Schrodinger's Squirrel

Formal security proofs in a post-quantum world

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CISPA Helmholtz Center for Information Security

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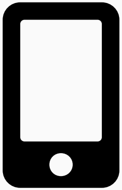
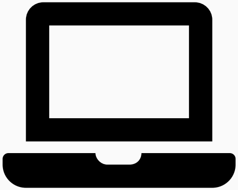
Formal Methods for Security and Privacy

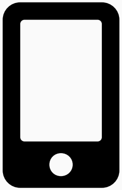
The beautiful and frightening technological revolution

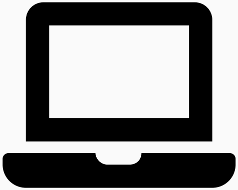




The beautiful and frightening technological revolution

It's my life!





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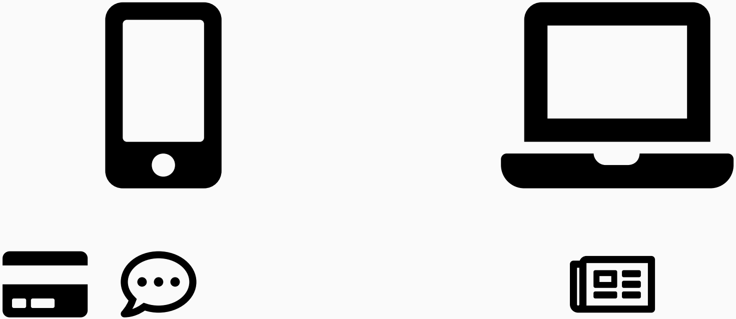

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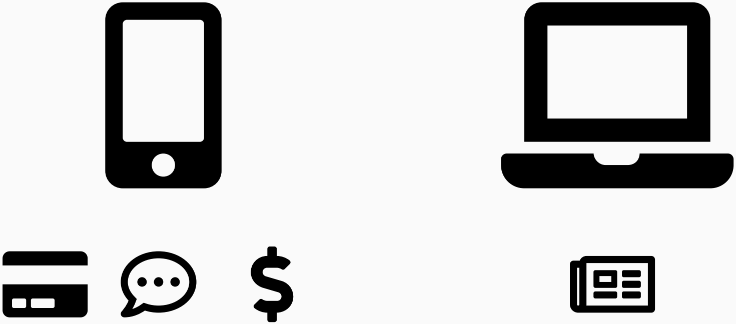

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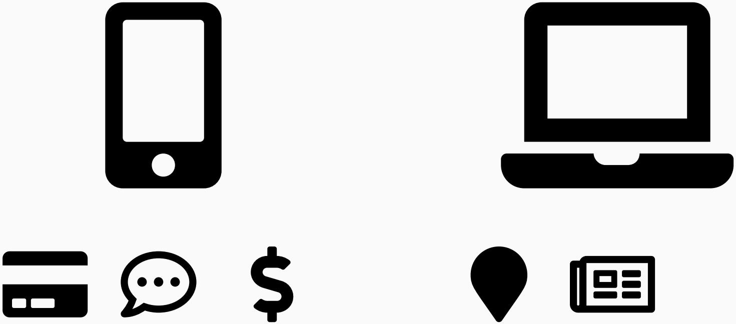

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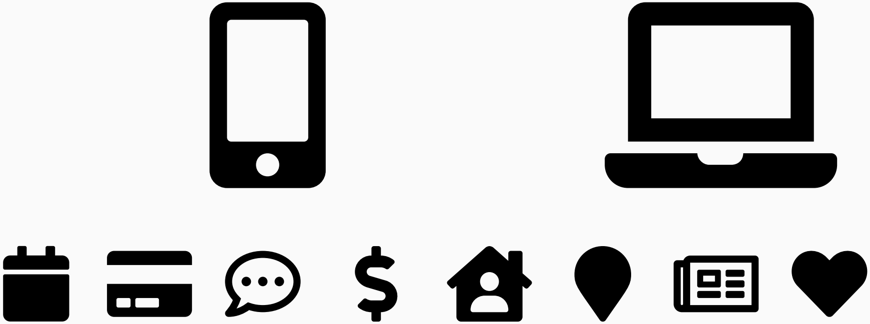

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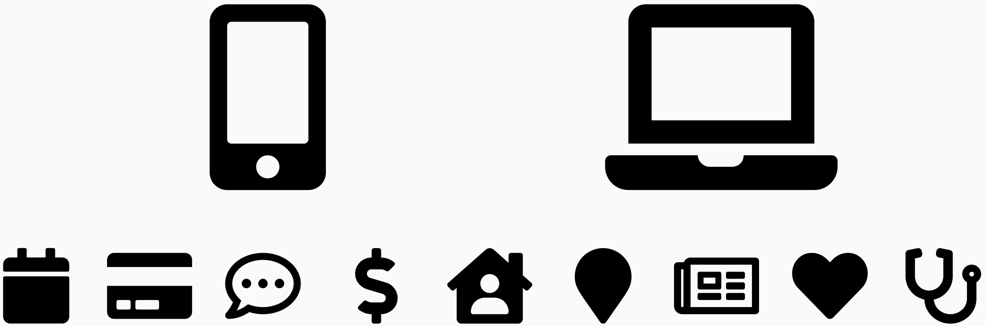

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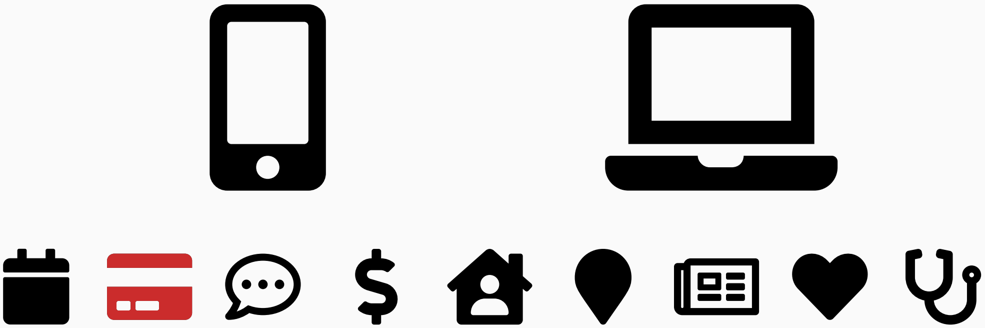

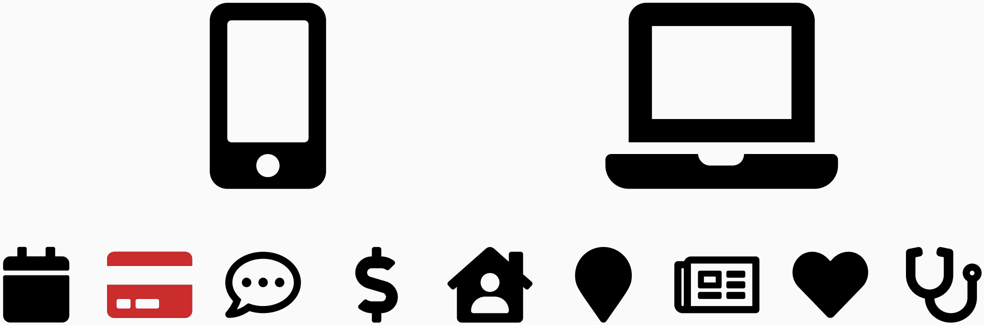

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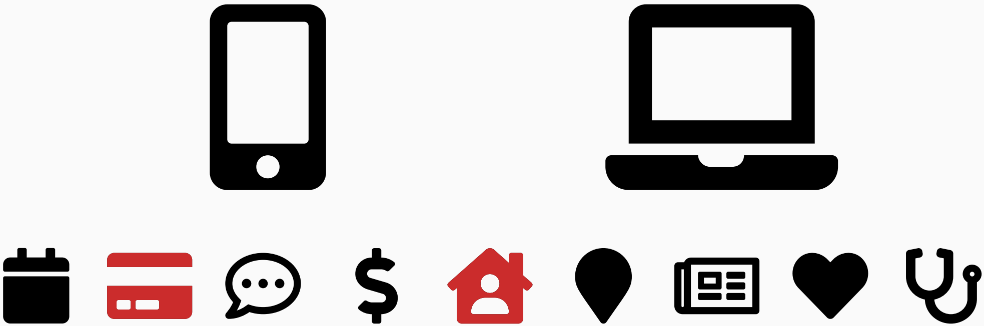

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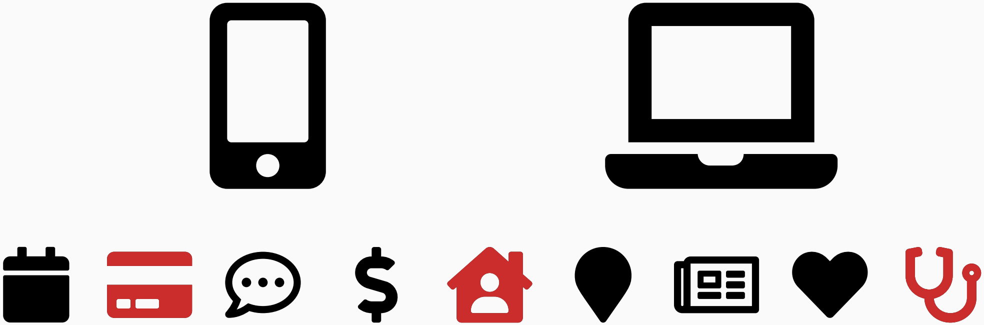

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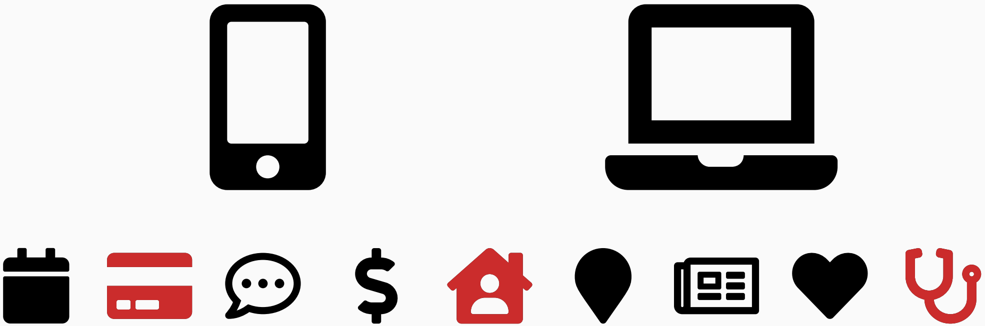

Sacrifice privacy in exchange of services...

but our data is used against us!

Some people even need privacy to survive:

- Reporters in dangerous countries.
- Homosexual in countries where it is punished by law (still 69 in the world...).
- Uighurs tracked through their smartphones in China.

If we can't have privacy, nobody can

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- used in practice.

The (first) difficulty

Protocols

SSH
TLS
GPG
...

The (first) difficulty

Primitives	Protocols
RSA	SSH
Elliptic curves	TLS
...	GPG
	...

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Implementation	Primitives	Protocols
C++	RSA	SSH
Java	Elliptic curves	TLS
Python	...	GPG
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OS	Implementation	Primitives	Protocols
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The (first) difficulty

If any link of the chain is broken, everything is.

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Provide guarantees on the protocol assuming that the other layers are secure.

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ϕ - security property

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Security Properties

- Secrecy, PFS, PCS
- Authentication
- Unlinkability

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It is very very very very very difficult

We want to prove over realistic models that something is impossible, even when considering all possible attackers.

- Undecidable;
- complexity of proofs grows very quickly, and cannot be managed by hand.

The solution

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Tools that help us carry-out, verify or automate the proofs.

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But. . .

- Inherent trade-off between the realism and automation/proof-size;
- no single tool will be the best at everything.

The landscape of computer-aided cryptography

Symbolic Tools | Computational Tools

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Symbolic Tools	Computational Tools
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State of the art

- Many tools used successfully, both to prove security or discover new vulnerabilities on complex systems.
- Still many limitations, and still very difficult to work on realistic models.

What I have been doing

Theory - Make proofs easier for realistic models

Practice - Actually make proofs for realistic models

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- Modular analysis of SSH in Squirrel, with optional feature of agent forwarding;
  Carried out first in the composition paper and then in the Squirrel one.

Today's presentation

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- What changes with a quantum attackers?
- Can tools already provide guarantees about them?
- If not, what can we do to fix them?

What is the fuss about quantum attackers?

Quantum computers

When?

No scaling quantum computers

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The issue

Quantum computers allow for a significant speed up for solving many problems

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$\hookrightarrow$ We need new primitives, new protocols and new proofs.

Attacker models

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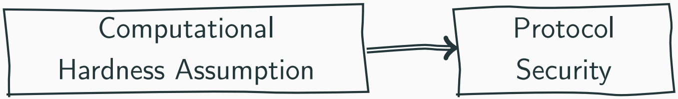
A first look at classical computational proofs



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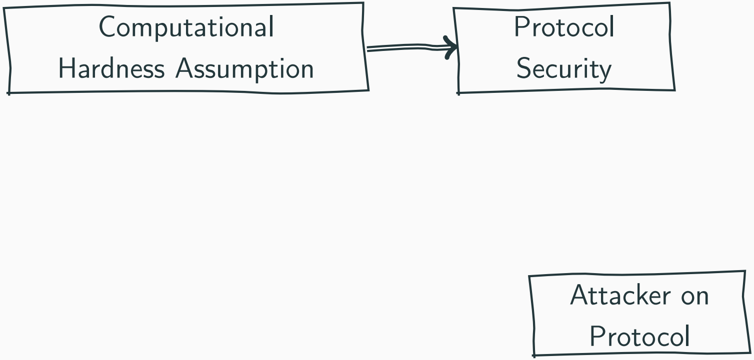

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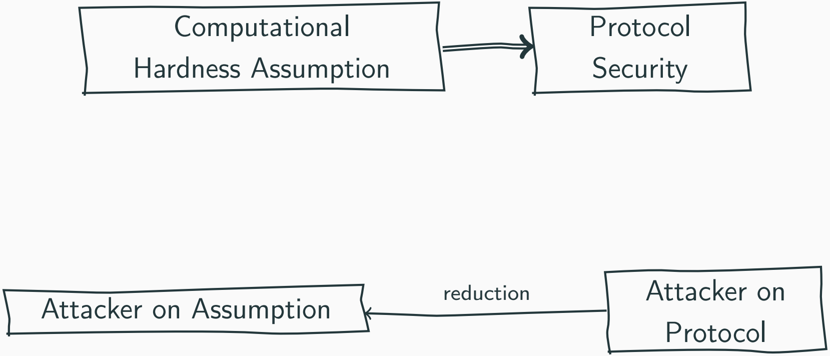

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- There are ways to manipulate a classical attacker that cannot be done with a quantum one.

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Impossible computation with a quantum computer

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$\hookrightarrow$ Reductions must not use techniques relying on this (e.g., rewinding)

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Many pitfalls

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$\hookrightarrow$ The computational tools do this kind of things...

Contributions

Our contributions[1]

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- Use it on some new protocols - KEM based post-quantum key exchanges

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Related work

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- EasyPQC - [BBFGHKSWZ - CCS'21] (parallel work)
  $\hookrightarrow$ Post-quantum sound EasyCrypt - hard to scale to protocols

A post-quantum BC logic

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A first-order logic to prove the security of protocols.

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Three main ingredients:

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- logical predicates and rules (with axioms about e.g. RSA) to reason over the terms;
- prove the soundness of the rules, i.e., they correspond to valid reduction.

  $\hookrightarrow$ if there is an attack on the protocol, there is an attack against the axioms.

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new sk;
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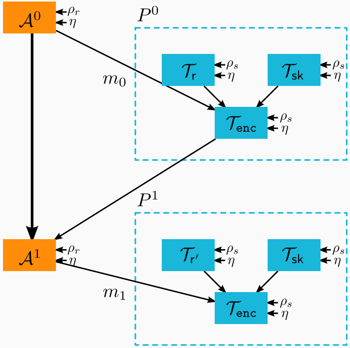
$\hookrightarrow$ Solved by specifying that $\mathcal{T}_{\mathsf{att}_1}$ always starts by recomputing the state of $\mathcal{T}_{\mathsf{att}_0}$

Real world interaction vs BC interaction



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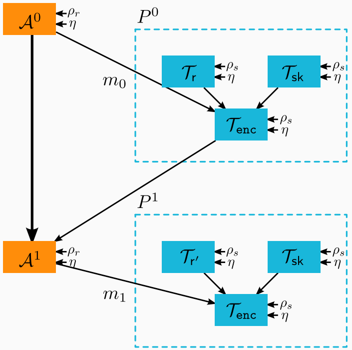

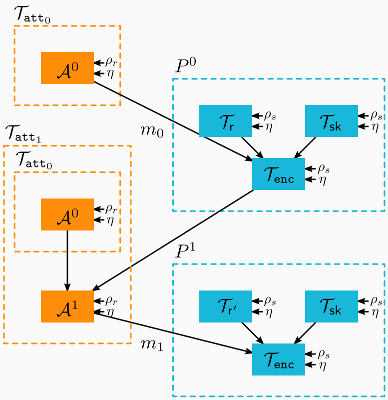

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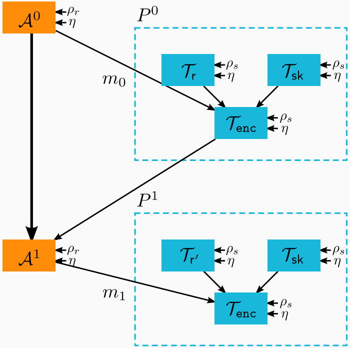

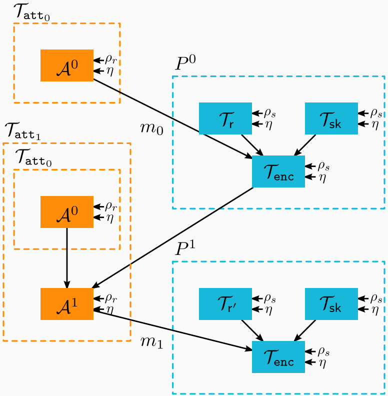

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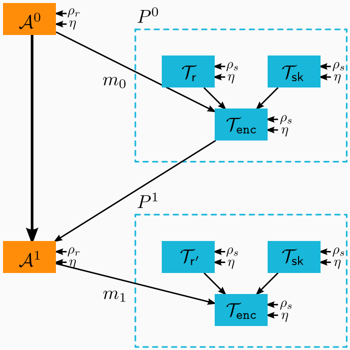

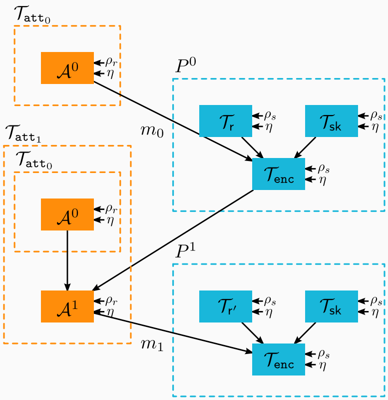

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Going post-quantum

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Behind the curtain, the interpretation of terms crucially rely on two facts:

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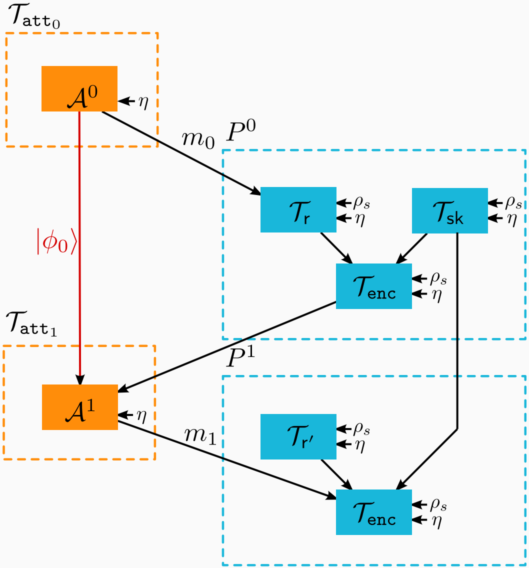
Our main contribution

An interpretation sound for interactive black-box attackers, where the interpretation directly depends a single interactive Turing Machine $\mathcal{T}_{\mathcal{A}}$, instead of many $\mathcal{T}_{\mathsf{att}_i}$.

New (natural) interpretation



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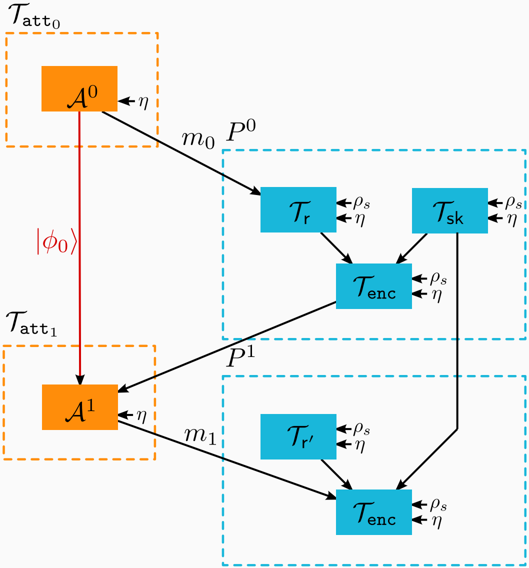

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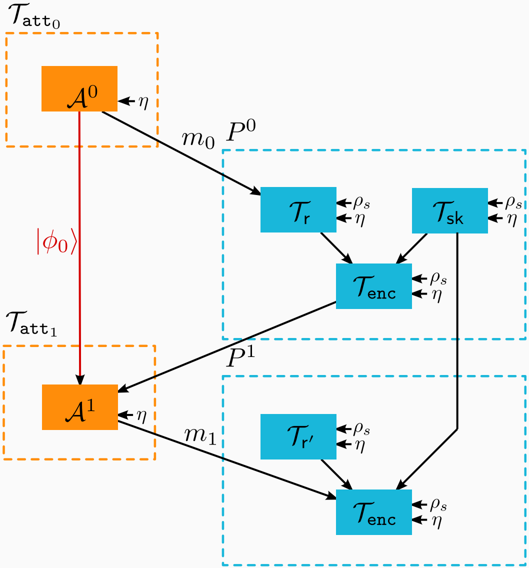

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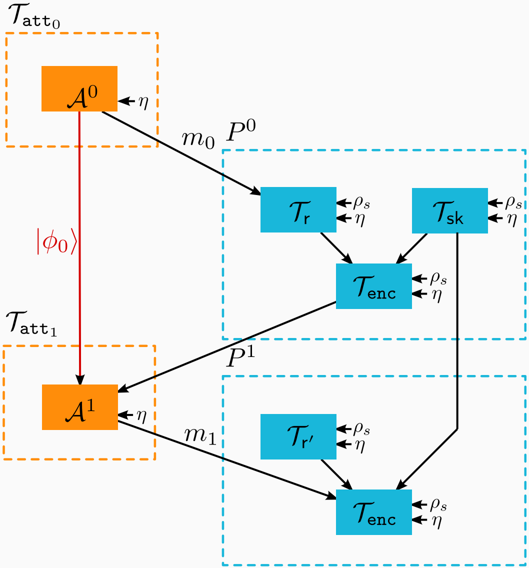

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$$\sim$$

$$\mathsf{att}_0(\mathsf{sk}), \mathit{ok}$$

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  $\hookrightarrow$ he single interactive attacker will know how many time it was called on both sides!

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Syntactic conditions

A set of three simple syntactic conditions over terms and formulas.

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- Sufficient to obtain the soundness of the BC logic;
- Simple and syntactic, so we were able to integrate them inside Squirrel with a few hundred lines of code, only at the cost of a small expressivity loss.

What is Squirrel

In a nut: an interactive prover for the BC logic

- Relies on a meta-logic to allow for mechanized proofs of protocol for an unbounded number of sessions;
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Some figures

- 5 people core team: David Baelde, Stéphanie Delaune, Charlie J., Adrien Koutsos, Solène Moreau (and expanding)
- 30 000 lines of code and celebrating our 2 000 commit!
- about 15 real life case studies of protocols

Implementation and Case-studies

Protocol	LoC	Assumptions	Security properties
Key exchange protocols			
$\text{IkeV1}_{\text{psk}}$	680	PRF, EUF-CMA	Strong Secrecy & Authentication
$\text{IkeV2}_{\text{psk}}^{\text{sign}}$	300	PRF, EUF-CMA	Strong Secrecy & Authentication
KE_{BCGNP}	355	PRF, IND-CCA, XOR	Strong Secrecy & Implicit Authentication
KE_{FSXY}	660	PRF, IND-CCA, XOR	Strong Secrecy & Implicit Authentication
SC-AKE	650	PRF, IND-CCA, SUF-CMA, XOR	Strong Secrecy & Authentication
Proving post-quantum soundness of Squirrelcase studies			
Basic Hash	100	PRF, EUF-CMA	Authentication & Unlinkability
Hash Lock	130	PRF, EUF-CMA	Authentication & Unlinkability
LAK (with pairs)	250	PRF, EUF-CMA	Authentication & Unlinkability
MW	300	PRF, EUF-CMA, XOR	Authentication & Unlinkability
Feldhofer	270	ENC-KP, INT-CTXT	Authentication & Unlinkability
Private Authentication	100	IND-CCA, ENC-KP	Anonymity

What's next?

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Natural next step

Foundations for proving Key-Exchanges in Squirrel:

- Define how to express complex properties such as PFS or PCS in Squirrel, and simplified with our composition result.
- Link proofs in Squirrel with existing framework (BR, CK,eCK,. . .)
- Perform an extensive case-study (KEMTLS)

The landscape

What we now have (thanks to 40 years of research!)

Many tools, attacker models and associated proof techniques. For instance:

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- Squirrel to verify precisely the core of a protocol.

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Our goal

Build bridges inside the different groups in the community, as well as outside the community.

Medium-term goal

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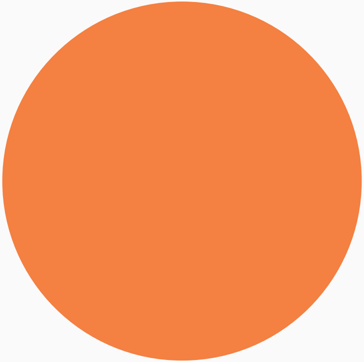
Design a platform that allows to formally combine the guarantees of multiple tool:

- First for Tamarin and Proverif, to combine there complementary strengths;
- Then integrate Squirrel;
- Make a concrete multi-level analysis.

Long term goal

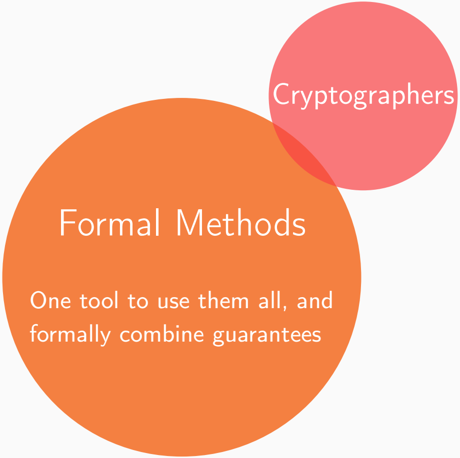


Long term goal

Formal Methods

One tool to use them all, and formally combine guarantees

Long term goal



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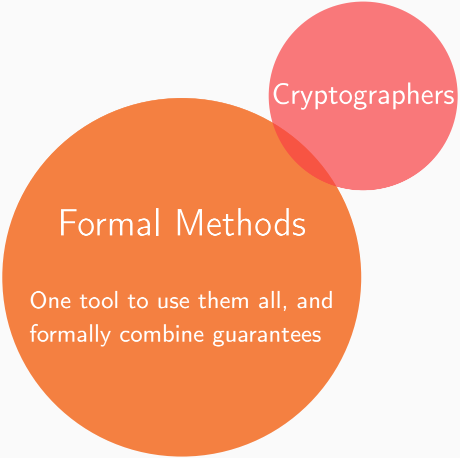
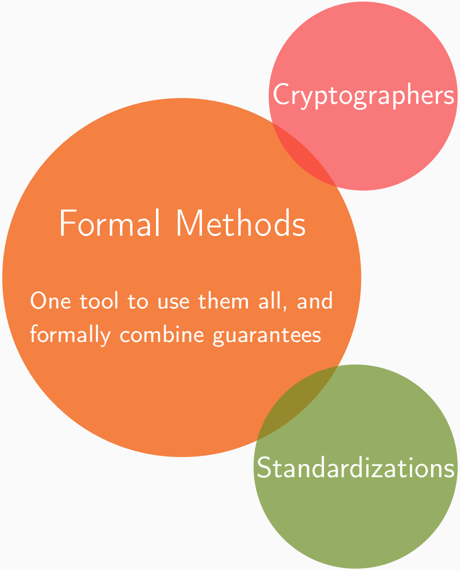


- Use the tools straight away in new protocol designs

Long term goal



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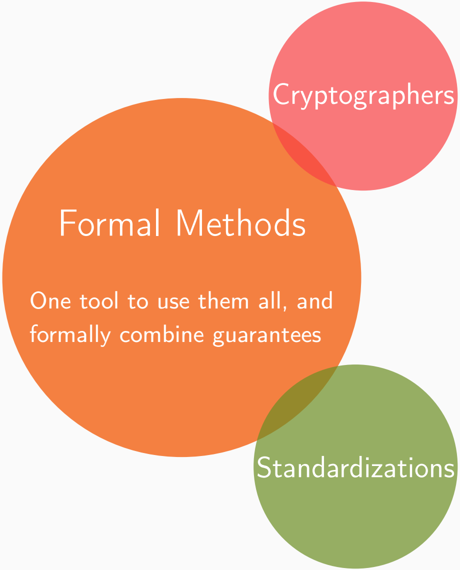

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- Use the tools straight away in new protocol designs
- Make some techniques available to non-experts
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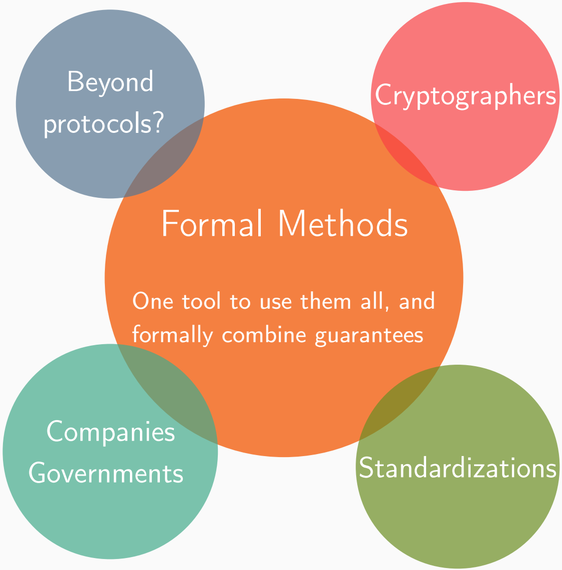

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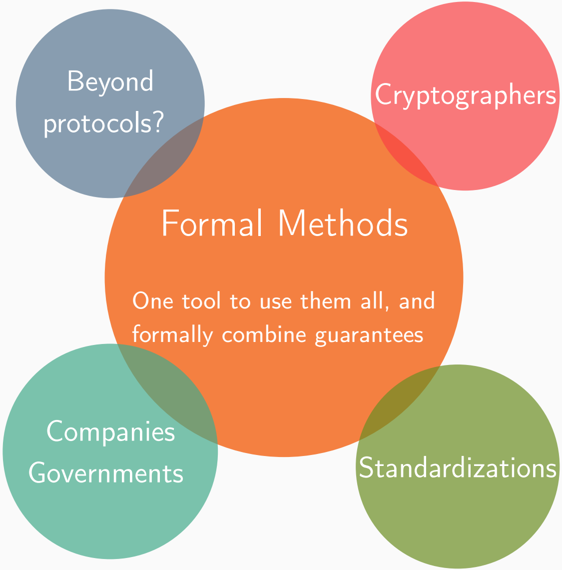
Long term goal

- attacker models for code level analysis, e.g. for fault-injection
- Make some techniques available to non-experts



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