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Research using the Tamarin Prover

Session 4 - Summer School on real-world crypto and privacy 2024

Research using the Tamarin Prover

The two main categories

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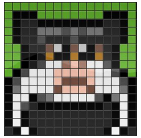
Improving the Tool / Expressibility

Security Protocol Analysis

Research using the Tamarin Prover

The two main categories



Improving the Tool / Expressibility

- Automatic Lemma Generation
- Natural Numbers
- Subterm Reasoning
- Custom Proof Tactics
- Better Models for Crypto Primitives

Security Protocol Analysis

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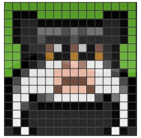

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- 5G AKA
- WPA2
- Wireguard
- EMV

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- **EMV**

You will hear about EMV later again!

“Historic” Examples of Interesting Attacks

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- **1999: Duplicate Signature Key Selection (DSKS) attacks**

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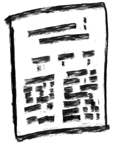
- **2014: Small subgroups**

  Diffie-Hellman protocols expect to receive an element of a prime order group, but often don't check this. *This is usually not a problem?*

First Idea

2016

Let's write a paper!



"Better Dolev-Yao abstractions of cryptographic primitives"

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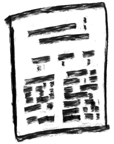

"Better Dolev-Yao abstractions of cryptographic primitives"

Plan:

- Revisit all Dolev-Yao primitives
  (signatures, exponentiation, encryption, hashes, etc.)
- Make better versions
- Submit
- ???
- Profit!!

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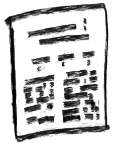

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Too hard!

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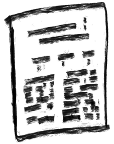

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Too hard!

Let's start with the easiest thing, **signatures**

Let’s start with Signatures

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Definition: Signature Scheme

A signature scheme **(gen,sign,verify)** is a triple of algorithms:

gen():
randomized alg. outputs a key pair **(pk, sk)**

sign(msg∈M, sk):
outputs signature sig

verify(sig, msg, pk):
outputs 'accept or 'reject'

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Correctness

for all **(pk, sk)** output by **gen()**
and for all **msg**∈M:

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Unforgeability

The adversary cannot generate a valid pair **(msg,sig)** that verifies using **pk** with **(pk, sk)** being the output by **gen()** and not knowing **sk**

How do we model Signatures?

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```
functions:   verify/2, sign/2, pk/1

equations:   verify(sign(DATA,A),DATA,pk(A)) = true
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$$\texttt{verify}(\overbrace{\texttt{sign}(\underbrace{\texttt{DATA,A}}_{\text{The Message}})}^{\text{The Signature}},\texttt{DATA},\overbrace{\texttt{pk(A)}}^{\text{The Signer}}) = \underbrace{\texttt{true}}_{\text{The Result}}$$

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First published in 2001, used by all contemporary tools

Thinking back: Key Substitution

1999: Key Substitution [Blake-Wilson, Menezes]

Given **sig**, **pk**, and **msg**:
Calculate (**sk'**,**pk'**) such that (**sig**,**msg**,**pk'**) verifies

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2005: Exclusive Ownership [Pornin, Stern]

A signature fails to provide **Conservative Exclusive Ownership** (CEO) if there is an efficient algorithm **`CEOgen(pk,(sig, msg)_i)`** outputs a new keypair (sk',pk'), s.t., **`verify(sig_j,msg_j,pk')=true`** for some j.

Applies to, e.g., RSA-PKCSv1.5, RSS-PSS, DSA, ECDSA with Free BP

Modelling: Key Substitution Attacks

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functions: verify/2, sign/2, pk/1, CEOgen/1

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```
functions: verify/2, sign/2, pk/1, CEOgen/1

equations: verify(sign(DATA,A),DATA,pk(A)) = true


equations: verify(sign(DATA,A),DATA,pk(CEOgen(sign(DATA,A)))) = true
```

Modelling: Key Substitution Attacks

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functions: verify/2, sign/2, pk/1, CEOgen/1

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$$\texttt{equations: verify(}\overbrace{\texttt{sign(DATA,A)}}^{\textit{The Signature}}\texttt{,}\underbrace{\texttt{DATA}}_{\textit{The Message}}\texttt{,pk(}\overbrace{\texttt{CEOgen(sign(DATA,A))}}^{\textit{Generating a new secret key from signature}}\texttt{)) = true}$$

Other Attacks on Signature Schemes

Destructive Exclusive Ownership (DEO) Attack

A CEO attack where the attacker can additionally choose/change the message

Colliding

The attacker can produce a **sig** and **pk**, s.t., **sig** verifies different messages using **pk**

Re-signing

Without knowing the message, the attacker can resign a given **sig** under different **sk**

Malleability

The attacker can create different signatures that verify under the same **(m,pk)**

Other Attacks on Signature Schemes

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Destructive Exclusive Ownership (DEO) Attack

```
verify(sign(m1,sk),m2,pk(DEOgen(sign(m1,sk),m2))) = true
```

Colliding

```
verify(sign(n,x),m,pk(weak(x))) = true
```

Re-signing

```
resign(sign(m,sk1),sk2) = sign(m,sk2)
```

Malleability

```
mutate(sign(m,r1,sk),r2)) = sign(m,r2,sk)
```

Was that it?

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No! We only enumerated attacks…

We should find a more general approach!

Better Signature Model (using Restrictions)

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   `honest(pk)`

2. Any step where an honest party generates a public key, we label it with '**honest**'.

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$$\text{State 1} \xrightarrow{\texttt{verified(sig,m,pk,true)}} \text{State 2}$$

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Note:
We only get guarantees for keys from **gen()**!

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Note:
We only get guarantees for keys from **gen()**!

2. Any step where an honest party generates a public key, we label it with ‘**honest**’.

3. Now we can use *restrictions* to control when the ‘**verified**’ event can occur.

The Restrictions!

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Correctness

```
Honest(pk(a)) & Verified(sign(m,r,a),m,pk(a),False) => ⊥
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Honest(pk(a)) & Verified(sign(m,r,a),m,pk(a),False) => ⊥
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Unforgeability

```
Honest(pk(a)) & Verified(s,m,pk(a),true) => s = sign(m,r,a)
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The Restrictions!

Correctness

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Honest(pk(a)) & Verified(sign(m,r,a),m,pk(a),False) => ⊥
```

Unforgeability

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Honest(pk(a)) & Verified(s,m,pk(a),true) => s = sign(m,r,a)
```

Consistency

```
Verified(s,m,pk(a),r1) & Verified(s,m,pk(a),r2) => r1 = r2
```

Stepping Back

Initial Idea

Automation research

Reading About DSKs

Hearing about Small subgroups

Learning about Length Extension attacks

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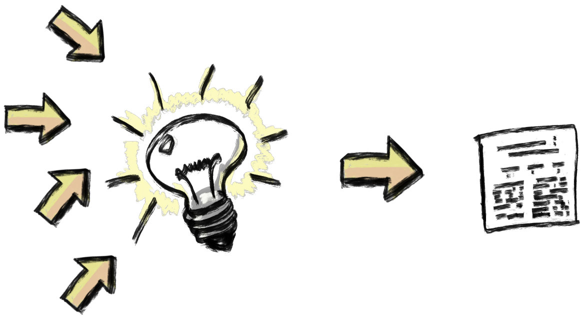

Better Dolev-Yao

Initial Idea vs. Results

Automation research

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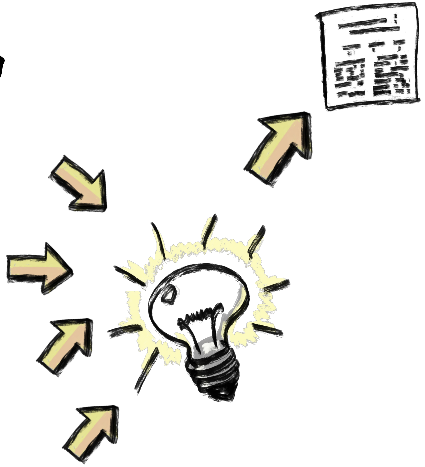
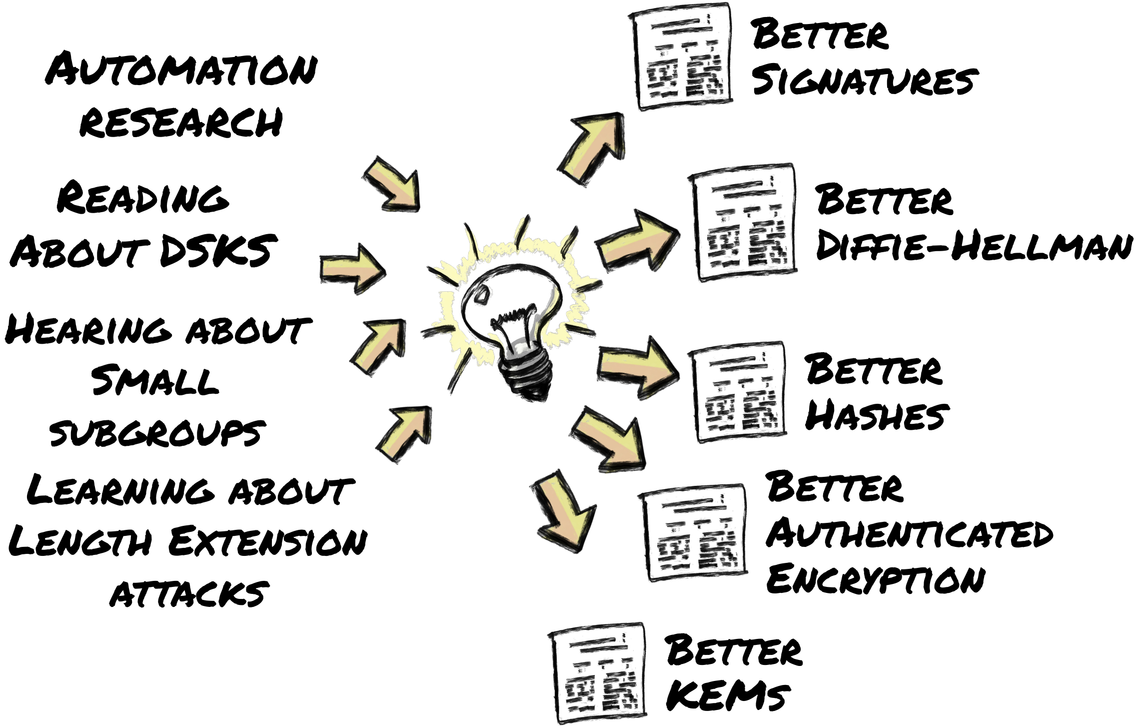
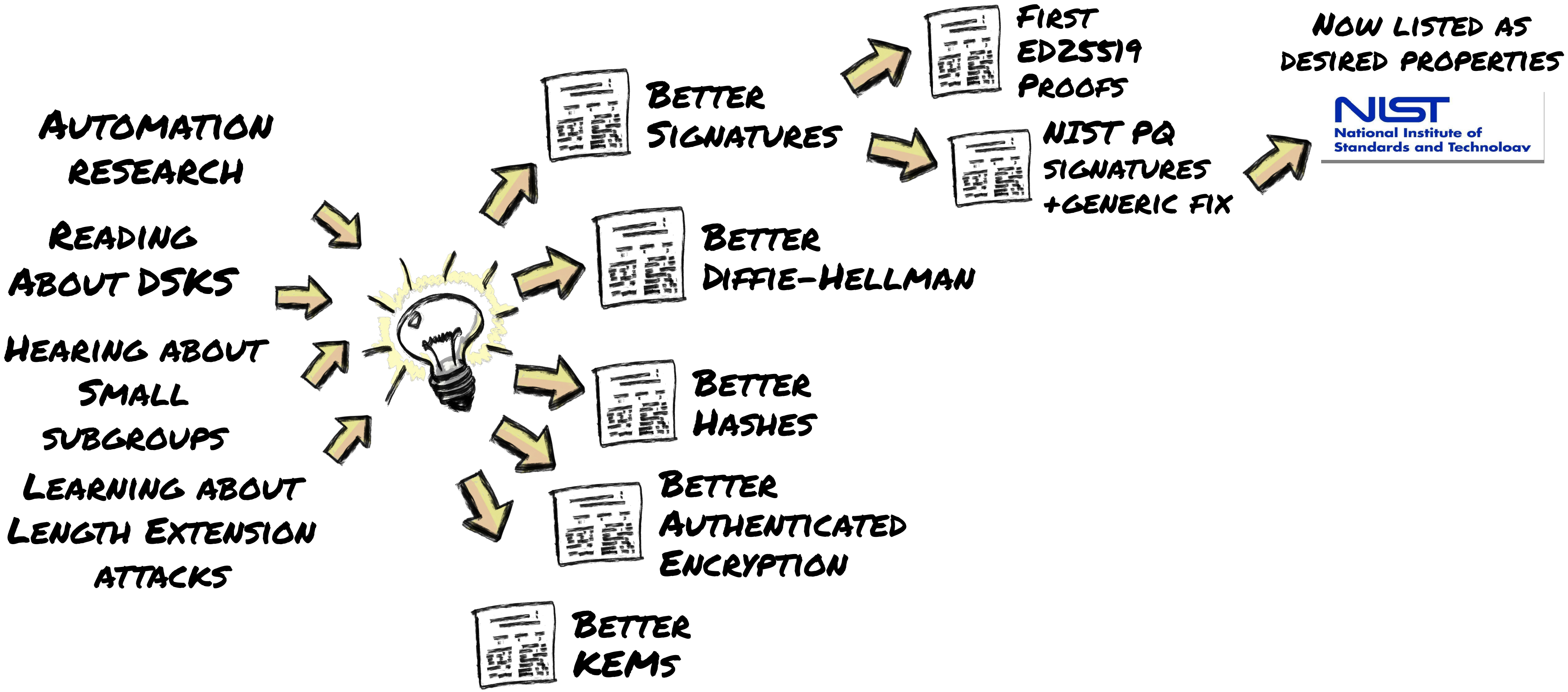


Better Signatures

Initial Idea vs. Results



Initial Idea vs. Results and their Impact



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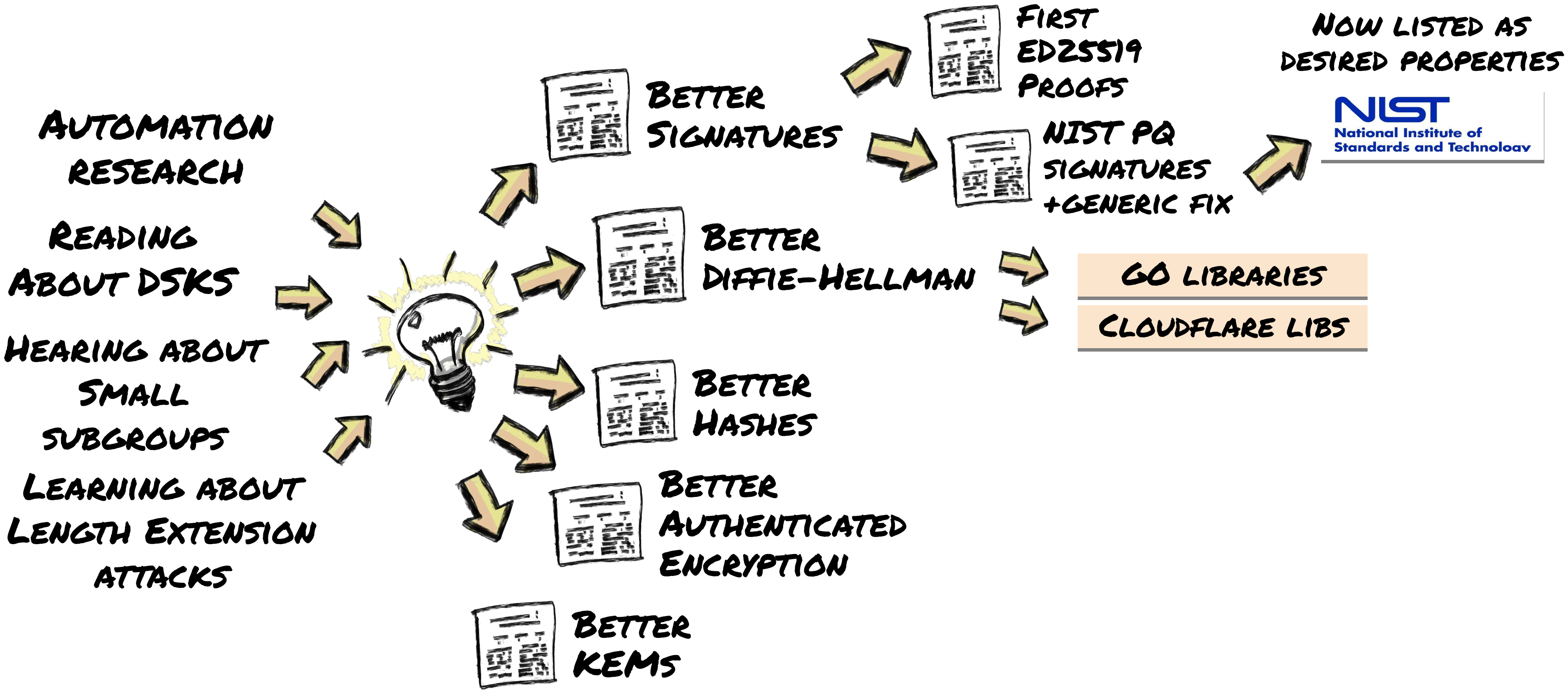

Initial Idea vs. Results and their Impact

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AUTOMATION RESEARCH

READING ABOUT DSKS

HEARING ABOUT SMALL SUBGROUPS

LEARNING ABOUT LENGTH EXTENSION ATTACKS

BETTER SIGNATURES

FIRST ED25519 PROOFS

NIST PQ SIGNATURES +GENERIC FIX

NOW LISTED AS DESIRED PROPERTIES

NIST National Institute of Standards and Technology

BETTER DIFFIE-HELLMAN

GO LIBRARIES

CLOUDFLARE LIBS

BETTER HASHES

BETTER AUTHENTICATED ENCRYPTION

I E T F

DRAFT ON AEAD PROPERTIES

BETTER KEMS

MAY LEAD TO CHANGES IN ML-KEM AND IETF STANDARDS

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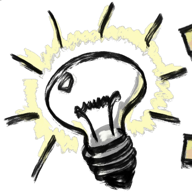

Better Signatures

First Ed25519 proofs

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Now listed as desired properties

National Institute of Standards and Technology

Better Diffie-Hellman

Go libraries

Cloudflare libs

Better Hashes

Better Authenticated Encryption

IETF

Draft on AEAD properties

Better KEMs

May lead to changes in ML-KEM and IETF Standards

IETF

National Institute of Standards and Technology

??

Wider Research Questions

Is there still more work to do?

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Which attacks are covered by computational protocol proofs, but cannot be captured symbolically?