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2024-08-30

How to build post-quantum cryptographic protocols and why wall clocks are not to be trusted.

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https://rosenpass.eu

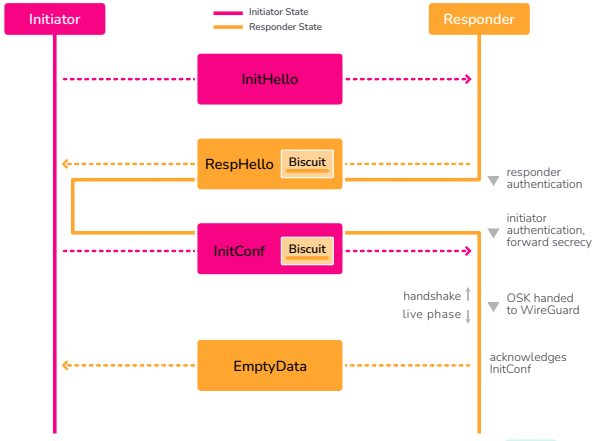
This is the Plan

1. **Introducing Rosenpass,** briefly.
2. **The Design of Rosenpass** and basics about post-quantum protocols.
3. **Hybrid Security** – how it can be done and how we do it.
4. **ChronoTrigger Attack** and not trusting wall clocks.
5. **Protocol Proofs** – big old rant!
6. **Q&A** – and probably “more of a comment”.

Follow the talk at:
rosenpass.eu/docs/presentations/hackmas-2024/

Introducing Rosenpass, briefly

- A post-quantum secure key exchange **protocol** based on the paper Post-Quantum WireGuard [PQWG]
- An open source Rust **implementation** of that protocol, already in use
- A way to secure WireGuard VPN setups against quantum attacks
- A **post-quantum secure VPN**
- A governance **organization** to facilitate development, maintenance, and adoption of said protocol



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The Design of Rosenpass

and how to build post-quantum protocols

In the following slides you will learn ...

... that, to a crypto protocol designer, post-quantum cryptography is not much more than a subtle difference in function interface.

Glossary: Post-Quantum Security

Pre-quantum cryptography is ...

... susceptible to attacks from quantum computers.

- specifically, to *Shor's Algorithm*
- quite fast
- widely trusted

Post-quantum cryptography is ...

... not susceptible to attacks from quantum computers.

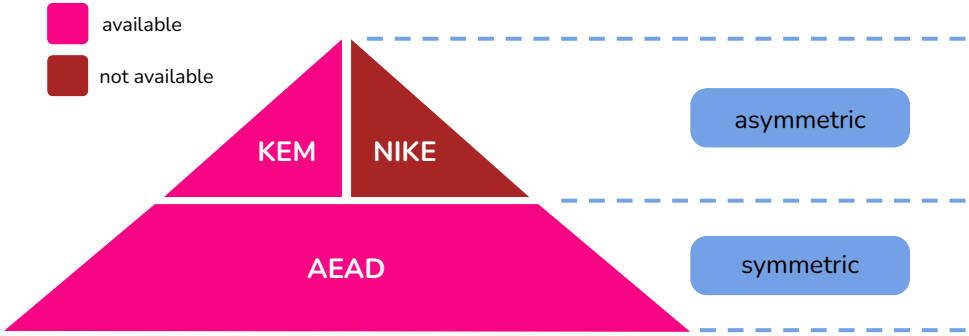
- generally less efficient.
- much bigger ciphertexts.
- less analyzed.

Hybrid cryptography combines ...

... the combination of the previous two. It is ...

- about as inefficient as post-quantum cryptography.
- not widely adopted, which is a major problem.

What Post-Quantum got



KEMs and NIKEs

Key Encapsulation Method

```
fn Kem::encaps(Pk) -> (Shk, Ct);
fn Kem::decaps(Pk, Ct) -> Shk;

(shk, ct) = encaps(pk);
assert!(decaps(sk, ct) = shk)
```

Think of it as encrypting a key and sending it to the partner.

- secrecy
- implicit authentication of recipient (assuming they have the shared key, they must also have their secret key)

Non-Interactive Key Exchange

```
fn nike(sk: Sk, pk: Pk) -> Shk;

assert!(nike(sk1, pk2) =
        nike(sk2, pk1));
```

Aka. Diffie-Hellman. Note how the keypairs are *crossing over* to each other.

- secrecy
- implicit mutual authentication (for each party: assuming they have the shared key, they must also have their secret key)

Protocol Security Properties

Implicit authentication

“If you have access to this shared symmetric key then you must have a particular asymmetric secret key.”

Explicit authentication

“I know you have access to this shared key because I checked by making you use it, therefore you also have a particular asymmetric secret key.”

Secrecy

“The data we exchange cannot be decrypted unless someone gets their hands on some of our static keys!”

Forward secrecy

“Even if our static keys are exposed, the data we exchanged cannot be retroactively decrypted!”*

* Terms and conditions apply:
We are using an extra key that we do not call a *static* key. This key is generated on the fly, not written to disk and immediately erased after use, so it is more secure than our static keys. Engaging in cryptography is a magical experience but technological constructs can – at best – be asymptotically indistinguishable from miracles.

KEMs and NIKEs: Key Exchange

Key Encapsulation Method

Responder Authentication: Initiator encapsulates key under the responder public key.

Initiator Authentication: Responder encapsulates key under the initiator public key.

Forward Secrecy: In case the secret keys get stolen, either party generates a temporary keypair and has the other party encapsulate a secret under that keypair.

How to do this properly? See Rosenpass.

Non-Interactive Key Exchange

Responder Authentication: Static-static NIKE since NIKE gives mutual authentication.

Initiator Authentication: Static-static NIKE since NIKE gives mutual authentication.

Forward secrecy: Another NIKE, involving a temporary keypair.

How to do this properly? See the Noise Protocol Framework. [NOISE]

KEMs and NIKEs

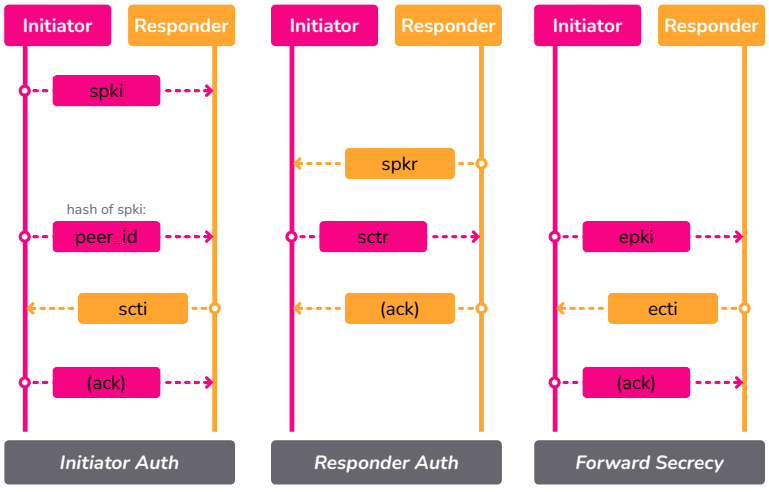
Key Encapsulation Method

```
trait Kem {
  // Secret, Public, Symmetric, Ciphertext
  type Sk; type Pk; type Shk; type Ct;
  fn genkey() -> (Sk, Pk);
  fn encaps(pk: Pk) -> (Shk, Ct);
  fn decaps(sk: Pk, ct: Ct) -> Shk;
}
#[test]
fn test<K: Kem>() {
  let (sk, pk) = K::genkey();
  let (shk1, ct) = K::encaps(pk);
  let shk2 = K::decaps(sk, ct);
  assert_eq!(shk1, shk2);
}
```

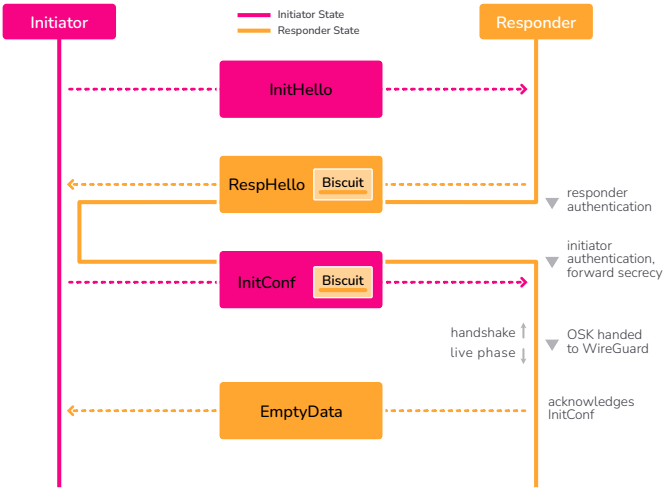
Non-Interactive Key Exchange

```
trait Nike {
// Secret, Public, Symmetric
  type Sk; type Pk; type Shk;
  fn genkey() -> (Sk, Pk);
  fn nike(sk: Sk, pk: Pk) -> Shk;
}
#[test]
fn test<N: Nike>() {
  let (sk1, pk1) = N::genkey();
  let (sk2, pk2) = N::genkey();
  let ct1 = N::nike(sk1, pk2);
  let ct2 = N::nike(sk2, pk1);
  assert_eq!(ct1, ct2);
}
```

Rosenpass Key Exchange Parts



Rosenpass Protocol Features



- authenticated key exchange
- three KEM operations interleaved to achieve mutual authentication and forward secrecy
- no use of signatures
- first package (InitHello) is unauthenticated
- stateless responder to avoid disruption attacks

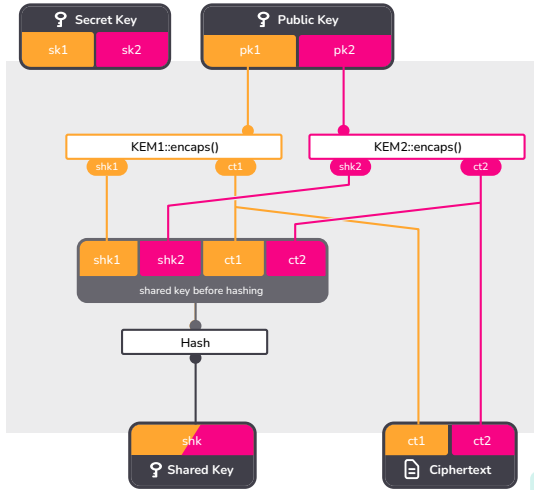
Hybridization

In the following slides you will learn ...

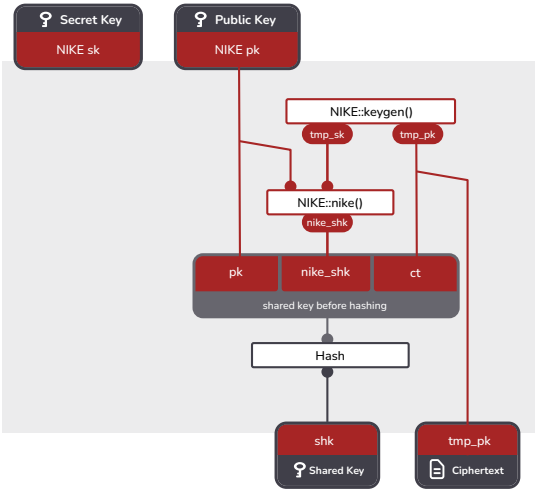
... that hybrid security can be achieved by building hybrid primitives and that it is not always wise to do so.

Combining two KEMs with the GHP Combiner

- “Giacon-Heuer-Poettering” [GHP]
- running both KEMs in parallel
- secret keys, public keys, and ciphertexts are concatenated
- shared keys are hashed together
- ciphertexts included in hash for proof-related reasons



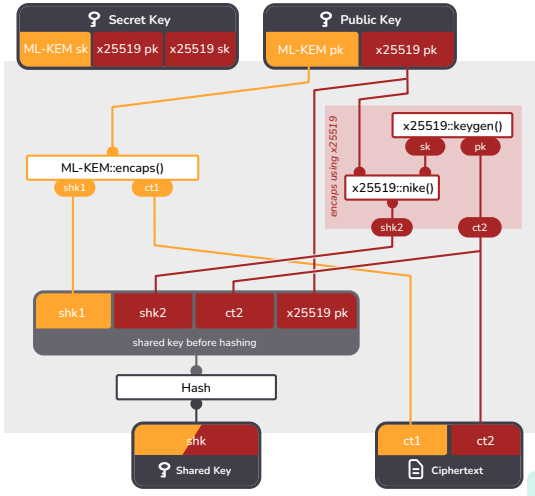
Turning a NIKE into a KEM



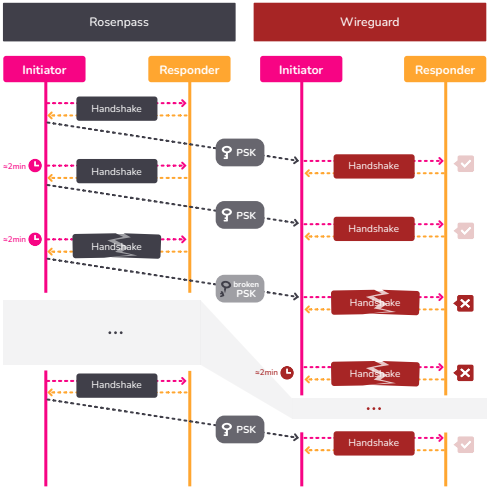
- from the HPKE RFC [HPKE]
- *remote* keypair is static keypair
- *local* keypair is temporary keypair
- local keypair public key is treated as ciphertext
- for proof-related reasons, ciphertext and public key are included in hash
- RFC work by Barnes, Bhargavan, Lipp, Wood supported by analysis work by Alwen, Blanchet, Hauck, Kiltz, Lipp, Riepel [HPKE]

X-Wing [XWING]

- combines ML-KEM and X25519
- techniques from DHKEM to turn X25519 into a KEM
- techniques from GHP to combine the two
- optimizations applied to make hashing more efficient
- bespoke proof of security
- work by Barbosa, Connolly, Duarte, Kaiser, Schwabe, Varner, Westerbaan [XWING]



Rosenpass & WireGuard Hybridization



- Rosenpass and WireGuard are hybridized on the procol level
- preserving efficiency of and trust in WireGuard
- straightforward transition path; existing WireGuard implementation remains in use
- key from Rosenpass used as PSK in WireGuard

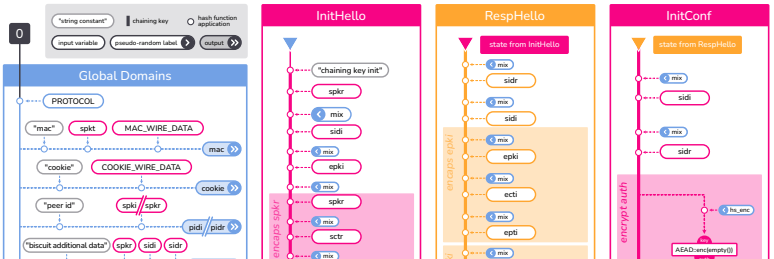
Full Protocol Reference in the Whitepaper

Initiator Code	Responder Code	Comments

1 — InitHello { sidi, epki, sctr, pidiC, auth } — 2

Line	Variables ← Action	Variables ← Action	Line	Comment
IHI1	ck ← lhash("chaining key init", spkr)	ck ← lhash("chaining key init", spkr)	IHR1	Initialize the chaining key, and bind to the responder's public key.
IHI2	sidi ← random_session_id();			The session ID is used to associate packets with the handshake state.
IHI3	eski, epki ← EKEM::keygen();			Generate fresh ephemeral keys, for forward secrecy.
IHI4	mix(sidi, epki);	mix(sidi, epki)	IHR4	InitHello includes sidi and epki as part of the protocol transcript, and so we mix them into the chaining key to prevent tampering.
IHI5	sctr ← encaps_and_mix<SKEM>(spkr);	decaps_and_mix<SKEM>(sskr, spkr, ct1)	IHR5	Key encapsulation using the responder's public key. Mixes public key, shared secret, and ciphertext into the chaining key, and authenticates the responder.
IHI6	pidiC ← encrypt_and_mix(pidi);	spki, psk ← lookup_peer(decrypt_and_mix(pidiC))	IHR6	Tell the responder who the initiator is by transmitting the peer ID.
IHI7	mix(spki, psk);	mix(spki, psk);	IHR7	Ensure the responder has the correct view on spki. Mix in the PSK as optional static symmetric key, with epki and spkr serving as nonces.
IHI8	auth ← encrypt_and_mix(empty())	decrypt_and_mix(auth)	IHR8	Add a message authentication code to ensure both participants agree on the session state and protocol transcript at this point.

...



rosenpass.eu/docs

rosenpass.eu/whitepaper.pdf

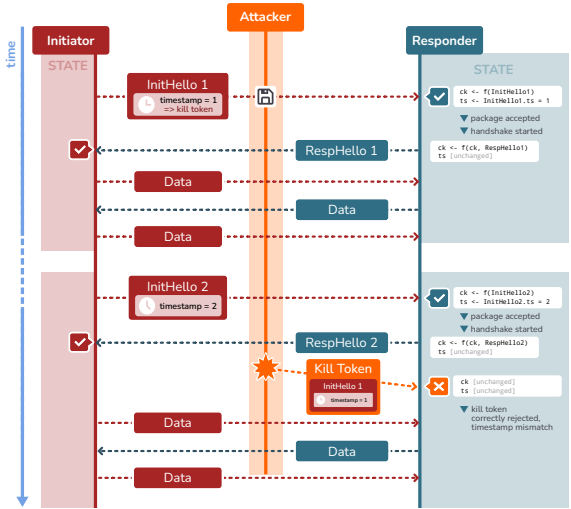
Trials ~ Attacks found

ChronoTrigger

In the following slides you will learn ...

how to perform a protocol-level DoS attack against WireGuard, why wall clocks are not to be trusted and how to face replay attacks without fear.

Retransmission Protection in WireGuard



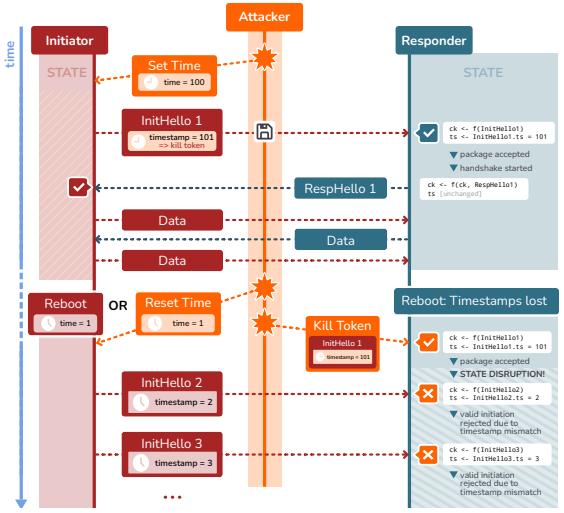
- replay attacks thwarted by counter
- counter is based on real-time clock
- responder is semi-stateful (one retransmission at program start may be accepted, but this does not affect protocol security)

⇒ WG requires *either* reliable real-time clock *or* stateful initiator

⇒ adversary can attempt replay, but this cannot interrupt a valid handshake by the initiator

! Assumption of reliable system time is invalid in practice!

ChronoTrigger Attack



A. Preparation phase:

1. **Attacker** sets *initiator system time* to a future value
2. **Attacker** records *InitHello* as *KillToken* while both peers are performing a valid handshake

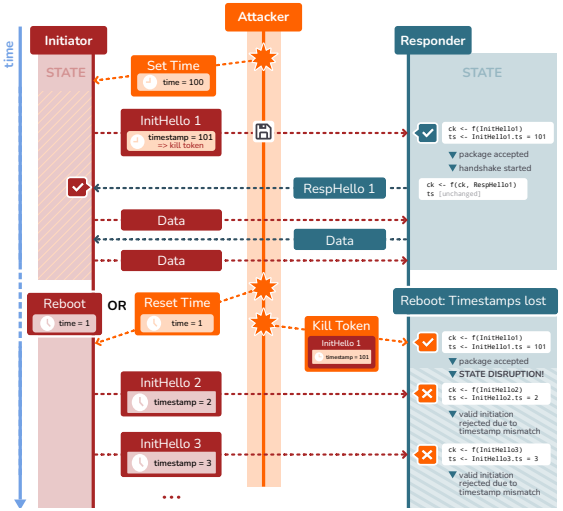
... both peers are being reset ...

B. Delayed execution phase:

1. **Attacker** sends *KillToken* to responder, setting their timestamp to a future value

⇒ Initiation now fails again due to timestamp mismatch

ChronoTrigger Attack

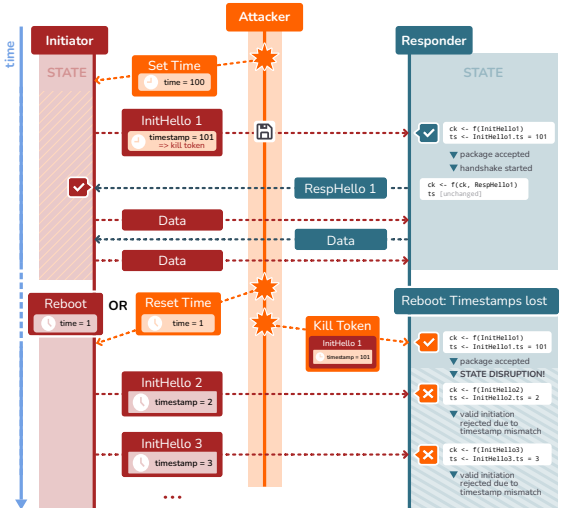


Gaining access to system time:

- Network Time Protocol is insecure, mitigations are of limited use

⇒ break NTP *once*; kill token lasts forever

ChronoTrigger Attack



Attacker gains

- extremely cheap protocol-level DoS

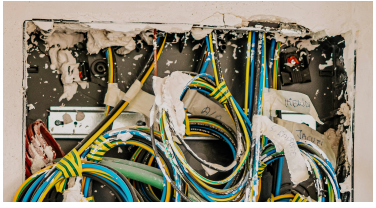
Preparation phase, attacker needs:

- eavesdropping of initiator packets
- access to system time

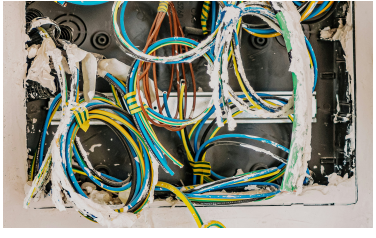
Delayed execution, attacker needs:

- no access beyond message transmission to responder

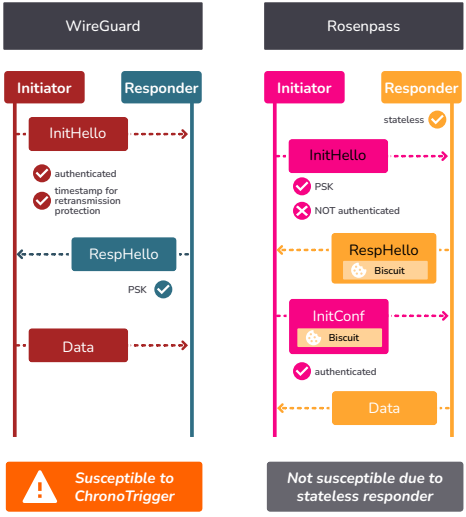
What are State Disruption Attacks?



Protocol-level DoS



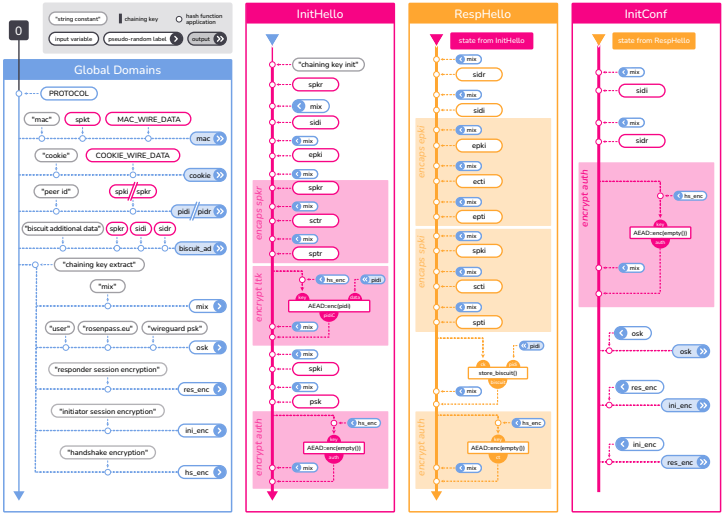
ChronoTrigger: Changes in Rosenpass



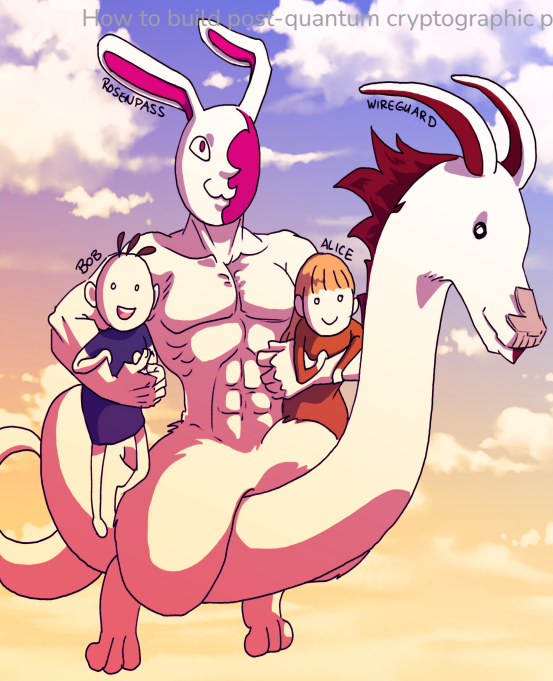
- InitHello is unauthenticated because responder still needs to encapsulate secret with initiator key
- since InitHello is unauthenticated, retransmission protection is impossible
- responder state is moved into a cookie called *Biscuit*; this renders the responder stateless
- retransmission of InitHello is now easily possible, but does not lead to a state disruption attack

⇒ stateless responder prevents ChronoTrigger attack

Rosenpass Key Derivation Chain: Spot the Biscuit



Rosenpass Protocol Messages: Spot the Biscuit



Tribulations ~ Tooling

Oh These Proof Tools

Vive la Révolution! Against the

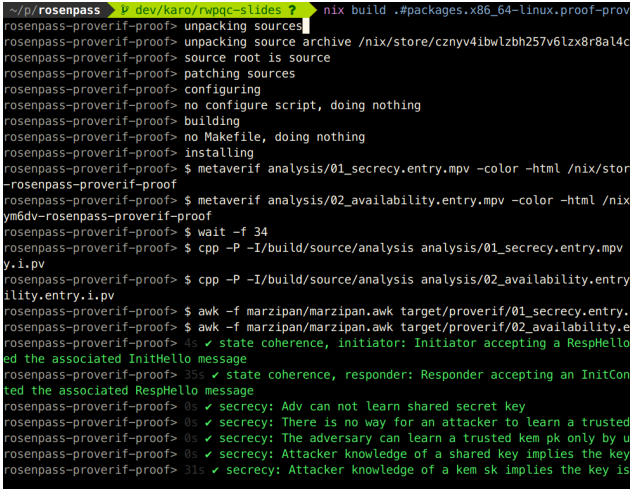
Bourgeoisie of Proof Assistants!

Pen and Paper

Bellare and Rogaway: [BR06]
many “essentially unverifiable” proofs, “crisis of rigor”

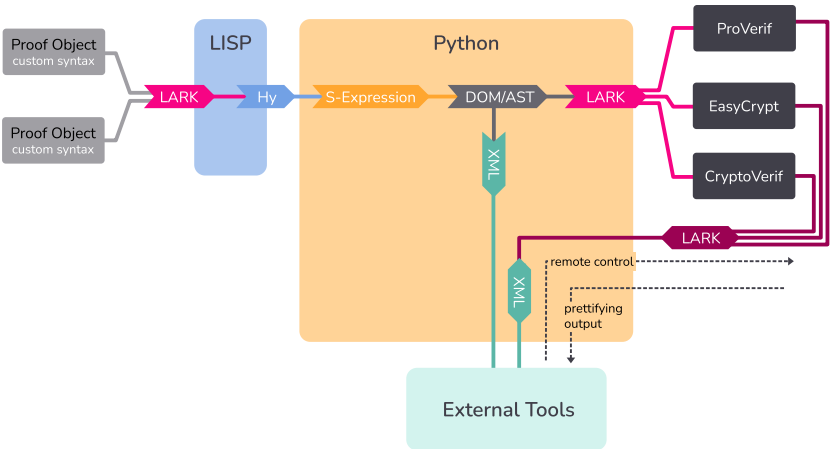
Halevi: [Hal05]
some reasons are social, but “our proofs are truly complex”

Symbolic Modeling of Rosenpass



- symbolic modeling using ProVerif
- proofs treated as part of the codebase
- uses a model internally that is based on a fairly comprehensive Maximum Exposure Attacks (MEX) variant
- covers non-interruptability (resistance to disruption attacks)
- mechanized proof in the computational model is an open issue

Rosenpass going Rube-Goldberg



We will build a framework around existing tools

Keep expressivity and preciseness

Generate & Parse their languages

Make these tools available to other ecosystems using Python, Lisp, XML

Epilogue

Epilogue

Rosenpass

- post-quantum secure AKE
- same security as WireGuard
- improved state disruption resistance
- transfers key to WireGuard for hybrid security

rosenpass.eu

About Protocols

- it is possible to treat NIKEs as KEMs with DHKEM
- the GHP Combiner can be used to combine multiple KEMs
- X-Wing makes this easy
- wall clocks are not to be trusted

Talk To Us

- adding syntax rewriting to the tool belt of mechanized verification in cryptography
- using broker architectures to write more secure system applications
- using microvms to write more secure applications
- more use cases for rosenpass

Appendix — Here Be Dragons

Bibliography

[PQWG]: https://eprint.iacr.org/2020/379

[GHP]: https://eprint.iacr.org/2018/024

[HPKE]: https://eprint.iacr.org/2020/1499 (analysis) &
https://www.rfc-editor.org/rfc/rfc9180.html (RFC)

[XWING]: https://eprint.iacr.org/2024/039

[NOISE]: https://www.noiseprotocol.org/noise.html

[BR06]: https://eprint.iacr.org/2004/331

[Hal05]: https://eprint.iacr.org/2005/181

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