# Update on the NIST Post-Quantum Cryptography Project

http://indianajones.wikia.com/wiki/Raiders_of_the_Lost_Ark

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# Classical vs Quantum Computers

- The security of crypto relies on intractability of certain problems to modern computers
  - Example: RSA and factoring

- Quantum computers
  - Exploit quantum mechanics to process information
  - Use quantum bits = “qubits” instead of 0’s and 1’s
  - Superposition – ability of quantum system to be in multiples states at the same time
  - Potential to vastly increase computational power beyond classical computing limit

# The Sky is Falling?

- If a large-scale quantum computer could be built then….

- Public key crypto:
  - RSA
  - ECDSA (and Elliptic Curve Cryptography)
  - DSA (and Finite Field Cryptography)
  - Diffie-Hellman key exchange

- Symmetric key crypto:
  - AES
  - Triple DES

- Hash functions:
  - SHA-2 and SHA-3

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- Vulnerable NIST standards
  - FIPS 186, *Digital Signature Standard*
    - Digital Signatures: RSA, DSA, ECDSA
  - SP 800-56A/B, *Recommendation for Pair-Wise Key Establishment Schemes*
    - Discrete Logs: Diffie-Hellman, MQV
    - Factorization based: RSA key transport

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- Symmetric key crypto:
  - AES — Need longer keys
  - Triple DES — Need longer keys

- Hash functions:
  - SHA-2 and SHA-3 — Use longer output

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# How soon do we need to worry?

- Potentially as early as 15 years to break RSA-2048
  - 15 years, $1 billion USD, small nuclear power plant (Mariantoni, 2014)
  - 50% chance (Michele Mosca)

- PQC needs time to be ready for applications
  - Confidence – cryptanalysis
  - Implementations
  - Usability and interoperability (IKE, TLS, etc. … use public key crypto)
  - Standardization

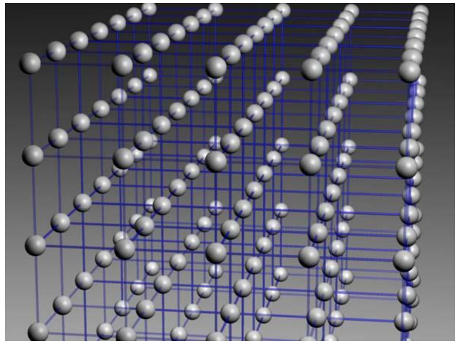
- Transition has to be soon enough that any data compromised by quantum computers is no longer sensitive when compromise occurs

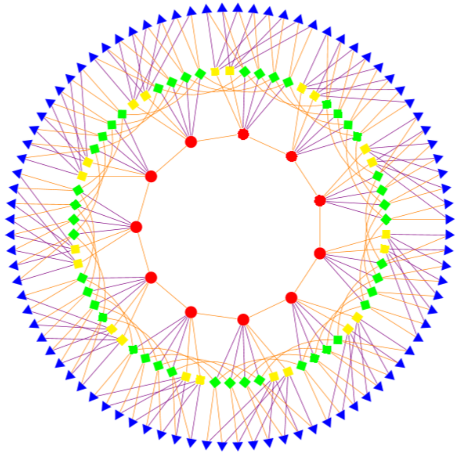
# Possible Replacements

- Lattice-based
- Code-based
- Multivariate
- Others
  - Hash-based signatures
  - Isogeny-based signatures
  - Etc….

- All have their pros and cons

```
01010111  01101001  01101011
01101001  01110000  01100101
01100100  01101001  01100001
```





$$
\begin{aligned}
f_1(x_1,\ldots,x_n) &= \sum_{1\le i\le j\le n} a_{ij}^{(1)} x_i x_j + \sum_{1\le i\le n} b_i^{(1)} x_i + c^{(1)} = d_1,\\
f_2(x_1,\ldots,x_n) &= \sum_{1\le i\le j\le n} a_{ij}^{(2)} x_i x_j + \sum_{1\le i\le n} b_i^{(2)} x_i + c^{(2)} = d_2,\\
&\vdots\\
f_m(x_1,\ldots,x_n) &= \sum_{1\le i\le j\le n} a_{ij}^{(m)} x_i x_j + \sum_{1\le i\le n} b_i^{(m)} x_i + c^{(m)} = d_m,
\end{aligned}
$$

# Initial Observations

- For most of the potential PQC replacements, the times needed for encryption, decryption, signing, verification are acceptable
- Some key sizes are significantly increased
  - For most protocols, if the public keys do not need to be exchanged, it may not be a problem
- Some ciphertext and signature sizes are not quite plausible
- Key pair generation time for the encryption schemes is not bad at all
- **No easy "drop-in" replacements**
- Would be nice to have more benchmarks

# Gathering Steam

- PQCrypto Workshop series
- ETSI workshops
- European PQCrypto project, Quantum flagship
- Japan’s SAFECRYPTO project
- IETF hash-based signatures
- ISO/IEC JTC 1 SC 27 – study period on PQC
- Fall 2015: NSA announced it would be transitioning in the “not too distant” future https://www.iad.gov/iad/programs/iad-initiatives/cnsa-suite.cfm

# The NIST PQC Project http://www.nist.gov/pqcrypto

- Biweekly seminars since 2012
- Guest researchers and invited speakers
- Research: publications and presentations
  - PQCrypto, AWACS, ICICS, CRYPTO, Qcrypt, Eurocrypt, ETSI Quantum-safe workshops, etc.
- Out Reach
  - PKI community, Automotive industry talks

- 2015: NIST PQC workshop http://www.nist.gov/itl/csd/ct/post-quantum-crypto-workshop-2015.cfm
- Feb 2016: NIST report on PQC- http://csrc.nist.gov/publications/drafts/nistir-8105/nistir_8105_draft.pdf
- Feb 2016: NIST announced preliminary standardization plan at PQCrypto https://pqcrypto2016.jp/data/pqc2016_nist_announcement.pdf

# Collaboration

- IETF – CFRG
- ISO/IEC JTC 1 SC 27
- ETSI
  - Workshops, white papers
- Universities
  - University of Maryland (QuiCS)
  - University of Waterloo (Cryptoworks 21)
- Guest Researchers and Speaker
  - Lyubachevsky, Ding, Takagi, Petzoldt, Faugere, Gligoroski, Perret, etc…

# Timeline

- June 2016 – Draft Call For Proposals released for public comment
- Fall 2016 – formal Call For Proposals finalized
- Nov 2017 – Deadline for submissions
- 3-5 years – Analysis phase
  - NIST will report its findings
- 2 years later - Draft standards ready (2023-2025)

- Workshops
  - Early 2018 – submitter's presentations
  - One or two during the analysis phase

# Call for Proposals

- NIST is calling for quantum-resistant cryptographic algorithms for new public-key crypto standards
  - Digital signatures
  - Encryption/key-establishment
- We see our role as managing a process of achieving community consensus in a **transparent** and timely manner
- We do not expect to “pick a winner”
  - Ideally, several algorithms will emerge as ‘good choices’
- We may pick one (or more) for standardization
  - Only algorithms publicly submitted considered

# Differences with AES/SHA-3 competitions

- Post-quantum cryptography is more complicated than AES or SHA-3
  - No silver bullet - each candidate has some disadvantage
  - Not enough research on quantum algorithms to ensure confidence for some schemes
- We do not expect to “pick a winner”
  - Ideally, several algorithms will emerge as “good choices”
- We may narrow our focus at some point
  - This does not mean algorithms are “out”
- Requirements/timeline could potentially change based on developments in the field

# Minimal acceptability requirements

- Publicly disclosed and available with no IPR
    - Signed statements, disclose patent info
- Implementable in wide range of platforms
- Provides at least one of: signature, encryption, or key exchange
- Theoretical and empirical evidence providing justification for security claims
- Concrete values for parameters meeting target security levels

# Specification

- Implementation
  - Reference version
  - Optimized version
- Cryptographic API will be provided
  - Can call approved hash functions, block ciphers, modes, etc…
- Known Answer tests
- Optional – constant time implementation

# Evaluation criteria

- To be detailed in the formal Call
  - Security
  - Cost (computational and memory)
  - Algorithm and implementation characteristics
- Draft criteria will be open for public comment
- We strongly encourage public evaluation and publication of results concerning submissions
- NIST will summarize the evaluation results and report publicly

# Security Analysis

- Security definitions
  - IND-CCA2 for encryption, EUF-CMA for signatures, CK best for key exchange?
  - Used to judge whether an attack is relevant
- Quantum/classical algorithm complexity
  - Stability of best known attack complexity
  - Precise security claim against quantum computation
  - Parallelism?
- Security proofs (not required but considered as support material)
- Quality and quantity of prior cryptanalysis

# Target Security Levels

| | Classical Security | Quantum Security | Examples |
|---|---|---|---|
| I | 128 bits | 64 bits | AES128 (brute force key search) |
| II | 128 bits | 80 bits | SHA256/SHA3-256 (collision) |
| III | 192 bits | 96 bits | AES192 (brute force key search) |
| IV | 192 bits | 128 bits | SHA384/SHA3-384 (collision) |
| V | 256 bits | 128 bits | AES256 (brute force key search) |

# Cost

- Computational efficiency
  - Hardware and software
    - Key generation
    - Encryption/Decryption
    - Signing/Verification
    - Key exchange
- Memory requirements
  - Concrete parameter sets and key sizes for target security levels
  - Ciphertext/signature size
- May need more than one algorithm for each function to accommodate different application environments

# Algorithm and Implementation Characteristics

- Ease of implementation
  - Tunable parameters
  - Implementable on wide variety of platforms and applications
  - Parallelizable
  - Resistance to side-channel attacks
- Ease of use
  - How does it fit in existing protocols (such as TLS or IKE)
  - Misuse resistance
- Simplicity

# The Evaluation Process

- Initial evaluation phase (12-18 months)
  - No tweaks/modifications allowed
  - Workshops at beginning and end of initial evaluation phase
- Report findings and narrow candidate pool
- Second evaluation phase (12-18 months)
  - Small modifications allowed
  - Workshop towards end of second phase
- Report findings and narrow candidates
- Select algorithms for standardization or decide more evaluation needed

# Call for Feedback

- How is the timeline?
  - Do we need an ongoing process, or is one time enough?
- How to determine if a candidate is mature enough for standardization?
  - hash-based signatures for code signing
- We are focusing on signatures and encryption/key-establishment. Should we also consider other functionalities?
- How can we encourage people to study practical impacts on the existing protocols?
  - For example, key sizes may be too big

# Conclusion

- NIST is calling for quantum-resistant algorithms
  - We see our role as managing a process of achieving community consensus in a transparent and timely manner
  - Different from (but similar to) AES/SHA-3 competitions

- PQC Standardization is going to be a long journey

- We don’t have all the answers

- Be prepared to transition to new (public-key) algorithms in 10 years
  - The transition will not be painless
    - NIST will provide transition guideline when PQC standards are developed
  - Prepare the application designers
    - Focus on crypto-agility