Towards Standardization of Threshold Schemes at NIST

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Presentation at the
Theory of Implementation Security (TIS’19) Workshop
November 11, 2019 @ London, UK

Some slides are based on previous presentations (NTCW’19; ICMC’19; ACS’19).
The NIST Threshold Cryptography project, on which this presentation is based, has so far also counted with the participation of Apostol Vassilev, Michael Davidson, Nicky Mouha.
Outline

1. Crypto standards at NIST
2. Threshold intro
3. Threshold project
4. Threshold preliminary roadmap
5. Concluding remarks
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Goals of this presentation:

- Overview of the NIST standardization effort
- Present the new “preliminary roadmap” (NISTIR 8214A)
- Encourage feedback and collaboration
Outline 1

1. Crypto standards at NIST

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Some NIST data

National Institute of Standards and Technology (NIST)

- Non-regulatory federal agency (within the U.S. Department of Commerce)
- **Mission** (keywords): innovation, industrial competitiveness, measurement science, standards and technology, economic security, quality of life.

Aerial photo of Gaithersburg campus (source: Google Maps, August 2019)
Some NIST data

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Wide spectrum of competences
- \( \sim 6-7 \times 10^3 \) workers
- Five laboratories and two centers
- Laboratories → Divisions → Groups → Projects
- Standards, research and applications

Aerial photo of Gaithersburg campus (source: Google Maps, August 2019)
Laboratories, divisions, groups

Information Technology Laboratory (ITL):
advancing measurement science, standards, and technology through research and development in information technology, mathematics, and statistics.
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► Documents: FIPS, SP 800, NISTIR.

► International cooperation: government, industry, academia, standardization bodies.

FIPS = Federal Information Processing Standards; SP 800 = Special Publications in Computer Security; NISTIR = NIST Internal or Interagency Report.
Some projects of crypto primitives/applications at NIST

1. Crypto standards at NIST

* (Some projects/programs involve several groups, divisions or labs)
Some standardized cryptographic primitives

Traditional focus on “basic” primitives:
Some standardized cryptographic primitives

**Traditional focus on “basic” primitives:**

- Block ciphers
- Cipher modes of operation
- Hash functions
- Signatures
- Pair-wise key agreement
- DRBGs
Some standardized cryptographic primitives

Traditional focus on “basic” primitives:

- Cipher modes of operation (1980–): CBC, CT, CCM, GCM ...
- Pair-wise key agreement, e.g., based on DH (2006) and RSA (2009)
- DRBGs (2006): CTR_, Hash_, HMAC_, Dual_EC_ (withdrawn in 2015 due to concerns of potential subversion)

(Not an exhaustive list; years indicated for perspective; some documentation has subsequent updates)

(Further details in “NIST Cryptographic Standards and Guidelines Development Program Briefing Book”)

Legend:
- AES = Advanced Encryption Standard
- CBC = Cipher block chaining (mode)
- CT = Counter (mode)
- CCM = Counter with Cipher-block chaining
- DES = Data Encryption Standard
- DH = Diffie–Hellman
- DSA = Digital Signature Algorithm
- DSS = Digital Signature Standard
- DRBG = Deterministic Random Bit Generator
- ECDSA = Elliptic curve DSA
- EdDSA = Edwards curve DSA
- EES = Escrowed Encryption Standard
- GCM = Galois counter mode
- RSA = Rivest–Shamir–Adleman
- SHA = Secure Hash Algorithm
- SHS = Secure Hash Standard
- TDEA = Triple Data Encryption Algorithm
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**Several methods:**

- Internal or interagency developed techniques
- Adoption of external standards
- Open call, competition, “competition-like”
Other processes (examples)
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Ongoing evaluations:

- Post-quantum cryptography: signatures, public-key encryption, key encapsulation
- Lightweight cryptography: ciphers, authenticated encryption, hash functions
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The crypto group has other ongoing projects: https://www.nist.gov/itl/csd/cryptographic-technology
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Previous considerations:


Development process:

▶ NISTIR 7977: NIST Cryptographic Standards and Guidelines Development Process (2016). Formalizes several principles to follow:

  ▶ transparency  ▶ integrity  ▶ global acceptability
  ▶ openness    ▶ technical merit ▶ continuous improvement
  ▶ balance     ▶ usability      ▶ innovation and intellectual property
  (and overarching considerations)
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Beyond defining basic crypto primitives?

Security often hinges on a good application of cryptography
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Specially relevant: key-based cryptographic primitives
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**Security often hinges on a good application of cryptography**

**Specially relevant:** key-based cryptographic primitives

**Security relies on:**

- secrecy, correctness, availability ... of cryptographic keys
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- secrecy, correctness, availability ... of cryptographic keys
- implementations that use keys to operate an algorithm
- operators to decide when/where to apply the algorithms

Some things can go wrong!
Crypto can be affected by vulnerabilities!
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Attacks can exploit differences between ideal vs. real implementations.
Crypto can be affected by vulnerabilities!

Attacks can exploit differences between ideal vs. real implementations

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Operators of cryptographic implementations can go rogue
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How can we address single-points of failure?

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How can we address single-points of failure?

The threshold approach

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The red dancing devil is from clker.com/clipart-13643.html
The threshold approach

At a high-level:
use redundancy & diversity to mitigate the compromise of up to a threshold number \((f\text{-out-of-}n)\) of components
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use redundancy & diversity to mitigate the *compromise* of up to a threshold number \((f\text{-out-of-}n)\) of components

The intuitive aim:
improve security
vs.
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The threshold approach

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NIST-CSD wants to standardize threshold schemes for cryptographic primitives
The threshold approach

At a high-level: use redundancy & diversity to mitigate the compromise of up to a threshold number (\(f\)-out-of-\(n\)) of components.

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Potential primitives: sign, decrypt (PKE), encipher/decipher, key generate, ...
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(PKE) = within a public-key encryption scheme

Some properties:

- **withstands** several compromised components;
- **needs** several uncompromised components;
- **prevents** secret keys from being in one place;
- **enhances** resistance against side-channel attacks; ...

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Secret Sharing Schemes (a starting point)

Split a secret key into $n$ secret “shares” for storage at rest.
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Example 2-out-of-$n$ secret sharing

- The secret $y_s$ is placed in the $y$-axis;
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Use threshold schemes for cryptographic primitives (next)
A simple example: RSA signature (or decryption) [RSA78]

\[ \sigma_1 = m^{d_1} \]
\[ \sigma_2 = m^{d_2} \]
\[ \sigma_3 = m^{d_3} \]
\[ \sigma = N^d \]

\[ d_1 + d_2 + d_3 = \phi \]
\[ \phi = (p - 1) \times (q - 1) \]
\[ N = p \times q \]
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Verification key: \( e \)
Sign key: \( d \)
\( e \cdot d = \phi \cdot 1 \)

About this threshold scheme:
SignKey \( d \) not recombined; can reshare \( d \) leaving \( e \) fixed;
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\textbf{Facilitating setting:} \( \exists \) dealer; \( \exists \) homomorphism; \textit{all parties learn} \( m \).
Threshold intro

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Not fault-tolerant: a single sub-signer can boycott a correct signing.
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e \cdot d = \phi 1
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**Facilitating setting:** \( \exists \) dealer; \( \exists \) homomorphism; all parties learn \( m \).

**Not fault-tolerant:** a single sub-signer can boycott a correct signing.

**Can other threshold schemes be implemented:**

\( \not\exists \) dealer, \( \not\exists \) homomorphisms, secret-shared \( m \), withstandning \( f \) malicious signers?
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Can other threshold schemes be implemented:

\(\nexists\) dealer, \(\nexists\) homomorphisms, secret-shared \(m\), withstanding \(f\) malicious signers?

**Yes,** using threshold cryptography.
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\[e \cdot d = \phi \cdot 1\]

**About this threshold scheme:**

SignKey \(d\) not recombined; can *reshare* \(d\) leaving \(e\) fixed; same \(\sigma\); efficient!

**Facilitating setting:** \(\exists\) dealer; \(\exists\) homomorphism; all parties learn \(m\).

**Not fault-tolerant:** a single sub-signer can boycott a correct signing.

**Can other threshold schemes be implemented:**

\(\nexists\) dealer, \(\nexists\) homomorphisms, secret-shared \(m\), withstanding \(f\) malicious signers?

**Yes**, using threshold cryptography *(with more complicated schemes)*

\[d_1 + d_2 + d_3 = \phi \cdot d\]

\[\phi = (p - 1) \times (q - 1)\]

\[N = p \times q\]
What do the thresholds $k$ and $f$ mean?
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**3-out-of-3 decryption:**

- **Availability:** 3 nodes needed to decrypt
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3-out-of-3 decryption:

- **Availability**: 3 nodes needed to decrypt ($k = 3, f = 0$)
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Reliability ($\mathcal{R}$) as one metric of security

Probability that a security property (e.g., secrecy) never fails during a mission time
**Reliability (\( \mathcal{R} \)) as one metric of security**

Probability that a security property (e.g., secrecy) never fails during a mission time

**A possible model:** each node fails (independently) with constant rate probability

Time normalized: \( \tau = 1 \) is the expected time to failure (ETTF) of a node

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<tr>
<th>Curve</th>
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<th>( n )</th>
<th>( f )</th>
<th>( \tau_{\text{max}} )</th>
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<tr>
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$\tau_{\text{max}} = \max \left( \{ \tau : \mathcal{R}_n^f(t) > \mathcal{R}_0^1(t) \} \right)$

[BB12] Time normalized: $\tau = 1$ is the expected time to failure (ETTF) of a node.
Reliability ($\mathcal{R}$) as one metric of security

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![Graph showing reliability and fault-tolerance thresholds](image)

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Increasing the fault-tolerance threshold $f$ may degrade reliability
Reliability ($\mathcal{R}$) as one metric of security

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Increasing the fault-tolerance threshold $f$ may degrade reliability, if nodes are not rejuvenated and the mission time is large.

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Another model

What if all nodes are compromised (e.g., leaky) from the start?
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Threshold scheme may still be effective, if it increases the cost of exploitation!

(e.g., if exploiting a leakage vulnerability requires exponential number of traces for high-order Differential Power Analysis)
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Challenge questions:

▶ which models are realistic / match state-of-the-art attacks?
▶ what concrete parameters (e.g., \( n \)) thwart real attacks?
Outline 3

1. Crypto standards at NIST
2. Threshold intro
3. Threshold project
4. Threshold preliminary roadmap
5. Concluding remarks
3. Threshold project

NIST Internal Report (NISTIR) 8214

Past timeline:

▶ 2018-July: Draft online 3 months for public comments
▶ 2018-October: Received comments from 13 external sources
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The report sets a basis for discussion:

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Characterizing threshold schemes

To reflect on a threshold scheme, start by characterizing 4 main features:
• Kinds of threshold
• Communication interfaces
• Executing platform
• Setup and maintenance

Each feature spans distinct options that affect security in different ways. A characterization provides a better context for security assertions. But there are other factors...
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The cliparts are from openclipart.org/detail/*, with * ∈ {71491, 190624, 101407, 161401, 161389}
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Deployment context
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- **Conceivable attack types.**
  - Active vs. passive
  - Static vs. adaptive
  - Stealth vs. detected
  - Invasive (physical) vs. non-invasive
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  - Parallel vs. sequential (wrt attacking nodes)
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A threshold scheme *improving* security against an attack in an application *may be powerless or degrade* security for another attack in another application.
The validation challenge
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Devise standards of **testable and validatable** threshold schemes **vs.**
devise **testing and validation for standardized** threshold schemes
The validation challenge

Devise standards of **testable and validatable** threshold schemes vs. devise **testing and validation for standardized** threshold schemes

**Validation is needed in the federal context:**

- need to use **validated** implementations [tC96] of **standardized** algorithms
- FIPS 140-2/3 defines, for cryptographic modules, 4 security levels: subsets of applicable security assertions [NIS01, NIS19]

(FIPS = Federal Information Processing Standards)
#NTCW2019

NIST Threshold Cryptography Workshop 2019

https://csrc.nist.gov/Events/2019/NTCW19
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March 11–12, 2019 @
NIST Gaithersburg MD, USA

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Proportions of registrations per country of affiliation

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- Canada 1%
- China 1%
- Denmark 2%
- Estonia 4%
- France 4%
- Israel 1%
- Italy 1%
- Switzerland 2%
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About 80 attendees

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A platform for open interaction:

- hear about experiences with threshold crypto;
- get to know stakeholders;
- get input to reflect on roadmap and criteria.

https://csrc.nist.gov/Events/2019/NTCW19
Format and content
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Accepted 15 external submissions:

- 2 panels
- 5 papers
- 8 presentations
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- 4 NIST talks
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Discussion of diverse topics:

- threshold schemes in general (motivation and implementation feasibility);
- NIST standardization of cryptographic primitives
- a post-quantum threshold public-key encryption scheme;
- threshold signatures (adaptive security; elliptic curve digital signature algorithm);
- validation of cryptographic implementations;
- threshold circuit design (tradeoffs, pitfalls, combined attacks, verification tools);
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Results

Threshold project

A step in driving an open and transparent process towards standardization of threshold schemes for cryptographic primitives. (See NISTIR 7977)

Some notes:
▶ differences in granularity (building blocks vs. full functionalities);
▶ separation of single-device vs. multi-party;
▶ importance of envisioning applications;
▶ stakeholders' willingness to contribute;
▶ usefulness of explaining rationale (e.g., as complimented for the NISTIR);
▶ encouragement to move forward.

These elements are helpful for the next step ... designing a roadmap.
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2. deciding where to go
3. thinking how to get there
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A “preliminary” roadmap

1. getting a map *(mapping layers)*
2. deciding where to go *(weighting factors)*
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[Diagram of a map with arrows and points.]
A “preliminary” roadmap

1. getting a map (**mapping layers**)  
2. deciding where to go (**weighting factors**)  
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(doi:10.6028/NIST.IR.8214A-draft)

**Lays the basis towards a roadmap:**

- Map/organize potential items for standardization  
- Motivating applications  
- Features to consider  
- Levels of difficulty / complexity  
- Solicit preliminary input  
- Identify phases of the standardization effort
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Open to public comments: 2019/Nov/11 – 2020/Feb/10.
Mapping the space of potential “schemes”

Space of threshold schemes for cryptographic primitives

Single-device (domain)

Primitive a

Mode e ...

Mode f

Multi-party (domain)

Primitive c ...

Mode g ...

Mode h
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**Single-device:**
- rigid configuration of components
- strictly defined physical boundaries
- dedicated communication network

**Multi-party:**
- enable modularized patching of components
- possible dynamic configurations of parties
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Each *domain* also represents a *track* in the standardization effort.
Some conceivable primitives (focus on NIST-approved)

**Less complex:**

- Multi-party: RSA decrypt & sign; EdDSA/Schnorr* sign; ECC key-gen.
- Single-device: AES threshold circuit design against leakage.

Research interest (but not focus of standardization):
- Multi-party: post-quantum signing & PKE decryption; ...
- Single-device: threshold lightweight-crypto; ...

Notes:
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- Other cases: distributed RNG; some can have similarities across tracks.
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Threshold modes (features in the perspective of the client)
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**Input/Output interface:** client communication with the module / threshold entity?

**Conventional (non-threshold)**

**Not-shared-IO**

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<th>(Conventional) Cryptographic Module</th>
<th>reply</th>
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**Shared-I and Shared-O are other modes where only the input and only the output are shared, respectively**

**Auditability:** can the client prove (or be convinced) the operation was thresholdized?

**Examples:**
- **Shared-I:** signature protecting the secrecy of the input
- **Shared-O:** decryption protecting the secrecy of the output
- Auditable: succinct multi-signature verifiable against several public-keys
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  - request
  - reply
- (Conventional) Cryptographic Module
  - Component $C_1$
  - Component $C_2$
  - Component $C_n$

**Not-shared-IO**

- Client
  - request
  - reply
- Inter-node network

**Shared-IO**

- Client
  - request to $C_1$
  - reply from $C_1$
  - request to $C_2$
  - reply from $C_2$
  - request to $C_n$
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- Component $C_1$
- Component $C_2$
- Component $C_n$

(Shared-I and Shared-O are other modes where only the input and only the output are shared, respectively)

4. Threshold preliminary roadmap
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Threshold modes (features in the perspective of the client)

**Input/Output interface:** client communication with the module / threshold entity?

**Conventional** (non-threshold)
- Client requests to the Cryptographic Module
- Module replies to Client

**Not-shared-IO**
- Components $C_1, C_2, \ldots, C_n$ communicate with each other through the Inter-node network
- Inter-node network exchanges requests and replies between components

**Shared-IO**
- Components $C_1, C_2, \ldots, C_n$ communicate with each other through a shared input and output

(Shared-I and Shared-O are other modes where only the input and only the output are shared, respectively)

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- Auditable: succinct multi-signature verifiable against several public-keys
Standardization vs. adoption

“not every conceivable possibility is suitable for standardization”
Standardization vs. adoption

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Example motivating applications:

1. Secrets protected at rest (e.g., for high-value signature keys)
2. Confidential communication (e.g., via shared-O decryption)
3. Distributed key generation (e.g., to avoid dealers)
4. Leakage-resistant hardware (e.g., via threshold circuit design)
5. Accountable transactions (e.g., via multi-signatures)
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*best practices; minimum defaults; interoperability; innovation.*
The modularity challenge

Do we need to compromise between:

- ideal functionalities vs. concrete protocols of threshold schemes?
- building blocks vs. complex constructions?
The modularity challenge

Do we need to compromise between:

▶ ideal functionalities vs. concrete protocols of threshold schemes?
▶ building blocks vs. complex constructions?

- Construction complexity
- Complex compositions
- Building blocks
- Specification detail
- Security definitions
- Concrete instantiations (inc. security proof)
The modularity challenge

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![Diagram showing construction complexity and specification detail with Q_A, Q_B, Q_C, Q_D points]

Complex compositions

Building blocks

Construction complexity

Security definitions

Concrete instantiations (inc. security proof)

Specification detail
The modularity challenge

Do we need to compromise between:

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All have a place in the process:
- $Q_D$ as a goal;
- $Q_C$ as a criterion;
- $Q_B$ as a module;
- $Q_A$ as a reference definition.
The modularity challenge

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Example possible gadgets: secret sharing; distributed/correlated randomness; consensus; oblivious transfer; garbled circuits; ...
Designing concrete threshold schemes

Additional features to consider:

- Configurability of threshold parameters
- Rejuvenation of components (shares, parties, ...)
- Security (functionality/properties): composable?, adaptive?, graceful degradation?, ...
- Suitability for testing and validation
- ...

Important:
- Useful to get feedback from stakeholders about concrete examples
- These may help define criteria for calls / evaluation / selection
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Development process

Generic possible sequence of phases:

(Each phase to include public feedback. Some Threshold Cryptography workshops along the way?)
Development process

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(Each phase to include public feedback. Some Threshold Cryptography workshops along the way?)

Different standardization *items* can have **different**:

- **calls for contributions**: feedback on reference protocols; new protocols; reference implementations showing feasibility; research results, ...

- **timelines** (e.g., depending on complexity; existing rationale for choices)

- **final formats**: addendum vs. standalone standard, reference to other standards, implementation/validation guidelines, reference definitions,
Public feedback: a main pillar of the process

Promotes: openness, transparency and scrutiny, technical merit, trust, ...
Public feedback: a main pillar of the process

**Promotes:** openness, transparency and scrutiny, technical merit, trust, ...

**Useful feedback now — potential to shape the roadmap and criteria:**

- **Standardization items:** domain / primitive / mode;
- **Context:** application motivation, deployment setting, adversarial model
- **Desirable features:** rejuvenation, dynamic thresholds; robustness; composability; testability; ...
- **Concrete protocols/algorithms:** comparisons of state-of-the-art references
- **Reference implementations:** feasibility, benchmarks, open source, ...
- **Intellectual property:** information on known patents, licenses, ...
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**Useful feedback later:**

- Answers to subsequent calls for contributions
Intellectual property claims

The topic of intellectual property is relevant:

- Asking for disclosure of patents: call for disclosure, conditions for submitting
- Promote "FRAND" license: fair, reasonable, and nondiscriminatory
  - The NIST-ITL patent policy puts it as "reasonable and demonstrably free from unfair discrimination"
- Cannot force third party to disclose or enable FRAND terms but can choose to specify guidance based on expectation of FRAND terms.

Excerpt from NIST-ITL patent policy: "assurance [ ... ] that [ ... ] party does not hold [ ... ] any essential patent claim(s); or that a license [ ... ] will be made available [ ... ] under reasonable terms and conditions that are demonstrably free of any unfair discrimination; [possibly without compensation]"

Excerpt from NISTIR 7977: "NIST has noted a strong preference among its users for solutions that are unencumbered by royalty-bearing patented technologies. NIST has observed that widespread adoption of cryptographic solutions that it has developed has been facilitated by royalty-free licensing terms. "NIST will explicitly recognize and respect the value of IP and the need to protect IP if it is incorporated into standards or guidelines."
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Outline 5

1. Crypto standards at NIST
2. Threshold intro
3. Threshold project
4. Threshold preliminary roadmap
5. Concluding remarks
Concluding remarks
Concluding remarks

- NIST-CSD is driving an effort to standardize threshold schemes for NIST-approved cryptographic primitives

- Collaboration with stakeholders is essential

- We are in the stage of building a roadmap ... your feedback can (and should) help determine the outcome

- A two-track approach (multi-party and single-device)

- Various standardization items in each track, with various complexities
The test of time

70 years from now, will *threshold schemes* (still) be used to enable distributed trust in the implementation and operation of cryptographic primitives?
The test of time

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The NIST Stone Test Wall: “Constructed [in 1948] to study the performance of stone subjected to weathering. It contains 2352 individual samples of stone, of which 2032 are domestic stone from 47 states, and 320 are stones from 16 foreign countries.”

5. Concluding remarks

- Project webpage: https://csrc.nist.gov/Projects/Threshold-Cryptography
- Project email address: threshold-crypto@nist.gov
- TC-forum: https://list.nist.gov/tc-forum
Project webpage: https://csrc.nist.gov/Projects/Threshold-Cryptography

Project email address: threshold-crypto@nist.gov

NISTIR 8214: https://csrc.nist.gov/publications/detail/nistir/8214.final


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Thank you for your attention

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Presentation at the Theory of Implementation Security (TIS’19) Workshop
November 11, 2019 @ London, UK
luis.brandao@nist.gov

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