Quantum computers
Vs.
Modern cryptography

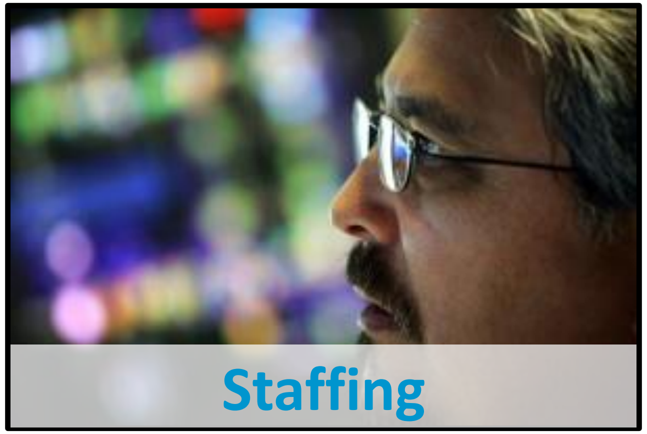
Kristof Verslype
Cryptographer, PhD
Smals Research

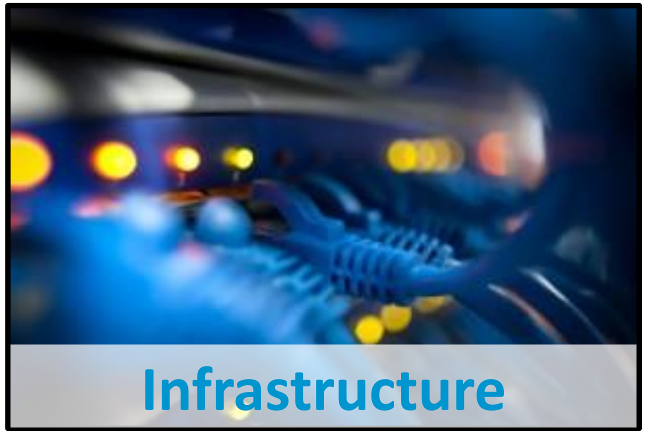
Smals
ICT for society

Smals – ICT for Society

Smals
ICT for society

SUPPORT FOR E-GOVERNMENT





g-cloud

top EMPLOYER
BELGIË
BELGIQUE
CERTIFIED EXCELLENCE IN EMPLOYEE CONDITIONS

WWW.SMALS.BE

Smals
ICT for society

Smals Research 2023

Innovation with new technologies

Consultancy & expertise

Internal & external knowledge transfer

Support for going live

- AI-Augmented Software Development
- Customer Service Automation
- Custom Assistant
- On-prem Voice2voice Translation
- Workshops AI
- Recommender System Portal
- Causal AI
- Diffusion Models
- Language Model for social security
- **Innovation Smals & OISZ**
- Event Driven Architecture
- Digital EU Wallet
- Data protection in Legacy
- GIS Analytics
- Graph Machine Learning
- Linkurious in practice
- Pseudonymization Service
- Confidential Computing
- Synthetic Data in practice
- Best Practices in Cryptography

Me

Kristof Verslype
Cryptographer, PhD
Smals Research

Smals
ICT for society
Belgian public sector

kristof.verslype@smals.be
+32(0)2 7875376
www.smals.be
www.smalsresearch.be
www.cryptov.net

@KristofVerslype
linkedin.com/in/verslype

KU Leuven

PhD. of Engineering
Dept. CS, KU Leuven (2011)
Applied cryptography

Smals

- Cryptography for privacy
- Advice on cryptography
- Blockchain

No background in quantum physics

Google claims quantum supremacy

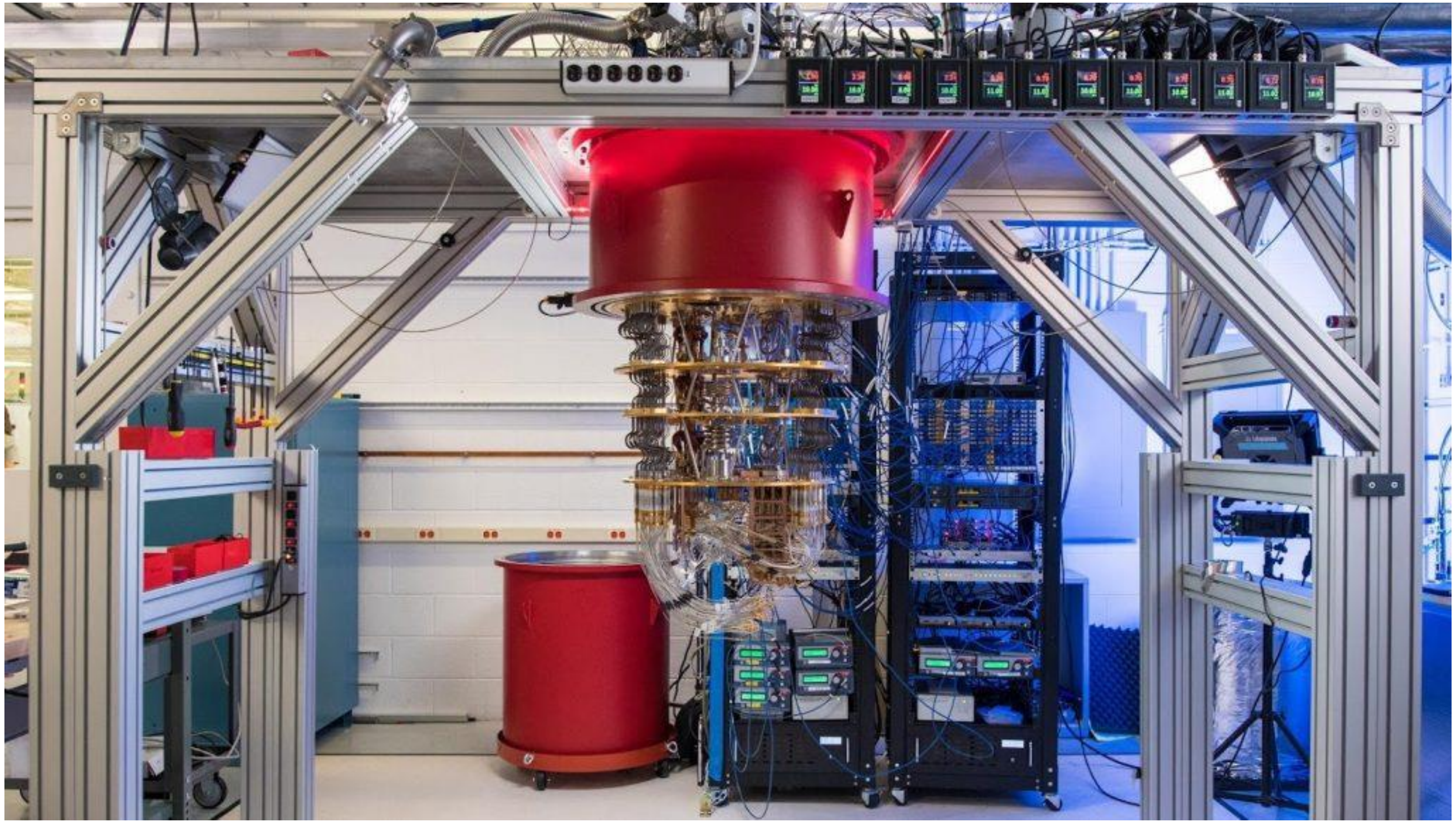
23 oktober 2019

Google

Article

Quantum supremacy using a programmable superconducting processor

nature
International journal of science



Smals
ICT for society

China claims quantum primacy

27 oktober 2021

PHYS.ORG

Two Chinese teams claim to have reached primacy with quantum computers

by Bob Yirka , Phys.org

The Pan team's optical quantum computer uses a 144-mode interferometer to solve a Gaussian boson ...

Two teams in China are claiming that they have reached primacy with their individual quantum computers. Both have published the details of their work in the journal *Physical Review Letters*.

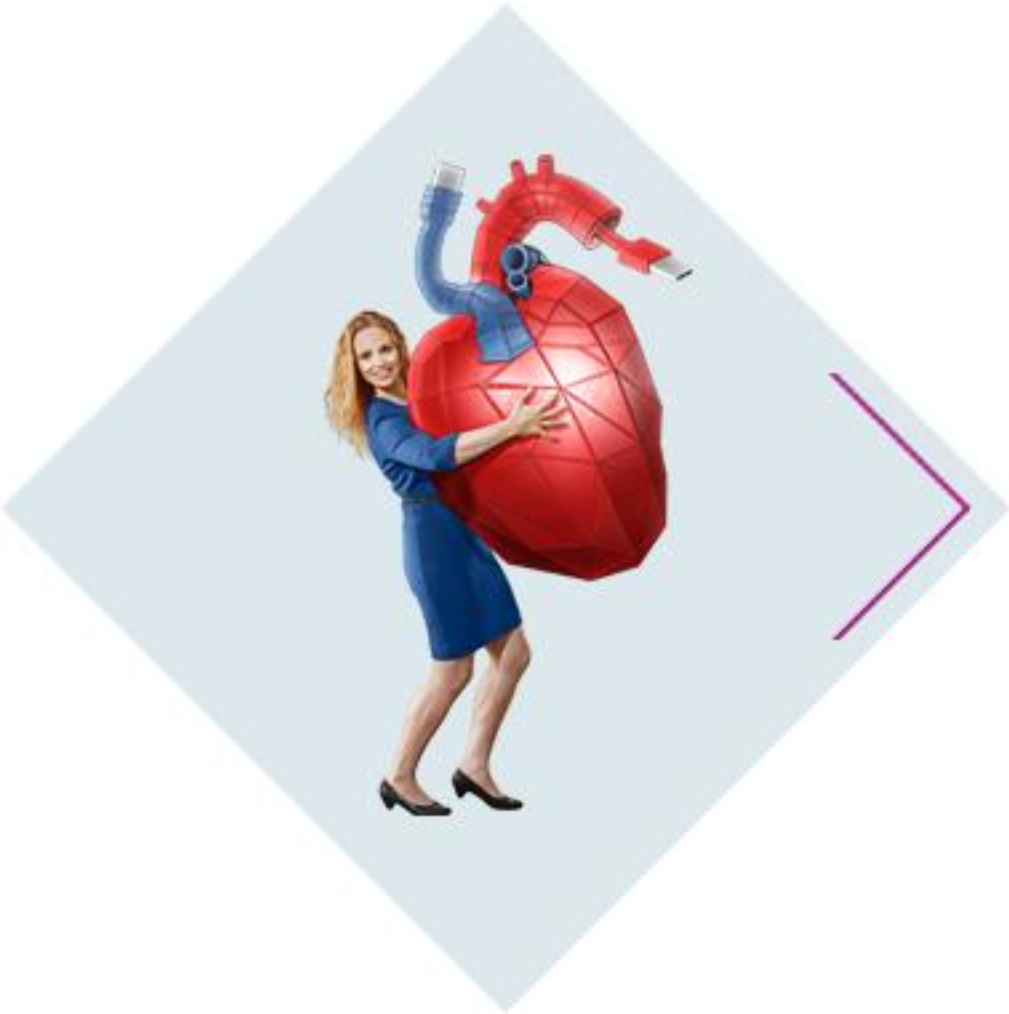
Smals
ICT for society

THE BYTE.

27 januari 2022

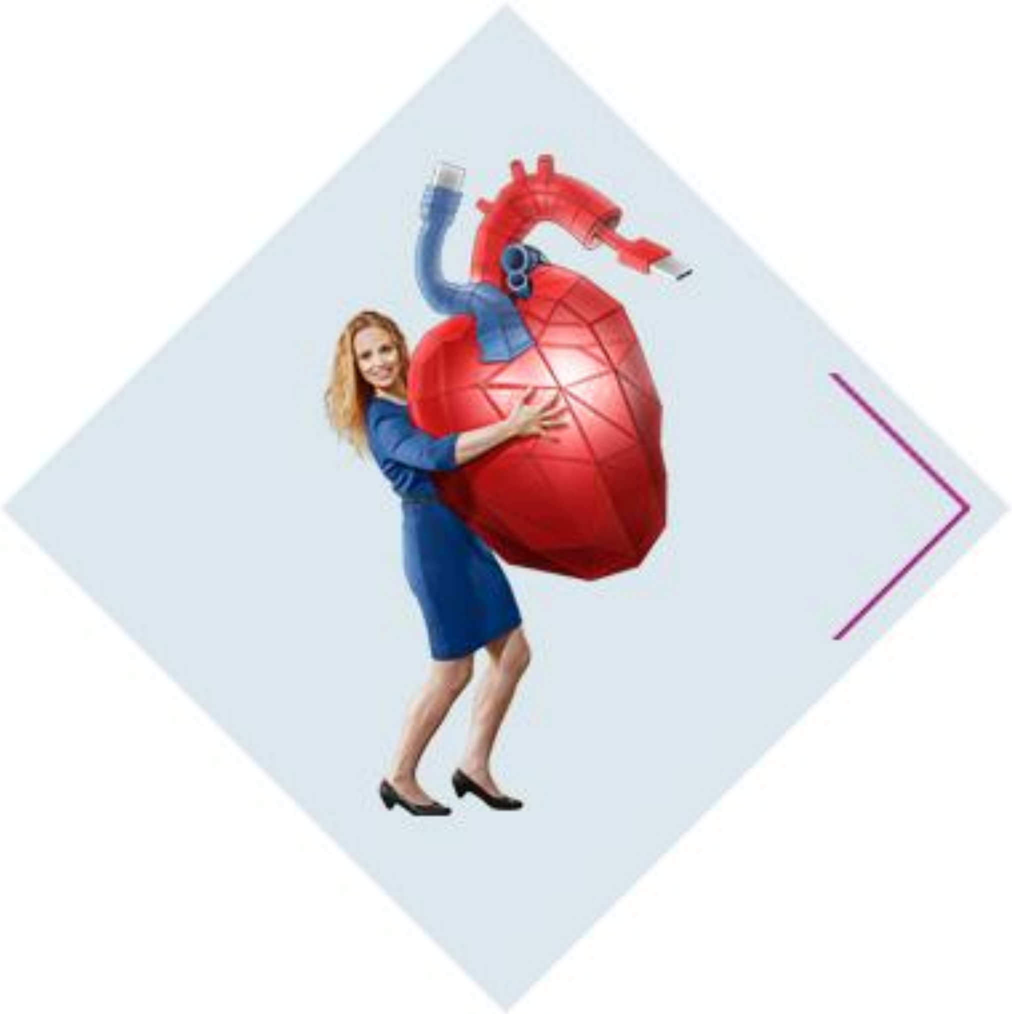
Experts are warning that quantum computers could eventually overpower conventional **encryption methods**, a potentially dangerous fate for humanity that they're evocatively dubbing the "quantum apocalypse,

Is the quantum army advancing at a rapid pace?



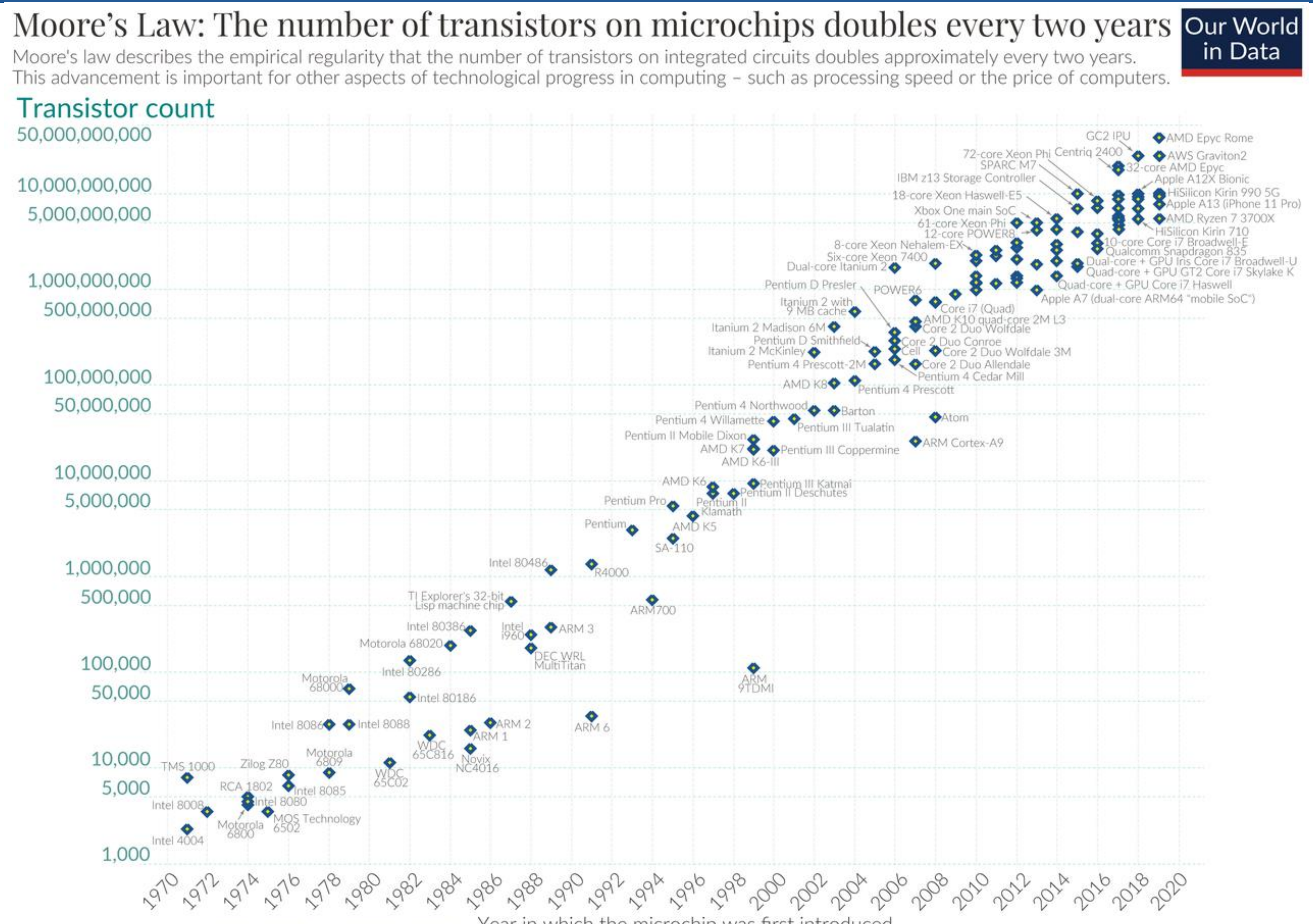
Agenda

- Quantum computer Vs. classical computer
- Quantum computers in practice
- Crypto-apocalypse now?
- Quantum-resistant cryptography
- Conclusions



Agenda

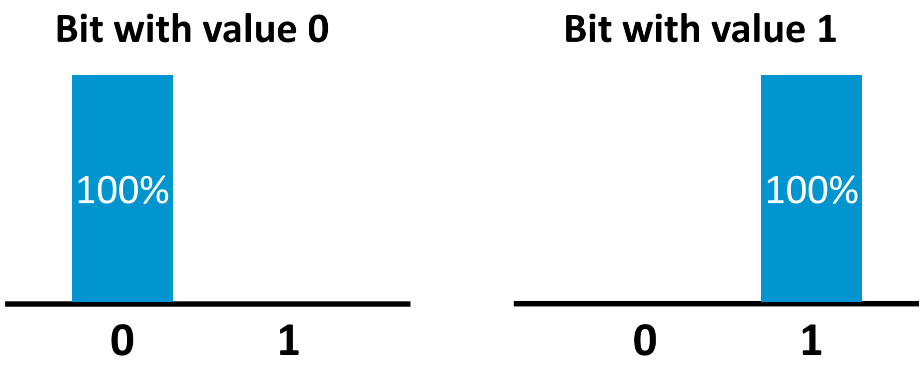
- **Quantum computer Vs. classical computer**
- Quantum computers in practice
- Crypto-apocalypse now?
- Quantum-resistant cryptography
- Conclusions



- Extrapolation
- Number of transistors on a chip doubles every x (12, 18, 24, 30) months
- Forecast: Moore's law will end in 2025 (?)
- Collides with laws of Newtonian physics
- More powerful classical computers increasingly challenging
- Quantum computing?

Superposition simplified

Classical computer

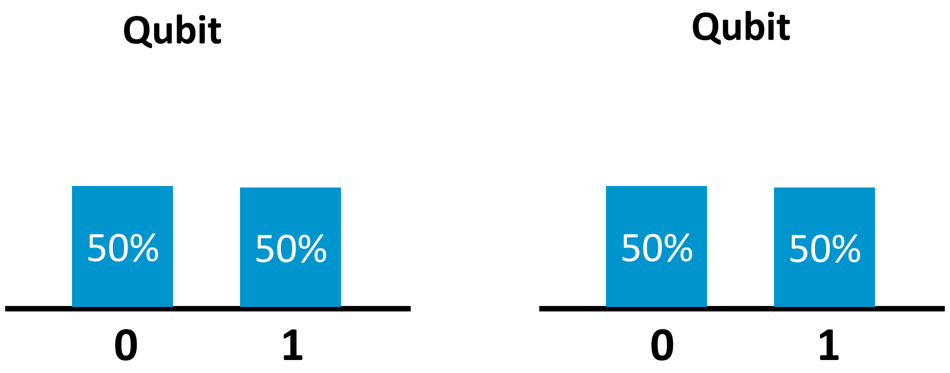


Electrical charge

The value is already fixed before the measurement

Measurement no impact on state bit

Quantum Computer



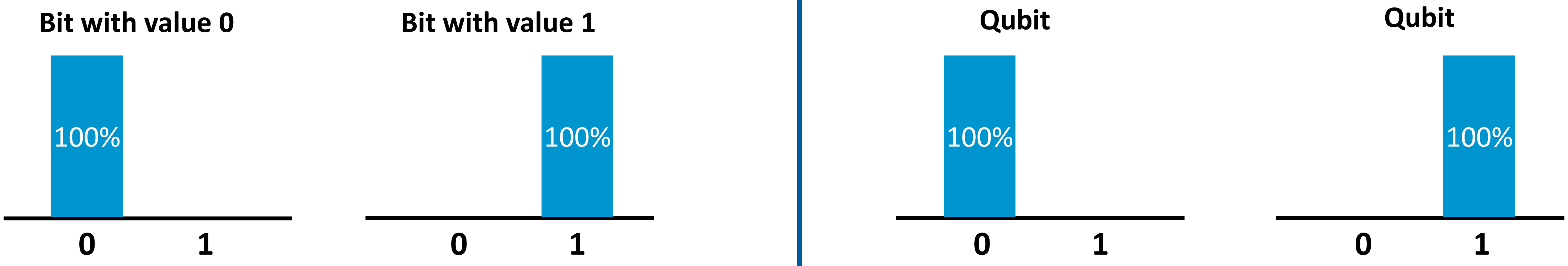
(Sub)atomic 'particle' (e.g.. Polarization photon, spin electron)

Value undetermined (smeared out) until measurement

Measurement destroys quantum state: The possible becomes a concrete value

Classical computer

Quantum Computer



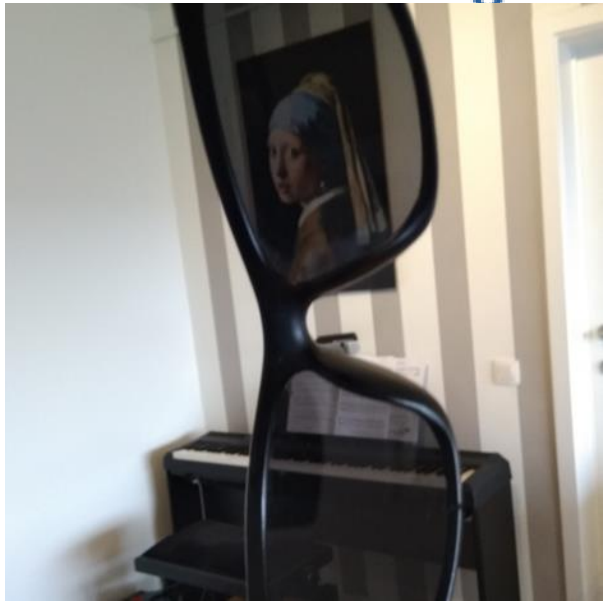
Classical computer: Measurement → 0 **Or** Measurement → 1

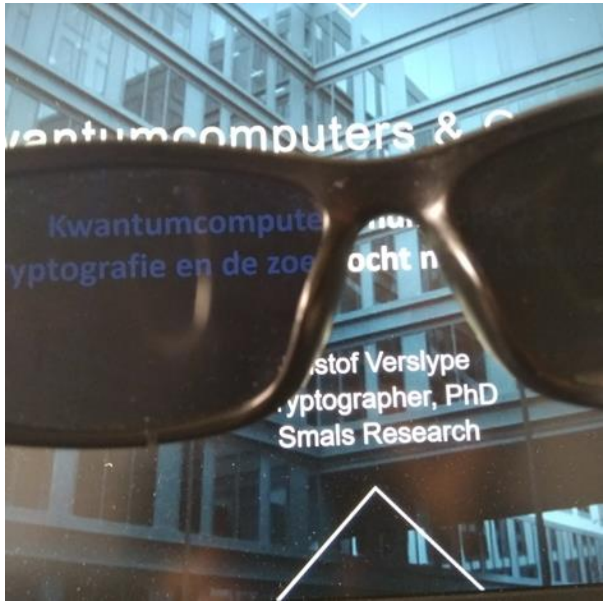
Quantum Computer: Measurement → 0 **Or** Measurement → 1

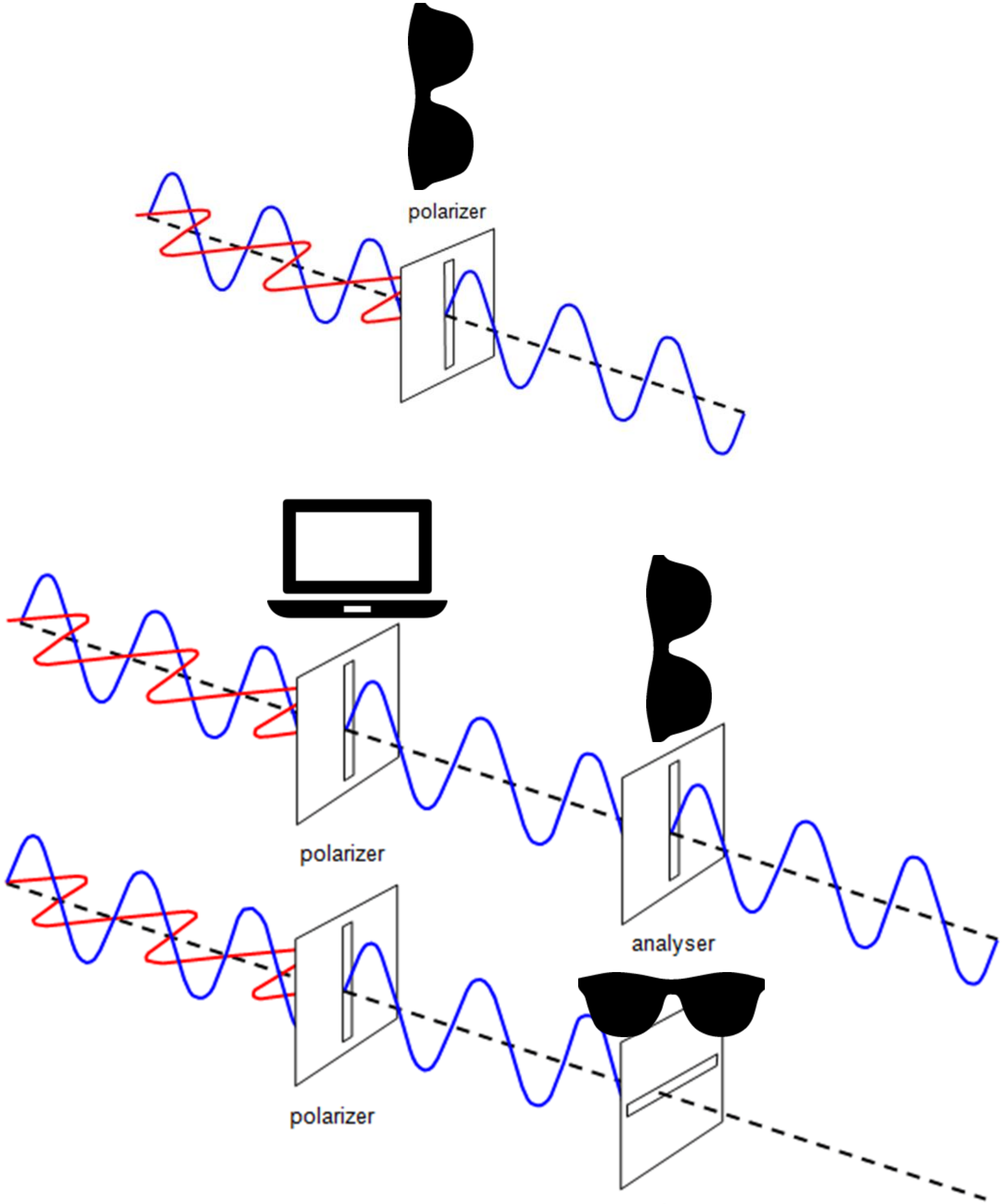
Classical computer		
Electrical charge	The value is already fixed before the measurement	Measurement no impact on state bit

Quantum Computer		
(Sub)atomic 'particle' (e.g.. Polarization photon, spin electron)	Value undetermined (smeared out) until measurement	Measurement destroys quantum state: The possible becomes a concrete value

Polarisation of photons – Sun glasses experiment

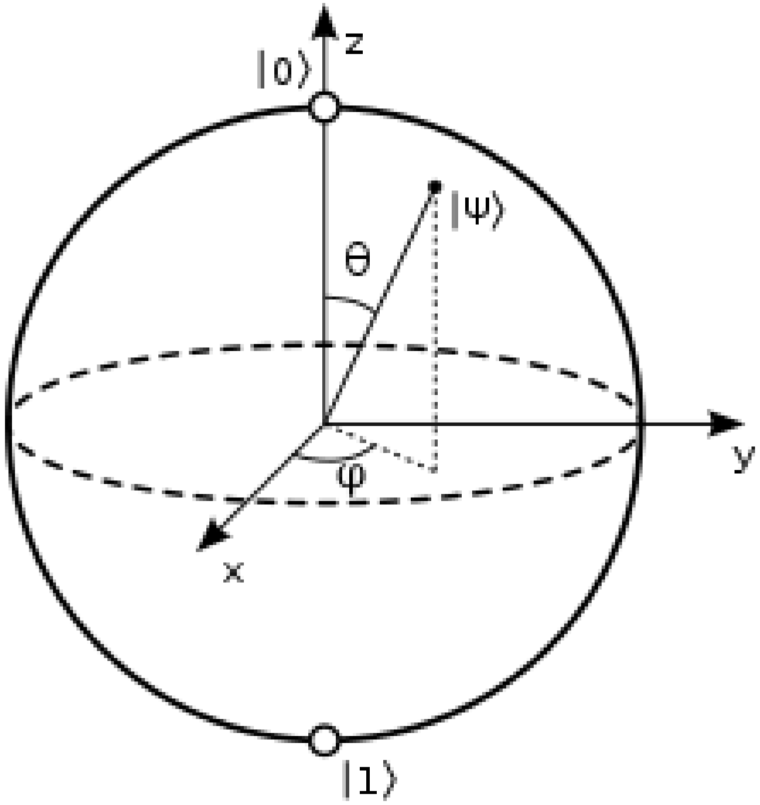






Disclaimer: Reality is more complicated

Bloch Sphere

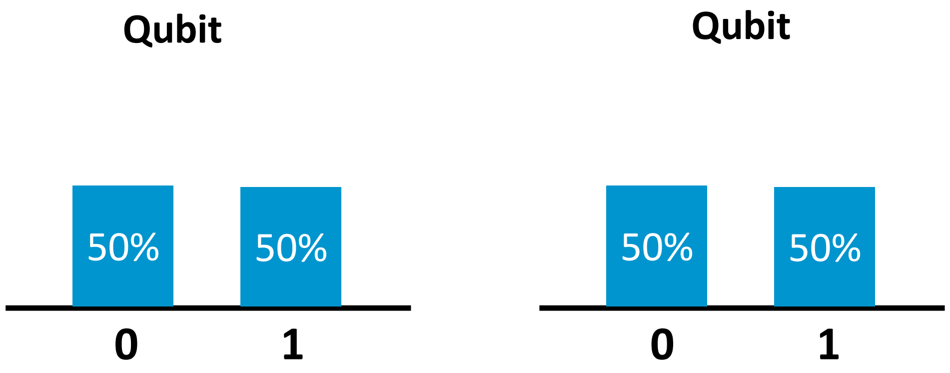


Dirac or Bra-ket notation of qubit

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Smals ICT for society

Entanglement



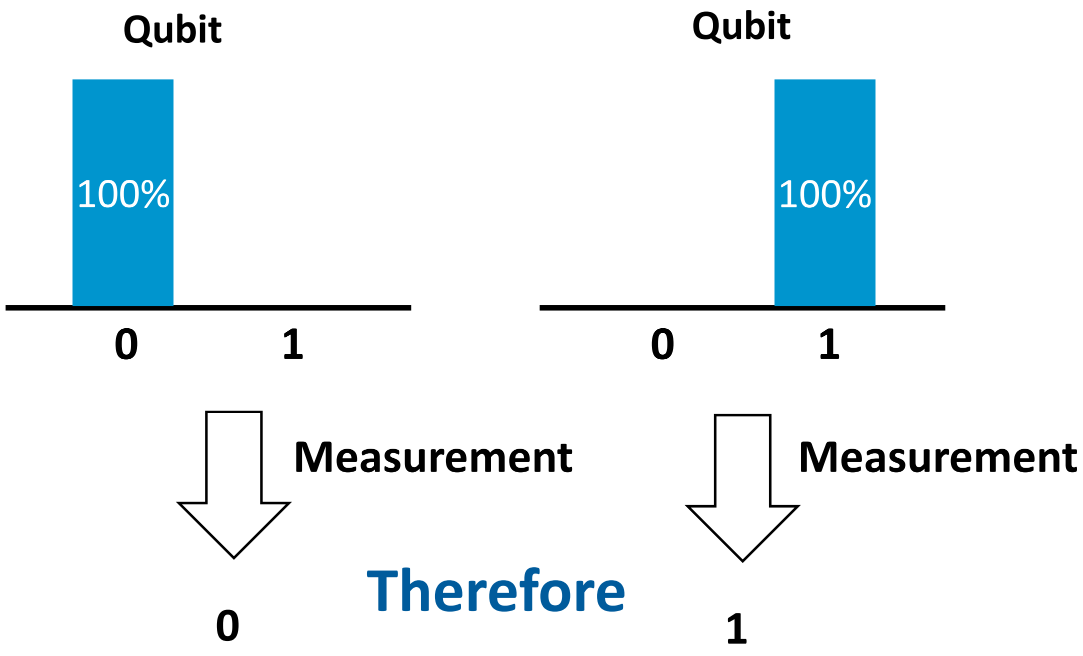
Correlation between measurements of related particles

Measuring one qubit is sufficient to know the result of another

Independent of distance between qubits
(↔ Newtonian physics)

Entanglement of more than 2 qubits is also possible

Entanglement



Correlation between measurements of related particles

Measuring one qubit is sufficient to know the result of another

Independent of distance between qubits (↔ Newtonian physics)

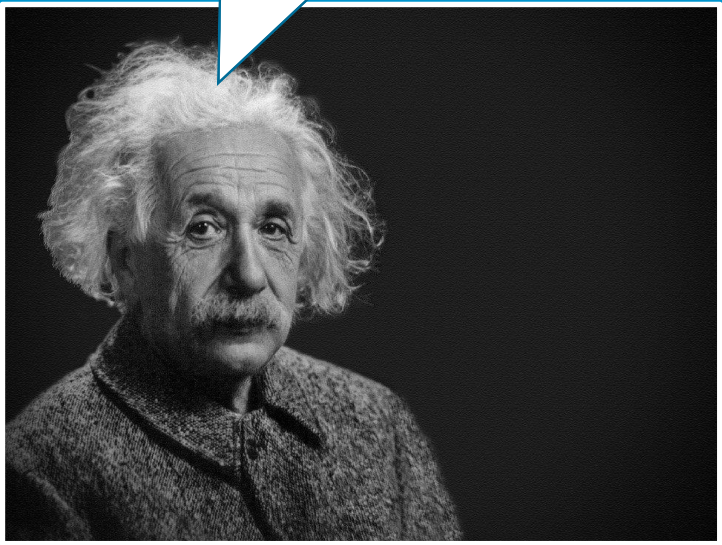
Entanglement of more than 2 qubits is also possible

Entanglement

Superposition
Value is undetermined until the time of measurement

Entanglement
Measurement of one qubit has impact on the outcome of measurement of another qubit

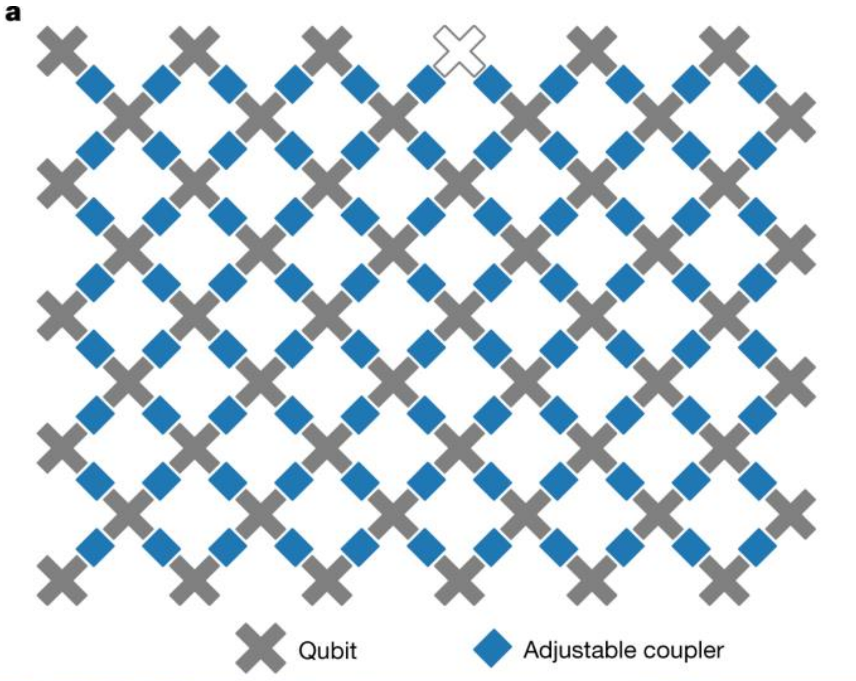
At the time of measurement of one qubit, the value of the other qubit is determined
→ Type of connection, independent of distance



Confirmed with high probability by experiments
(e.g. Bell test experiments)
No “hidden variables”

Quantum state

- **Superposition**
  Value qubit undetermined until time of measurement
- **Entanglement**
  Measurement of one qubit has an impact on the outcome of measurement of another qubit



Quantum logic gates
Pauli-X, Hadamard, SWAP, …

Quantum state

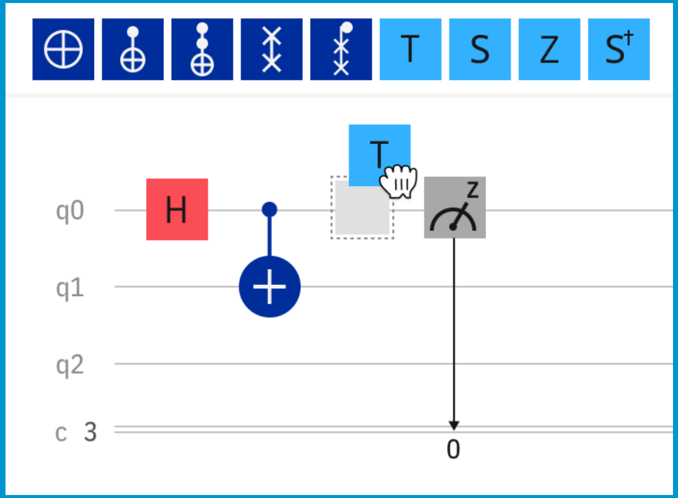
Smals
ICT for society

Building bricks for calculations: Logic gates

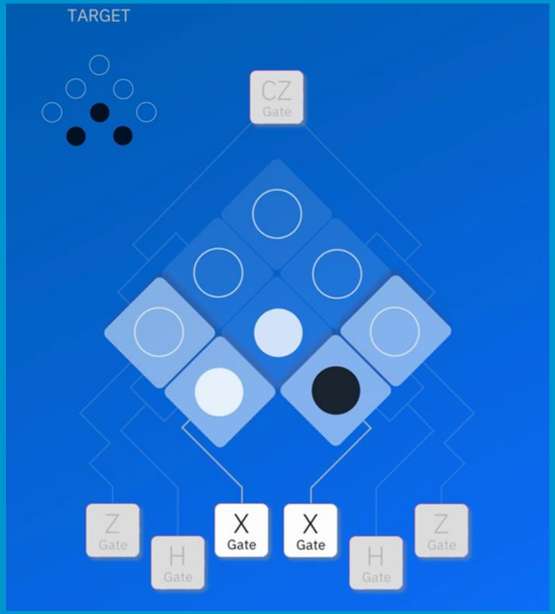
Classical computer
Logic gates:
AND, NOT, OR, XOR, …

Quantum Computer
Quantum logic gates:
Pauli-X, Hadamard, SWAP, …

- **Quantum instruction sets**
  Convert algorithms to quantum processor instructions
  vb. Quil, OpenQASM
- **Quantum software development kits**
  Tools to create and manipulate
  vb. Qiskit, ProjectQ, Forest
  Often extensions existing programming languages
- **Quantum programming languages**
  Quantum Computation Language (QCL), Q#, Q language



IBM Quantum Experience



IBM Hello quantum app

Observation
When people don't understand something, they may attribute mythical properties to it

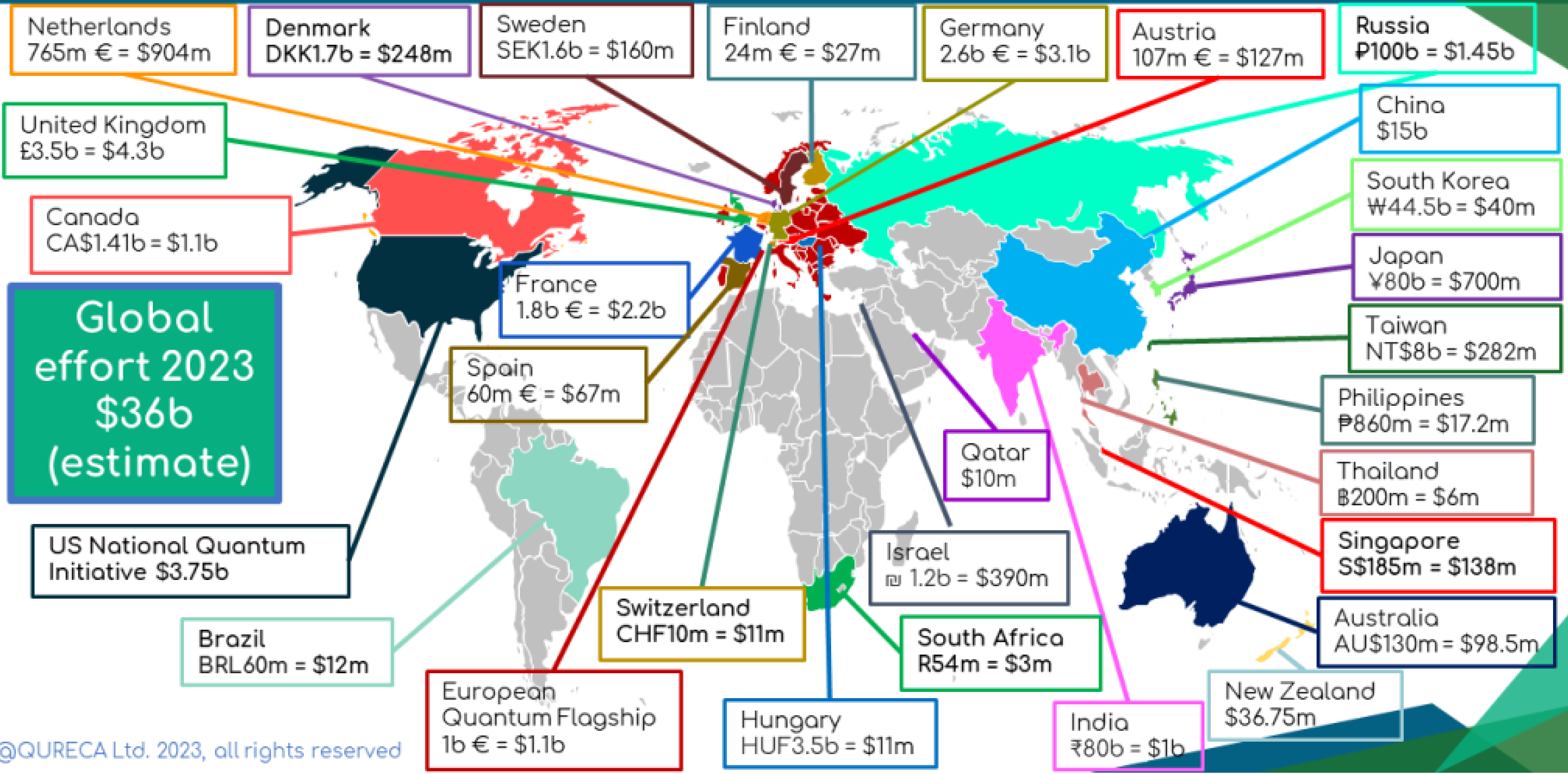
Misconception
“Quantum computers will be able to solve all problems that are difficult (or even impossible) for classical computers.”

Depends on problem

- Probably no significant added value
  E.g. Combinatorial search problems such as traveling salesman problem (NP-hard)
- Potentially added value
  E.g. *Deep learning*
- Clear added value
  E.g. Simulations natural processes
  E.g. Breaking modern cryptography

Quantum effort worldwide

Global quantum technology market is projected to reach $42.4 billion by 2027



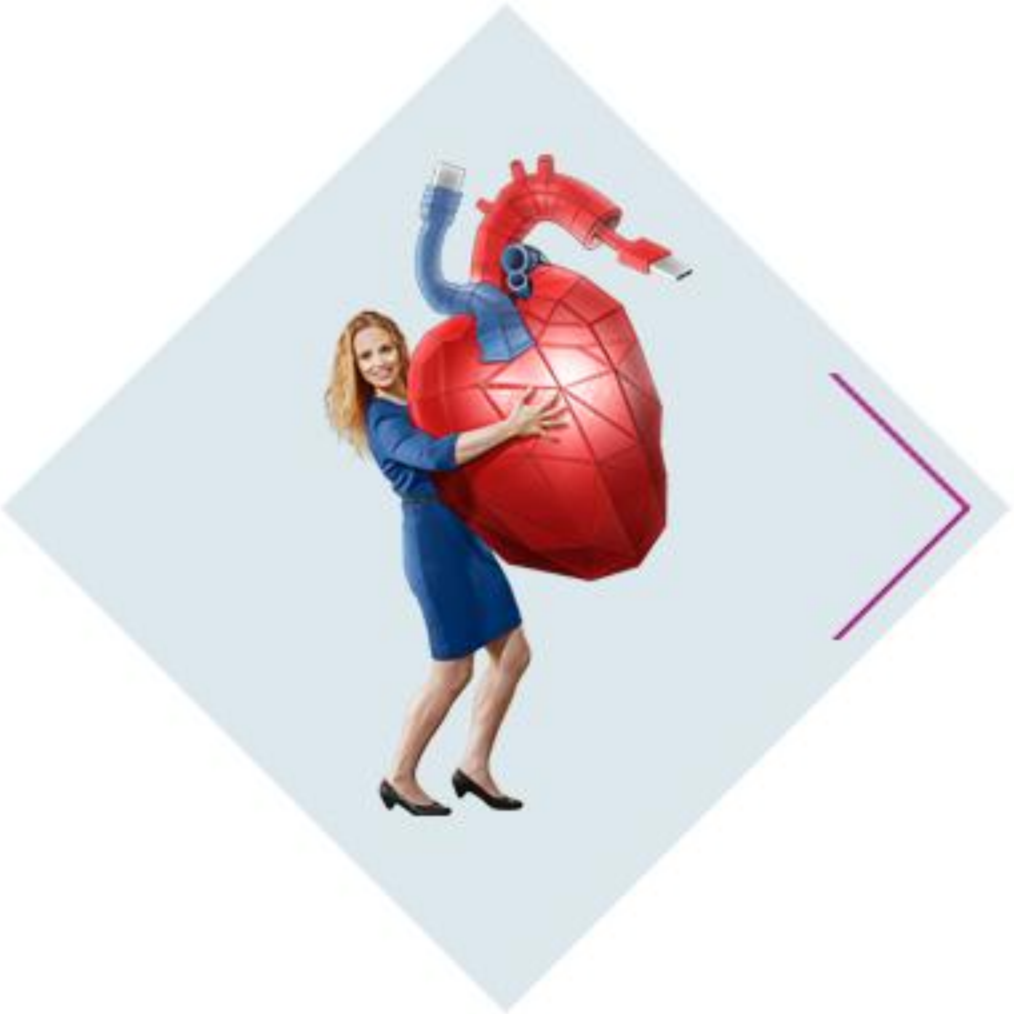
Universal quantum computers

- Relying on unintuitive principles such as entanglement and superposition
- Have Qubits – (sub)atomic particles / waves – as the smallest storage and calculation unit
- Calculation is done in a fundamentally different way than with classical computers
- Are – on paper – powerful for a limited group of problems

"However, how many times faster [quantum computers will be] remains to be seen. Maybe 10 times, maybe 100 times. Some even talk about 100 million times faster. "

Koen Bertels
Belgian professor at TU Delft
Head Quantum Computer Architectures Lab TU Delft

https://www.vrt.be/vrtnws/nl/2019/12/24/vlaamse-topwetenschappers-blikken-vooruit-naar-2030-kwantumcomp/



Agenda

- Quantum computer Vs. classical computer
- **Quantum computers in practice**
- Crypto-apocalypse now?
- Quantum-resistant cryptography
- Conclusions

Google claims quantum supremacy

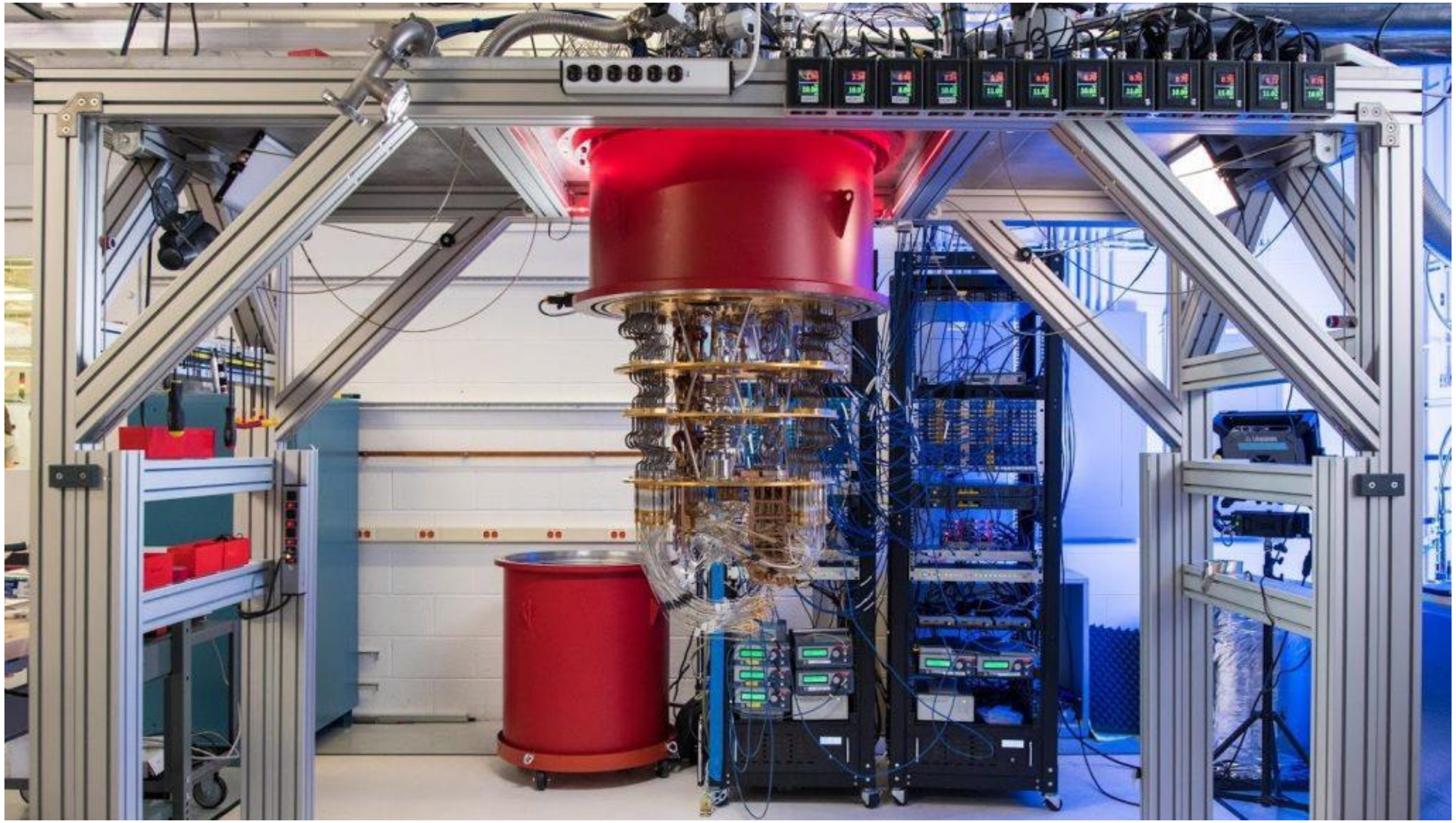
23 October 2019

Google

Article

Quantum supremacy using a programmable superconducting processor

nature
International journal of science



https://www.nature.com/articles/s41586-019-1666-5

Smals
ICT for society

Google claims quantum supremacy

23 oktober 2019

Google

Article

Quantum supremacy using a programmable superconducting processor

nature
International journal of science

Quantum supremacy / Primacy

Quantum computers can solve a problem that is **practically impossible** for classical computers.

One, practically useless problem, is enough!

John Preskill, Theoretical physicist, 2012

Nevertheless, building a quantum computer with 53 qubits is a very strong achievement

The problem

- Randomly choose numbers according to specific distribution
- Tailored to quantum computers
- Not really useful

The claim

"Our Sycamore quantum computer does in 200 seconds what a classical computer would take 10,000 years to do."

The response

- **IBM**
  "Conservatively estimated, this can be done in 2.5 days with a conventional computer, and with a much higher accuracy"
- **Koen Bertels**
  Head Quantum Computer Architectures Lab, TU Delft
  "Simply not true"

als
ociety

China claims quantum primacy

27 oktober 2021

PHYS ORG

Two Chinese teams claim to have reached primacy with quantum computers

by Bob Yirka , Phys.org

The Pan team's optical quantum computer uses a 144-mode interferometer to solve a Gaussian boson ...

Two teams in China are claiming that they have reached primacy with their individual quantum computers. Both have published the details of their work in the journal *Physical Review Letters*.

The problem

- Simulation for calculating probabilities output circuit with photons (quantum effects)
- Tailored to quantum computers
- Not really useful

The claim

"10^{23} x faster than a classical supercomputer"

The response

- Not contested
- This time, quantum supremacy / primacy reached

Another very strong performance!
(I.e. calculations with 56 qubits)

smals
ICT for society

 https://phys.org/news/2021-10-chinese-teams-primacy-quantum.html

Timeline quantum computers

1st half 20th century
Development
Quantum Mechanics

By 1930 QM formalized by
Hilbert, Dirac, Neuman

1980-1982
Idea quantum computer
(Benioff, Feynman, Manin)

1998
First quantum computer
2 qubits

1/2017
D-Wave 2000Q
2048 qubits

11/2017
IBM Q 20 Tokyo
20 qubits

12/2017
Rigetti 19Q Acorn
19 qubits

3/2018
Google Bristlecone
72 qubits

11/2018
Rigetti 16Q Aspen-1
16 qubits

7/2019
Google Sycamore
54 qubits (53 effectief)

10/2019
IBM Q 53
53 qubits

9/2020
D-Wave Advantage
5000 qubits

11/2021
Jiuzhang 2
60 qubits

11/2021
IBM EAGLE
127 qubits

11/2022
IBM Osprey
433 qubits

More extensive timeline https://en.wikipedia.org/wiki/List_of_quantum_processors

Properties

- Requires less entanglement
- But more qubits
- Quantum annealing: combinatorial optimization problems (i.e. search space is discrete, s.a. traveling salesmen problem)
- Machines being sold ($10M-$15M)
- No quantum advantage yet

Quantum advantage

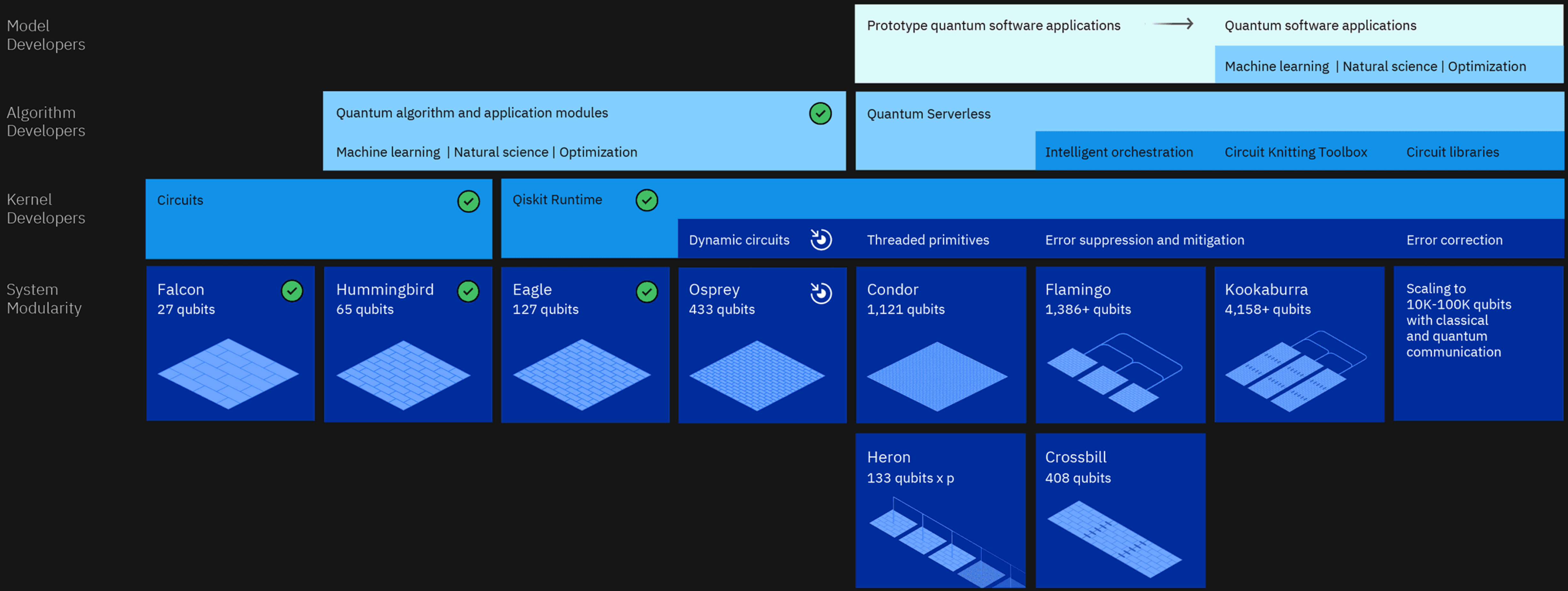
Quantum computers can solve a problem **FASTER** than classical computers.

One, practically useless problem, is enough!

Development Roadmap | Executed by IBM ✓ On target

IBM **Quantum**

2019 ✓	2020 ✓	2021 ✓	2022	2023	2024	2025	Beyond 2026
Run quantum circuits on the IBM cloud	Demonstrate and prototype quantum algorithms and applications	Run quantum programs 100x faster with Qiskit Runtime	Bring dynamic circuits to Qiskit Runtime to unlock more computations	Enhancing applications with elastic computing and parallelization of Qiskit Runtime	Improve accuracy of Qiskit Runtime with scalable error mitigation	Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime	Increase accuracy and speed of quantum workflows with integration of error correction into Qiskit Runtime



More qubits ≠ more computation power

Type quantum computer
- Universal (Rigetti, Google, IBM)
- Adiabatic (D-Wave)

Noise / Accuracy

…

→ IBM prefers the term ***Quantum Volume***
→ Not easy to compare. Companies are not always transparent about inner workings & specs

Why is building a quantum computer so complex?

- Isolation
- Error correction
- Scalability

Challenge 1: Isolation

Interference

- Quantum state extremely sensitive for external interference
- Temperatures close to absolute zero (-273,15° C)
- Schielded from vibrations, light & magnetic radiation

Coherence time

- Challenge: keeping quantum state sufficiently long coherent
- Googles Sycamore: tenths or hundredths of a microsecond

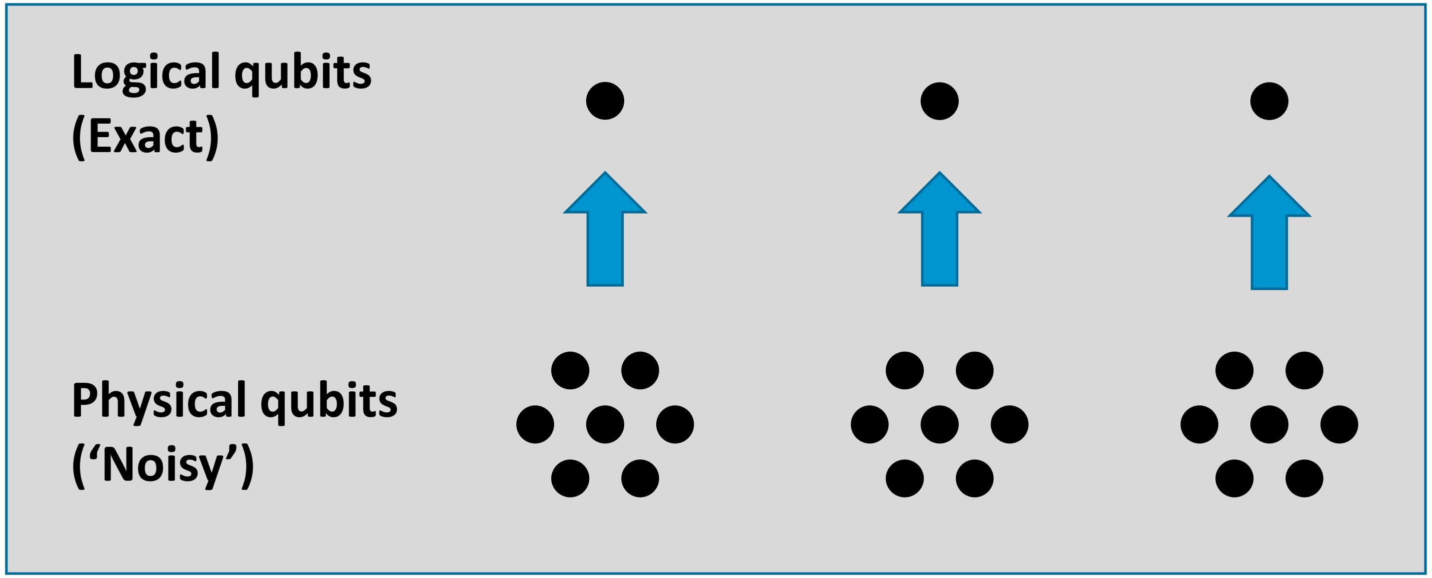
Manipulation

- Quantum logic gates sensitive to errors
- Reading (Measuring qubits)

Evolution

- Significant progress in recent years
- Errors most likely unavoidable

Errors may be unavoidable → error correction necessary
Multiple physical qubits together form 1 logical qubit



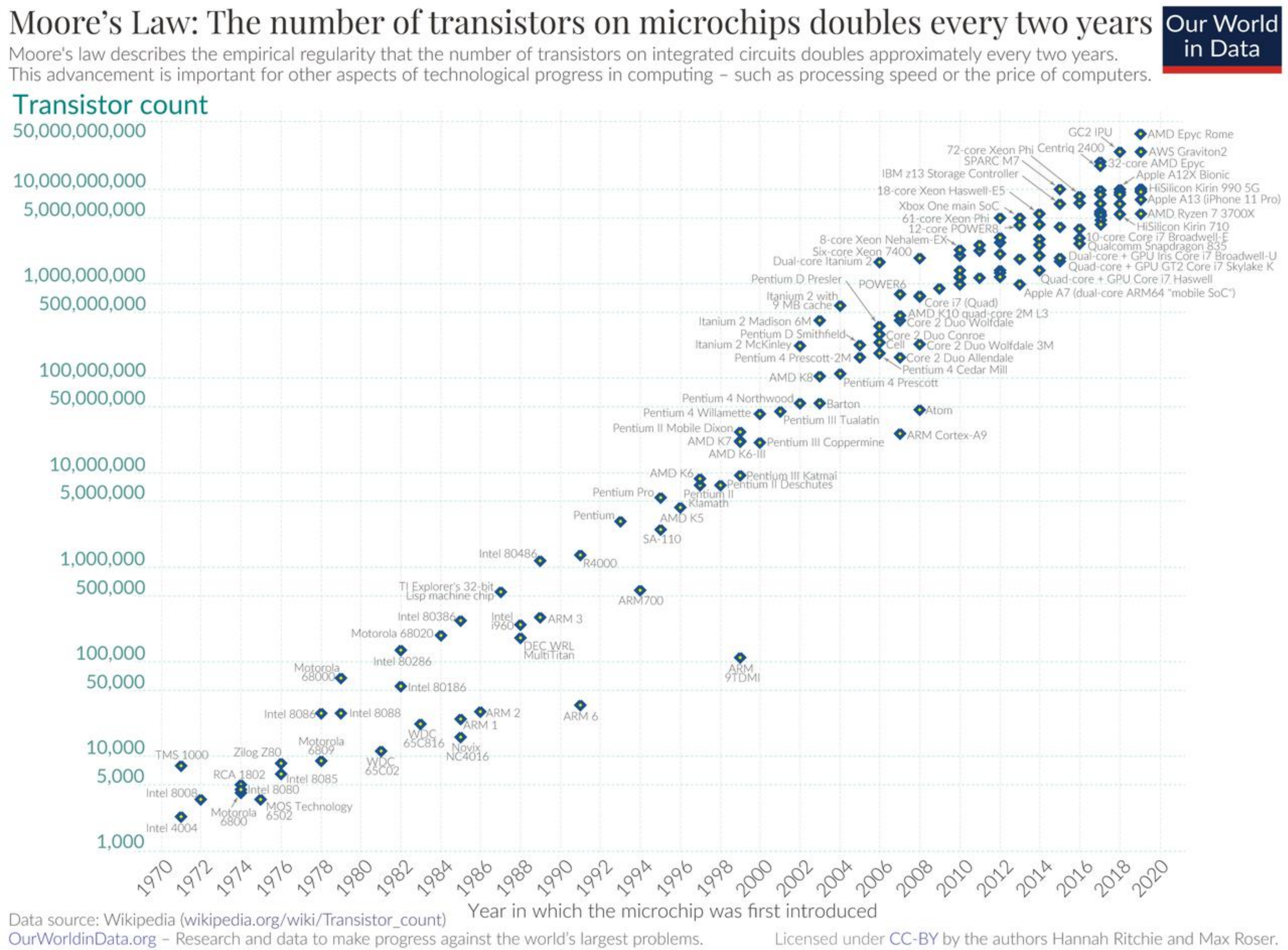
Evolution

- Years '80 and '90: "*impossible!*"
- First experiments

Requirments

- Sufficiently long coherence time
- Estimates: 1000 to 100 000 physical qubits for a logical qubit
  - Noise physical qubits
  - Length of the circuit

Challenge 3: Scalability



Classical computer

- Number of transistors on a chip doubles every x (12, 18, 24, 30) months

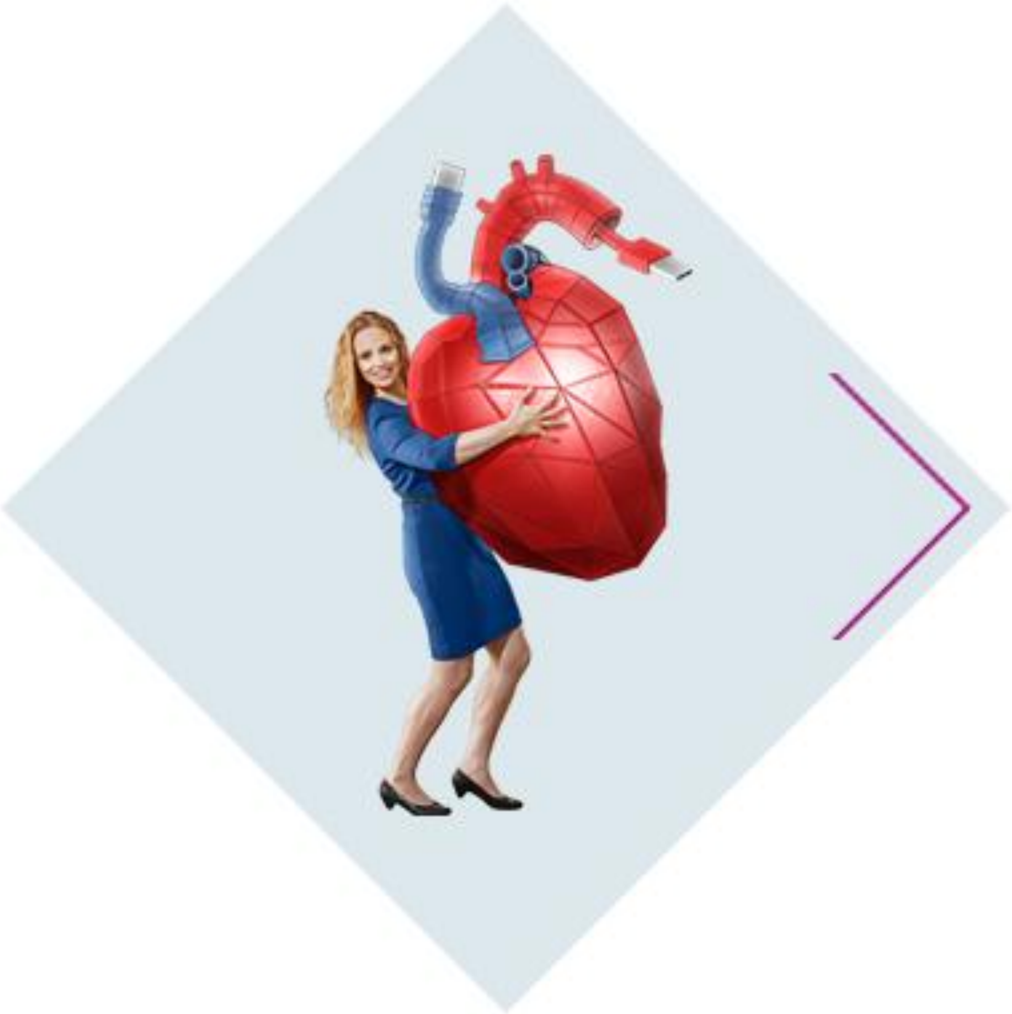
Quantum computer

- $O(10) \longrightarrow O(10^7)$
- Requires exponential growth
- That can be maintained long enough
- In number of qubits AND in accuracy

Why is building a quantum computer so complex?

- Isolation
- Error correction
- Scalability

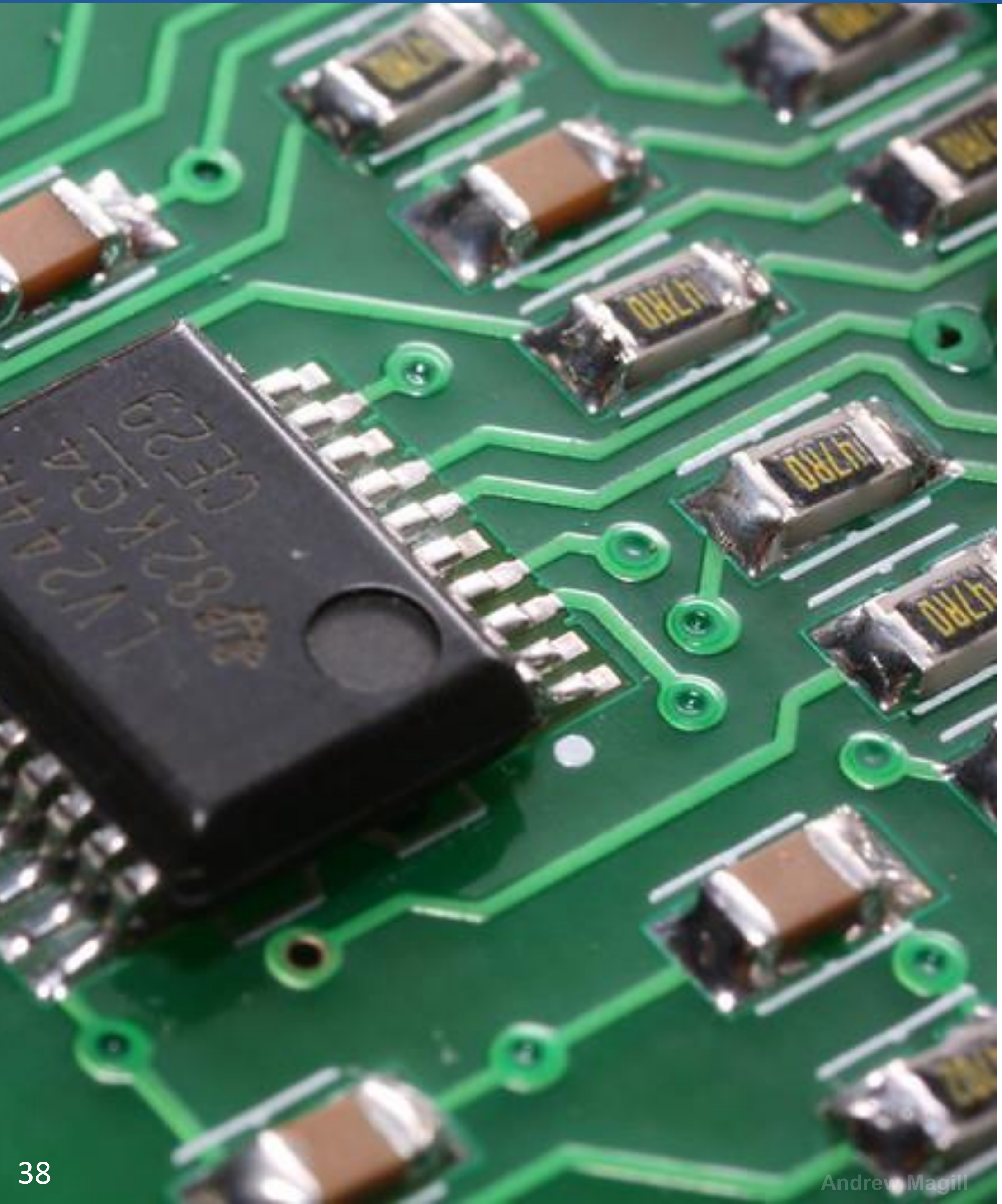
Challenges are astronomical



Agenda

- Quantum computer Vs. classical computer
- Quantum computers in practice
- **Crypto-apocalypse now?**
- Quantum-resistant cryptography
- Conclusions

Modern cryptography

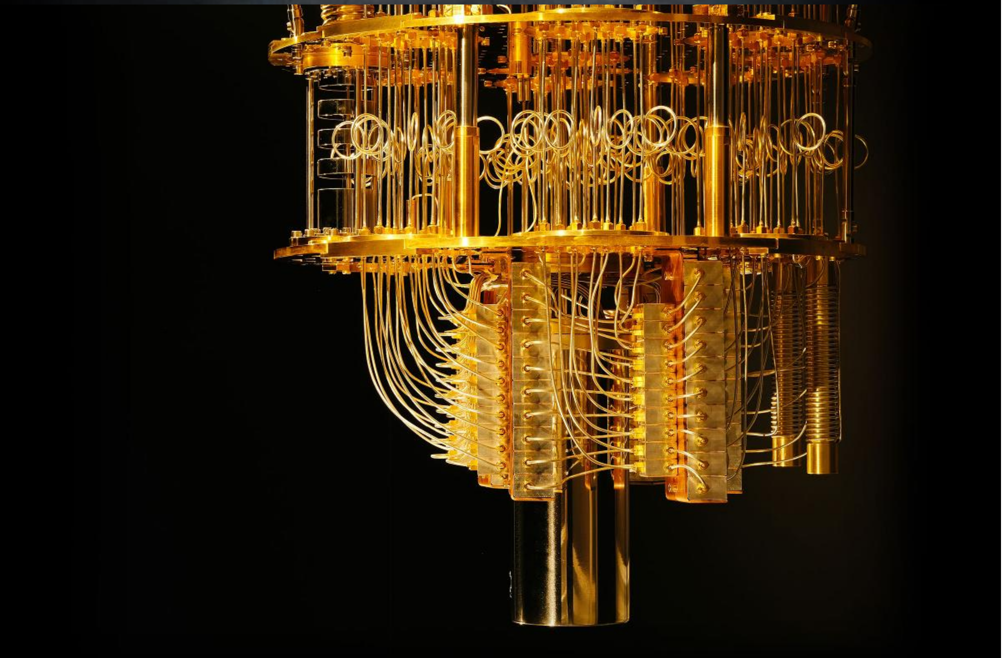


- ► Since the advent of classical computers (1970s)
- ► Public algorithms, secret keys
- ► Security based on assumptions
  (from which security of algorithm is proven)
- ► Much more than confidential communications

CRYPTO WORKHORSES

Encryption DES, AES, ElGamal, RSA, …	**Digital signatures** RSA, DSA, Schnorr, …
Authentication SSH, CHAP, …	**Hashing** MD5, RipeMD, SHA-1, SHA-2, SHA-3
Key exchange Diffie–Hellman, …	**Message authentication code** HMAC, …

Crypto assumptions & Quantum computers



Modern cryptography

INSECURE Crypto primitive	INSECURE Crypto primitive	INSECURE Crypto primitive	Crypto primitive

Quantum resistant cryptography

Crypto primitive	Crypto primitive	Crypto primitive	Crypto primitive

Assumptions

Smals
ICT for society

Impact quantum computers on modern cryptography?

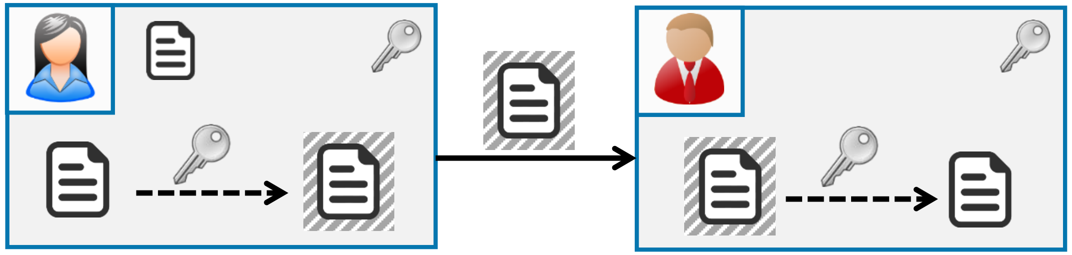
Symmetric cryptography

Cryptographic hash function

Public-key cryptography

Symmetric cipher

- Encryption and decryption with same secret key
- AES (KU Leuven)



Breaking = finding secret key

Toy classical computer

- Key length = ~~6 bits~~ 128 bits
- $8^2 = 2^6 = 64$ potential keys (= search space)
- Security = 6 bit
- Best attack is ± exhaustively testing each possible key
- On average, key found after 32 attempts

Toy quantum computer

- Promises quadratic speedup
  Size search space decreases from 64 to $\sqrt{64} = 8$
- Security decreased to 3 bit (because $8 = 2^3$)
- On average, key found after 4 attempts

Toy measure

128 → 256 bits

- Double key length: ~~6 → 12 bits~~
- Size of search space classical computer: $2^{12} = 64^2 = 4096$
- Size search space quantum computer: $\sqrt{4096} = 64$

Search space

0	1	2	3	4	5	6	7
8	9	10	11	12	13	14	15
16	17	18	19	20	21	22	23
24	25	26	27	28	29	30	31
32	33	34	35	36	37	38	39
40	41	42	43	44	45	46	47
48	49	50	51	52	53	54	55
56	57	58	59	60	61	62	63

Smals ICT for society

Grover's Algorithm on a quantum computer

Number of LOGICAL qubits required

- AES-128: 2953
- AES-192: 4449
- AES-256: 6681
- **Entangled**

Personal thought

First, a "quantum oracle" must be built. This step MAY negate the performance gain of Grover's algorithm

Zoekruimte

0	1	2	3	4	5	6	7
8	9	10	11	12	13	14	15
16	17	18	19	20	21	22	23
24	25	26	27	28	29	30	31
32	33	34	35	36	37	38	39
40	41	42	43	44	45	46	47
48	49	50	51	52	53	54	55
56	57	58	59	60	61	62	63

Smals
ICT for society

Quantum resistant cryptography – BSI

Bundesamt
für Sicherheit in der
Informationstechnik

“At the present time, there is no evidence that symmetric cryptographic mechanisms are threatened in any significant way by quantum computers.

Generally, an adversary which has access to k universal quantum computers can perform a key recovery attack against a block cipher with a key length of n bits by executing the Grover algorithm in parallel on all available quantum computers within $\approx \pi 2^{\frac{n-4}{2}}/\sqrt{k}$ / k time units, where one unit of time corresponds to the time needed to execute the block cipher on a single quantum computer”

TR-02102-1: Cryptographic Mechanisms: Recommendations and Key Lengths
January 2023

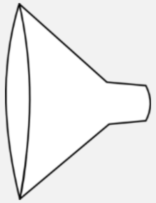
https://www.bsi.bund.de/SharedDocs/Downloads/EN/BSI/Publications/TechGuidelines/TG02102/BSI-TR-02102-1.html

Powerful quantum computers pose no threat to symmetric cryptography

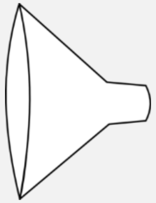
(As a precaution, take sufficiently long keys)

Cryptographic hash function

- Integrity
- Very commonly used (e.g. electronic signatures, files, blockchain)
- Examples: SHA1, SHA2, SHA3

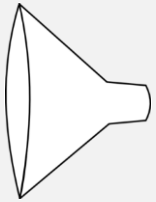



5e 50 6e 82 7f d5 50 ec 4e 08 8e e7 75 8f 34 b3
a6 8e 34 93 d5 89 98 52 97 48 f0 c6 c1 70 f3 3c

5f 3b fa 41 9c 63 be 2a 3a 09 ad bd 06 30 c5 1f
64 5e b0 3a ba fc d5 f2 ad 39 63 7a 30 6b 41 77

"Hello world!"



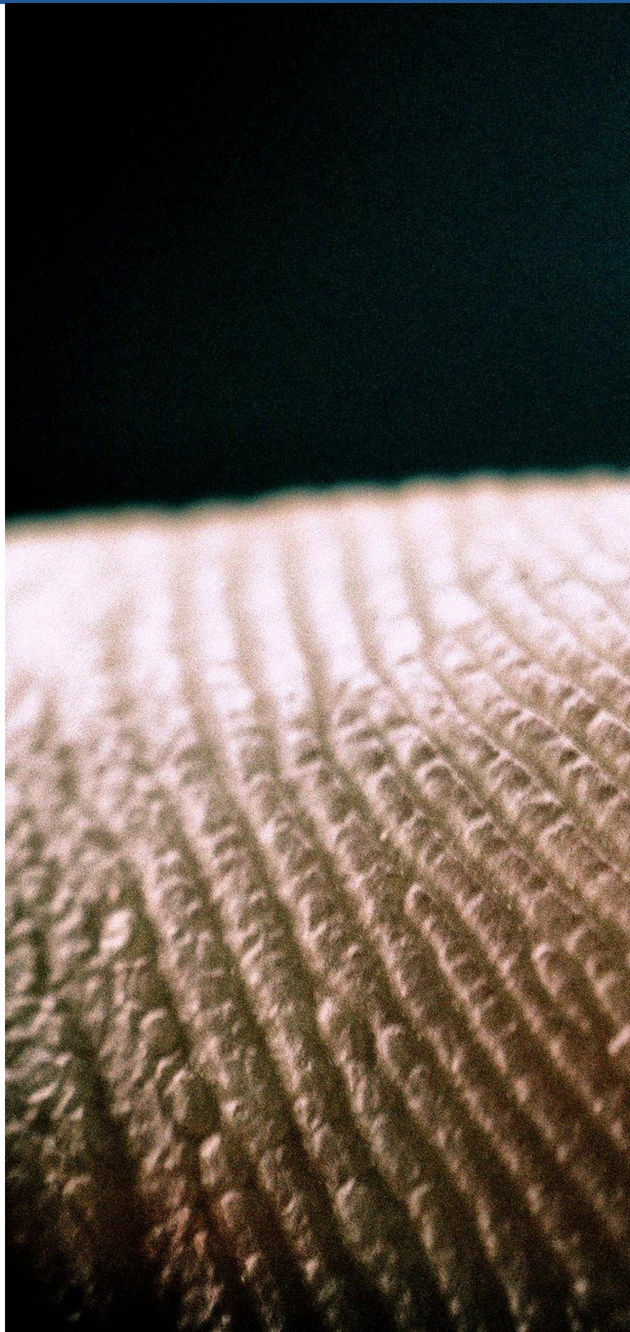
c0 53 5e 4b e2 b7 9f fd 93 29 13 05 43 6b f8 89
31 4e 4a 3f ae c0 5e cf fc bb 7d f3 1a d9 e5 1a

Fixed-length output

Collision resistance

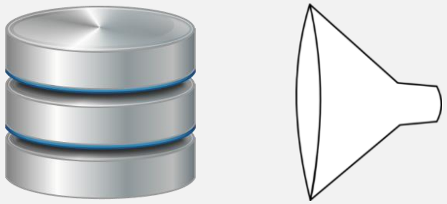
Pre-image resistance

Second pre-image resistance

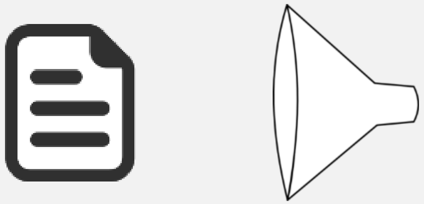


Cryptographic hash function

- Integrity
- Very commonly used (e.g. electronic signatures, files, blockchain)
- Examples: SHA1, SHA2, SHA3

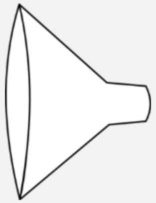


5e 50 6e 82 7f d5 50 ec 4e 08 8e e7 75 8f 34 b3
a6 8e 34 93 d5 89 98 52 97 48 f0 c6 c1 70 f3 3c



5f 3b fa 41 9c 63 be 2a 3a 09 ad bd 06 30 c5 1f
64 5e b0 3a ba fc d5 f2 ad 39 63 7a 30 6b 41 77

“Hell0 world!”



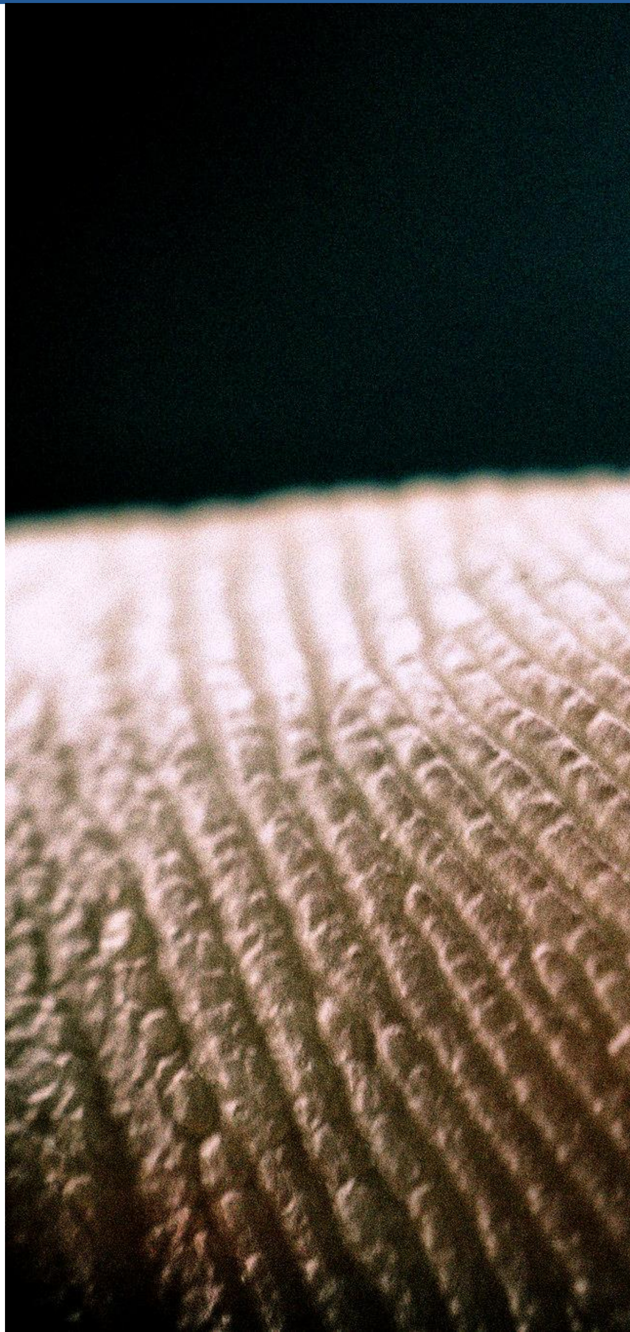
c3 5e 79 4b cf 52 34 c4 5a fc 19 c0 04 79 3d e7
d3 d2 4b 20 12 d0 3b f6 13 8b 23 c9 97 41 8a 50

Fixed-length output

Collision resistance

Pre-image resistance

Second pre-image resistance



Collision attack

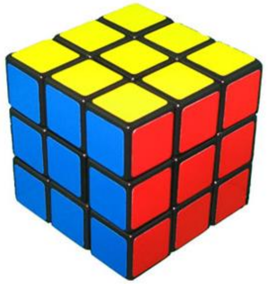
- ▶ Finding two inputs that result in the same output
- ▶ Successful attack against SHA1 in 2017

Classical computer

- ▶ 256 bits outputs results in 128 bits security
  P[collision] ≈ 50% after $\sqrt{2^{256}} = 2^{128}$ attempts
- ▶ Cfr. Birthday paradox

Quantum computer

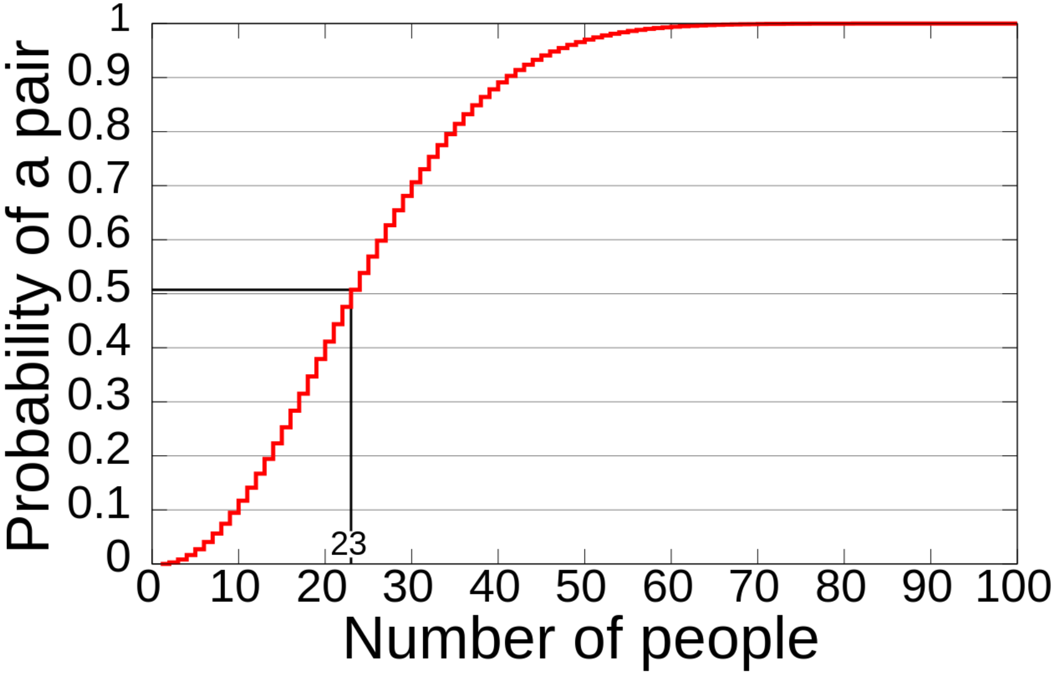
- ▶ Grover's algorithm
- ▶ Security decreases
  from $\sqrt{2^{256}} = 2^{128}$
  to $\sqrt[3]{2^{256}} = 2^{85} \approx 10^{26}$ (insecure)



Measure

- ▶ Output length x 1,5: 256 → 384 bits ($\sqrt[3]{2^{384}} = 2^{128}$)
- ▶ Manageable!

Birthday paradox



https://arxiv.org/pdf/1804.00200.pdf

Smals
ICT for society

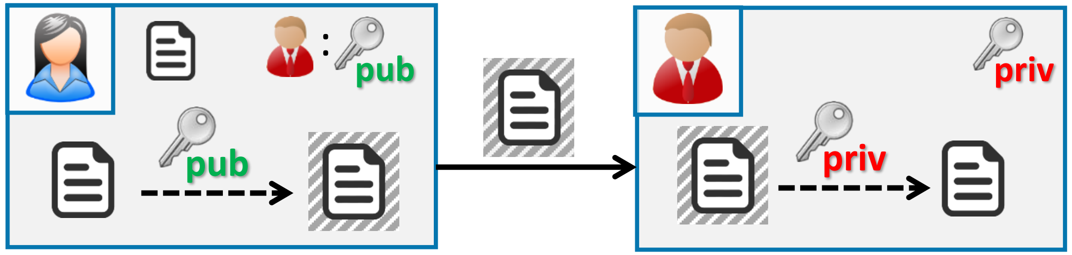
Powerful quantum computers pose no threat to cryptographic hash functions

(Make sure the output is long enough)

Public-key cryptography

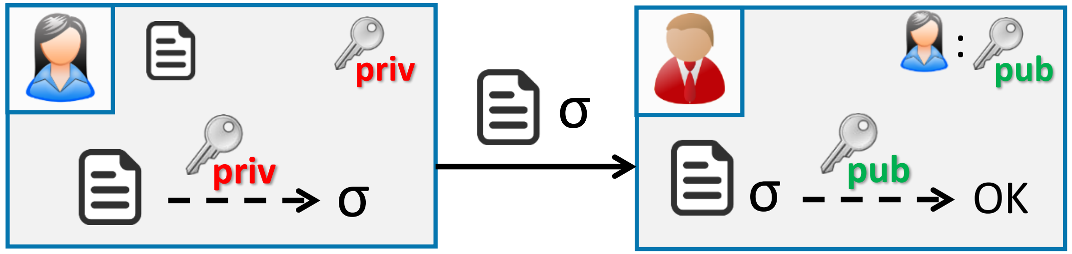
Public-key encryption

- ▶ Confidentiality
- ▶ Encryption with public key, decryption with private key



Digital signatures

- ▶ Integrity, data authenticity
- ▶ Vb. Belgian eID card



Ook authentication & establishing secure channels (TLS)

Most common systems based on
RSA or elliptic curves

Prime number

Natural number only divisible by 1 and itself
E.g. 2, 3, 5, 7, 11, 13, 17, 19, 23, …

Factoring a number in prime factors

Unique for each number
Example: $12 = 2^2 * 3$

RSA assumption

There is no efficient algorithm for factoring a number that is the product of two large prime numbers. In practice infeasible when sufficiently large primes are chosen.

Powerful quantum computer could do this efficiently with the help of Shor's algorithm

Example

RSA-250 (829 bits) published in 1991

214032465024074496126442307283933356300861
471514475501779775492088141802344714013664
334551909580467961099285187247091458768739
626192155736304745477052080511905649310668
769159001975940569345745223058932597669747
1681738069364894699871578494975937497937
=
641352894770715802787901901705773890848250
147429434472081168596320245323446302386235
98752668347708737661925585694639798853367
×
333720275949781565562260106053551142279407
603447675546667845209870238417292100370802
57448673296881877565718986258036932062711

Was factored by classical computers in February 2020

Public key cryptography – Factorisation

Biggest RSA number factored by classical computer
RSA-250 (829 bits)

2140324650240744961264423072839333563008614715144755017797754920881418023447140136643345519095804679610992851872470914587687396261921557363047454770520805119056493106687691590019759405693457452230589325976697471681738069364894699871578494975937497937

(in 2020, 2700 core-years)

Biggest RSA number factored
With Shor's algorithm by quantum computer…

21

(in 2012)

RSA-2048 (2048 bits)

25195908475657893494027183240048398571429282126204032027777137836043662020707595556264018525880784406918290641249515082189298559149176184502808489120072844992687392807287776735971418347270261896375014971824691165077613379859095700097330459748808428401797429100642458691817195118746121515172654632282216869987549182422433637259085141865462043576798423387184774447920739934236584823824281198163815010674810451660377306056201619676256133844143603833904414952634432190114657544454178424020924616515723350778707749817125772467962926386356373289912154831438167899885040445364023527381951378636564391212010397122822120720357

Disclaimer

- Quantum computers already factored larger, very specifically chosen numbers without Shor's algorithm.
- Quantum factoring criticized for relying heavily on classical computers

Shor’s Algorithm (1994)

- Quantum algorithm to find the prime factors of an integer (RSA)
- Also applicable on cryptography based on elliptic curves (EC)

RSA

Algoritme	# bits security	# logical qubits	# physical qubits
*RSA-**1024***	80	± 2048	
*RSA-**2048***	112	± 4096	**20 million** (8 hours, 2019)
*RSA-**3072***	128	± 6144	
*RSA-**7680***	192	± 15360	
*RSA-**15360***	256	± 30720	

x2

Elliptic curves

Algoritme	# bits security	# logical qubits	# physical qubits
*P-**256** = secp256r1*	128	± 1536	**13 million** (24 hours, 2022)
*P-**384** = secp384r1*	192	± 2304	
*P-**521** = secp521r1*	256	± 3126	

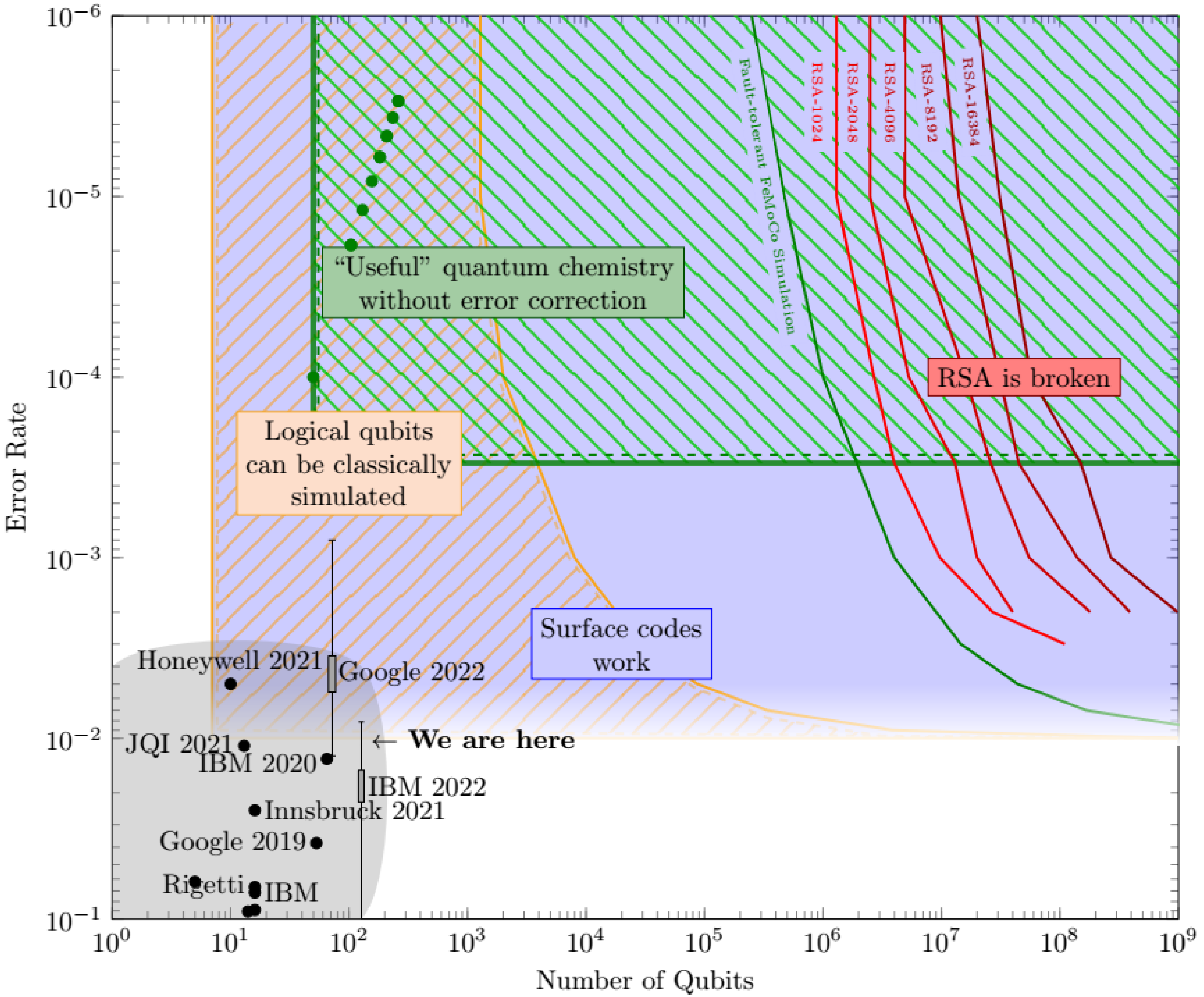
x6

https://arxiv.org/abs/1905.09749
https://avs.scitation.org/doi/10.1116/5.0073075

Powerful quantum computers with tens of millions of physical qubits threaten public key cryptography

(But we're not there yet)

Overview



Surface codes = error correction

"Longer algorithm's like Shor's algorithm (to break RSA) likely require more than 1000 physical qubits per logical qubit."

"We need Moore's-law type scaling for quantum computers to ever be useful"

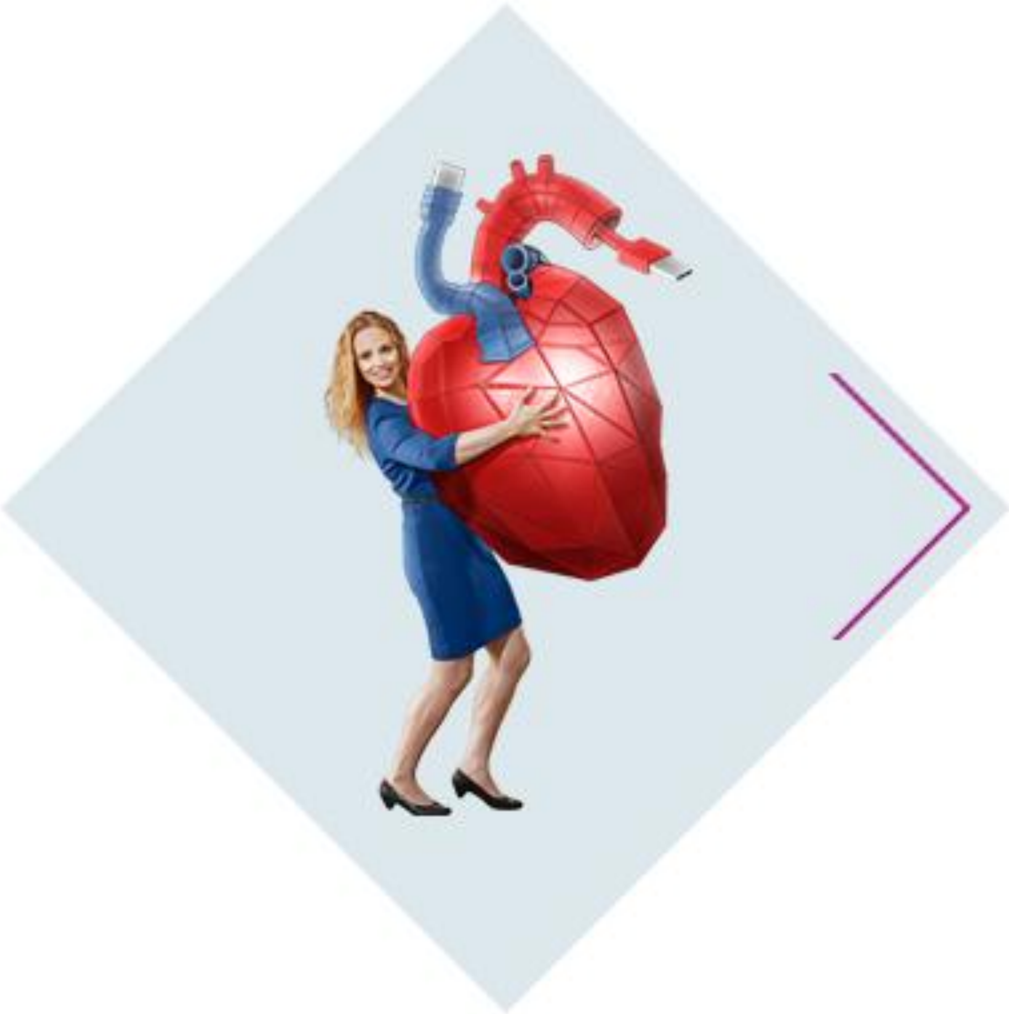
By Samuel Jaques,
University of Oxford, 2022
https://sam-jaques.appspot.com/quantum_landscape_2022

Impact of quantum computers on modern cryptography

	Symmetric cryptography	Cryptographic hash function	Public-key cryptography
Quantum Threat	Grover’s algorithm	Grover’s algorithm	Shor’s algorithm
Number of qubits	Several thousand logical = several million physical qubits		
What if?	**Key length x 2**	**Output length x 1,5**	**Quantum resistant alternatives**
Impact efficiency	Requires 25% more time(*)	Nihil (*)	Mixed (see later)

(*) Indicative. Result testing performed on Thinkpad laptop with core i5 processor

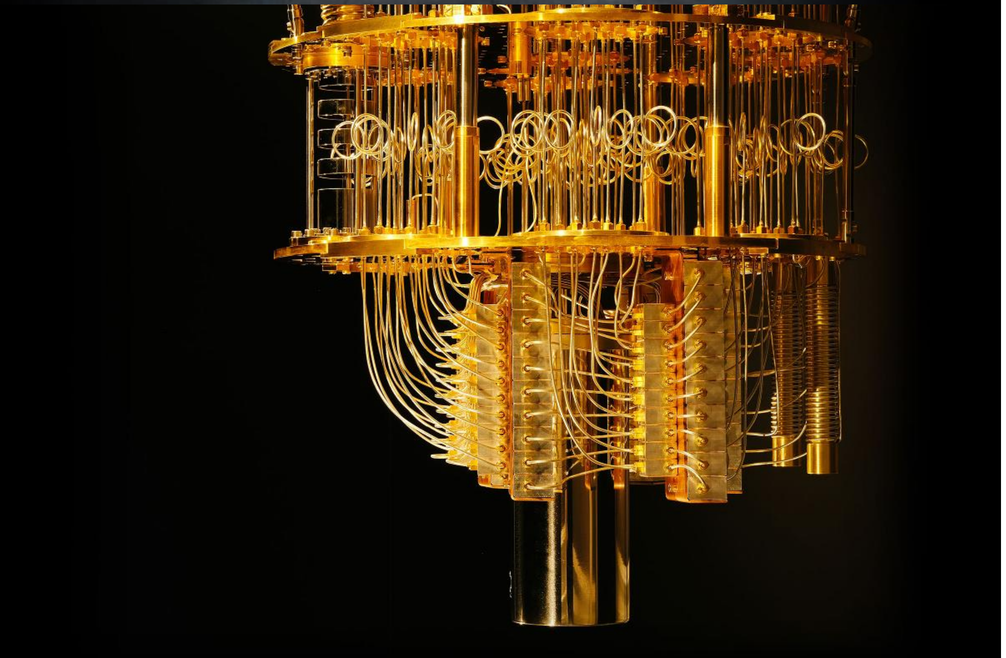
Smals ICT for society



Agenda

- Quantum computer Vs. classical computer
- Quantum computers in practice
- Crypto-apocalypse now?
- **Quantum-resistant cryptography**
- Conclusies

Crypto assumptions & Quantum computers



Modern cryptography

INSECURE Crypto primitive | INSECURE Crypto primitive | INSECURE Crypto primitive | Crypto primitive

Quantum resistant cryptography

Crypto primitive | Crypto primitive | Crypto primitive | Crypto primitive

Assumptions

Smals
ICT for society

Quantum resistant cryptography – NIST standardisation procedure

Two parts

- Public-key Encryption and Key-establishment Algorithms
- Digital Signature Algorithms

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

12/2016
Publication
Call for proposals

11/2017
End
Call for proposals
82 submissions

12/2017
Start 1e round
69 candidates
withold

01/2019
1st round
finished
26 candidates left

07/2020
2nd round finished
7 finalists
8 alternatives

2022
Selection
4 algorithms

08/2022
Publication Call for proposals
Digital signatures

2024 (?)
Standardisation
& selection from
alternatives

Algorithms are ASSUMED to be secure against both Classical and quantum computers

KU Leuven submission (SABER and LUOV) didn't make it

Smals
ICT for society

Public-key Encryption and Key-establishment Algorithms

Chosen algorithm: Kyber

- Kyber-512 ≈ 128 bit security
- Kyber-768 ≈ 192 bit security
- Kyber-1024 ≈ 256 bit security

	Quantum Resistant	**Size public key** (in bytes)	**Data transmission** (in bytes)	**Client-side computation** (higher is better)	**Server-side computation** (higher is better)
RSA-2048	Nee	256	512	29 ops / sec	150 000 ops / sec
Curve25519	Nee	32	64	15 000 ops / sec	15 000 ops / sec
Kyber-512	Ja	800	1568	57 000 ops / sec	80 000 ops / sec

Alternative candidates

- BIKE, Classic McEliece and HQC
- Goal: select at least a 2nd KEM standard by 2028
- Alternative in case weaknesses against Kyber found
- Fourth alternative candidate, SIKE, has been broken (summer 2022)

https://pq-crystals.org/kyber/
https://blog.cloudflare.com/nist-post-quantum-surprise/
https://www.wired.com/story/new-attack-sike-post-quantum-computing-encryption-algorithm/

SECURITYWEEK
CYBERSECURITY NEWS, INSIGHTS & ANALYSIS

DATA PROTECTION

AI Helps Crack NIST-Recommended Post-Quantum Encryption Algorithm

The CRYSTALS-Kyber public-key encryption and key encapsulation mechanism recommended by NIST for post-quantum cryptography has been broken using AI combined with side channel attacks.

By Kevin Townsend
February 21, 2023

Correction

Not the algorithm was cracked, but an implementation of it

https://www.securityweek.com/ai-helps-crack-a-nist-recommended-post-quantum-encryption-algorithm/

Digital Signature Algorithms

	Quantum Resisteat	Size public key (in bytes)	Size signature (in bytes)	CPU time Signing (lower is better)	CPU time Verification (lower is better)
Ed25519	Nee	32	64	1 (baseline)	1 (baseline)
RSA-2048	Nee	256	256	70	0,3
Dilitium2	Ja	1 312	2 420	4,8	0,5
Falcon512[1]	Ja	897	666	8	0,5
SPHINCS+128s	Ja	32	7 856	8 000	2,8
SPHINCS+128f	Ja	32	17 088	550	7

[1] Falcon Has a high implementation complexity => Higher risk of vulnerabilities
In particular floating point operations in constant time

Lack of an efficient and generically usable quantum-resistant signature scheme prompted NIST to initiate a new standardization procedure.

Also: Stateful hash-based signatures (XMSS, LMS)

National Security Agency (NSA)

2021

- “Cryptographically Relevant Quantum Computer” (CRQC)
- **NSA does not know when or even if a [CRQC] will exist**
- The cryptographic systems that NSA produces, certifies, and supports often have very long lifecycles. NSA has to produce requirements today for systems that will be used for many decades in the future
- **New cryptography can take 20 years or more to be fully deployed** to all National Security Systems

2022

- Given foreign pursuits in quantum computing, **now is the time to plan, prepare and budget for a transition** to QR algorithms to assure sustained protection of [classified and critical information] in the event a CRQC becomes an achievable reality.
- We want people to take note of these requirements to plan and budget for the expected transition, but **we don’t want to get ahead of the standards process**

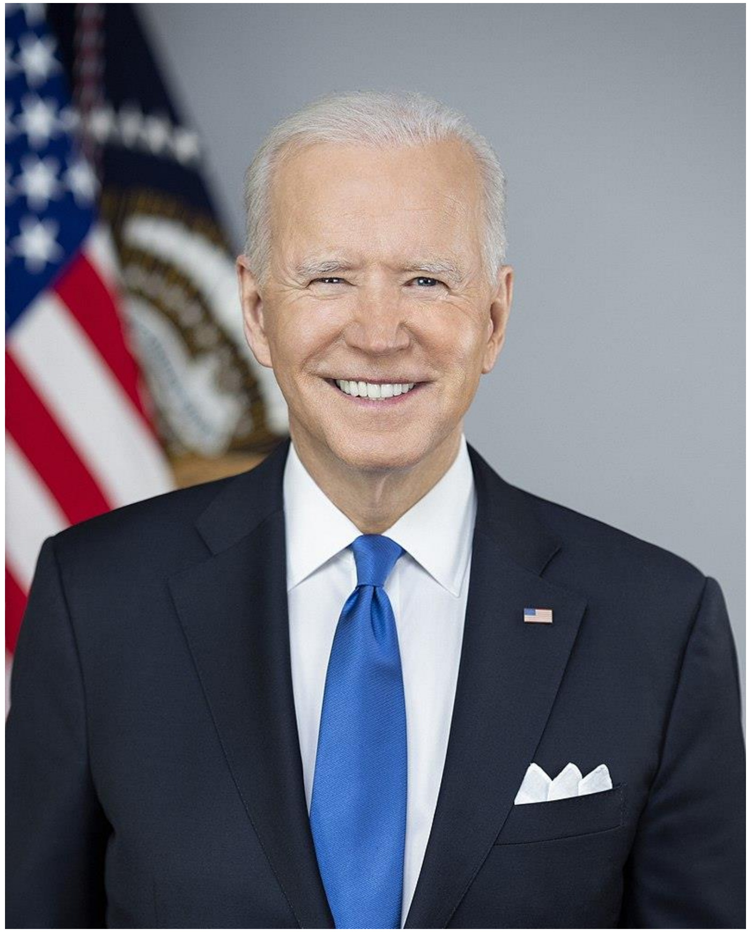
“Unfortunately, the growth of elliptic curve use has bumped up against the fact of continued progress in the research on quantum computing, which has made it clear that elliptic curve cryptography is not the long term solution many once hoped it would be.”

IAD, defensieve tak NSA, 2015

Law signed by Biden on 21 December 2022

Quantum Computing Cybersecurity Preparedness Act

- Cryptography essential for national security and the functioning of the economy
- Potential risks posed by "**harvest now, decrypt later**" attacks
- Prioritize the post-quantum cryptography migration within a year after the NIST issues post-quantum cryptography standards
- Within six months, federal agencies must develop a strategy for migrating to post-quantum cryptography



 https://www.congress.gov/bill/117th-congress/house-bill/7535

Quantum resistant cryptography – BSI

Bundesamt für Sicherheit in der Informationstechnik

“The quantum computer resistant algorithms that are currently being standardized are not yet analyzed as well as the "classical" algorithms (RSA and ECC). This is especially true with regard to weaknesses that become largely apparent in applications, such as typical implementation errors, possible side-channel attacks, etc. Therefore, ***the BSI does not recommend using post-quantum cryptography alone, but only "hybrid" if possible, i.e. in combination with classical algorithms.****”*

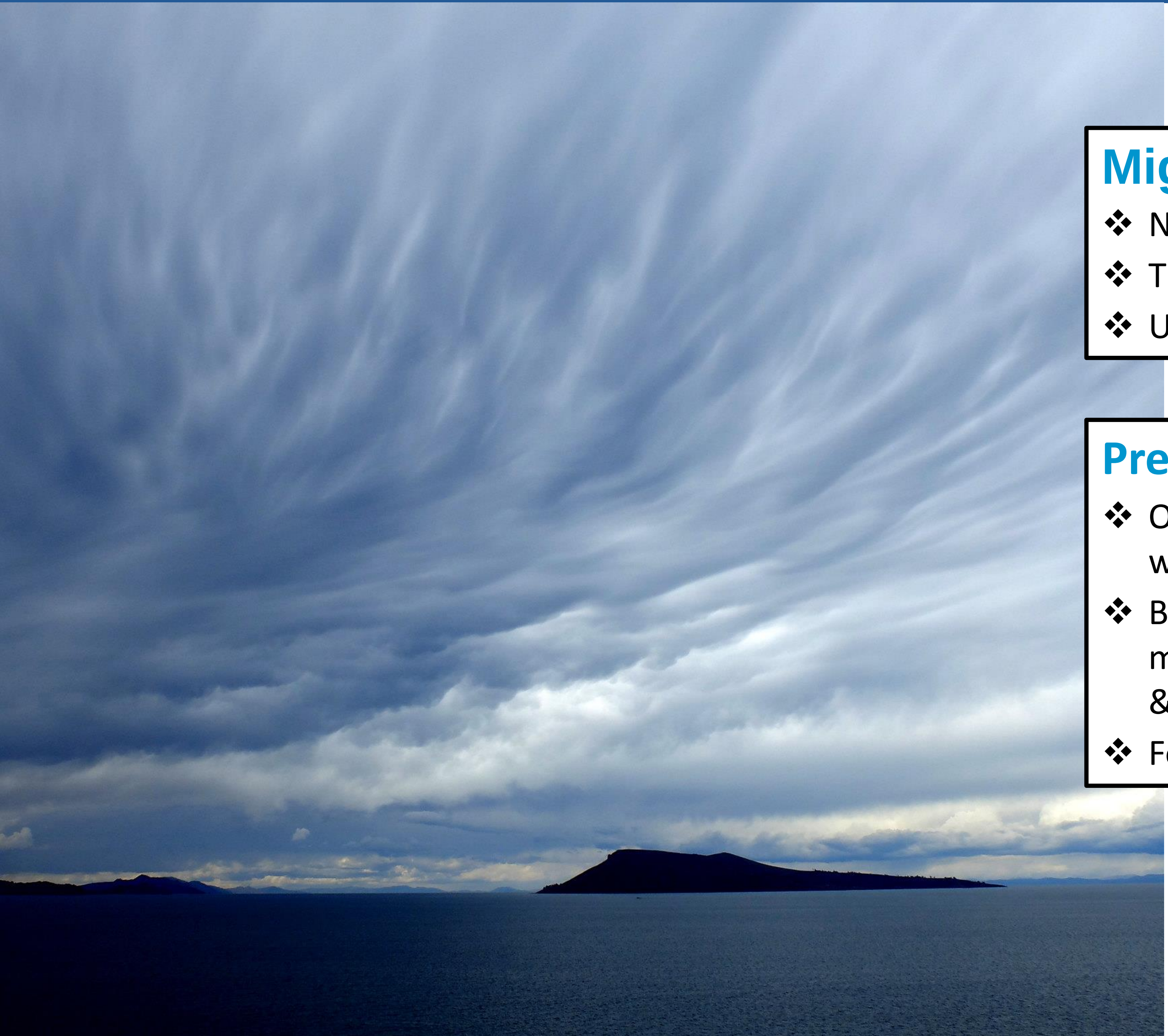
Migration to Post Quantum Cryptography
May 2021

“Corresponding standards are expected in the coming years. Introducing current, non-standardised mechanisms in new cryptographic systems is therefore always associated with the risk of creating systems that are ***incompatible with standards*** *that are foreseeable for the near future. However, in applications that are intended to guarantee the confidentiality of information with a* ***high value and a long-term need for protection****, these problems* ***weigh less heavily in the BSI’s view than the possibility of future attacks****.”*

TR-02102-1: Cryptographic Mechanisms: Recommendations and Key Lengths
January 2023

https://www.bsi.bund.de/SharedDocs/Downloads/EN/BSI/Crypto/Migration_to_Post_Quantum_Cryptography.pdf
https://www.bsi.bund.de/SharedDocs/Downloads/EN/BSI/Publications/TechGuidelines/TG02102/BSI-TR-02102-1.html

Quantum resistant cryptography – Conclusion

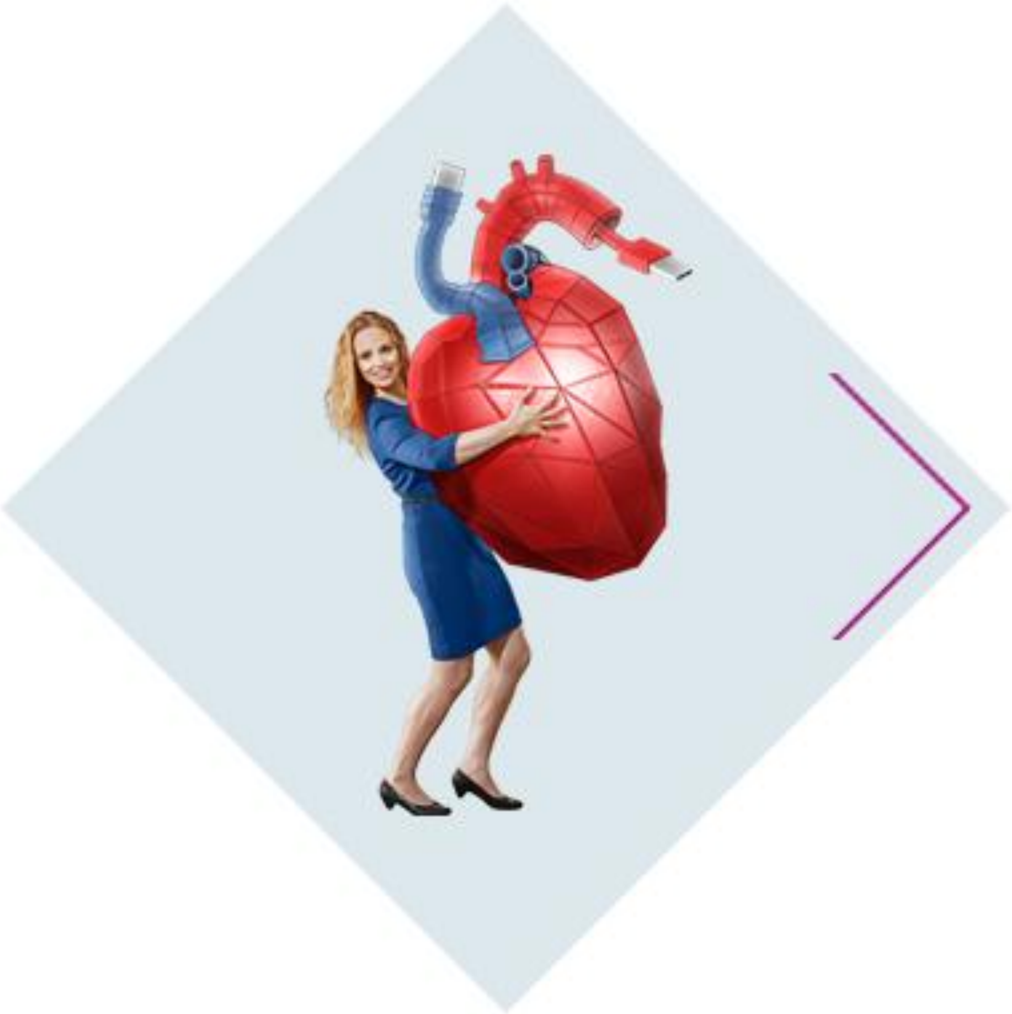


Migration

- NIST standardisation procedure ongoing
- Then consider migration (or wait a bit?)
- Urgency depends on risk assessment

Prepare with crypto agility

- Overview: Which cryptography and keys where and why?
- Build systems sufficiently flexible to minimize friction when replacing crypto keys & algorithms
- Foresee migration procedures



Agenda

- Quantum computer Vs. classical computer
- Quantum computers in practice
- Crypto-apocalypse now?
- Quantum-resistant cryptography
- **Conclusions**

Conclusion

Quantum computers are based on principles from quantum physics (entanglement & superposition)

Building quantum computers extremely complex (Isolation, error correction, scalability)

Longer symmetric keys and hash output
Several million physical qubits required to crack public key cryptography → Alternatives needed

The NIST standardization process is ongoing

Agenda

- Quantum computer Vs. classical computer
- Quantum computers in practice
- Crypto-apocalypse now?
- Quantum-resistant cryptography

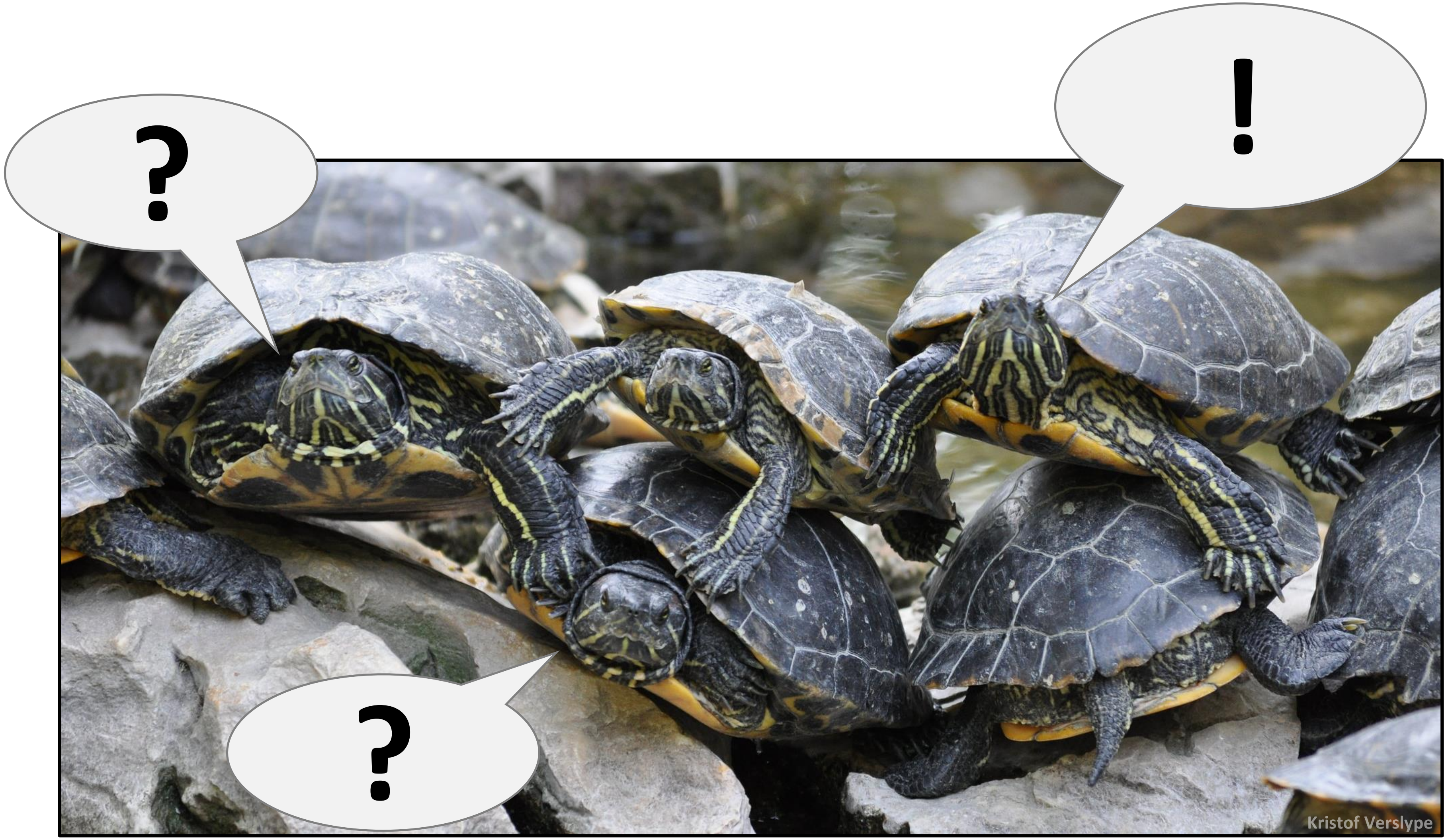
Questions / Discussion

Kristof Verslype
Cryptographer, PhD
Smals Research

Smals
ICT for society
Belgian public sector

kristof.verslype@smals.be
+32(0)2 7875376
www.smals.be
www.smalsresearch.be
www.cryptov.net

@KristofVerslype
linkedin.com/in/verslype



Referenties

- F. ARUTE, K. ARYA, […] J. MARTINIS. *Quantum supremacy using a programmable superconducting processor*. Nature, 23 October 2019
  https://www.nature.com/articles/s41586-019-1666-5
- *Post-Quantum Cryptography – Project overview*. NIST.
  https://csrc.nist.gov/projects/post-quantum-cryptography
- *Commercial National Security Algorithm Suite*. NSA.
  https://apps.nsa.gov/iaarchive/programs/iad-initiatives/cnsa-suite.cfm
- *Post-Quantum Cybersecurity Resources*. NSA.
  https://www.nsa.gov/what-we-do/cybersecurity/post-quantum-cybersecurity-resources/
- S. DAS SARMA. *Quantum computing has a hype problem. MIT Technology Review*. 22 Maart 2022
  https://www.technologyreview.com/2022/03/28/1048355/quantum-computing-has-a-hype-problem/
- M. GRASS, B. LANGENBERG, M. ROETTELER, R. STEINWANDT. *Applying Grover's algorithm to AES: quantum resource estimates*. Post-Quantum Cryptography, Springer, Cham, 2016.
  https://arxiv.org/pdf/1512.04965.pdf
- C. GIDNEY, M. EKERA. *How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits*. arXiv preprint arXiv:1905.09749, 2019.
  https://arxiv.org/abs/1905.09749
- M. DYAKONOV. *The Case Against Quantum Computing*. EEE Spectrum 56.3, 15 November 2018.
  https://spectrum.ieee.org/computing/hardware/the-case-against-quantum-computing
- H. HELSMOORTEL, W. DE MAESENEER. *Vlaamse topwetenschappers blikken vooruit: Staat er in 2030 een kwantumcomputer in onze woonkamer?* VRT Nieuws, 15 January 2020,
  https://www.vrt.be/vrtnws/nl/2019/12/24/vlaamse-topwetenschappers-blikken-vooruit-naar-2030-kwantumcomp/
- D. MASLOV, J. GAMBETTA. On "Quantum Supremacy". IBM Research Blog, 21 October 2019.
  https://www.ibm.com/blogs/research/2019/10/on-quantum-supremacy/
- V. MAVROEIDIS, K. VISHI, M. Zych, A Jøsang. *The impact of quantum computing on present cryptography*. arXiv preprint arXiv:1804.00200, 2018 Mar 31.
  https://arxiv.org/pdf/1804.00200.pdf
- J. Preskill. *Quantum computing in the NISQ era and beyond*. Quantum. 2018 Aug 6;2:79.
  https://arxiv.org/abs/1801.00862

Externe bronnen foto's

- IBM. Q System One quantum. https://www.ibm.com/quantum-computing/systems/
- Andrew Magill. JTAG board 1 https://flickr.com/photos/amagill/2877921712/
- Max Roser – Transistor count. https://ourworldindata.org/uploads/2019/05/Transistor-Count-over-time-to-2018.png
- Alex Does Physics. Polarization http://alexdoesphysics.blogspot.com/2018/11/mathematical-description-of-polarization.html
- Orren Jack Turner. Einstein in 1947 https://en.wikipedia.org/wiki/Albert_Einstein#/media/File:Albert_Einstein_Head.jpg
- INTVGene. Puzzle. https://www.flickr.com/photos/intvgene/370973576/
- Nature. Layout Sycamore processor. https://www.nature.com/articles/s41586-019-1666-5
- D-Wave Systems. D-Wave 2000Q Quantum Computer. https://www.dwavesys.com/press-releases/d-wave%C2%A0announces%C2%A0d-wave-2000q-quantum-computer-and-first-system-order
- Quantum computing https://www.roche.com/quantum-computing.htm
- Pixabay. Jug Thermos Hot Cold Drink Coffee https://pixabay.com/photos/jug-thermos-hot-cold-drink-coffee-3638398
- Marcus Gripe, Garv... (writing) https://flickr.com/photos/neoeinstein/4503776883
- Willian Clifford. This is as close as you get. (fingerprint) https://www.flickr.com/photos/williac/2503890509/
- Birthday paradox https://commons.wikimedia.org/w/index.php?curid=10784025
- Natascha. Keys. https://www.flickr.com/photos/tasj/5207744064
- Kristof Verslype. Threatening clouds above Lake Titicaca, Peru. https://www.flickr.com/photos/verslype/23928588621