On Devising Recommendations for Multi-Party Threshold Schemes

Presented* in Singapore, on September 12th, 2023 at

DeCompute 2023

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 Joint work with René Peralta.

Outline

1. NIST Intro
2. NIST project on PEC and Threshold Crypto
3. The Threshold Call
4. A process toward recommendations

(Slides will be publicly available)

Crypto = Cryptography. NIST = National Institute of Standards and Technology. PEC = Privacy-Enhancing Crytpography.

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NIST: Laboratories → Divisions → Groups

- **Non-regulatory** federal agency (@ U.S. Dept. Commerce)
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INFORMATION TECHNOLOGY LABORATORY → **Computer Security Division (CSD):**

→ **Cryptographic Technology Group (CTG):** *research, develop, engineer, and produce guidelines, recommendations and best practices for cryptographic algorithms, methods, and protocols.*

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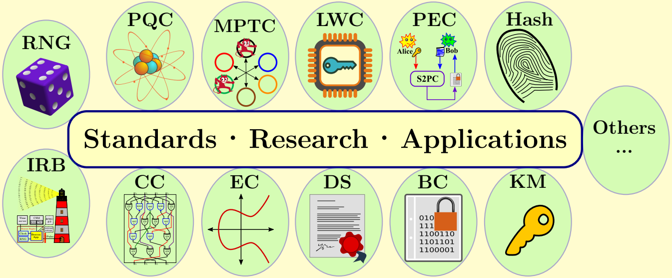
Activities in the “Crypto” Group



Legend: **BC** = **B**lock **C**iphers. **CC** = **C**ircuit **C**omplexity. **Crypto** = **Crypto**graphy. **DS** = **D**igital **S**ignatures. **EC** = **E**lliptic **C**urves. **FIPS** = **F**ederal **I**nformation **P**rocessing **S**tandards. **IR** = **I**nternal or **I**nteragency (denoting that the public NIST report was developed internally at NIST or in an interagency collaboration, respectively. **IRB** = **I**nteroperable **R**andomness **B**eacons. **KM** = **K**ey **M**anagement. **LWC** = **L**ight**w**eight **C**rypto. **PEC** = **P**rivacy-**E**nhancing **C**rypto. **PQC** = **P**ost-**Q**uantum **C**rypto. **RNG** = **R**andom-**N**umber **G**eneration. **SP 800** = **S**pecial **P**ublications in Computer Security. **TC** = [Multi-Party] **T**hreshold **C**rypto).

More details at https://www.nist.gov/itl/csd/cryptographic-technology

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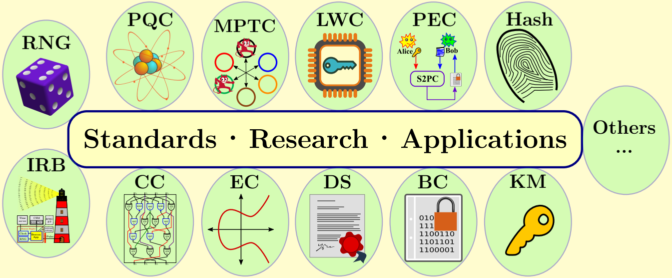

- **Public documentation:** FIPS; Special Publications (SP 800); NIST Reports (IR).
- **International cooperation:** government, industry, academia, standardization bodies.

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Some examples of NIST Crypto Projects

- **PQC:** [standardization] "**post-quantum**" signatures and key-encapsulation
- **LWC:** [standardization] "**lightweight**" **a**uth. **e**nc. w/ **a**ssoc. **d**ata, and hashing

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The "Threshold Call" (from MPTC+PEC): to gather **reference material** for public analysis ... aiming for **recommendations** (in a 1st phase), including about PEC.

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Cryptography (that can be) used to **enhance privacy**.

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ZKP	MPC	FHE	PSI	GRS	FnE	PIR	StE
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2. Promote development of PEC **reference material**.

- PEC tools
- STPPA (series of talks)
- PEC use-case suite
- Threshold schemes
- ZKProof collaboration
- Encounter metrics
- Email list (PEC Forum)

https://csrc.nist.gov/projects/pec

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Multi-Party Threshold Cryptography: NIST project

Cryptographic primitives:


Signing

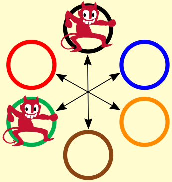
Encryption


KeyGen


Hashing

etc.

Threshold schemes (for cryptographic primitives):



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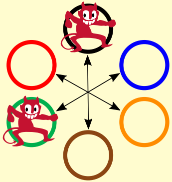

1. Split (**secret-share**) the secret/private-key across multiple parties.
2. Use **MPC** to perform needed operation (with split key), e.g., sign.
   (MPC = secure multiparty computation ... or call it "Threshold Cryptography")

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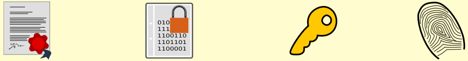

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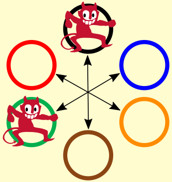

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- **"Threshold" (f):** Operation is secure if number of corrupted parties is $\leq f$.
- **Decentralized** trust about key **(not reconstructed)**: avoids single-point of failure.

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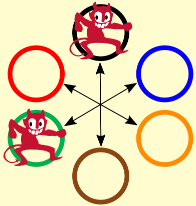

Calling for submissions of threshold schemes

(And gadgets for modular use)

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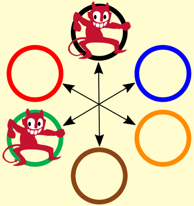

Calling for submissions of threshold schemes for:

- **[Cat1] Selected NIST-standardized primitives**
- **[Cat2] Other primitives (including FHE, IBE/ABE, ZKP)**

  (And gadgets for modular use)

FHE = Fully-homomorphic encryption.
IBE/ABE = Identity/Attribute-based encryption.
ZKP = Zero-knowledge proof.

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Category Cat1 of NIST Call for Multi-Party Threshold Schemes

Too many acronyms, we know. (Legend further below)

Subcategory: Type
C1.1: **Signing**
C1.2: **PKE**
C1.3: **2KA**
C1.4: **Symmetric**
C1.5: **Keygen**

Legend: **2KA**: **pair**-wise **k**ey-**a**greement. **2KE**: **pair**-wise **k**ey-**e**stablisment. **AES**: **A**dvanced **E**ncryption **S**tandard. **CDH**: **c**ofactor **D**iffie–**H**ellman. **ECC**: **E**lliptic-**c**urve **c**ryptography (or, if used as an adjective, **EC**-based). **ECDSA**: **E**lliptic-**c**urve **D**igital **S**ignature **A**lgorithm. **EdDSA**: **Ed**wards-curve **D**igital **S**ignature **A**lgorithm. **E**lliptic-**c**urve based **K**ey-**E**stablishment. **FIPS**: **F**ederal **I**nformation **P**rocessing **S**tandard. **KC**: **K**ey-**c**onfirmtion. **KDM**: **K**ey-**d**erivation **m**echanism. **Keygen**: **Key**-**gen**eration. **MQV**: Menezes-Qu-Vanstone. **PKE**: **p**ublic-**k**ey **e**ncryption. **RSA**: **R**ivest–**S**hamir–**A**dleman (signature and encryption schemes). **RSADSA**: **RSA** digital signature algorithm. **SP 800**: **S**pecial **P**ublication (in Computer Security). **Note:** In the 2nd column, each item within a subcategory is itself called a family of specifications, since it may include diverse primitives or modes/variants.

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C1.2: **PKE**	RSA decrypt, RSA encrypt (a secret value)	SP 800-56B Rev2

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Subcategory: Type	Families of specifications	NIST references
C1.4: **Symmetric**	AES encipher/decipher, KDM/KC (for 2KE)	FIPS 197, SP 800-56C Rev2, ...

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C1.2: **PKE**	RSA decrypt, RSA encrypt (a secret value)	SP 800-56B Rev2
C1.3: **2KA**	ECC-CDH, ECC-MQV	SP 800-56A Rev3
C1.4: **Symmetric**	AES encipher/decipher, KDM/KC (for 2KE)	FIPS 197, SP 800-56C Rev2, ...
C1.5: **Keygen**	ECC keygen, RSA keygen, bitstring keygen	(corresponding references above)

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Also to be added to Category Cat1

Primitives specified in NIST draft pubs emerging from the PQC and LWC projects:

- **ML-KEM** (based on KYBER) Draft FIPS 203: ***M**odule-**L**attice-Based KEM Standard*
- **ML-DSA** (based on DILITHIUM) Draft FIPS 204: ***M**odule-**L**attice-Based DSA*
- **SLH-DSA** (based on SPHINCS) Draft FIPS 205: ***S**tate**l**ess **H**ash-Based DSA*
- **Upcoming signature standard** (based on Falcon): Upcoming Draft FIPS pub
- **Upcoming XOF standard** (based on ASCON): Upcoming Draft FIPS pub

Legend: DSA = **d**igital **s**ignature **a**lgorithm. FIPS = **F**ederal **I**nformation **P**rocessing **S**tandard [Publication]. KEM = **k**ey-**e**ncapsulation **m**ethod. XOF = **ex**tendable **o**utput **f**unction. ML = **M**odule **L**attice. SLH = **S**tate**L**ess **h**ash.

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Category Cat2 of the NIST "Threshold" Call

Subcategory: Type
C2.1: **Signing**
C2.2: **PKE**
C2.3: **Key-agreem.**
C2.4: **Symmetric**
C2.5: **Keygen**

Note: While TF-QR is desired for any type of scheme, some examples show just TF to highlight that it is welcome even if not QR.

Legend: **agreem.** = **agreem**ent. **Keygen** = **key-gen**eration. **PKE** = **p**ublic-**k**ey **e**ncryption. **PRF** = **p**seudo**r**andom **f**unction [family]. **PRP** = **p**seudo**r**andom **p**ermutation [family]. **QR** = **q**uantum **r**esistant. **TF** = **t**hreshold-**f**riendly. **ZKPoK** = **z**ero **k**nowledge **p**roof **o**f **k**nowledge.

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Category Cat2 of the NIST "Threshold" Call

TF = **t**hreshold **f**riendly. QR = **q**uantum **r**esistant.

Subcategory: Type	Example types of schemes	Example primitives
C2.1: **Signing**	TF succinct & verifiably-deterministic signatures	Sign
|	TF-QR signatures	Sign

Note: While TF-QR is desired for any type of scheme, some examples show just TF to highlight that it is welcome even if not QR.

Legend: **agreem.** = **agreem**ent. **Keygen** = **key**-**gen**eration. **PKE** = **p**ublic-**k**ey **e**ncryption. **PRF** = **p**seudo**r**andom **f**unction [family]. **PRP** = **p**seudo**r**andom **p**ermutation [family]. **QR** = **q**uantum **r**esistant. **TF** = **t**hreshold-**f**riendly. **ZKPoK** = **z**ero **k**nowledge **p**roof **o**f **k**nowledge.

Category Cat2 of the NIST "Threshold" Call

Subcategory: Type
C2.6: **Advanced**
|
C2.7: **ZKPoK**
C2.8: **Gadgets**

Note: While TF-QR is desired for any type of scheme, some examples show just TF to highlight that it is welcome even if not QR.

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Category Cat2 of the NIST "Threshold" Call

TF = **t**hreshold **f**riendly. QR = **q**uantum **r**esistant.

Subcategory: Type	**Example types of schemes**	**Example primitives**
C2.6: **Advanced**	TF-QR fully-homomorphic encryption	Decryption; Keygen
|	TF identity-based and attribute-based encryption	Decryption; Keygens

Note: While TF-QR is desired for any type of scheme, some examples show just TF to highlight that it is welcome even if not QR.

Legend: agreem. = **agreem**ent. **Keygen** = **key-gen**eration. **PKE** = **p**ublic-**k**ey **e**ncryption. **PRF** = **p**seudo**r**andom **f**unction [family]. **PRP** = **p**seudo**r**andom **p**ermutation [family]. **QR** = **q**uantum **r**esistant. **TF** = **t**hreshold-**f**riendly. **ZKPoK** = **z**ero **k**nowledge **p**roof **o**f **k**nowledge.

Presented at DeCompute 2023

Category Cat2 of the NIST "Threshold" Call

Subcategory: Type	Example types of schemes	Example primitives
C2.7: **ZKPoK**	**Z**ero-**k**nowledge **p**roof **o**f **k**nowledge of private key	ZKPoK.Generate

Note: While TF-QR is desired for any type of scheme, some examples show just TF to highlight that it is welcome even if not QR.

Legend: **agreem.** = **agreem**ent. **Keygen** = **key**-**gen**eration. **PKE** = **p**ublic-**k**ey **e**ncryption. **PRF** = **p**seudo**r**andom **f**unction [family]. **PRP** = **p**seudo**r**andom **p**ermutation [family]. **QR** = **q**uantum **r**esistant. **TF** = **t**hreshold-**f**riendly. **ZKPoK** = **z**ero **k**nowledge **p**roof **o**f **k**nowledge.

Category Cat2 of the NIST “Threshold” Call

Subcategory: Type	Example types of schemes	Example primitives
C2.8: **Gadgets**	Garbled circuit (GC)	GC.generate; GC.evaluate

Note: While TF-QR is desired for any type of scheme, some examples show just TF to highlight that it is welcome even if not QR.

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Category Cat2 of the NIST "Threshold" Call

TF = **t**hreshold **f**riendly. QR = **q**uantum **r**esistant.

Subcategory: Type	**Example types of schemes**	**Example primitives**
C2.1: **Signing**	TF succinct & verifiably-deterministic signatures	Sign
|	TF-QR signatures	Sign
C2.2: **PKE**	TF-QR **p**ublic-**k**ey **e**ncryption (PKE)	Decrypt/Encrypt (a secret value)
C2.3: **Key-agreem.**	TF Low-round multi-party key-agreement	Single-party primitives
C2.4: **Symmetric**	TF blockcipher/PRP	Encipher/decipher
|	TF key-derivation / key-confirmation	PRF and hash function
C2.5: **Keygen**	Any of the above	Keygen
C2.6: **Advanced**	TF-QR fully-homomorphic encryption	Decryption; Keygen
|	TF identity-based and attribute-based encryption	Decryption; Keygens
C2.7: **ZKPoK**	**Z**ero-**k**nowledge **p**roof **o**f **k**nowledge of private key	ZKPoK.Generate
C2.8: **Gadgets**	Garbled circuit (GC)	GC.generate; GC.evaluate

Note: While TF-QR is desired for any type of scheme, some examples show just TF to highlight that it is welcome even if not QR.

Legend: **agreem.** = **agreem**ent. **Keygen** = **key**-**gen**eration. **PKE** = **p**ublic-**k**ey **e**ncryption. **PRF** = **p**seudo**r**andom **f**unction [family]. **PRP** = **p**seudo**r**andom **p**ermutation [family]. **QR** = **q**uantum **r**esistant. **TF** = **t**hreshold-**f**riendly. **ZKPoK** = **z**ero **k**nowledge **p**roof **o**f **k**nowledge.

Main components of a submission package

Check	#	Item
☐	M1	Written specification (S1–S16)
☐	M2	Reference implementation (Src1–Src4)
☐	M3	Execution instructions (X1–X7)
☐	M4	Experimental evaluation (Perf1–Perf5)
☐	M5	Additional statements

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☐	M5	Additional statements

The revised version of the call will detail better each component.

A submission package can propose various objects (schemes/gadgets).
Each component will then map all such objects.

Outline

1. NIST Intro
2. NIST project on PEC and Threshold Crypto
3. The Threshold Call
4. A process toward recommendations

Crypto = Cryptography. NIST = National Institute of Standards and Technology. PEC = Privacy-Enhancing Crytpography.

Assorted notes about the process

- **Setup:** A gathering of reference material (not a competition for a selection).
- **Expected:** The process will clarify relevant system models, best practices, ...
- **Aim:** Devise recommendations about advanced cryptography (PEC + MPTC)
  (Will support future standardization processes.)
  PEC = Privacy-Enhancing Crypto
  MPTC = Multi-Party Threshold Crypto
- **Ample room for participation:** Give feedback → Submit → Analyze
- **It's time:** Consider starting to organize a future submission (team, scope, ...)

Some technical notes

1. **Submission focuses**
2. **Threshold profile**
3. **Active security**
4. **Adaptive security**
5. **Modularity**
6. **Post-vs-Pre quantum crypto**
7. **Concrete implementation**

Some technical notes

1. **Submission focuses:** can specify a family of schemes (in various subcategories).
2. **Threshold profile:** open to choice: number of parties; dishonest proportion; ...
3. **Active security:** it is required, though open to diverse security formulations.
4. **Adaptive security:** at least "argued for" for major safety properties,
5. **Modularity:** modularize gadgets; encouraged proactive resharing module; ...
6. **Post-vs-Pre quantum crypto:** both in scope; pre-QC requires justification.
7. **Concrete implementation:** e.g., inc. communication (e.g., broadcast? P2P?).

Community participation

Various areas / possible synergies:

- Scope of the call is of interest to various crypto communities: MPC, ZKP, FHE, ...
- Work developed with other SDOs and in community efforts is also welcome.

(SDO = Standards Development Organization)

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Some variables:

- How will the community compose teams? (How to avoid effort duplication?)
- How will the scope of the call be covered? (primitives / models / approaches)

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- How will the scope of the call be covered? (primitives / models / approaches)

Upcoming: (Sep 26–28) Workshop on Multi-Party Threshold Schemes (MPTS) 2023

http://csrc.nist.gov/events/2023/mpts2023

Thank you for your attention! Questions?

On Devising Recommendations for Multi-Party Threshold Schemes

Presented at DeCompute 2023 | September 12th @ Singapore

Followup comments appreciated: luis.brandao@nist.gov

Threshold Call (Draft)

MPTS 2023 (Sept. 26–28)

MPTC-Forum (email list)

PEC-Forum (email list)

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Example ZKPoKs of interest (related to Cat1)

Related type	Related (sub)sub-category: Primitive	Example ZKPoK (including consistency with public commitments of secret-shares, when applicable)
Signing	C1.1.1/2: EC-signing	of pre-image of deterministic nonce (if applicable)
Keygen	C5.1.1: ECC keygen	of discrete-log (s or d) of pub key Q
|	C5.1.2: RSA keygen	of factors (p, q), or group order ϕ, or decryption key d
|	C5.1.3: AES keygen	of secret key k (with regard to secret-sharing commitments)
PKE	C1.2.1: RSA encryption	of secret plaintext m (encrypted)
|	C1.2.2: RSA decryption	of secret-shared plaintext m (after SSO-threshold decryption)
Symmetric	C1.4.1: AES enciphering	of secret key k (with regard to plaintext/ciphertext pair)
|	C1.4.2: Hashing in KDM	of secret pre-image Z

Source: Table 12 or NISTIR 8214C ipd

Vision: techniques demonstrated for these cases also enable more generic cases

Auxiliary slide

Legend: AES = Advanced Encryption Standard. Cat1 = Category 1. ECC = Elliptic-Curve Cryptography. ipd = initial public draft. keygen = key-generation. KDM = key-derivation mechanism. RSA = Rivest-Shamir Adleman. SSO = Secret-

Some expected revisions in the call

1. In Cat1, add subcategories for the NIST-selected PQC primitives
2. In Cat2, differentiate better the advanced subcats (e.g., what to thresholdize)
3. Clarify scope of “gadgets” subcategory (and how to motivate them)
4. Detail better some logistic requirements (e.g., code licensing)
5. Include LaTeX template for submission

Public comments received in first phase (April 2023)

#	Main topics (informal)
#1	Scope; quantum resistance.
#2	Innovation; models.
#3	Threshold motivation and alternatives; some expired patents.
#4	Mandatory checks; KAT values; implementation complexity.
#5	Fully homomorphic encryption (FHE).
#6	Threshold & oblivious pseudo-random functions (PRF); keygen; robustness; asynchronicity.
#7	Shamir Secret-sharing (safe evaluation points)
#8	Scope; keygen; adaptive security; key-refresh; bounds; broadcast; thresholds; party's state.
#9	Attribute-based encryption (ABE): ciphertext-policy, key-policy, multi-authority.
#10	All-or-nothing transform (AONT) and homomophic encryption.
#11	Implementation dependencies, KAT values in randomized multi-party runs.
#12	Robustness.

https://csrc.nist.gov/files/pubs/ir/8214/c/ipd/docs/nistir-8214c-ipd-public-feedback.pdf

Brainstorming on crypto standardization

1. On the **timing** & **speed** of processes: what is too soon, too late, too slow, and too fast?
2. What **value** is there in still pursuing new standards for **quantum-breakable** primitives?
3. How to handle the standardization tension between **innovation** and **interoperability**?
4. Which crypto functionalities/features make sense to **prioritize** for standardization?
5. What **synergies** to aim for between academia, industry, gov and standards bodies?

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