MAX PLANCK INSTITUTE
FOR SECURITY AND PRIVACY

Engineering Post-Quantum Cryptography

May 4, 2022

A brief introduction

- 2001–2007: Aachen

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- Since 2013: Nijmegen

Since Sep. 2020: MPI-SP

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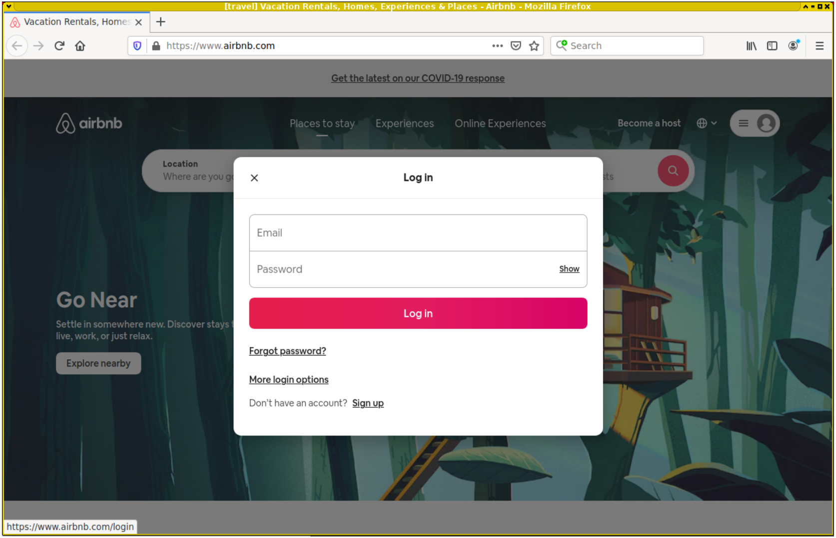
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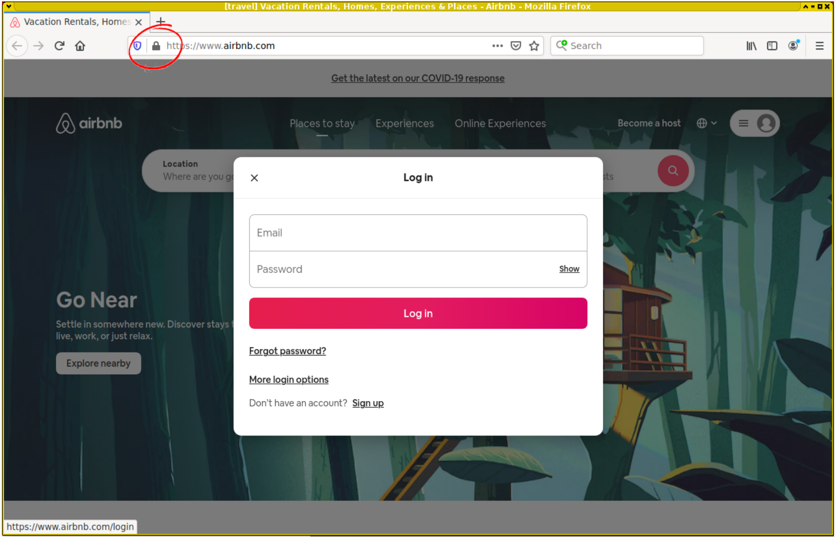
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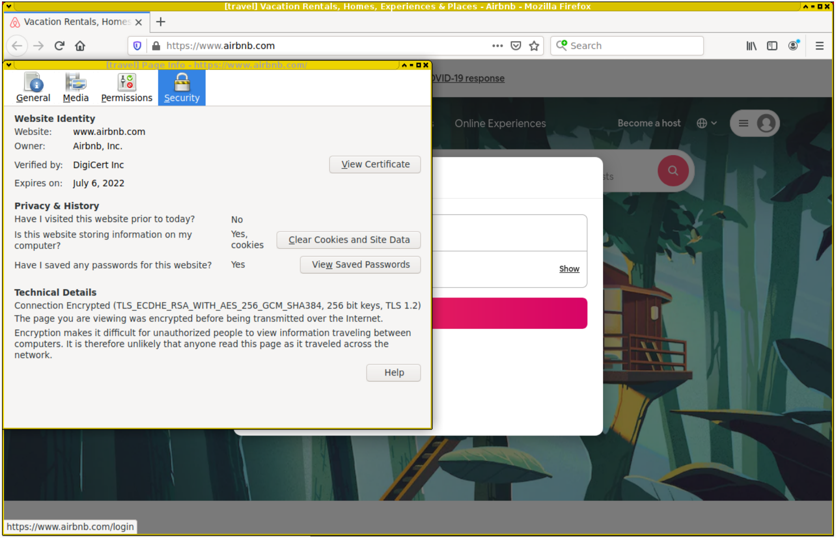
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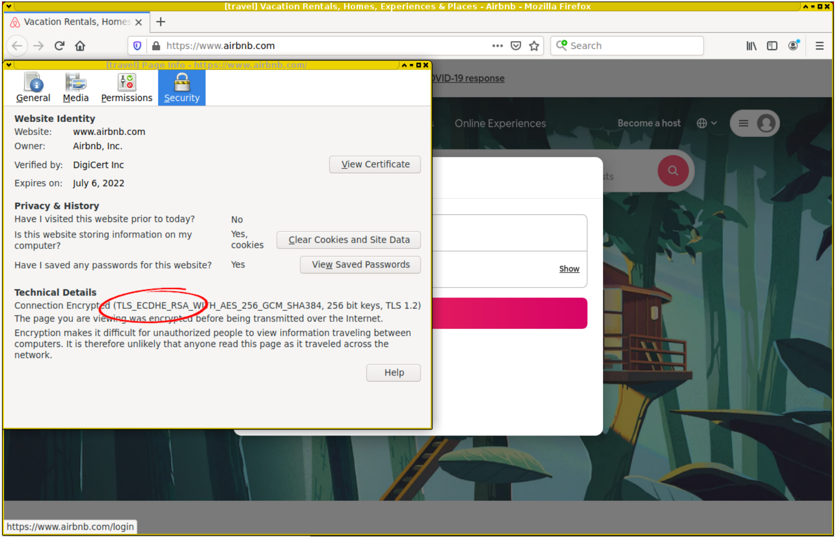
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Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer*

Peter W. Shor†

Abstract

A digital computer is generally believed to be an efficient universal computing device; that is, it is believed able to simulate any physical computing device with an increase in computation time by at most a polynomial factor. This may not be true when quantum mechanics is taken into consideration. This paper considers factoring integers and finding discrete logarithms, two problems which are generally thought to be hard on a classical computer and which have been used as the basis of several proposed cryptosystems. Efficient randomized algorithms are given for these two problems on a hypothetical quantum computer. These algorithms take a number of steps polynomial in the input size, e.g., the number of digits of the integer to be factored.

“In the past, people have said, maybe it’s 50 years away, it’s a dream, maybe it’ll happen sometime. I used to think it was 50. Now I’m thinking like it’s 15 or a little more. It’s within reach. It’s within our lifetime. It’s going to happen.”

—Mark Ketchen (IBM), Feb. 2012, about quantum computers

Post-quantum crypto

Definition

Post-quantum crypto is (asymmetric) crypto that resists attacks using classical *and quantum* computers.

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5 main directions

- Lattice-based crypto (PKE and Sigs)
- Code-based crypto (mainly PKE)
- Multivariate-based crypto (mainly Sigs)
- Hash-based signatures (only Sigs)
- Isogeny-based crypto (so far, mainly PKE)

The NIST PQC “not-a-competition”

- Inspired by two earlier NIST crypto competitions:
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  - SHA3, running from 2007 to 2012

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- Approach: NIST specifies criteria, everybody is welcome to submit proposals
- Selection through an open process and multiple rounds
- Actual decisions are being made by NIST
- PQC project:
  - Announcement: Feb 2016
  - Call for proposals: Dec 2016 (based on community input)
  - Deadline for submissions: Nov 2017

The NIST competition: initial overview

Count of Problem Category	Column Labels		
Row Labels	Key Exchange	Signature	Grand Total
?	1		1
Braids	1	1	2
Chebychev	1		1
Codes	19	5	24
Finite Automata	1	1	2
Hash		4	4
Hypercomplex Numbers	1		1
Isogeny	1		1
Lattice	24	4	28
Mult. Var	6	7	13
Rand. walk	1		1
RSA	1	1	2
Grand Total	**57**	**23**	**80**

Overview tweeted by Jacob Alperin-Sheriff on Dec 4, 2017.

The NIST competition: Jan 2019

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- 7 code-based
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Signature schemes

- 3 lattice-based
- 2 symmetric-crypto based
- 4 MQ-based

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Finalists

- 4 key-agreement schemes
  - 3 lattice-based
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- 3 signature schemes
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Finalists

- 4 key-agreement schemes
  - 3 lattice-based
  - 1 code-based
- 3 signature schemes
  - 2 lattice-based
  - 1 MQ-based

Alternate schemes

- 5 key-agreement schemes
  - 2 lattice-based
  - 2 code-based
  - 1 isogeny-based
- 3 signature schemes
  - 2 symmetric-crypto based
  - 1 MQ-based

The NIST competition right now

"Yes - the 3rd round will shortly be ending. NIST is actively writing the 3rd Round report which will explain our rationale for which algorithms we will standardize. We hope to be able to announce the results and report not later than the end of March."

—Dustin Moody (NIST), Feb 9, 2022

The NIST competition right now

"We wanted to give another quick update.

We've received a few inquiries about whether NIST's talk at the PKC conference next week will be where we announce the candidates we will select for standardization. The short answer is no - it will not be.

We are still hoping to make our announcement by the end of this month (March)."

—Dustin Moody (NIST), Mar 4, 2022

The NIST competition right now

"Another update:

We had been hoping to announce the results of our PQC standardization process by the end of March. We ask for a little bit more patience since we are not ready to make the announcement today. We still expect to make it very soon."

—Dustin Moody (NIST), Mar 31, 2022

The NIST competition right now

"Everybody,

We appreciate your patience. The announcement of the algorithms we will standardize is still coming very soon. This is a major milestone of our project, and the delay is not due to technical considerations but is due to some legal and procedural steps that are taking more time than we anticipated. Again, thank you for your patience."

—Dustin Moody (NIST), Apr 19, 2022

The NIST competition right now

Expectation

- NIST is expected to announce winners **very soon**
- $\approx$ one year later get standards

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Mission accomplished – The world is safe again!

. . . or is it?

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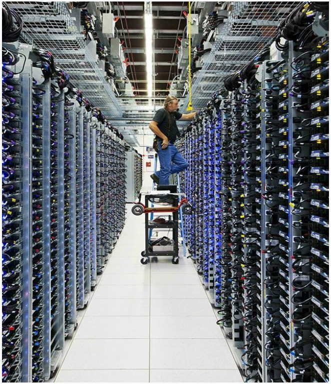
Replacing MD5 was "easy"!

Challenge 1: Performance



- 10% performance difference matters!
  - Reduce cost for busy servers
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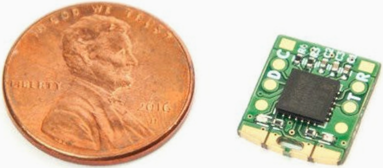

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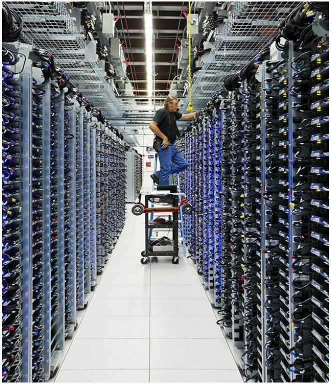

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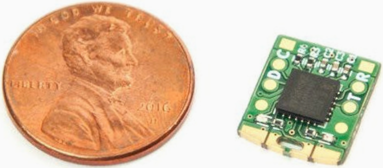
  - Reduce cost for busy servers
  - Fit into constrained devices
- Small routines executed many times
- Often hand-optimized on assembly level



Challenge 1: Performance (ctd.)

Elliptic-curve cryptography

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- SPHINCS$^+$ signatures: $\approx$16 KB
- SPHINCS$^+$ signing: $\approx$3 billion cycles
- Kyber (all ops): $<$80 kcycles
- Kyber data sent: $<$1.2 KB

Challenge 2: Security

Security reductions

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- reductions are often not *tight*
- "hard problem" may turn out to be easier than expected
- proofs may be wrong

Challenge 2: Security (ctd.)

The case of OCB2

- 2004: Rogaway proposes OCB2
  - Security reduction guaranteeing confidentiality and authenticity
- 2009: OCB2 is standardized by ISO
- 26 Oct. 2018: Break of authenticity by Inoue and Minematsu
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- Round-2 MQDSS attack "hidden inside non-tightness"
- Round-2 qTesla proof wrong (?) $\Rightarrow$ devastating attack

Challenge 3: Implementation Security

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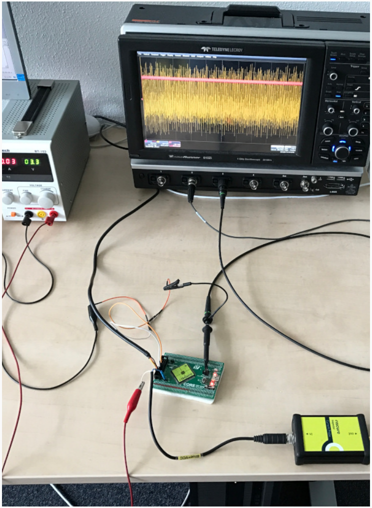

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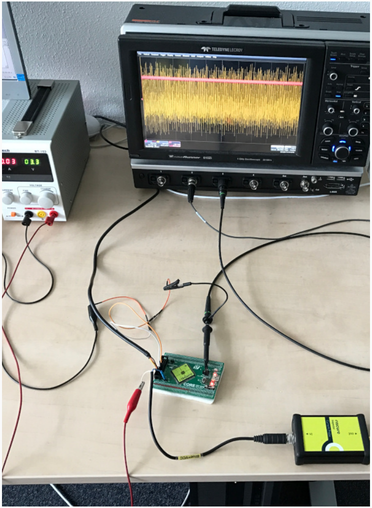

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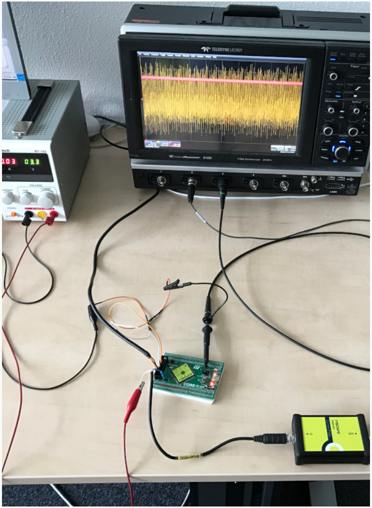

- Attackers see more than input/output:
  - Power consumption
  - Electromagnetic radiation
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- **Side-channel attacks:**
  - Measure information
  - Use to obtain secret data
- Timing attacks can be done **remotely**
- Cost of countermeasures heavily depends on the scheme

Challenge 3: Implementation Security (ctd.)

“the implementation security aspect of lattice-based cryptography is still a vastly unexplored and open topic”

— Primas, Pessl, Mangard, 2017.

Challenge 3: Implementation Security (ctd.)

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- Other “realms” of PQC less explored than lattices
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For many applications, implementations are not ready.

Challenge 4: The curious case of Diffie-Hellman

Alice		Bob
$A \leftarrow g^a$		$B \leftarrow g^b$
	$\xrightarrow{\quad A \quad}$	
	$\xleftarrow{\quad B \quad}$	
$K \leftarrow B^a = (g^b)^a = g^{ab}$		$K \leftarrow A^b = (g^a)^b = g^{ab}$

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KEMs: as close as you'll get to DH

Initiator		Responder
$(\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{KEM.Gen}$		
	$\xrightarrow{\mathsf{pk}}$	
		$(\mathsf{ct}, K) \leftarrow \mathsf{KEM.Enc}(\mathsf{pk})$
	$\xleftarrow{\mathsf{ct}}$	
$K \leftarrow \mathsf{KEM.Dec}(\mathsf{ct}, \mathsf{sk})$		

KEMs: as close as you'll get to DH*

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$K \leftarrow \mathsf{KEM.Dec}(\mathsf{ct}, \mathsf{sk})$		

*Except with CSIDH (Castryck, Lange, Martindale, Renes, Panny, 2018)

Challenge 5: “Huge foot cannons”

- We already have post-quantum RFCs
- Hash-based signatures XMSS and LMS

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- Hash-based signatures XMSS and LMS
    - Reasonable performance
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    - Application-specific tradeoffs
    - Conservative security

Challenge 5: “Huge foot cannons”

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- Hash-based signatures XMSS and LMS
    - Reasonable performance
    - Reasonable signature sizes
    - Small keys
    - Application-specific tradeoffs
    - Conservative security
- NIST fast-track standardization of XMSS and LMS

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  - Updates are as easy as 1 – 2 – 3 . . .
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"It's a huge foot cannon" — Adam Langley

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How long do we need today's communication to be secure?

How long does it take us to migrate?

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- Will we **know** when, say, NSA has a quantum computer?
- May need to prepare devices today!
- Signatures are used for, e.g., software updates
- What if I cannot update anymore in 15 years?
  - What’s the lifetime of a car?
  - What’s the lifetime of smart-home appliances?

Plan for today

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- Programming exercise

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Hash-based signatures

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