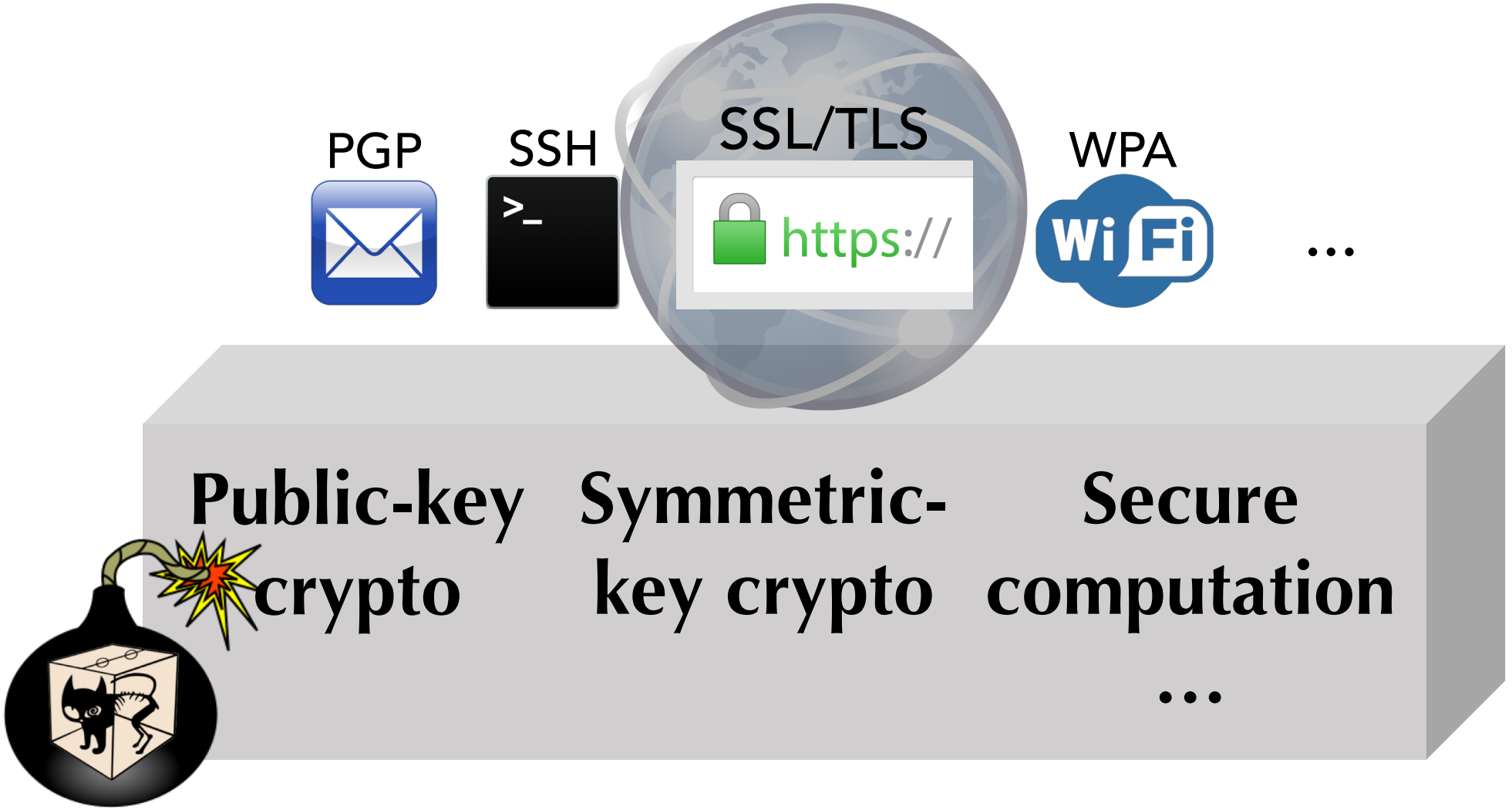
~~Portland State U~~

Texas A&M U fang.song@tamu.edu

Secure Internet will be shattered by quantum computers in x years

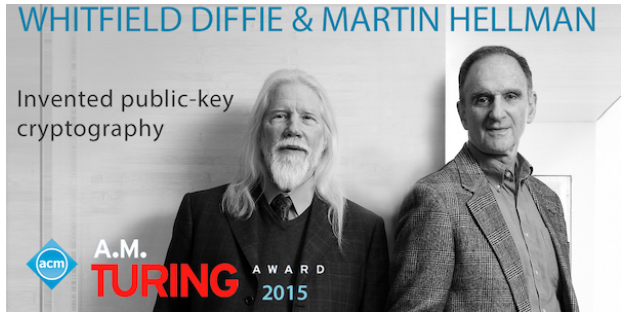


Break at a foundation: Cryptography



How do quantum attackers break cryptography?

1. Crack hard problems



Assumption: (better be) hard to solve

Public-key crypto

- RSA encryption
- Digital signature
- DH key-exchange

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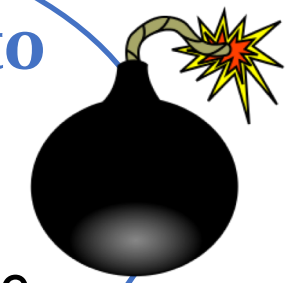


Factoring
Discrete Logarithm

[a][Shor94]

Quantum computer solves them[a], **fast!**

2. Transform security methodology

- Alert: unique quantum attacks
  - A classical protocol proved "unconditionally" secure,
  - Broken by quantum entanglement (vs. shared randomness) [b]

[b][CSST11]

"… created mathematical structures that turned cryptography from an art into a science"

- Formal framework of modern crypto

Crypto scheme Σ

- ~~Security model~~
- ~~Security Analysis (Proof)~~
  - Breaking Σ is as hard as solving Π

Hard problem Π

- Computational assumption

Post-Quantum Cryptography

How to secure cryptography against quantum attackers?

Hard problems cracked

Security framework failed

1 Build on alternative problems

2 Quantum security framework

My work on Post-Quantum Crypto

1. Design efficient quantum algorithms [5,8]

- Solve algebraic problems exponentially faster
- Break candidate quantum-safe problem & cryptosystems
- Develop new quantum algorithmic tools

5.SODA16
8. STOC14, QIP15

2. Acquire quantum-safe crypto

i. Develop formal methodology for quantum security [4,7,10]

- Model quantum security: composable protocols, …
- Develop general techniques: "quantum-friendly" reductions, fined-grained quantum complexity …

ii. Construct and analyze quantum-secure schemes [1,2,6,9,10]

- Two-party computation protocols
- Hash functions and random-oracle heuristic
- Block ciphers and message-authentication

1.PQCrypto18
2.Crypto17
4.PKC16
6.TQC15
7.PQCrypto14
9.TCC13
10.Crypto11,QIP11

What is x, after all?

universal, fault-tolerant (e.g., run Shor's factoring alg.)

x=?: born of a quantum computer

S. Aaronson (UT Austin)

G. Kalai (Hebrew U)

$X = -10$?

D-Wave
The Quantum Computing Company™

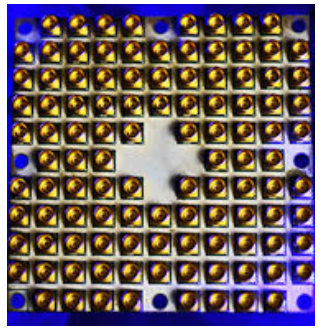
x — 2007 — 2018 — ∞

Google

IBM

intel

rigetti



CES 2018: Intel's 49-Qubit Chip Shoots for Quantum Supremacy

Quantum threat is pressing

- x=?: universal quantum computer (breaking public-key crypto)

A: time to transit to new cryptosystems
B: how long your data needs to be safe

⟵ >>>> your expected time!

Theorem. If $A + B > X$, then act now!

- $x \leq 0$: quantum attack on cryptography ⟵ Available now!

"… we announce preliminary plans for transitioning to quantum resistant algorithms."

Aug 19, 2015

www.nsa.gov/ia/programs/suiteb_cryptography/

NIST National Institute of Standards and Technology U.S. Department of Commerce

Post-Quantum Cryptography Standardization

Feb 24-26, 2016	NIST Presentation at PQCrypto 2016: *Announcement* *Dustin Moody*
April 28, 2016	NIST releases NISTIR 8105, Report on Post-Quantum
Dec 20, 2016	Formal Call for Proposals
Nov 30, 2017	Deadline for submissions
Dec 4, 2017	NIST Presentation at AsiaCrypt 2017: *The Ship Has Sa* *Dustin Moody*
Early 2018	Workshop - Submitter's Presentations
3-5 years	Analysis Phase - NIST will report findings *1-2 workshops during this phase*
2 years later	Draft Standards ready

Quantum cryptography: another approach

Let's play quantum too!

- Supplement (and **outperform**) classical cryptography
  - Quantum key distribution: secure against **unbounded** eavesdroppers
- Protect **quantum** information
  - Encrypt & authenticate quantum data …

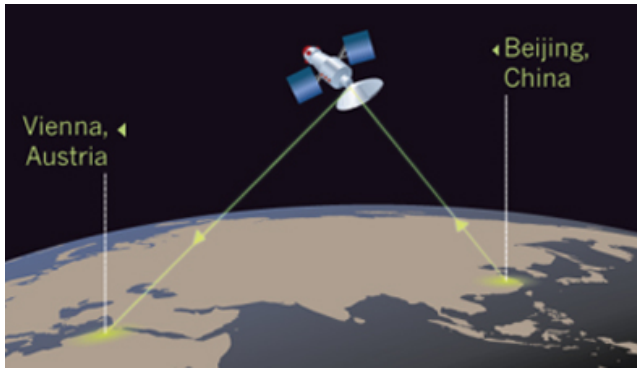
Impossible by classical crypto

Technology closer: commercial QKD products on the market

QIA

QUANTUM INTERNET ALLIANCE

http://quantum-internet.team/



https://en.wikipedia.org/wiki/Quantum_Experiments_at_Space_Scale

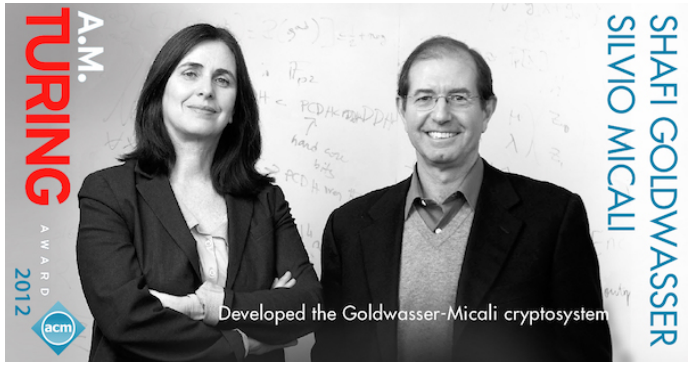
My work on quantum cryptography

- Construct quantum protocols bypassing classical impossibility [9]

[9]TCC13

- Construct zero-knowledge proof systems for Quantum NP [3]

[3]FOCS16



Triumph of zero-knowledge proof, classically

"… pioneered new methods for efficient verification of mathematical proofs"

- Construct pseudorandom quantum states and quantum money *

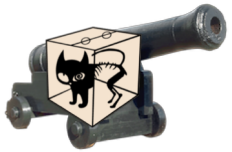
Analogous to pseudorandom number generator

* JL**S**'Preprint17

Summary of my main work

Post-Quantum Cryptography

1. Design efficient quantum algorithms
   - Solve algebraic problems exponentially faster
   - **Break** candidate quantum-safe problem & cryptosystems



5.SODA16
8. STOC14, QIP15

2. Acquire quantum-safe crypto

   i. Establish a formal methodology for quantum security

   ii. Construct and analyze quantum-secure schemes

   - Two-party computation, hash functions …
   - Block ciphers & message-authentication

1.PQCrypto18
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Quantum Cryptography

- Quantum protocols bypassing classical impossibility
- Zero-knowledge for Quantum NP, quantum money …

3.FOCS16
7.TCC13

This Talk

1 Design efficient quantum algorithms

- Solve algebraic problems exponentially faster
- **Break** candidate quantum-safe problem & cryptosystems
- Develop new quantum algorithmic tools

2 Acquire quantum-safe crypto-systems

- Challenges of analyzing quantum security
- Block cipher domain-extension & message-authentication

Become a quantum expert in 3 minutes

- **Quantum = ++ Prob. theory**
  - $p_0, p_1 \in \mathbb{C}$ (negative OK)
  - $|p_0|^2 + |p_1|^2 = 1$ (ℓ_2-normalized)

- **Probability theory**
  - $0 \le p_0, p_1 \le 1$
  - $p_0 + p_1 = 1$ (ℓ_1-normalized)

Physicists: Quantum weirdness

- Quantum Superposition
  - → No-cloning of unknown QState

Qubit

$$= \frac{1}{\sqrt{2}}|\rangle - \frac{1}{\sqrt{2}}|\rangle$$

- Quantum Entanglement
  - (A non-classical correlation)

$$\frac{1}{\sqrt{2}}|\rangle - \frac{1}{\sqrt{2}}|\rangle$$

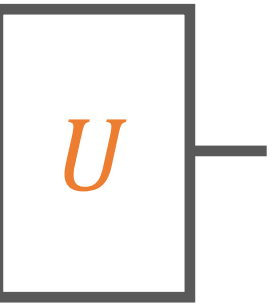
Computer scientists: a novel computer?

Build a quantum computer

Qubits

$\sum_{x\in\{0,1\}^n} p_x|x\rangle$

with $\sum_x |p_x|^2 = 1$



Quantum

gates & circuits

- Is it any good?
  - Classical computer cannot simulate
    (300 qubits ~ 2^{300} bits to describe)
  - Solve hard problems faster
    by constructive interference (≠ mass parallelism)

exponentially

Which problems admit faster |quantum⟩ algorithms than classical algorithms?

∃ Poly-time quantum algorithms for:

- Factoring and discrete logarithm [Shor'94]
- Basic problems in algebraic number theory

	Unit group	Principal ideal problem	Class group
Constant degree number fields	[Hallgren'02'05,SV05]		
Arbitrary degree	[EHKS'STOC14]	[BS'SODA16]	

Best known classical algorithms need (at least) sub-exponential time

Our contributions

Unit group	S-units
Principal ideal problem	Norm equations
Class group	…

- Efficient quantum algorithms for basic problems in number fields of **arbitrary**-degree

- More examples of quantum **exponential** speedup

- New **quantum** algorithmic tools

- **Break** several lattice cryptosystems **believed quantum-safe before**

QUANTA MAGAZINE illuminating science

CRYPTOGRAPHY

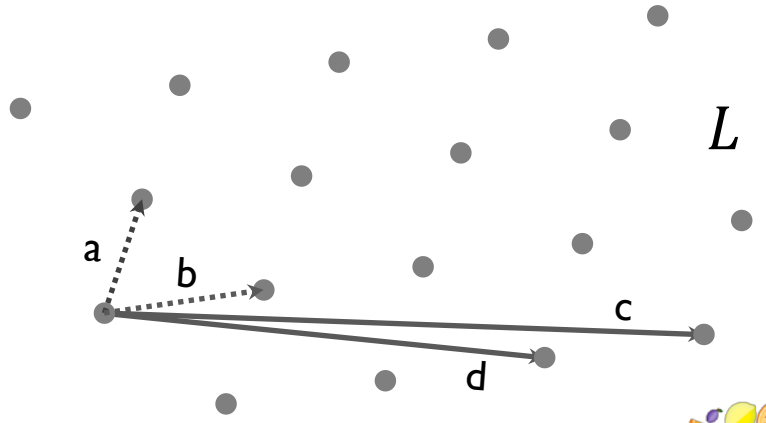
A Tricky Path to Quantum-Safe Encryption

https://www.quantamagazine.org/quantum-secure-cryptography-crosses-red-line-20150908/

Lattice-based cryptography

- Lattice problems
  - Shortest vector problem, …

Conjecture: hard even for quantum computers



- A neo-tree of crypto grows

Hash function, signature

Public-key encryption, ID-based encryption

Fully homomorphic encryption, program obfuscation …

Breaking some lattice crypto

- For efficiency, often use lattices with more structures

Short-PIP ✗ | Ring-LWE ? | …

[CramerDW'Eurocrypt17]: extension to break more

- Short-PIP based cryptosystems broken!

FHE[c], Multilinear mapping[d], PKE by GCHQ[e]…

broken

Our quantum alg's find a generator

Short-PIP → **PIP**

Find A generator of a principal ideal lattice

Classical procedure: reduce size of generator in cyclotomic fields[e,f]

[c]SmartV10
[d]GargGH13
[e]CampellGS15
[f]CramerDPR15

Our algorithms: a generalized framework

- **The Hidden Subgroup Problem (HSP) framework**
  (captures most instances of quantum exponential speedup)

- **Our contribution**
  - **a** A **continuous** HSP framework
    - subsumes standard HSP
    - conceptually a lot simpler
  - **b** Employ quantum power in reduction already

Interesting HSP instances

Computational Problems	HSP on G
Factoring	$\mathbb{Z}$
Discrete logarithm	$\mathbb{Z}_N \times \mathbb{Z}_N$
Number fields (PIP etc.)	Continuous $\mathbb{R}^{O(n)}$
Simon's problem (Crypto app later)	$\mathbb{Z}_2^n$

Abelian groups
∃ efficient quantum algs

Graph isomorphism	Symmetric group
Unique shortest vector problem	Dihedral group

Non-abelian
Open question:
? efficient quantum algs

This Talk

1 Design efficient quantum algorithms

- Solve algebraic problems exponentially faster
- **Break** candidate quantum-safe problem & cryptosystems
- Develop new quantum algorithmic tools

2 Acquire quantum-safe crypto-systems

- Challenges of analyzing quantum security
- Block cipher domain-extension & message-authentication

Recall: classical security framework fails

Crypto scheme ?

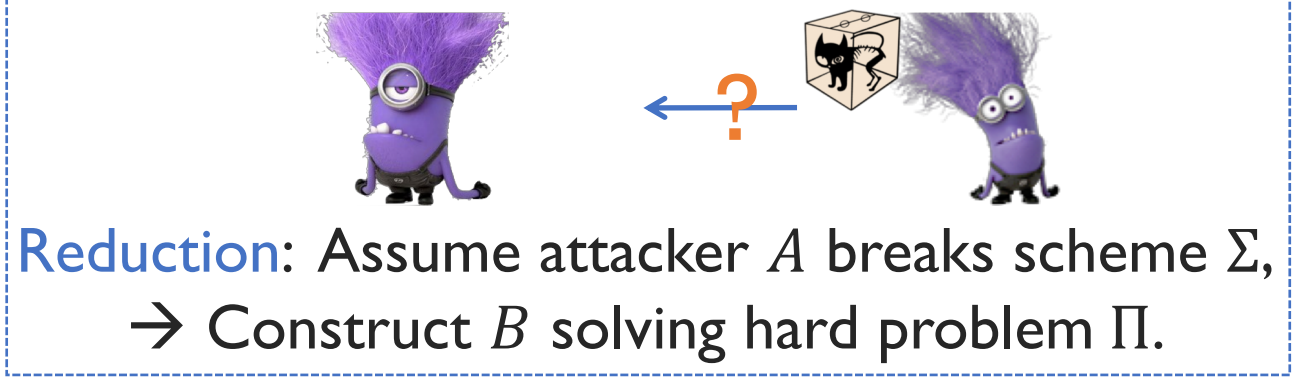
Quantum hard problem

- Security models: inadequate for Q attacks

  ➡ Quantum security models: catching up and a lot to do

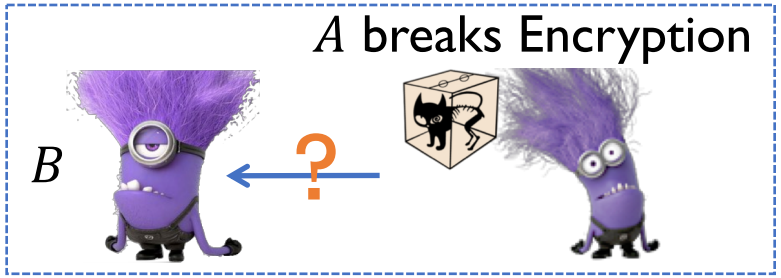
- Security analysis: can fail against Q attackers

  ➡ Quantum security analysis: subtle & challenging

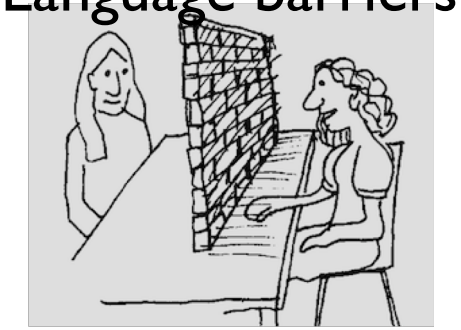


Reduction: Assume attacker A breaks scheme Σ,
→ Construct B solving hard problem Π.

Difficulties of analyzing quantum security



"Language barriers"



(Classical) probability	Quantum
Fix randomness of A	Quantum A no explicit random coins (inherently randomized)
If "A does Z", B works	Event "A does Z" ill-defined
Rewinding: B take snapshots of A at various points, run it back and forth	Quantum rewinding, really? • Quantum no-cloning • Observations destructive
…	

We are not totally clueless…

ge barriers”

Quantum (difficulties)

Quantum A no explicit random coins (inherently randomized)

Event “A does Z” ill-defined

Quantum rewinding, really?

Some progress (in my work [1,4,6,9,10])

- Hardness of search ➔ security
- Restore random-oracle heuristic & hash function security in the quantum world

- Special Q-rewinding [Watrous09]
- Quantum-secure zero-knowledge proofs of knowledge & 2-party computation

??? Constant round Zero-Knowledge, …

Quantum attackers,
is that the best you can do?

Fine, I know you can

- Solve factor, DL, some lattice problem, and break most public-key crypto
- Make my life miserable to struggle with new security models & analysis methodology

Apparently, you haven't broken symmetric-key crypto yet

I've still got AES, try it…

Break symmetric-key crypto (block-cipher related)

- Block Cipher
  - Apps: hash functions (SHA-2), authentication, encryption, …
  - Examples: DES, AES (Advanced Encryption Standard)

Broken!

Core of DES	**3-round Feistel Cipher**
Simplified AES	**Even-Mansour Cipher**
Message authentication	**CBC-MAC**
Authenticated encryption	**Galois/Counter mode**
	…

[KM10'12]
[KLL+16]

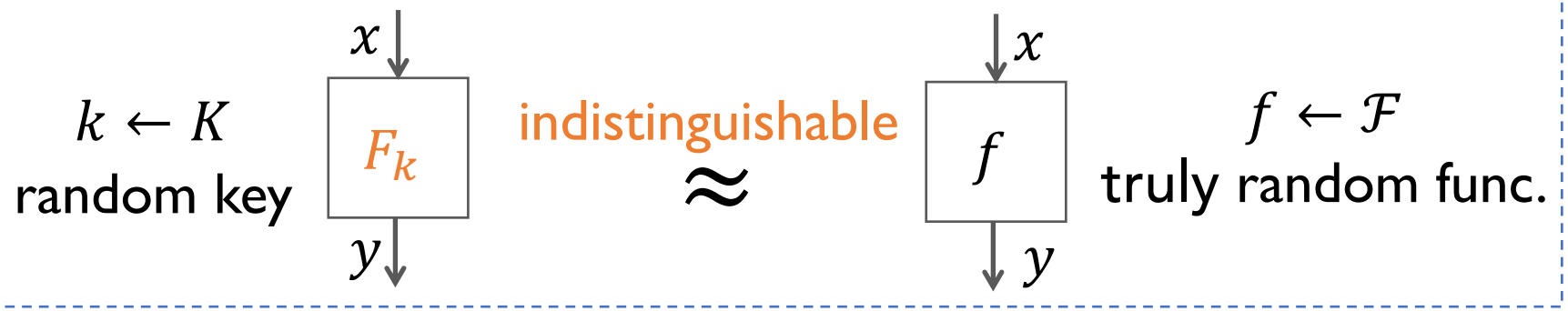
Easy on a quantum computer

Simon's Problem
≡
HSP on $\mathbb{Z}_2^n$

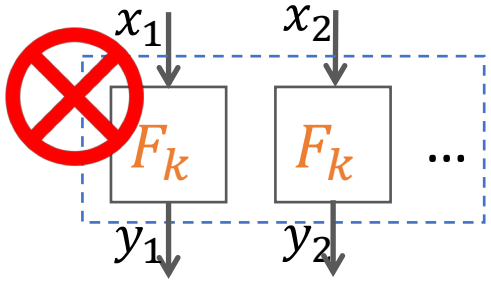
Block cipher and domain extension

- Block Cipher $\{F_k\}$
  - "Efficiently computable permutation that looks random (with random key k)"

$$\{F_k\} \subseteq \mathcal{F} := \{f : \{0,1\}^n \to \{0,1\}^n\} \text{ (e.g., } n = 128)$$

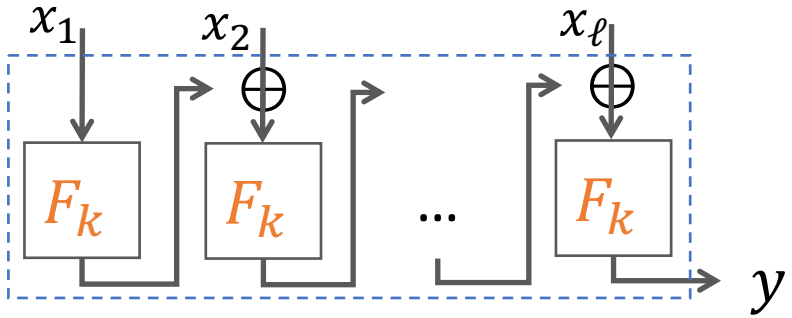


- How about long inputs: domain-extension
  - **Given** psodorandom $\{F_k\}$ on n-bit input
  - **Construct** pseudorandom $\{G_k\}$ on $\ell \cdot n$-bit input



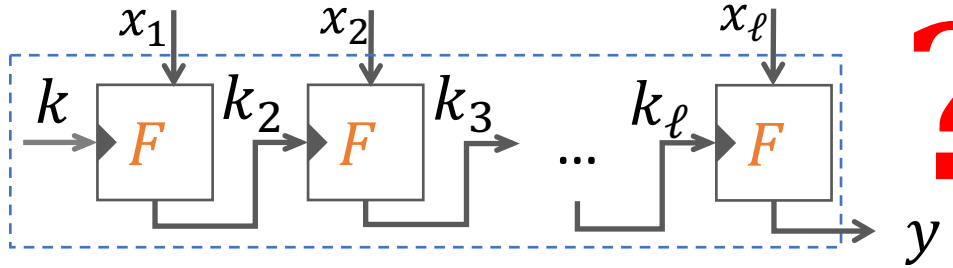
Classically secure domain-extension

- **CBC-MAC** ANSI X9.19, ISO/IEC 9797



Broken by quantum!

- **Cascade (NMAC, HMAC)** NIST.FIPS.198, IPSec, TLS



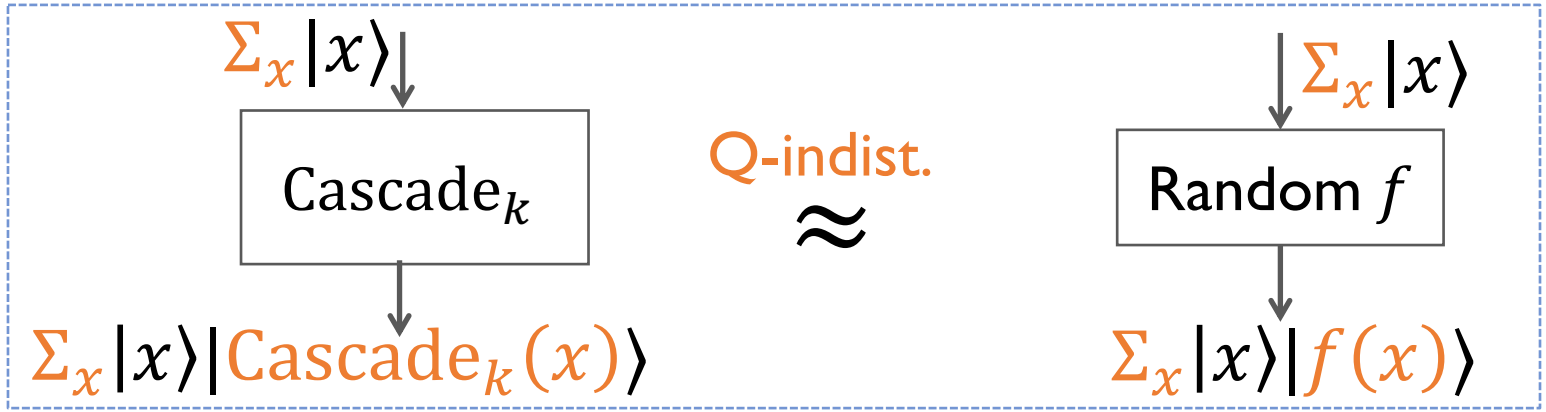
?

- Cascade (NMAC & HMAC) quantum-secure?
- Is quantum-secure domain-extension even possible?

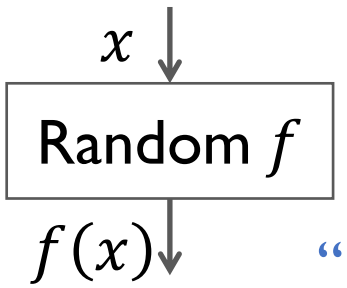
Our main result

Cascade, NMAC, HMAC (and more) are quantum-secure

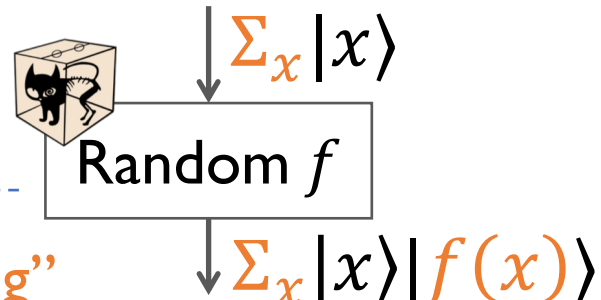
i.e., quantum-indistinguishable from a truly random function



Power of quantum-superposition attack



Local view, one by one ⟵ **Attacker** ⟶ Global view, observe all?



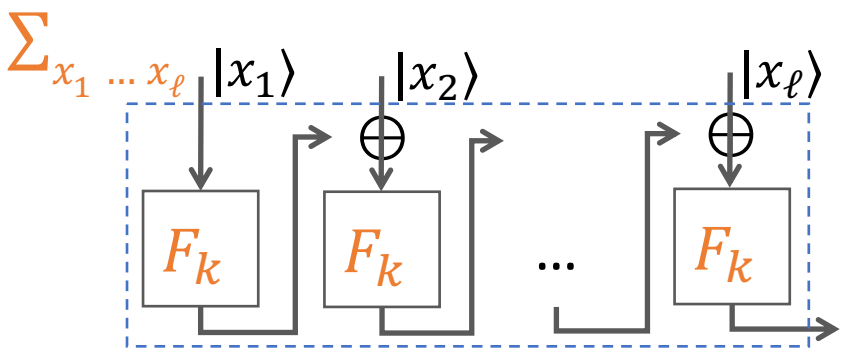
"Lazy" sampling
generate f *on-the-fly*

⟵ **You** (designer) ⟶

"Full committing"
sample entire f *ahead*

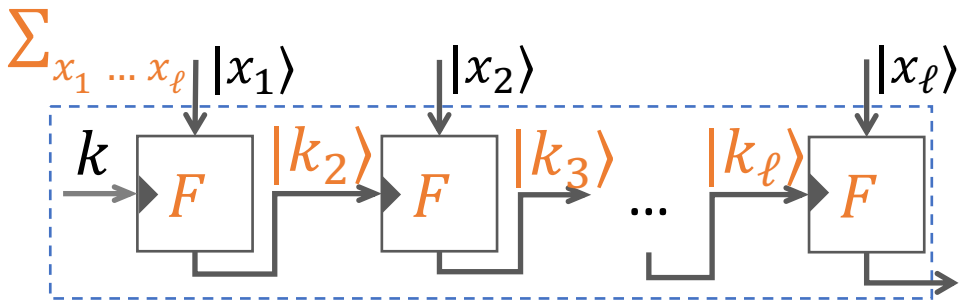
CBC-MAC **Broken!**

global view on F_k of a random k



Cascade

global view on F_k of all k!



we proved it's quantum secure

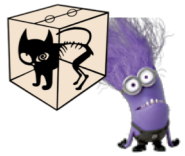
Future directions

Quantum-safe Crypto

Emerging security issues

Power of quantum computing

Future work: quantum-safe crypto

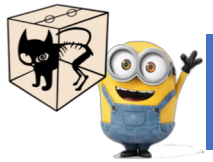


Post-quantum crypto

- Are new candidates indeed hard?
  - Break other lattice problems? Multivariate-equations? …
- How to get quantum-secure cryptosystems?
  - Fine-grained analysis of hash functions & block ciphers
  - Quantum-safe Bitcoin & blockchain

NSF:Medium:Collaborative

- New complexity foundation
- Q-secure auth., signature …



Quantum crypto

- What else are possible? & a formal framework?
  - Quantum money, quantum tokenized crypto…

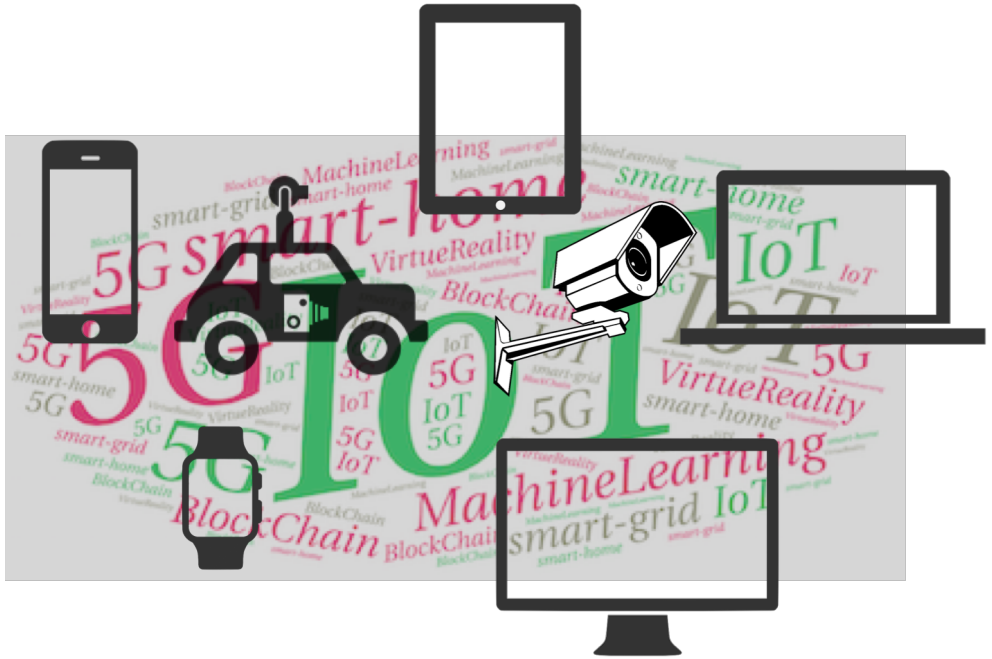
Future work: securing advancing technology

What do they bring?

IoT, 5G, Cloud, Big Data, ML …

- Diverse players of imbalanced resource

- Lightweight Cryptography
  - ☺ Memory-friendly, energy-friendly …
  - ☹ **Attack**-friendly too?
- Update security model
  - Always poly-time adversary too coarse
- Design protocols that better fit
  - Workload respects capacity



Future work: embracing quantum power

Quantum algorithms

- Machine learning
- Chemistry /Biology
- Big Data
- . . .

- Quantum sensing
- Q Software foundations
- Limitations of QC

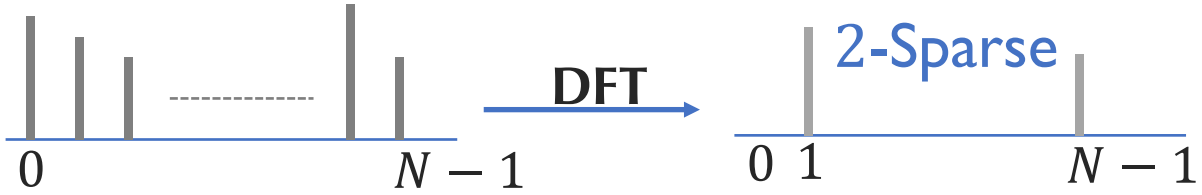
Quantum Fourier Transform

- Exponentially faster than classical FFT algorithm
- Using one quantum sample of input data

Expensive!

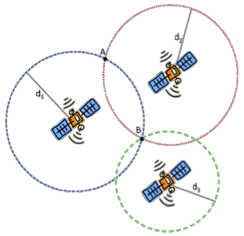
Sparse Quantum FT?

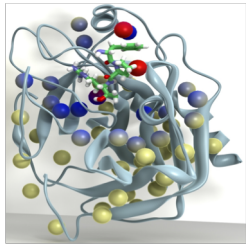
- Using a few classical samples? and even faster?
- Useful in **near-term** (noisy 100-qubit processor)?



Many apps in data analysis

MIT sFFT group





Quantum-safe Crypto

Emerging security issues

Power of quantum computing

Thank you!

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6. Making existentially unforgeable signatures strongly unforgeable in the quantum-random oracle model Authors: Edward Eaton and Fang Song. TQC 2015.
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8. A quantum algorithm for computing the unit group of an arbitrary degree number field. Kirsten Eisenträger, Sean Hallgren, Alexei Kitaev and Fang Song. STOC 2014.
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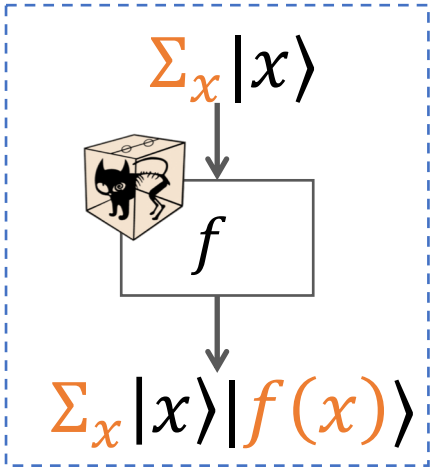
Is superposition attack realistic?

f: crypto-algorithm (Enc, Sign, etc..) with secret key



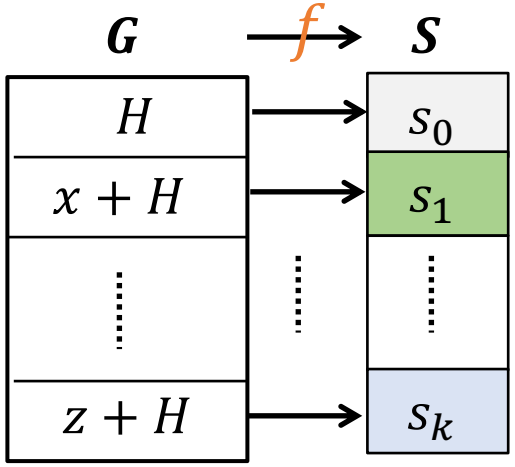
Attacker can implement f as a quantum circuit

- Could occur in public-key setting
  - Ex. Block cipher to Pub-key Enc via obfuscation
- Building block in big system
  - Be conservative (quantum & classical hybrid Internet)
- Makes our POSITIVE result stronger!

The Hidden Subgroup Problem (HSP) framework

Captures most quantum exponential speedup

- Standard Def.: HSP on finite group G



Given: oracle function $f: G \to S$, s.t. $\exists\, H \leq G$,

1. (Periodic on H) $\quad x - y \in H \Rightarrow f(x) = f(y)$
2. (Injective on G/H) $\quad x - y \notin H \Rightarrow f(x) \neq f(y)$

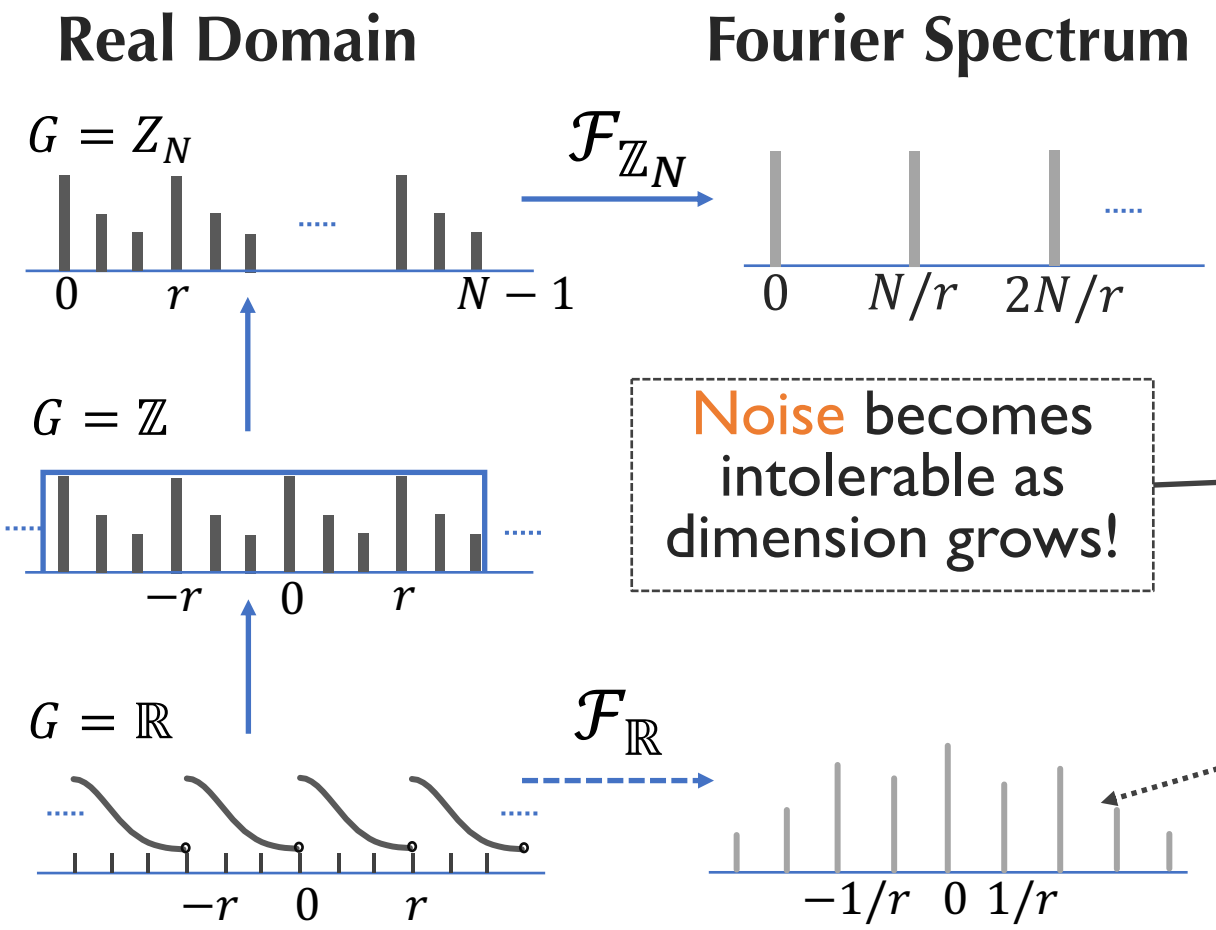
Goal: Find (hidden subgroup) H.

- Continuous $\mathbb{G}$ (e.g., $\mathbb{R}^n$) tricky, but we can handle [EHKS14]

Solving HSP: quantum Fourier sampling

Given: oracle $f: G \to S$ periodic on H & …

Goal: find H



Noise becomes intolerable as dimension grows!

Standard method for finite G

- Quantum Fourier Sampling: quantum Fourier transform & measure
- Recover H from samples

Old method for $\mathbb{R}^{constant}$

- Discretize & Truncate
- Reduce to finite G

Our method for continuous $\mathbb{R}^m$

- Informal: try to approx. sample the ideal Fourier spectrum directly!