Håck ma's 2024, Schloss in Ottenschlag
2024-08-29

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

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with support from Alice Bowman, and Marei Peischl
https://rosenpass.eu

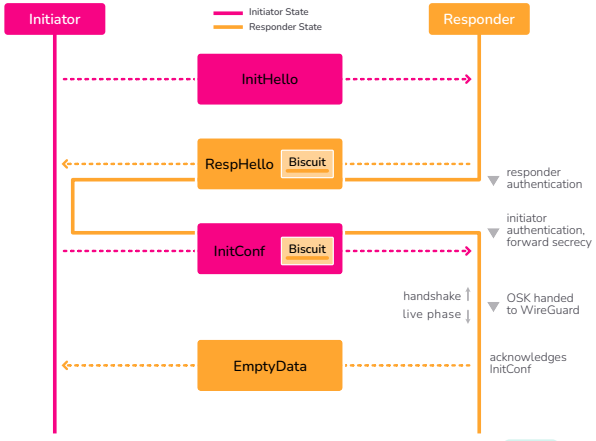
This is the Plan

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: https://github.com/rosenpass/slides/blob/main/2024-08-29-hackmas/slides.pdf

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.

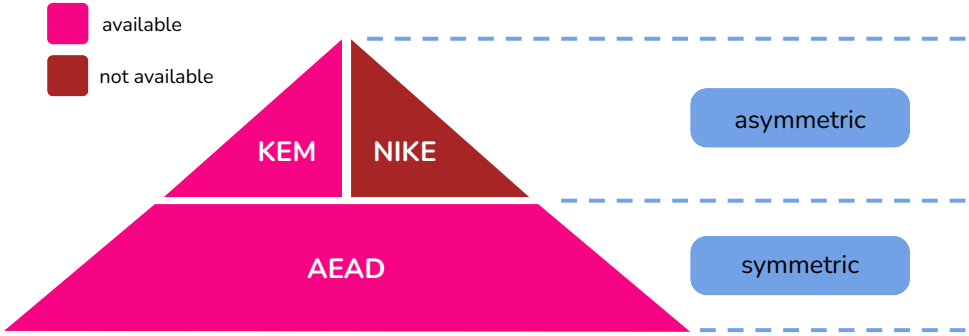
- generally less efficient.
- much bigger ciphertexts.
- less analyzed.

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.

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

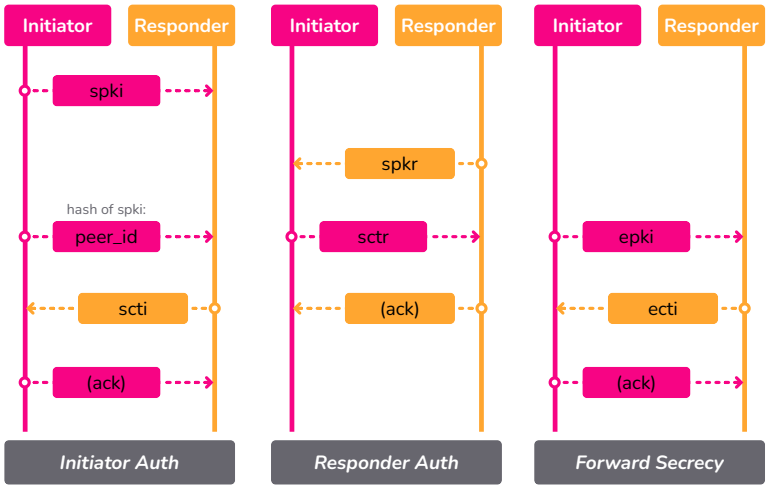
Key Encapsulation Method

```rust
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);
}
```

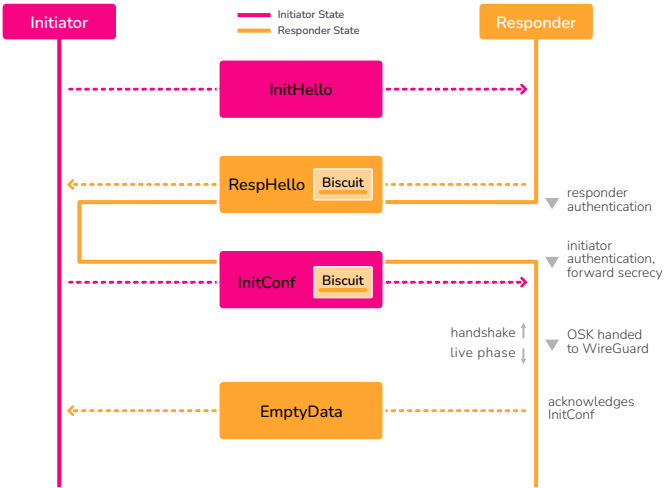
Non-Interactive Key Exchange

```rust
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

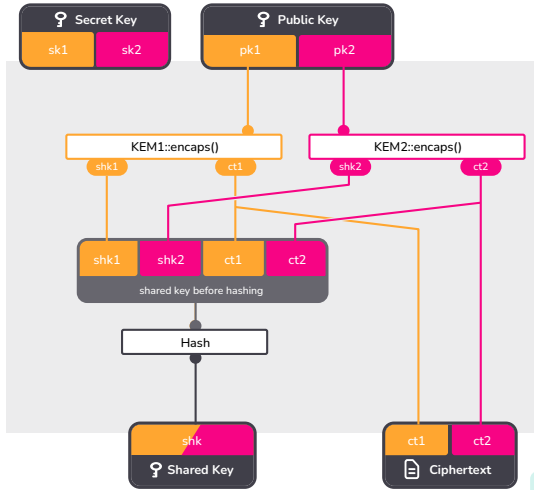
Hybridization

In the following slides you will learn ...

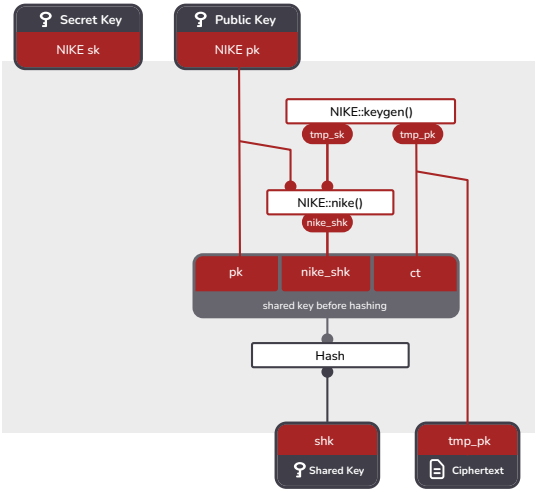
... that hybrid security can be achieved by building hybrid primitives and that it is not always wise to do so.

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



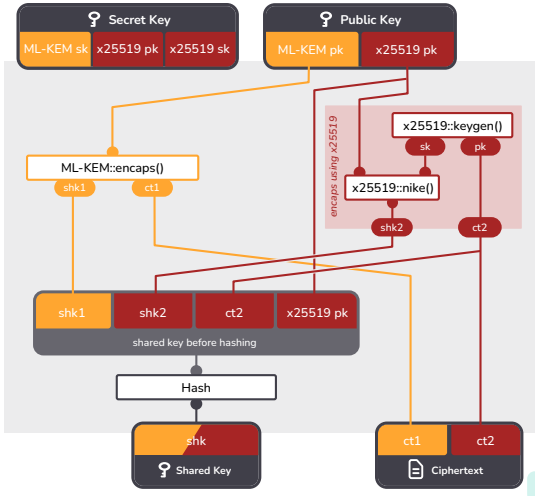
Turning a NIKE into a KEM



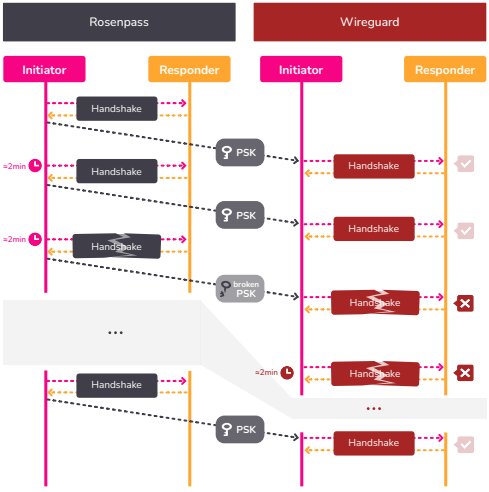
- from the HPKE RFC [HPKE]
- *remote* keypair is static keypair
- *local* keypair is temporary keypair
- local keypair public key is treated as ciphertext
- for proof-related reasons, ciphertext and public key are included in hash
- RFC work by Barnes, Bhargavan, Lipp, Wood supported by analysis work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

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



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.

4 RespHello { sidr, sidi, ecti, scti, biscuit, auth } **3**

Line	Variables ← Action	Variables ← Action	Line	Comment
RHI1		sidr ← random_session_id()	RHR1	Responder generates a session ID.
RHI2	ck ← lookup_session(sidi);		RHR2	Initiator looks up their session state using the session ID they generated.
RHI3	mix(sidr, sidi);	mix(sidr, sidi);	RHR3	Mix both session IDs as part of the protocol transcript.
RHI4	decaps_and_mix<EKEM>(eski, epki, ecti);	ecti ← encaps_and_mix<EKEM>(epki);	RHR4	Key encapsulation using the ephemeral key, to provide forward secrecy.
RHI5	decaps_and_mix<SKEM>(sski, spki, scti);	scti ← encaps_and_mix<SKEM>(spki);	RHR5	Key encapsulation using the initiator's static key, to authenticate the initiator, and non-forward-secret confidentiality.
RHI6	mix(biscuit)	biscuit ← store_biscuit();	RHR6	The responder transmits their state to the initiator in an encrypted container to avoid having to store state.
RHI7	decrypt_and_mix(auth)	auth ← encrypt_and_mix(empty());	RHR7	Add a message authentication code for the same reason as above.

5 InitConf { sidi, sidr, biscuit, auth } **6**

Line	Variables ← Action	Variables ← Action	Line	Comment
ICI1		biscuit_no ← load_biscuit(biscuit);	ICR1	Responder loads their biscuit. This restores the state from after RHR6.
ICI2		encrypt_and_mix(empty());	ICR2	Responder recomputes RHR7, since this step was performed after biscuit encoding.
ICI3	mix(sidi, sidr);	mix(sidi, sidr);	ICR3	Mix both session IDs as part of the protocol transcript.
ICI4	auth ← encrypt_and_mix(empty);	decrypt_and_mix(auth);	ICR4	Message authentication code for the same reason as above, which in particular ensures that both participants agree on the final chaining key.

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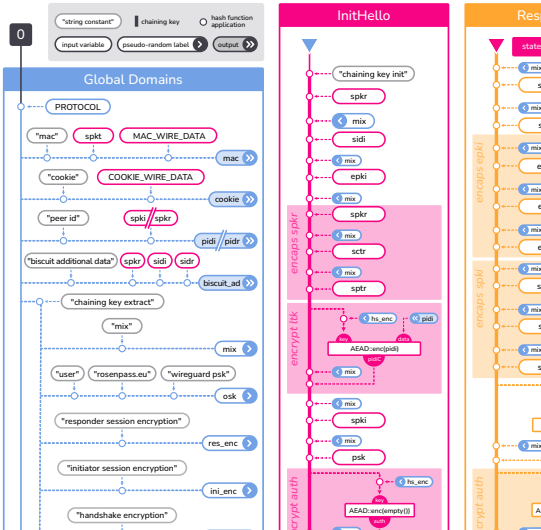
Full Protocol Reference in the Whitepaper



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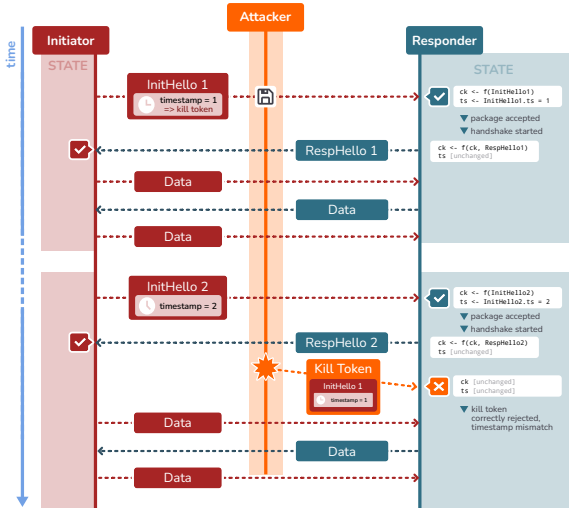
Trials ~ Attacks found

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



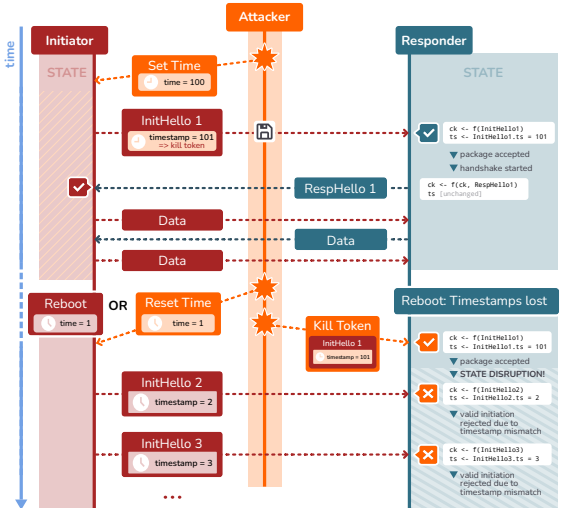
- replay attacks thwarted by counter
- counter is based on real-time clock
- responder is semi-stateful (one retransmission at program start may be accepted, but this does not affect protocol security)

⇒ 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

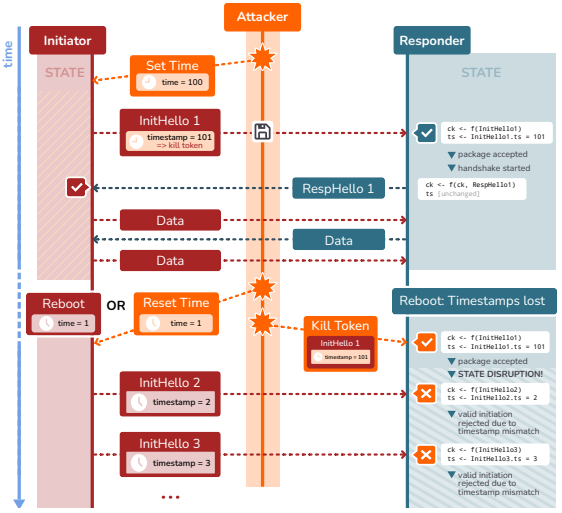
... both peers are being reset ...

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

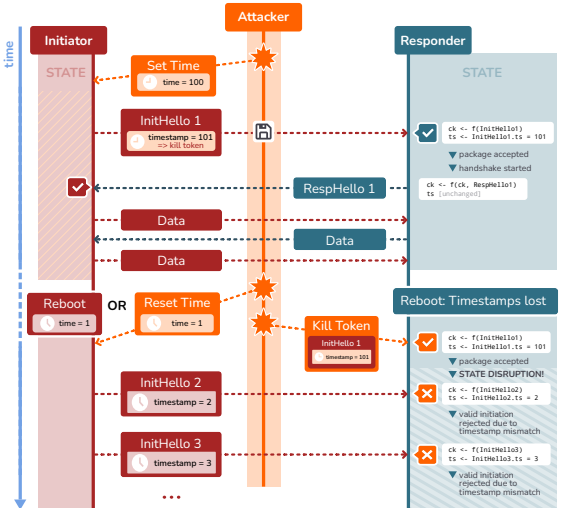


Gaining access to system time:

- 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

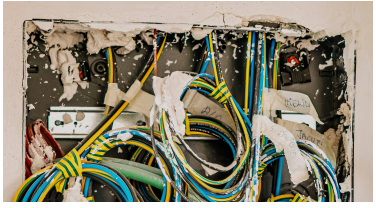
Preparation phase, attacker needs:

- eavesdropping of initiator packets
- access to system time

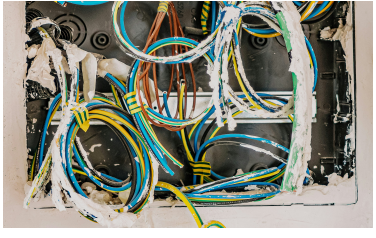
Delayed execution, attacker needs:

- no access beyond message transmission to responder

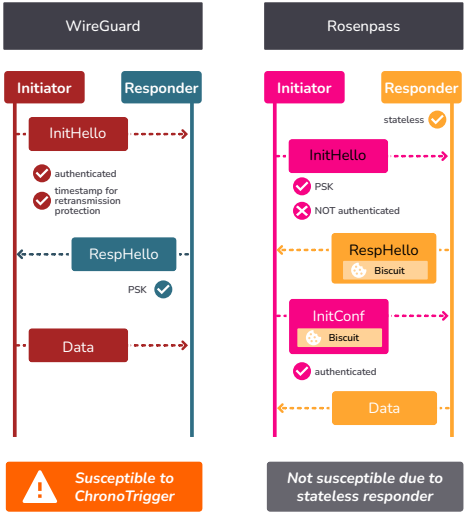
What are State Disruption Attacks?



Protocol-level DoS



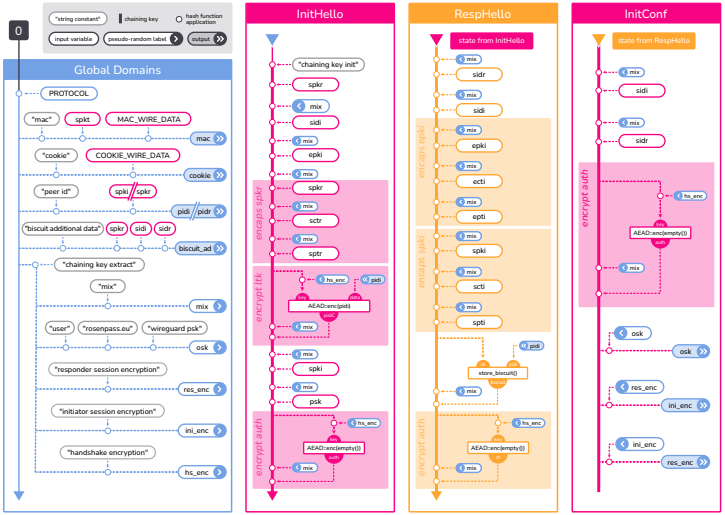
ChronoTrigger: Changes in Rosenpass



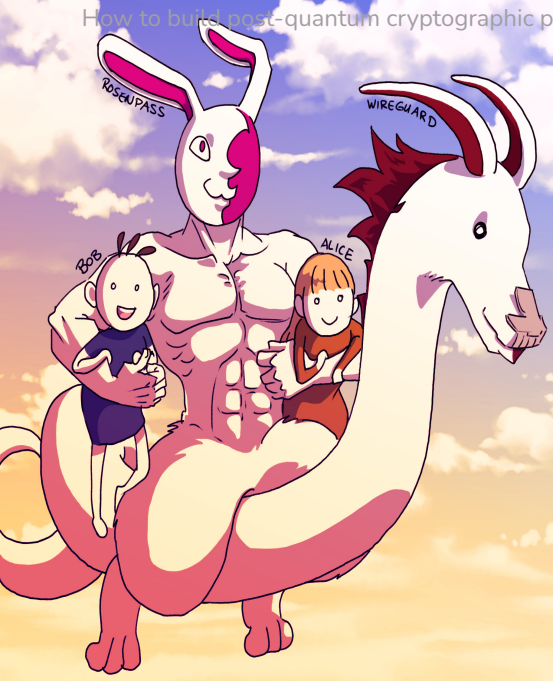
- InitHello is unauthenticated because responder still needs to encapsulate secret with initiator key
- since InitHello is unauthenticated, retransmission protection is impossible
- responder state is moved into a cookie called *Biscuit*; this renders the responder stateless
- retransmission of InitHello 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

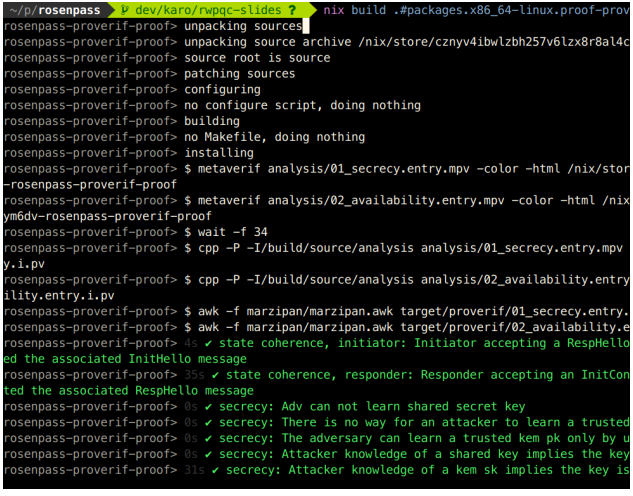
Bourgeoisie of Proof Assistants!

Pen and Paper

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

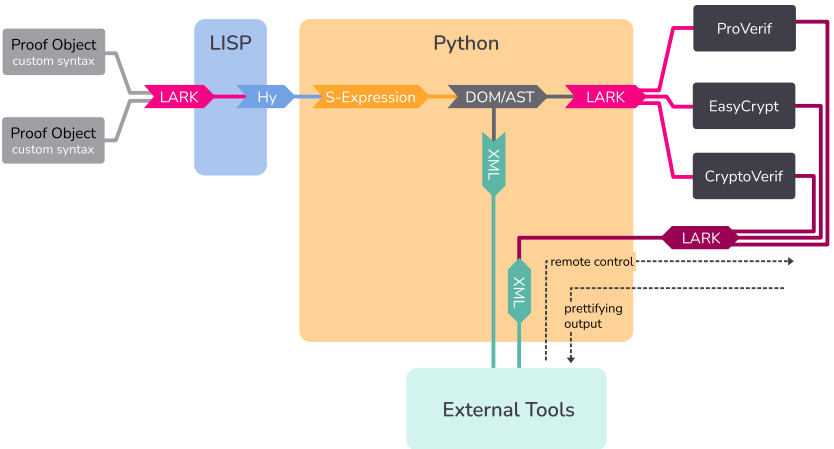
Halevi: [Hal05]
some reasons are social, but “our proofs are truly complex”

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

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

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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

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Random slides — The dragon just ate you!

Rosenpass and WireGuard: Advanced Security

Limited Stealth:

- Protocol should not respond without pre-auth.
- Proof of IP ownership (cookie mechanism) prevents full stealth
- Adv. needs to know responder public key

Limited Identity Hiding:

- Adversary cannot recognize peers unless their public key is known
- This is incomplete!

CPU DoS mitigation:

- Attacker should not easily trigger public key operations
- Preventing CPU exhaustion using network amplification
- Proof of IP ownership

Triumphs ~ Secrecy & Non-Interruptability

Modeling of Rosenpass

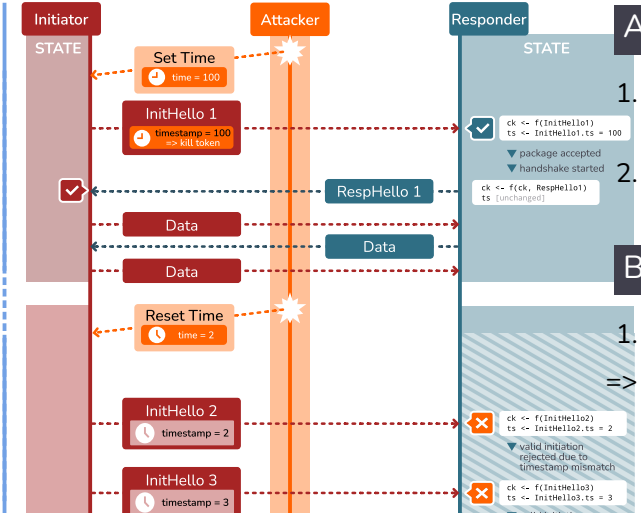
Using ProVerif

Non-Interruptability: More Formally

For every pair of traces `tmin`, `tmax` where trace `tmax` can be formed by insertion of messages/oracle calls into `tmin`, the result of `tmin` and `tmax` should remain the same.

- Let `Result` be the set of possible protocol results
- Let `Trace` be the set of possible protocol traces
- Let $\texttt{res}(\texttt{t}) : \texttt{Trace} \to \texttt{Result}$ determine the protocol result given $\texttt{t} : \texttt{Trace}$
- Let $\texttt{t1} \supseteq \texttt{t2} : \texttt{Trace} \to \texttt{Trace} \to \texttt{Prop}$ denote that $\texttt{t2}$ can be formed by insertion of elements into $\texttt{t1}$
- $\forall(\texttt{tmin}, \texttt{tmax}) : \texttt{Trace} \times \texttt{Trace}; \texttt{tmin} \supseteq \texttt{tmax} \to \texttt{res}(\texttt{tmin}) = \texttt{res}(\texttt{tmax})$

ChronoTrigger Attack: Immediate Execution



A. Preparation phase:

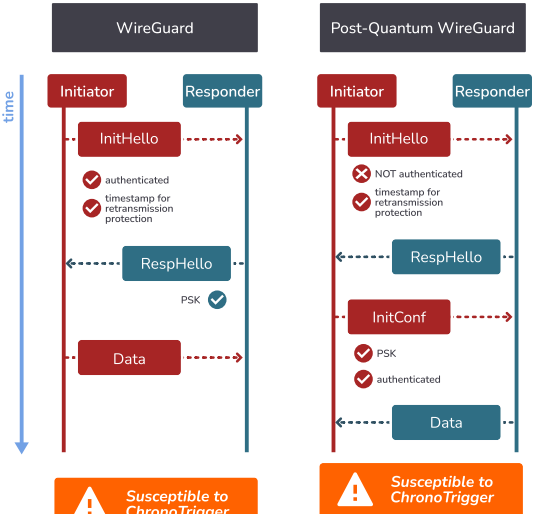
1. **Attacker** sets *initiator system time* to a future value
2. **Attacker** waits while both peers are performing a valid handshake

B. Direct execution phase:

1. **Attacker** lets system time on initiator reset

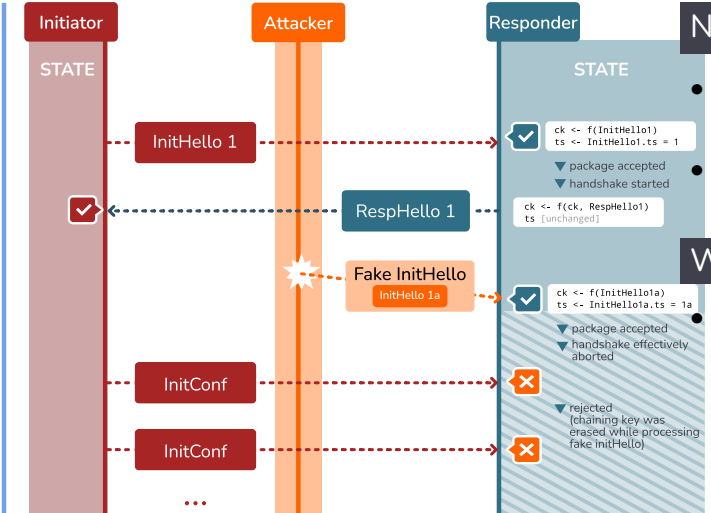
=> Initiation now fails due to counter mismatch

ChronoTrigger: Changes in Post-Quantum WG



- *InitHello* is unauthenticated
- Retransmission counter is kept
- PQWG assumes a pre-shared key to authenticate InitHello instead (the authors recommend deriving the PSK from both public keys)
- PSK evaluated twice, during InitHello *and* InitConf processing

ChronoTigger against Post-Quantum WireGuard



No PSK/Public keys as PSK

- Attacker needs access to public keys
- The attack is trivial (attacker just forges *InitHello*)

With PSK

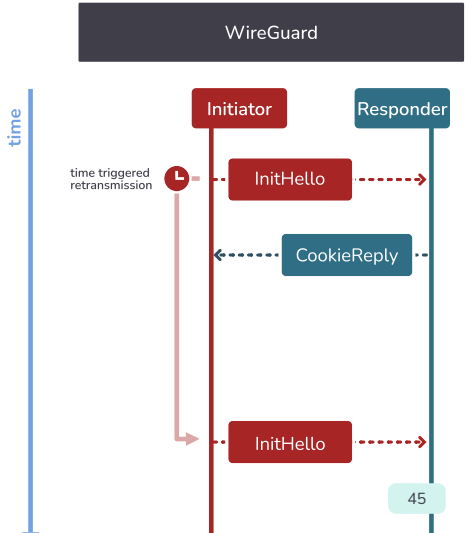
- Replay attack with NTP access from classic WireGuard still applies

Trials ~ Attacks found

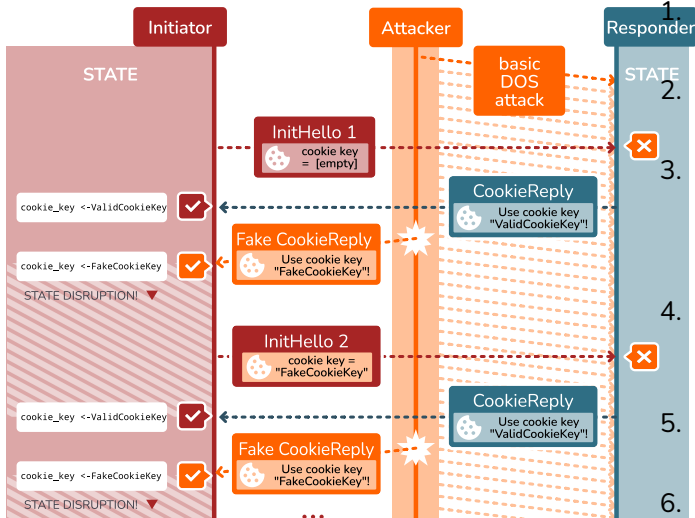
CookieCutter

CookieCutter Attack

> I am under load. Prove that you are not using IP address impersonation before I process your handshake!
> This message contains a *cookie key*. Use it to prove that you can receive messages sent to your address when retransmitting your *InitHello* packet.
>
> **A WireGuard CookieReply**, ca. 2014

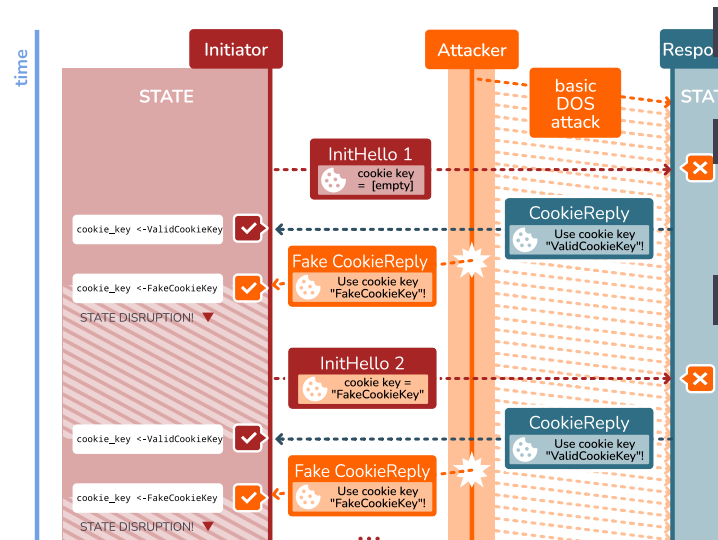


CookieCutter Attack



1. **Attacker** begins continuous DoS attack against responder
2. **Initiator** begins handshake, sends *InitHello*
3. **Responder** replies with *CookieReply*
   > **CookieReply:** I am under load. Prove you are not using an IP spoofing attack with this *cookie key*.
4. **Initiator** Initiator stores cookie key and waits for their retransmission timer
5. **Attacker** forges a cookie reply with a fake *cookie key*
6. **Initiator** Initiator overwrites the valid

CookieCutter Attack



Attacker gains:

- Cheap protocol-level DoS

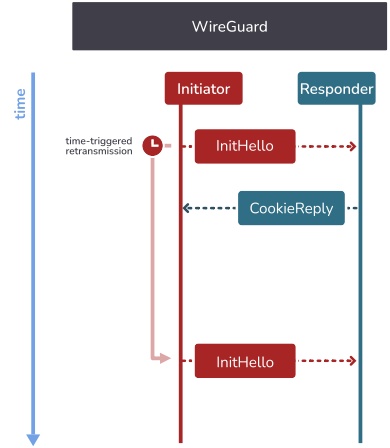
Attacker needs:

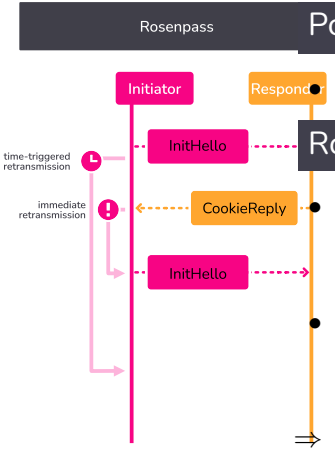
- Knowledge of public keys
- Good timing

Role switching:

- WireGuard sometimes uses role switching
- To account for that, the attack can be performed against both peers

CookieCutter: Post-Quantum WG & Rosenpass





Post-Quantum WireGuard

- No change.

Rosenpass

- Immediate retransmission of *InitHello* upon receiving *CookieReply*
- *CookieReply* and *InitHello* must be of same size to prevent DoS amplication attacks

⇒ Rosenpass is protected from CookieCutter attacks

Trials ~ Advanced Security Properties

Knock Patterns

Rosenpass and WireGuard: Advanced Security

CPU DoS mitigation:

- No change on the protocol level.

😐 Slightly worsened in practice because PQ operations are more expensive than elliptic curves

Limited Stealth:

- No change in Rosenpass, but we should have **full stealth**!

⇒ Remove cookie mechanism?

😐 This would affect the CPU DoS mitigation too much.

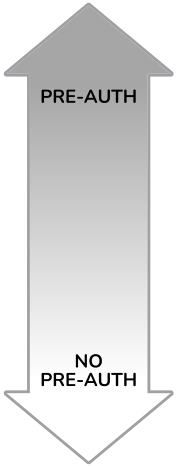
Limited Identity Hiding:

- No change in Rosenpass, but we should have **full identity hiding**!

⇒ Do not use pre-authentication with public key?

😐 This would affect the CPU DoS mitigation, possibly too much.

Choose Two: Stealth, Identity Hiding, CPU DoS Mit.



CPU DOS Protection

asymmetric functions are not called unless pre-auth has succeeded

KNOCK PATTERNS

proof of IP ownership

interactive proof of work

KNOCK PATTERNS

initiator public key

responder public keys

weaker + more performant form of authentication (e.g. EC-based NIKE)

WireGuard

Stealth

no interactive pre-auth allowed

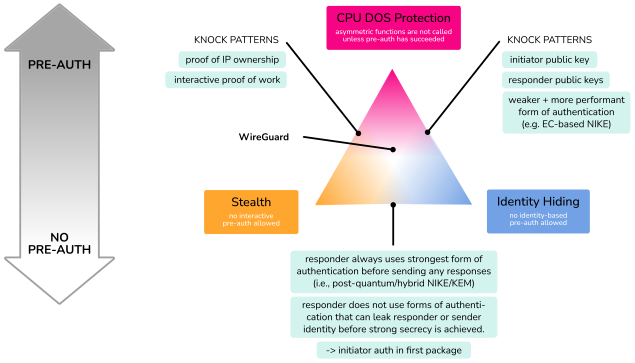
Identity Hiding

no identity-based pre-auth allowed

responder always uses strongest form of authentication before sending any responses (i.e., post-quantum/hybrid NIKE/KEM)

responder does not use forms of authenti-cation that can leak responder or sender identity before strong secrecy is achieved.

WireGuard and Rosenpass Trade-Offs



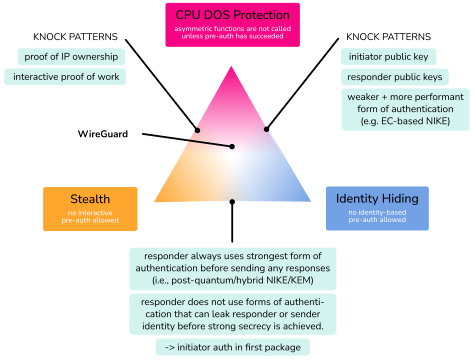
CPU DoS Mitigation:

- There is no clear optimum here.
- CPU DoS mitigation is never calling asymmetric crypto unless we know it succeeds (circular reasoning)

Stealth:

Identity hiding:

WireGuard and Rosenpass Trade-Offs



CPU DoS Mitigation:

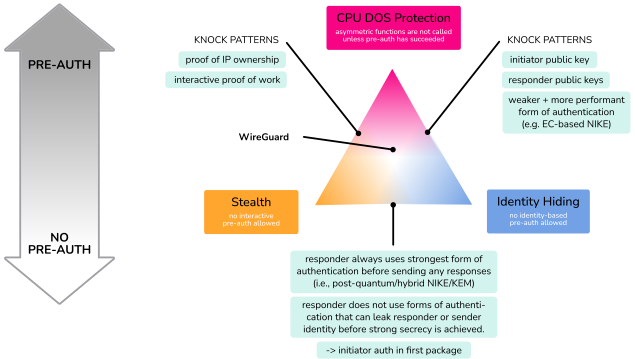
Stealth:

- Broken on DoS attacks assuming recipient is known

⇒ This seems acceptable

Identity hiding:

WireGuard and Rosenpass Trade-Offs



CPU DoS Mitigation:

Stealth:

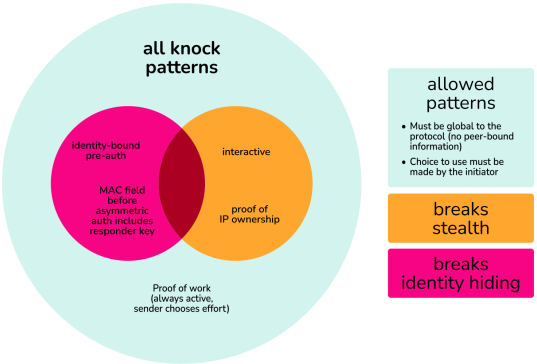
Identity hiding:

- Broken on knowledge of public keys

⇒ This seems inacceptable!

⇒ Investigate proper identity hiding without overly impacting stealth and CPU DoS mitig.

Knock Patterns



- We choose to think of WireGuard's and Rosenpass' pre-auth as "Knock Patterns"
- These knock patterns have severe trade-offs.
- Interactive knock pattern (cookie mechanism) breaks stealth
- Identity-based knock patterns (e.g., knowledge of public key) breaks identity hiding

⇒ Avoid identity-bound knock patterns

⇒ Minimize interactive knock patterns

⇒ Explore other (allowed) knock patter

Tools to the Table!

Bellare and Rogaway [BR06], Halevi [Hal05]:
Call for “automated tools, that can help write and verify game-based proofs”

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Do the tools *actually help*? And if yes, whom?

ProVerif, Tamarin, CryptoVerif, EasyCrypt:
We like these tools, they are good!

Tools to the Table!

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Do the tools *actually help*? And if yes, whom?

ProVerif, Tamarin, CryptoVerif, EasyCrypt:
We like these tools, they are good!

They mostly help the *formal verification experts* to:

- do analyses themselves, write papers
- develop proof methodologies, foundation work for formal methods

Epilogue

Conclusion

Rosenpass

- Post-quantum secure AKE
- Same security as WireGuard
- Improved state disruption resistance
- Transfers key to WireGuard for hybrid security

Protocol Findings

- **CookieCutter**: DoS exploiting WireGuard cookie mechanism
- **ChronoTrigger**: DoS exploiting insecure system time to attack WireGuard
- There is a **trade-off** between identity hiding, stealth, and CPU-exhaustion DoS protection

Talk To Us

- About why we should use Tamarin (or SAPIC+?) over ProVerif
- State disruption attacks
- Stealth and Identity hiding
- Adding syntax rewriting to the tool belt of mechanized verification in cryptography

Rosenpass going Rube-Goldberg: The Details

- Embed cryptographic proof syntax in Lisp S-Expressions
- Translate Lisp code to Python using the Hy language (Lisp that compiles to Python)
- Translate S-Expression code to AST or DOM
- Translate AST or DOM to ProVerif/Tamarin/CryptoVerif/EasyCrypt code using the LARK code parser/generator
- Remote control ProVerif/Tamarin/CryptoVerif/EasyCrypt by
  - Parsing their command line output using LARK
  - (Possibly using the language server interface for more interactive features)
- Provide custom syntax using
  - Lisp Macros
  - Extending LARK-based syntax parsers (to add custom syntactic elements)