



The Rosenpass protocol and attacks we found against WireGuard while developing it

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<https://rosenpass.eu>



This is the Plan

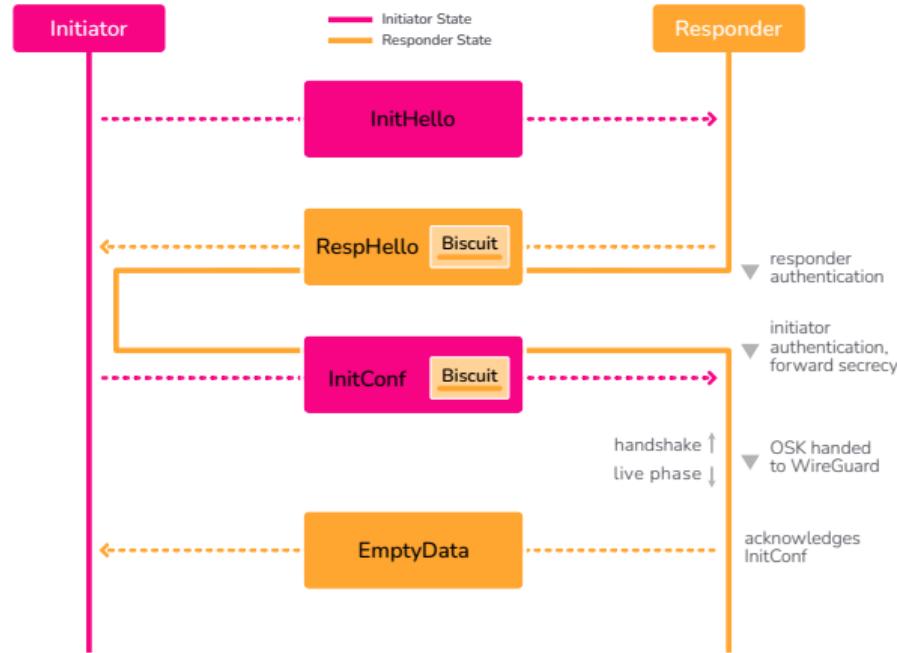
1. **Introducing Rosenpass**, briefly!
2. **The design of Rosenpass** and basics about post-quantum protocols!
3. **Hybrid Security** how it can be done and how we do it!
4. **Security trade-offs** in Rosenpass and WireGuard (aka attacks)!
5. **Protocol proofs** what they are and why they give me headaches!





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 setups against quantum attacks
- A **post-quantum secure VPN**
- A governance **organization** to facilitate development, maintenance and adoption of said protocol
- A translation research organization



The design of Rosenpass

and how to build post-quantum protocols





In the following slides, you will learn...

...that most cryprographic applications today are susceptible against attacks from quantum computers.

...that this is not fundamental to cryptography, but that pre-quantum protocols are simply a more efficient.

...that – cryptographically speaking – the difference between pre-quantum and post-quantum crypto is about 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 used
- Widely widely trusted

Post-quantum cryptography is...

...not susceptible to attacks from quantum computers.

- generally less efficient.
- much bigger ciphertexts.
- hard to use on embedded devices.
- adopted in the last decade.
- less analyzed.

Hybrid cryptography combines...

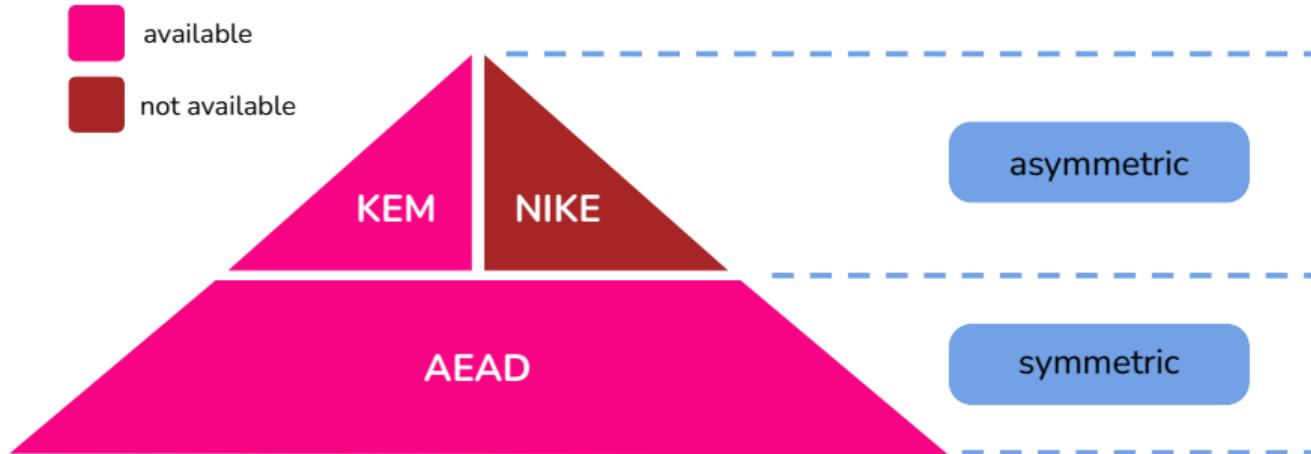
...the quantum-resistance of post-quantum cryptography and the trustedness of pre-quantum cryptography.

It is...

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



What post-quantum got





NIKEs and KEMs

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);
}
```



NIKEs and KEMs

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. Aka. Diffie-Hellman.

- 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(pk2, sk1));
```

I don't know a good analogy, but note how the keypairs are *crossing over* to each other.

- Secrecy
- Mutual authentication (for each party:
assuming they have the shared key, they must also have their secret key)



NIKEs and KEMs: 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 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.

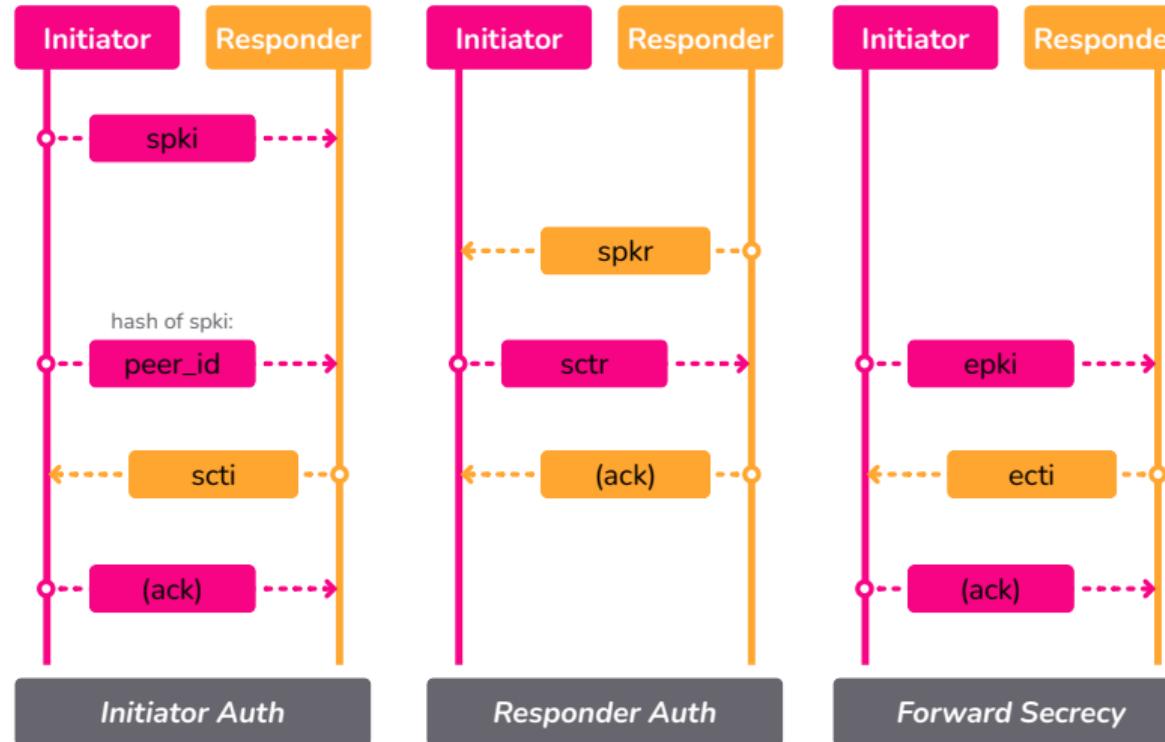
Initiator Authentication: Static-static NIKE since NIKE gives mutual authentication.

Forward-secrecy: Another nike, involving a temporary keypair.

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

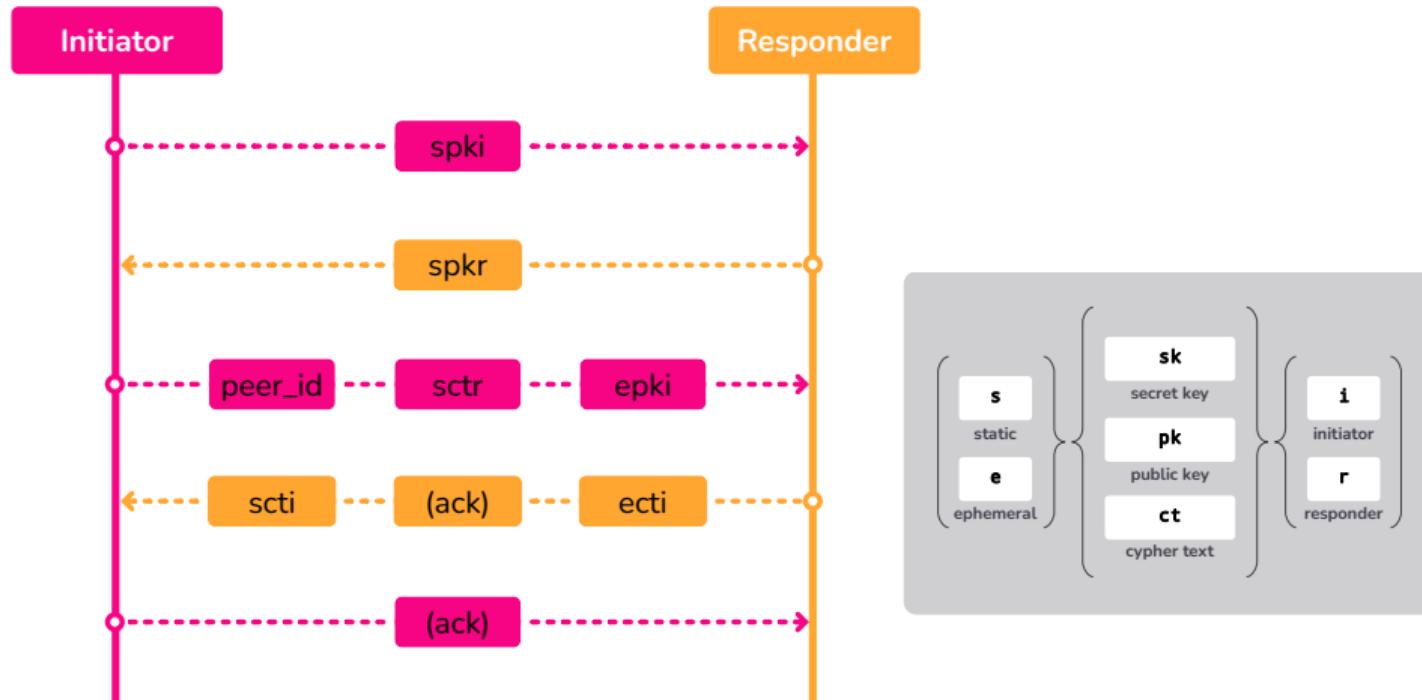


Rosenpass Kex Exchange Parts



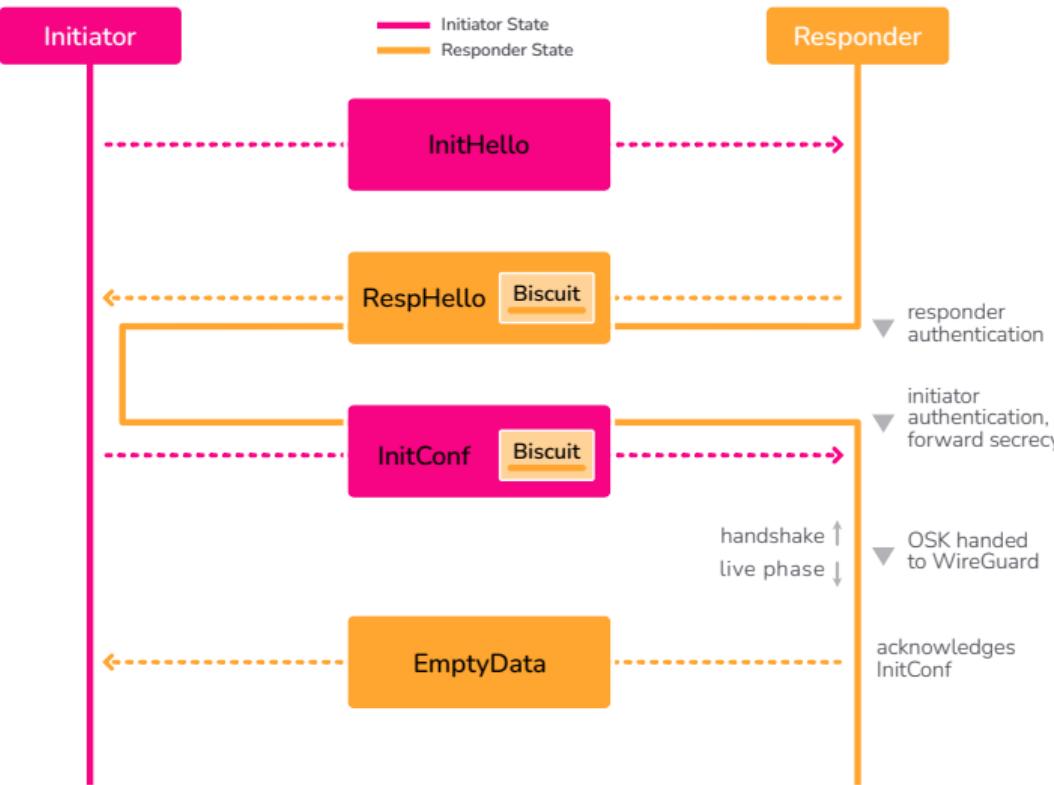


Rosenpass Unified Key Exchange





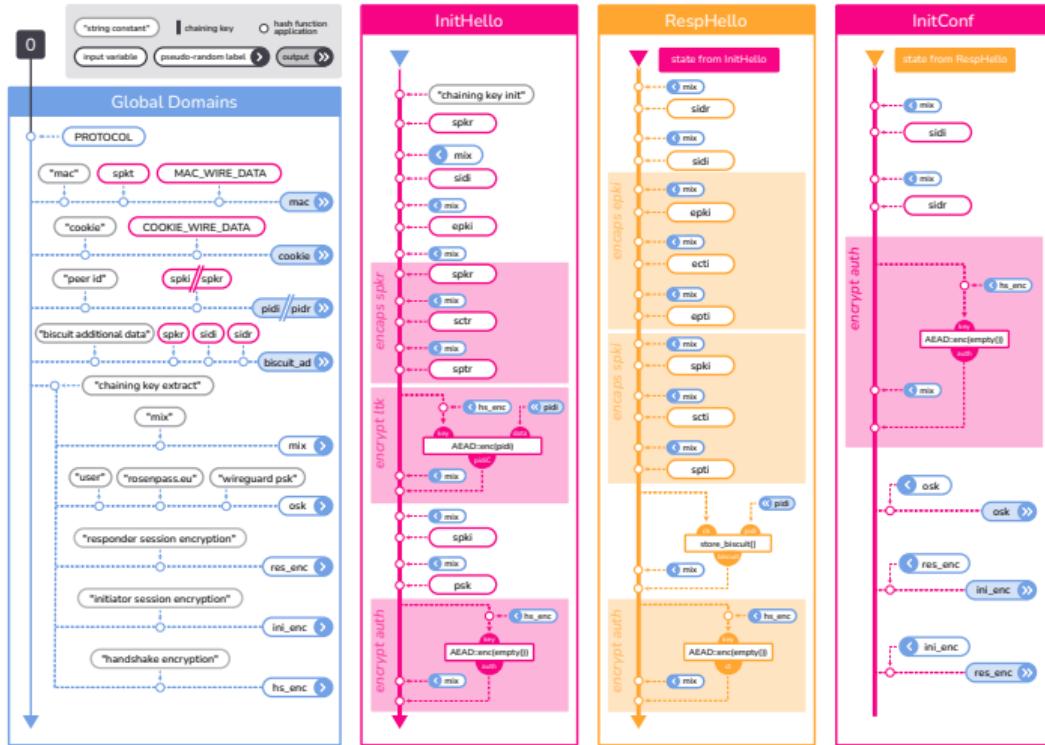
Rosenpass Protocol Features



- 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



Rosenpass Key Derivation Chain



Hybridization



In the following slides, you will learn...

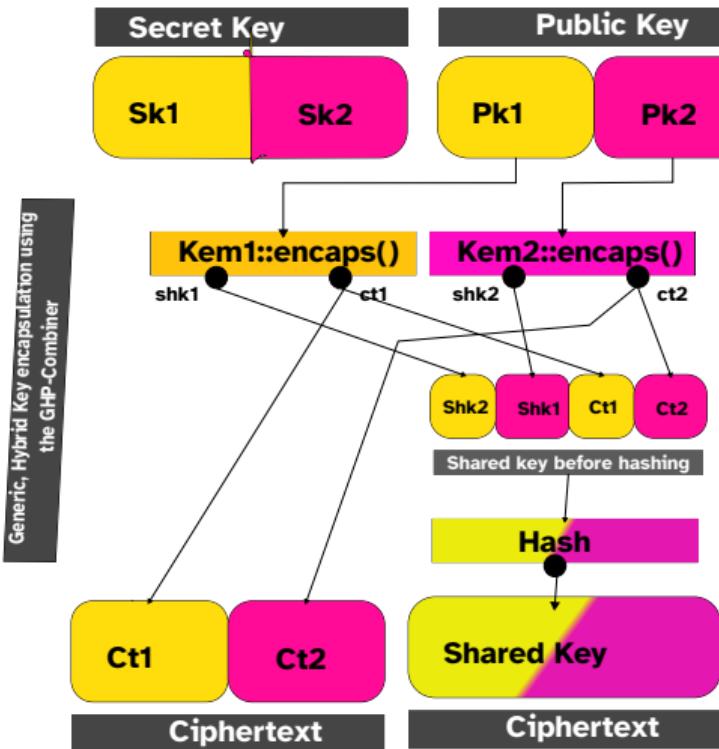
...that hybrid, practical, post-quantum cryptography is built by combining pre-quantum and post-quantum primitives.

...that key encapsulation methods can be combined, rendering a protocol like Rosenpass useful in pre-quantum as well as post-quantum settings.

...why combining protocols like WireGuard and Rosenpass directly is still useful to enable code-reuse and to avoid loosing trust in established systems like WireGuard.

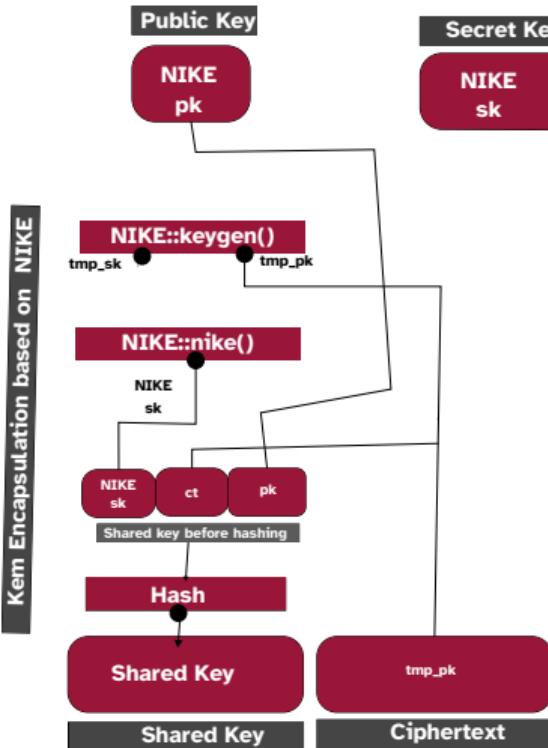


Combining two KEMs with the GHP-Combiner



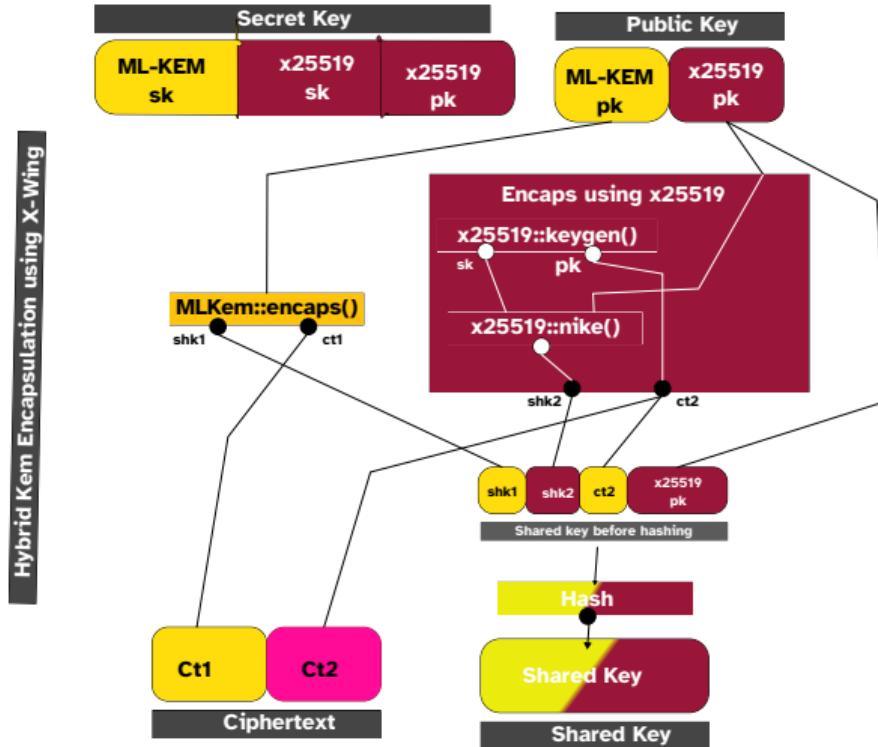


Turning a NIKE into a KEM

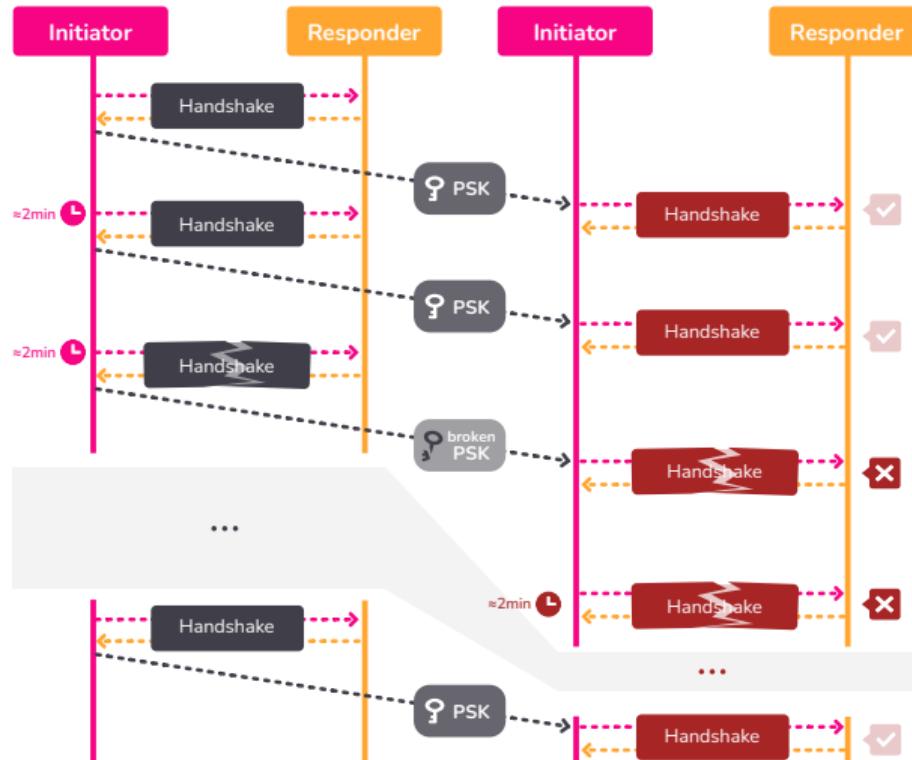




X-Wing



Rosenpass & WireGuard Hybridization



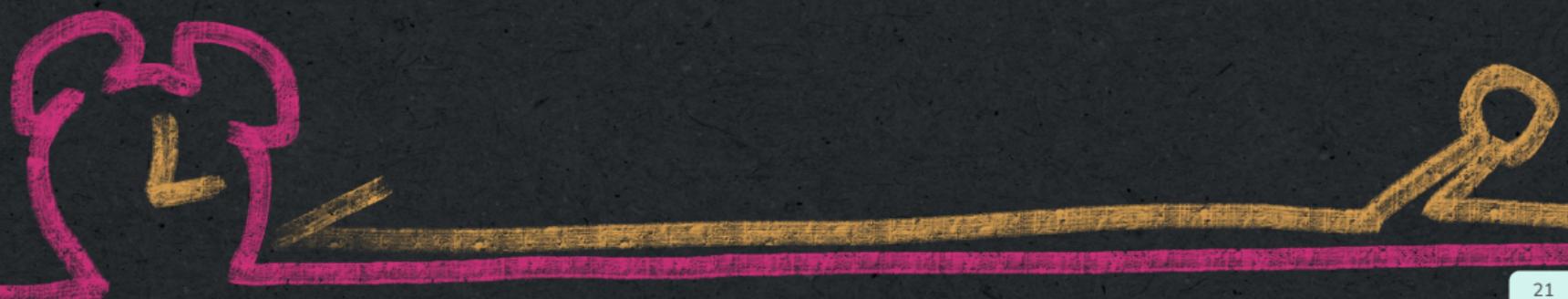


Full Protocol Reference in the Whitepaper

Initiator Code	Responder Code	Comments
1	InitHello { sidi, epki, sctr, pidIC, auth }	2
Line Variables \leftarrow Action IHR1 ck \leftarrow lhash("chaining key init", spkr) IHR2 sidr \leftarrow random_session_id(); IHR3 eski, epki \leftarrow EKEM:keygen(); IHR4 mix(sidi, epki); IHR5 sctr \leftarrow encaps_and_mix<SKEM>(spkr); IHR6 pidIC \leftarrow encrypt_and_mix(pid); IHR7 mix(epki, psk); IHR8 auth \leftarrow encrypt_and_mix(empty())	Variables \leftarrow Action ck \leftarrow lhash("chaining key init", spkr) IHR1 IHR4 mix(sidi, epki) IHR5 decaps_and_mix<SKEM>(sskr, spkr, ct1) IHR6 spki, psk \leftarrow lookup_peer(decrypt_and_mix(pidIC)) IHR7 mix(epki, psk); IHR8 decrypt_and_mix(auth)	Comment Initialize the chaining key, and bind to the responder's public key. The session ID is used to associate packets with the handshake state. Generate fresh ephemeral keys, for forward secrecy. InitHello includes sidr and epki as part of the protocol transcript, and so we mix them into the chaining key to prevent tampering. Key encapsulation using the responder's public key. Mixes public key, shared secret, and ciphertext into the chaining key, and authenticates the responder. Tell the responder who the initiator is by transmitting the peer ID. Ensure the responder has the correct view on spki. Mix in the PSK as optional static symmetric key, with spki and spkr serving as nonces. 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 \leftarrow Action RH1 sidr \leftarrow random_session_id(); RH2 ck \leftarrow lookup_session(sidr); RH3 mix(sidi, sidr); RH4 decaps_and_mix<EKEM>(eski, epki, ecti); RH5 decaps_and_mix<SKEM>(eski, spki, scti); RH6 mix(biscuit) RH7 decrypt_and_mix(auth)	Variables \leftarrow Action sidr \leftarrow random_session_id() RH1 RH2 ck \leftarrow lookup_session(sidr); RH2 RH3 mix(sidi, sidr); RH3 RH4 ecti \leftarrow encaps_and_mix<EKEM>(epki); RH4 RH5 scti \leftarrow encaps_and_mix<SKEM>(spki); RH5 RH6 biscuit \leftarrow store_biscuit(); RH6 RH7 auth \leftarrow encrypt_and_mix(empty()); RH7	Comment Responder generates a session ID. Initiator looks up their session state using the session ID they generated. Mix both session IDs as part of the protocol transcript. Key encapsulation using the ephemeral key, to provide forward secrecy. Key encapsulation using the initiator's static key, to authenticate the initiator, and non-forward-secret confidentiality. The responder transmits their state to the initiator in an encrypted container to avoid having to store state. Add a message authentication code for the same reason as above.
5	InitConf { sidi, sidr, biscuit, auth }	6
Line Variables \leftarrow Action IC1 biscuit_no \leftarrow load_biscuit(biscuit); IC2 encrypt_and_mix(empty()); IC3 mix(sidi, sidr); IC4 auth \leftarrow encrypt_and_mix(empty()); IC5 assert(biscuit_no > biscuit_used); IC6 biscuit_used \leftarrow biscuit_no; IC7 enter_live();	Variables \leftarrow Action biscuit_no \leftarrow load_biscuit(biscuit); IC1 IC2 encrypt_and_mix(empty()); IC2 IC3 mix(sidi, sidr); IC3 IC4 decrypt_and_mix(auth); IC4 IC5 assert(biscuit_no > biscuit_used); IC5 IC6 biscuit_used \leftarrow biscuit_no; IC6 IC7 enter_live(); IC7	Comment Responder loads their biscuit. This restores the state from after RHR6. Responder recomputes RHR7, since this step was performed after biscuit encoding. Mix both session IDs as part of the protocol transcript. Message authentication code for the same reason as above, which in particular ensures that both participants agree on the final chaining key. Biscuit replay detection. Biscuit replay detection. Derive the transmission keys, and the output shared key for use as WireGuard's PSK.

Trials ~ Attacks found

ChronoTrigger



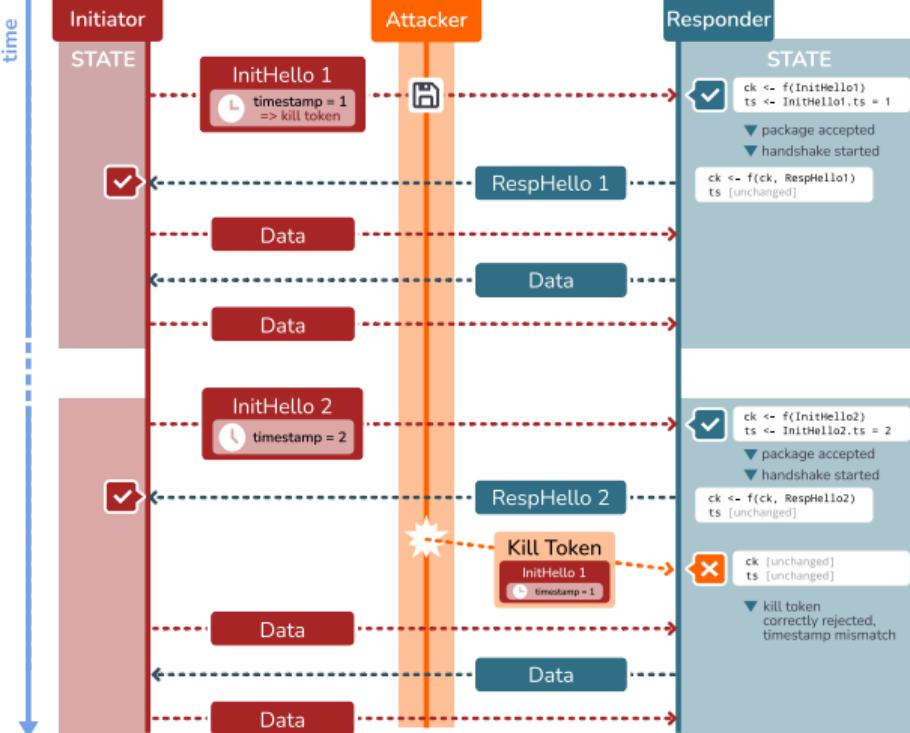


What are Non-Interruptability and State Disruption Attacks?

- Attacker trying to perform a protocol-level DOS attack
- Attacker may observe messages
- Attacker may insert messages, but they may not drop or modify messages
- Halfway between an active and passive attacker:
 - For a fully active attacker state disruption is trivial; they can just drop messages



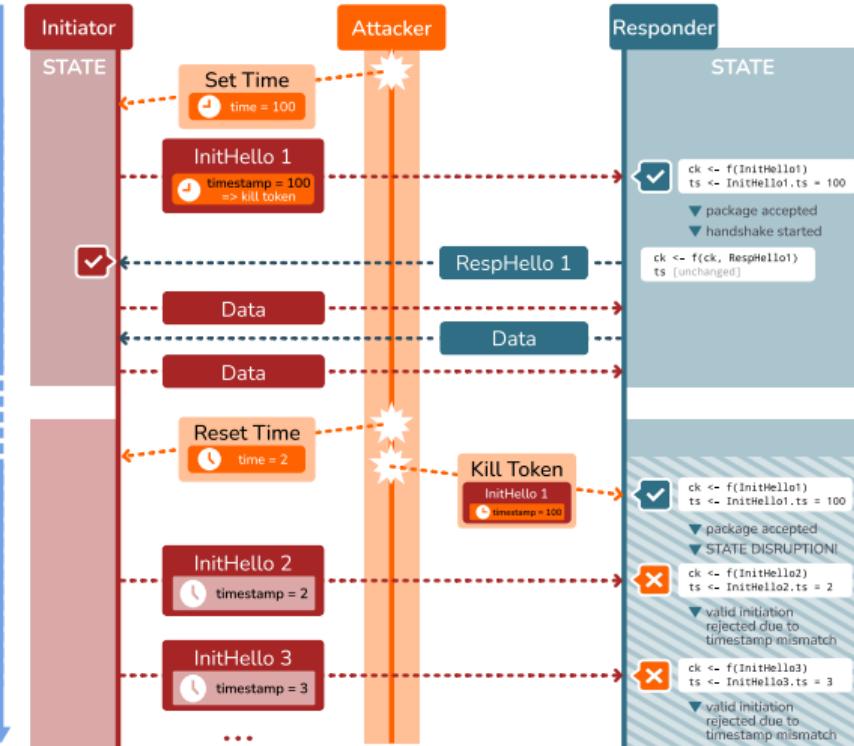
Retransmission Protection in WireGuard



- 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:

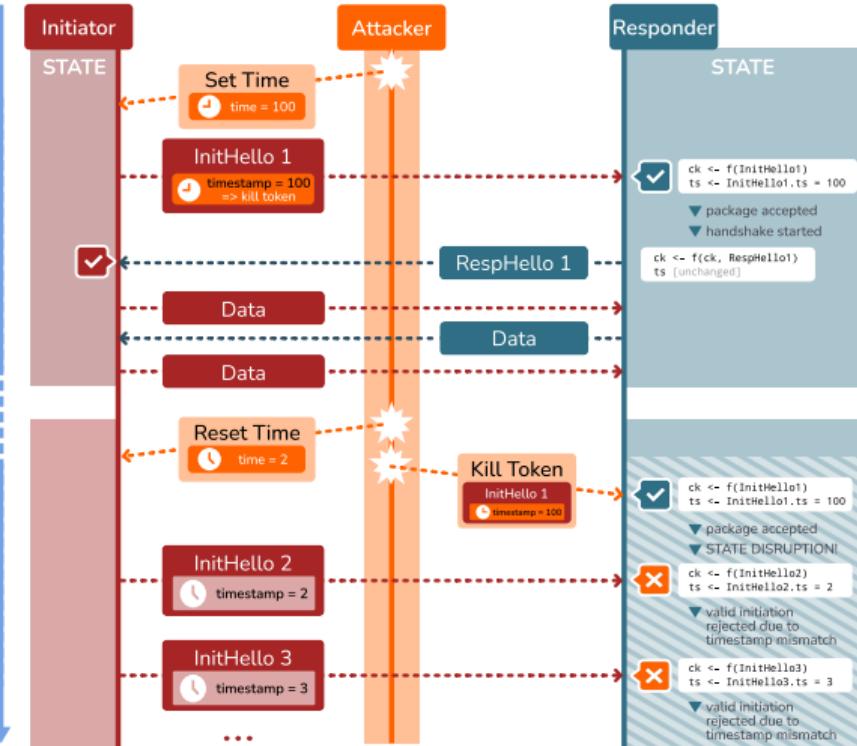
1. **Attacker** sets *initiator system time* to a future value
2. **Attacker** records *InitHello* as *KillToken* while both peers are performing a valid handshake

... 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

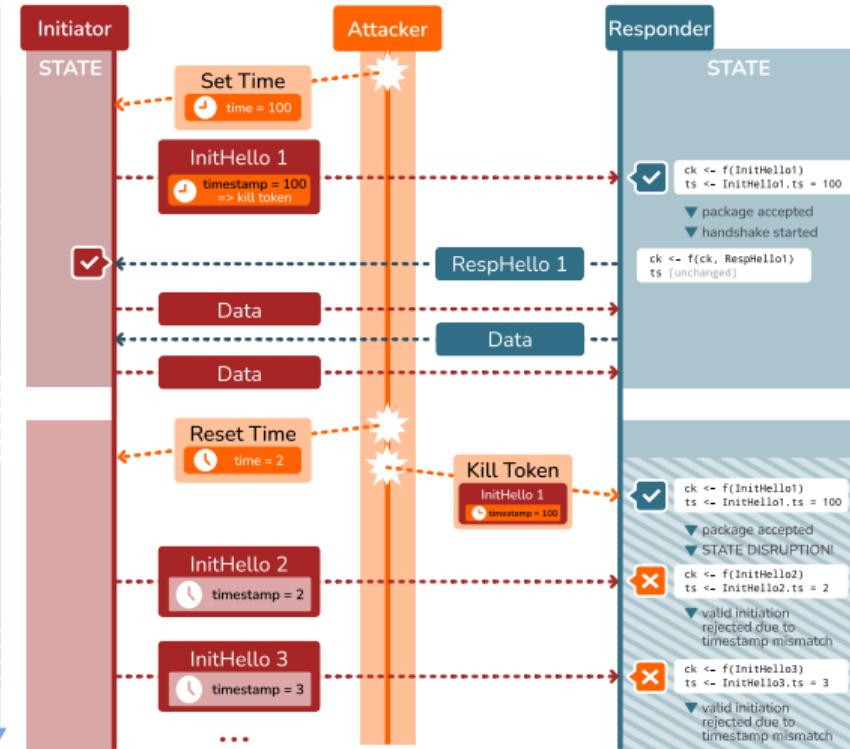


Gaining access to system time:

- 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:

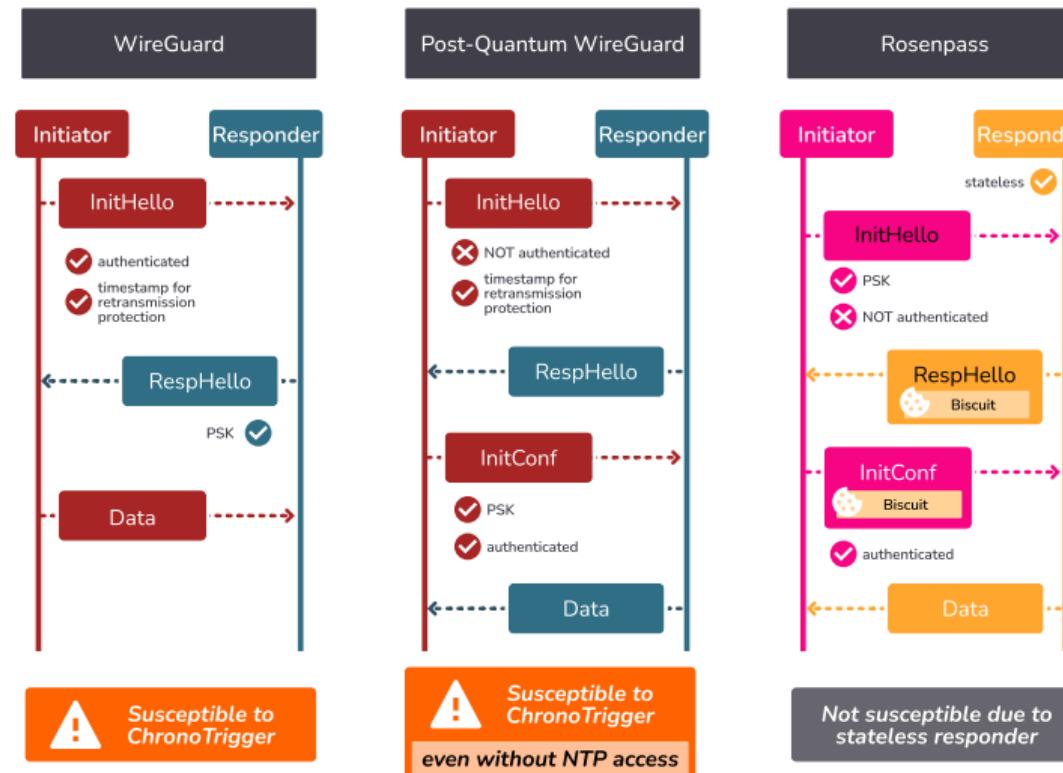
- Eavesdropping of initiator packets
- Access to system time

Delayed execution, attacker needs:

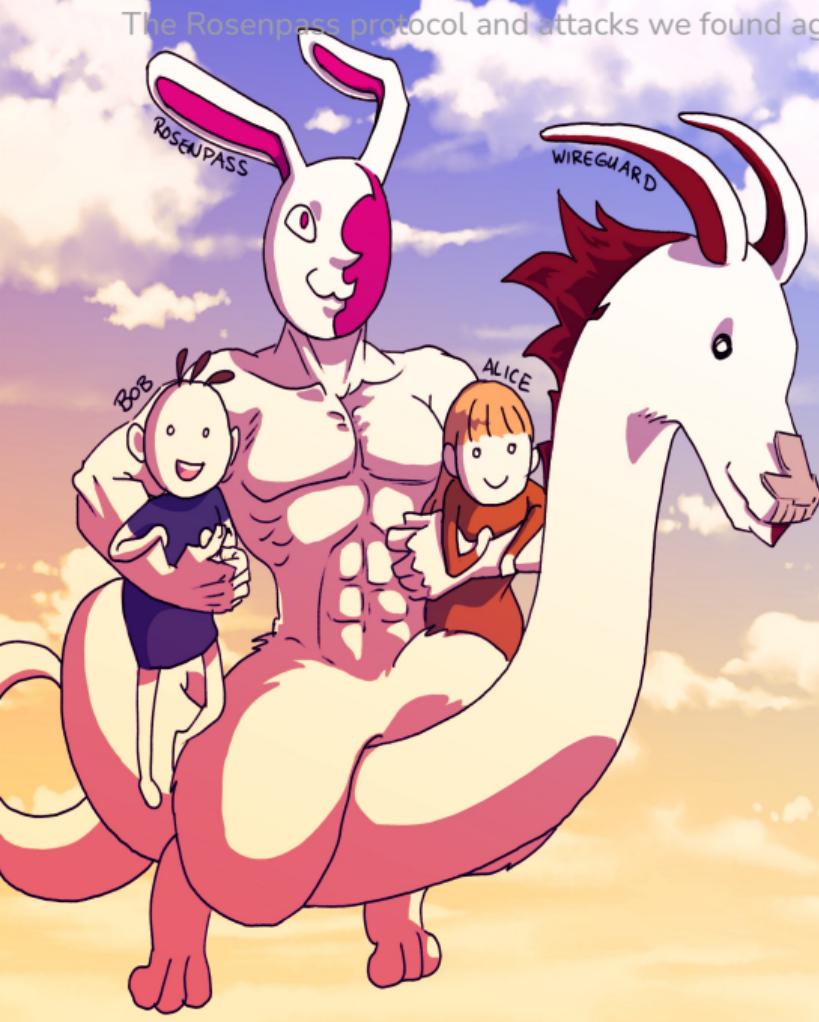
- No access beyond message transmission to responder



ChronoTrigger: Changes in Rosenpass



- **InitHello** remains unauthenticated
- PSK used in **InitHello** exclusively
- Responder state is moved into a cookie called *Biscuit*
- ⇒ Stateless responder prevents ChronoTrigger attack



Tribulations ~ Tooling

Oh These Proof Tools

Vive la Révolution! Against the
Bourgeoisie of Proof Assistants!



Symbolic Modeling of Rosenpass

```
~/p/rosenpass ➤ p dev/karo/rwqc-slides ? ➤ nix build .#packages.x86_64-linux.  
rosenpass-proverif-proof> unpacking sources  
rosenpass-proverif-proof> unpacking source archive /nix/store/cznyv4ibwlzbh257v6  
rosenpass-proverif-proof> source root is source  
rosenpass-proverif-proof> patching sources  
rosenpass-proverif-proof> configuring  
rosenpass-proverif-proof> no configure script, doing nothing  
rosenpass-proverif-proof> building  
rosenpass-proverif-proof> no Makefile, doing nothing  
rosenpass-proverif-proof> installing  
rosenpass-proverif-proof> $ metaverif analysis/01_secrecy.entry.mpv -color -html  
-rosenpass-proverif-proof  
rosenpass-proverif-proof> $ metaverif analysis/02_availability.entry.mpv -color  
ym6dv-rosenpass-proverif-proof  
rosenpass-proverif-proof> $ wait -f 34  
rosenpass-proverif-proof> $ cpp -P -I/build/source/analysis analysis/01_secrecy.  
y.i.pv  
rosenpass-proverif-proof> $ cpp -P -I/build/source/analysis analysis/02_availabi  
lity.entry.i.pv  
rosenpass-proverif-proof> $ awk -f marzipan/marzipan.awk target/proverif/01_se  
crecy  
rosenpass-proverif-proof> $ awk -f marzipan/marzipan.awk target/proverif/02_avai  
lity  
rosenpass-proverif-proof> 4s ✓ state coherence, initiator: Initiator accepting a  
ed the associated InitHello message  
rosenpass-proverif-proof> 35s ✓ state coherence, responder: Responder accepting  
ted the associated RespHello message  
rosenpass-proverif-proof> 0s ✓ secrecy: Adv can not learn shared secret key  
rosenpass-proverif-proof> 0s ✓ secrecy: There is no way for an attacker to learn  
rosenpass-proverif-proof> 0s ✓ secrecy: The adversary can learn a trusted kem pk  
rosenpass-proverif-proof> 0s ✓ secrecy: Attacker knowledge of a shared key implie  
rosenpass-proverif-proof> 31s ✓ secrecy: Attacker knowledge of a kem sk implies
```

- 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



Problematic Parts of Pen-and-Paper Proofs



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

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

Joseph Jaeger: [ProTeCS 2024, Workshop at Eurocrypt]
technical and social reasons
why and for whom do we write proofs?

We'd like to add:
pen-and-paper proofs are hard to maintain, update, reuse
especially for 3rd parties

Can proofs become part of a continuous engineering effort?

Appendix — Here Be Dragons



Bibliography

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

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

CPU DOS mitigation:

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

Limited Identity Hiding:

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

Triumphs ~ Secrecy & Non-Interruptability

Modeling of Rosenpass

Using ProVerif



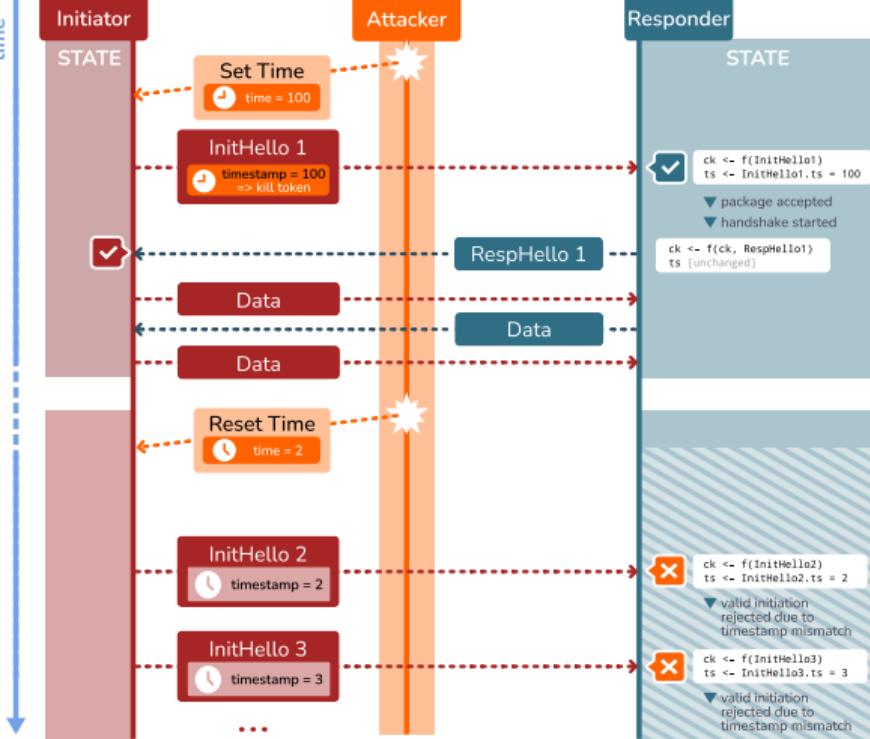
Non-Interruptability: More Formally

For every pair of traces t_{min}, t_{max} where trace t_{max} can be formed by insertion of messages/oracle calls into t_{min} , the result of t_{min} and t_{max} should remain the same.

- Let Result be the set of possible protocol results
- Let Trace be the set of possible protocol traces
- Let $\text{res}(t) : \text{Trace} \rightarrow \text{Result}$ determine the protocol result given $t : \text{Trace}$
- Let $t_1 \sqsupseteq t_2 : \text{Trace} \rightarrow \text{Trace} \rightarrow \text{Prop}$ denote that t_2 can be formed by insertion of elements into t_1
- $\forall(t_{min}, t_{max}) : \text{Trace} \times \text{Trace}; t_{min} \sqsupseteq t_{max} \rightarrow \text{res}(t_{min}) = \text{res}(t_{max})$



ChronoTrigger Attack: Immediate Execution



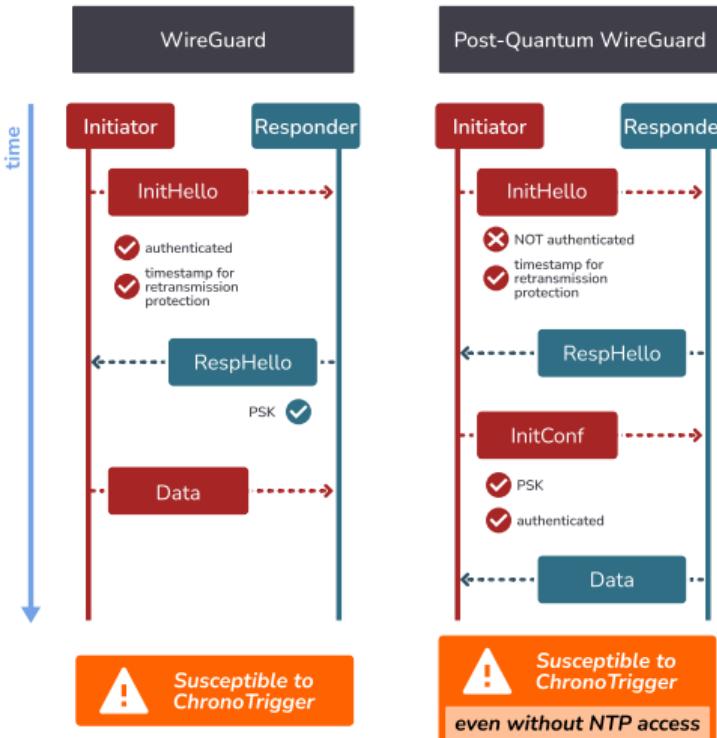
A. Preparation phase:

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

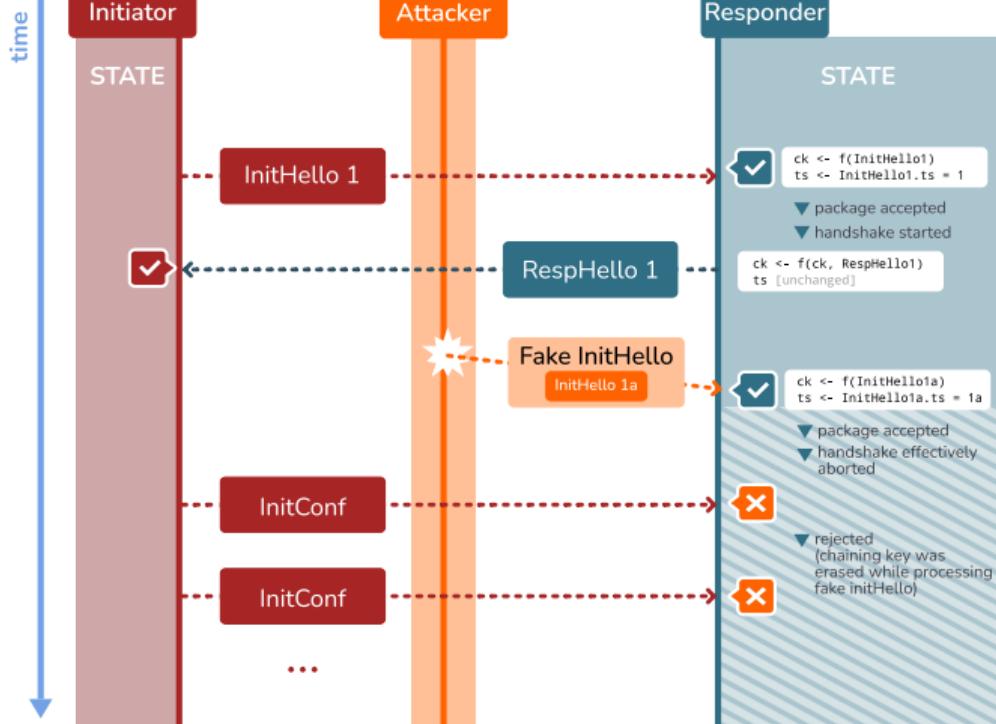
ChronoTrigger: Changes in Post-Quantum WG



- *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



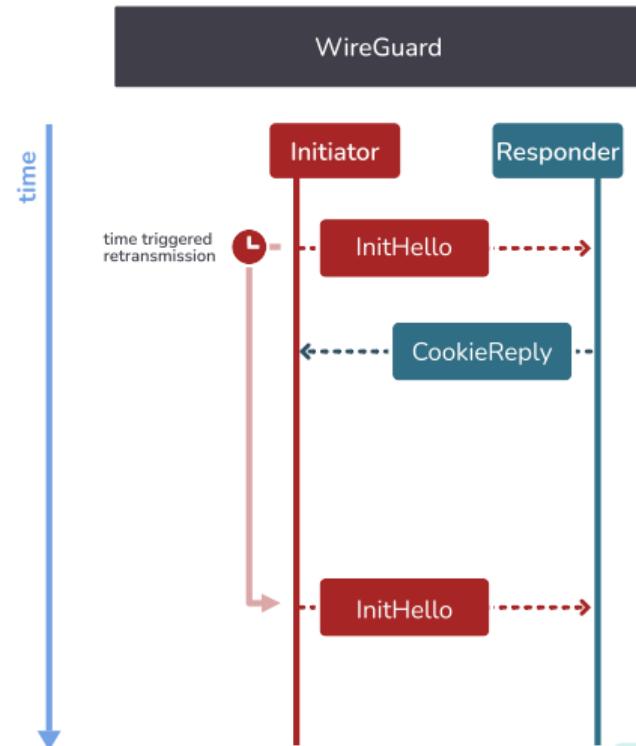


CookieCutter Attack

I am under load. Prove that you are not using IP address impersonation before I process your handshake!

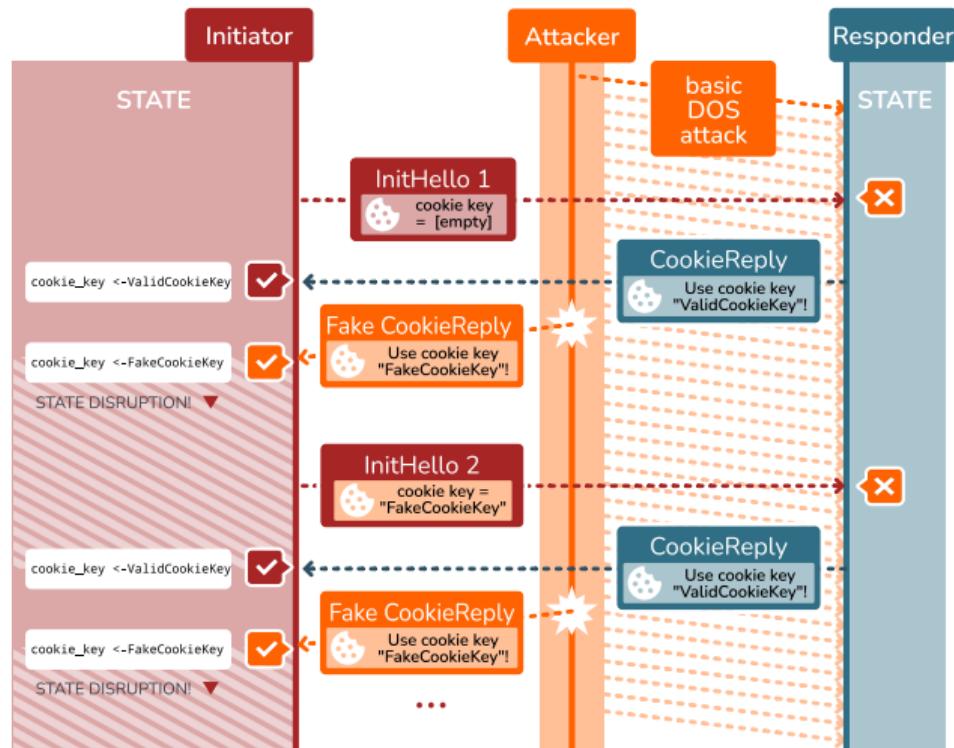
This message contains a cookie key. Use it to prove that you can receive messages sent to your address when retransmitting your *InitHello* packet.

A WireGuard CookieReply, ca. 2014





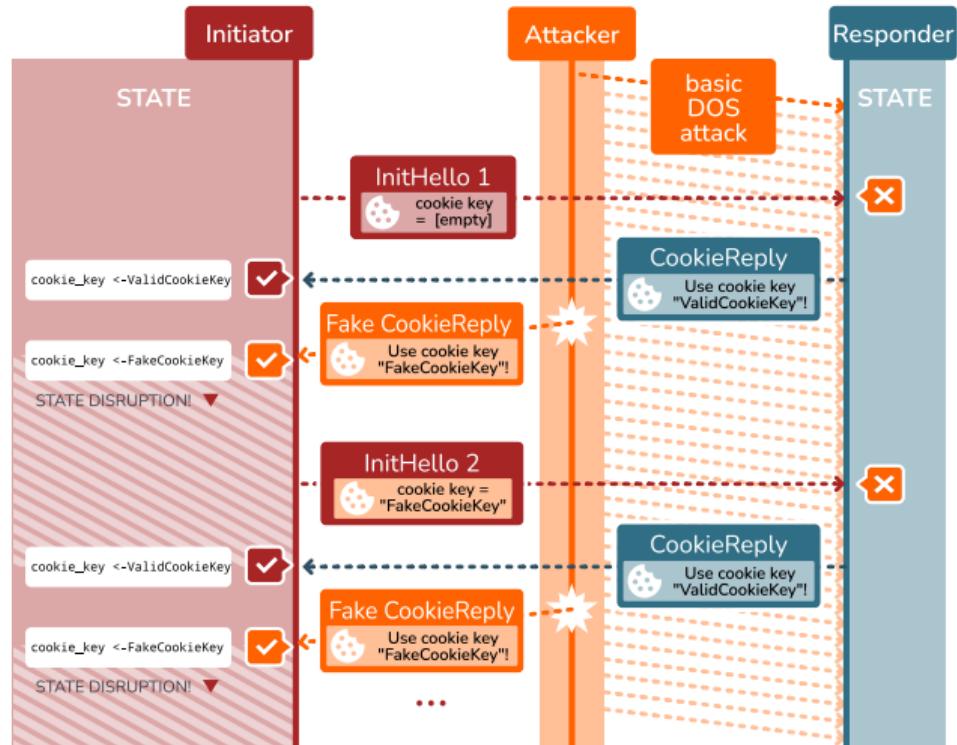
CookieCutter Attack



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 cookie key with the fake one
- ... Repeat ad nauseam



CookieCutter Attack



Attacker gains:

- Cheap protocol-level DOS

Attacker needs:

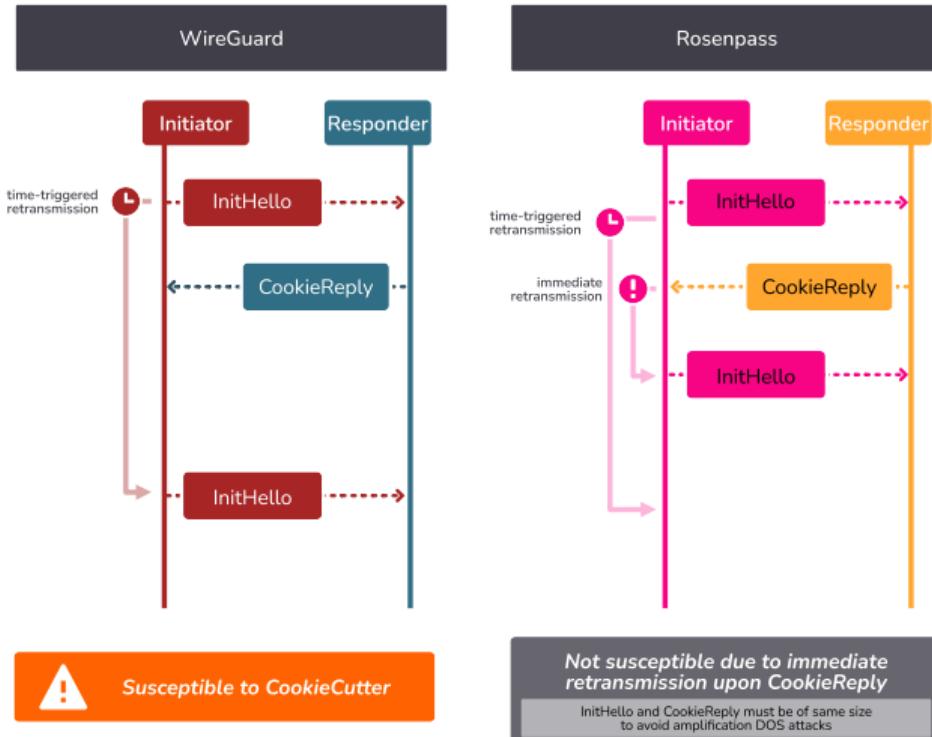
- Knowledge of public keys
- Good timing

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 amplification 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:

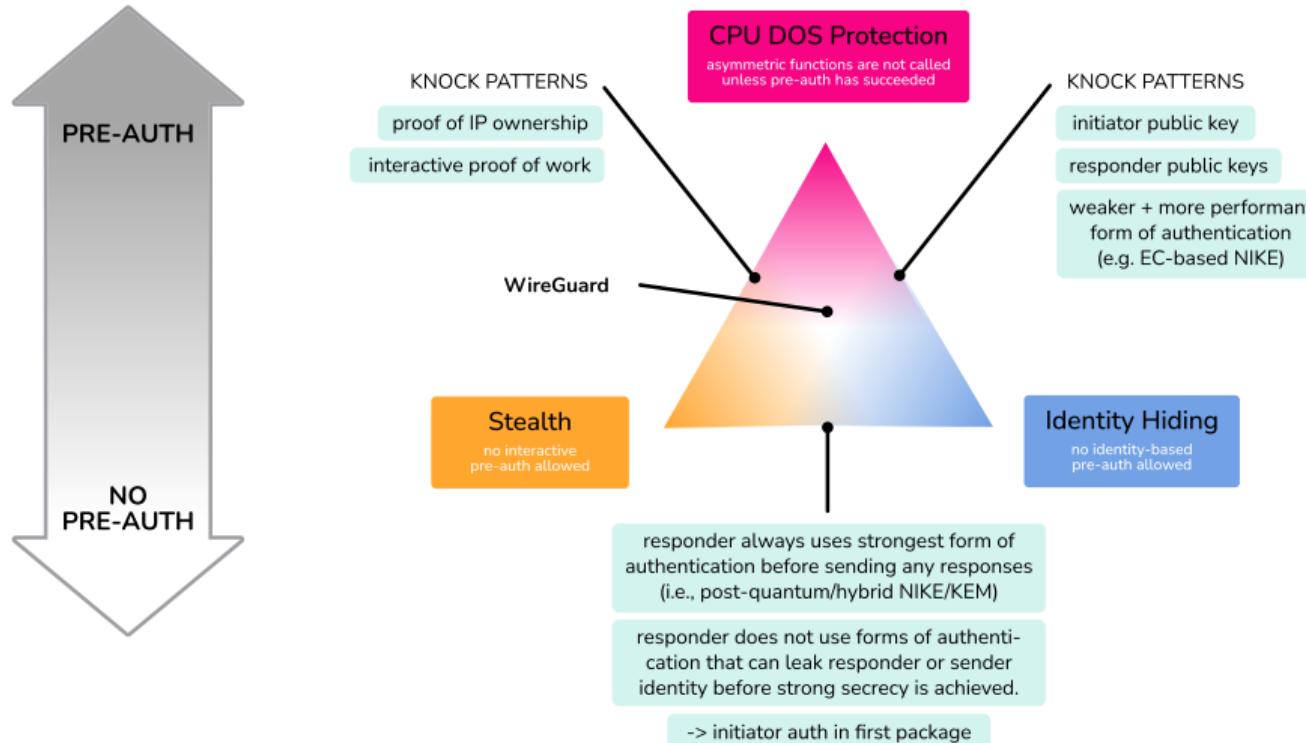
- No change in Rosenpass, but we should have **full stealth!**
- ⇒ Remove cookie mechanism?
- 😊 This would affect the CPU DOS mitigation too much.

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.

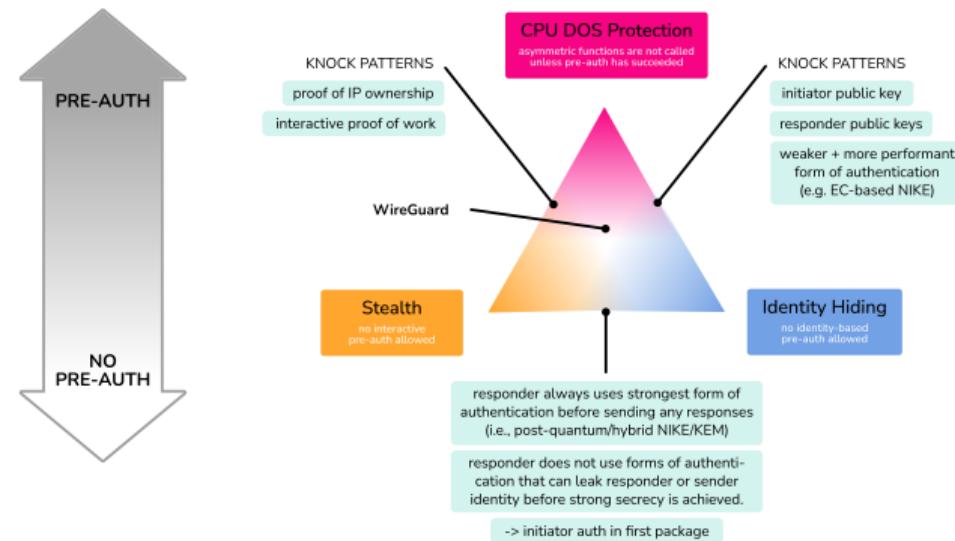


Choose Two: Stealth, Identity Hiding, CPU DOS Mit.





WireGuard and Rosenpass Trade-Offs



CPU DOS Mitigation:

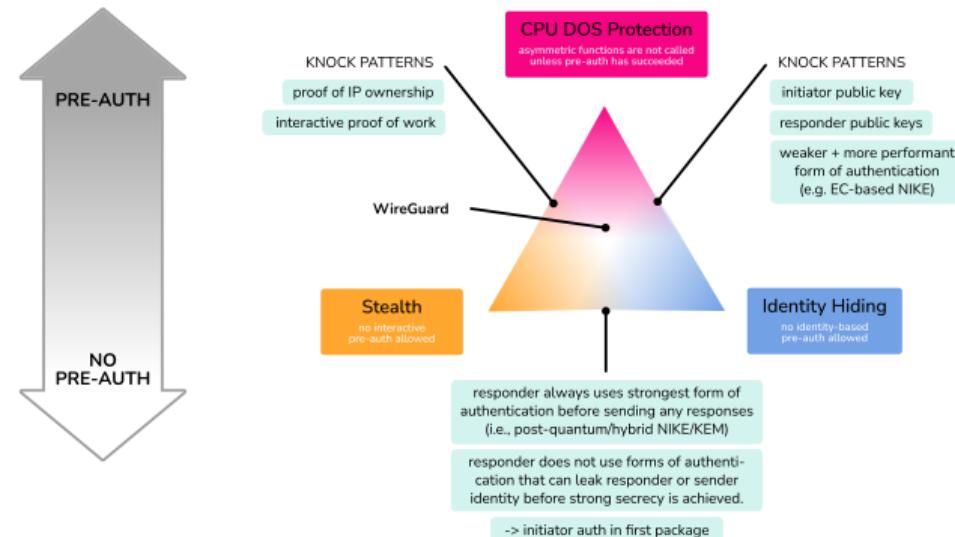
- There is no clear optimum here.
- CPU DOS mitigation is never calling asymmetric crypto unless we know it succeeds (circular reasoning)

Stealth:

Identity hiding:



WireGuard and Rosenpass Trade-Offs



CPU DOS Mitigation:

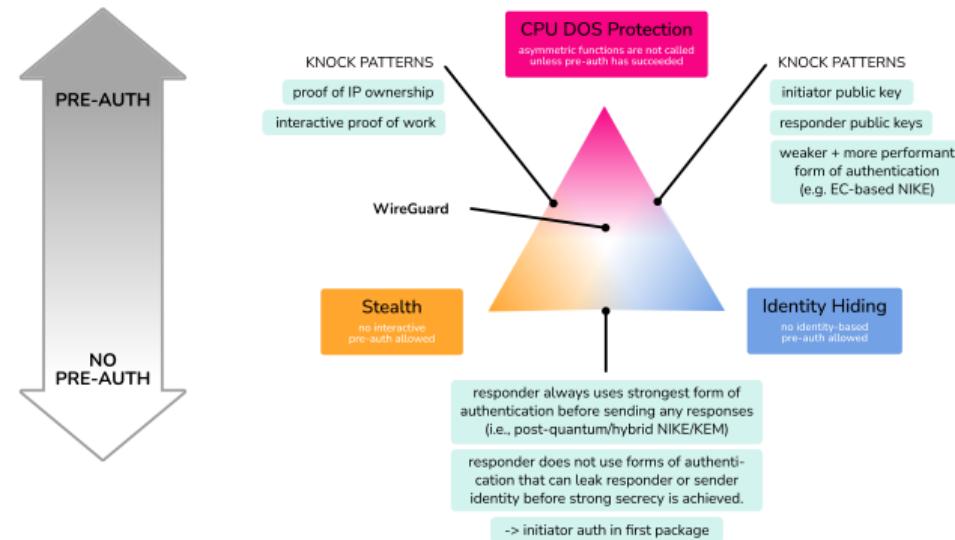
Stealth:

- Broken on DOS attacks assuming recipient is known
⇒ This seems acceptable

Identity hiding:



WireGuard and Rosenpass Trade-Offs



CPU DOS Mitigation:

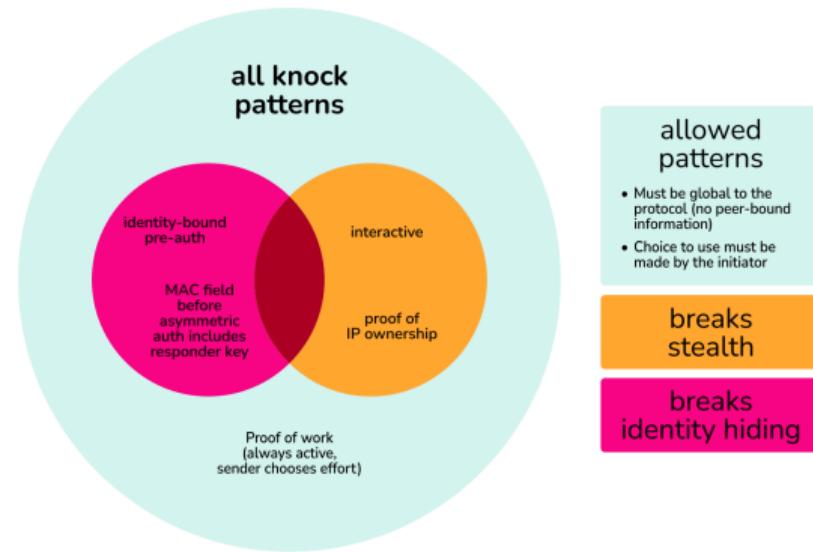
Stealth:

Identity hiding:

- Broken on knowledge of public keys
 - ⇒ This seems unacceptable!
 - ⇒ 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 patterns



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?

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We like these tools, they are good!



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They mostly help the *formal verification experts* to:

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



Friction+Frustration for the Working Cryptographer

Tooling

Documentation:

Output:

Input Language:

Proof Language:



Friction+Frustration for the Working Cryptographer

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- Syntax highlighting, favorite editor
- Engineering for large models: syntax rewriting, syntactic sugar, macros
- Comfortable tooling to inspect intermediate games (CryptoVerif)

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Proof Language: not enough flexibility and leeway compared to pen-and-paper

- hand-waving, unsafe blocks
- support for incremental process



Maths is something fundamentally communicative

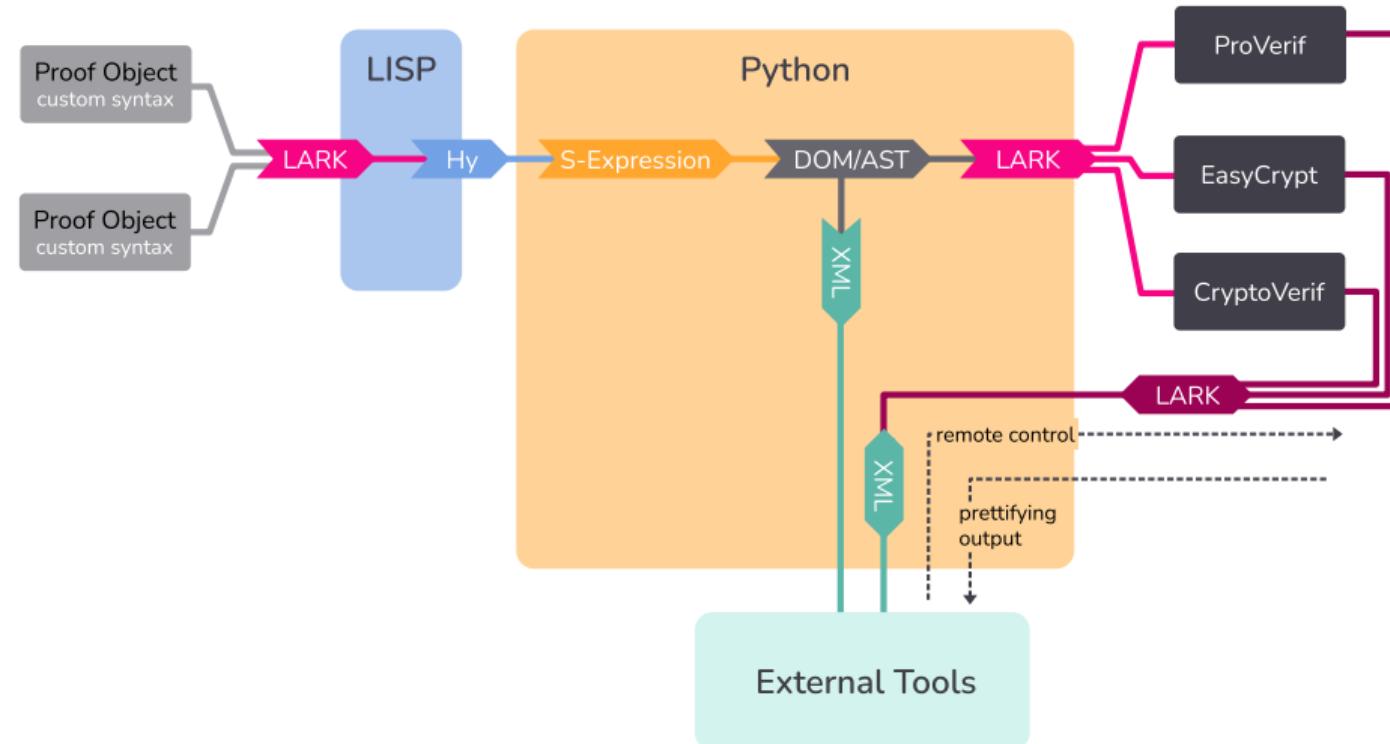
... and mechanised proofs have not covered this thus far.

Everything had a name, and each name gave birth to a new thought.

Helen Keller (1880-1968) in The Day Language Came into My Life



Rosenpass going Rube-Goldberg



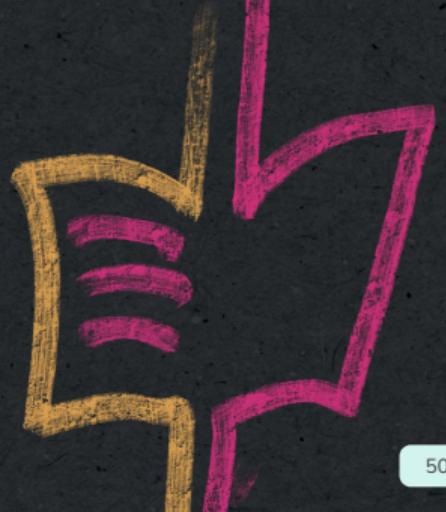
Idea: Build a framework around existing tools

Keep expressivity and precision

Generate and parse their languages

Open them up to ecosystems in Python, Lisp, XML

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.eu



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)
 - AST Rewriting for more complex adaption
- Integrate with external tools by exporting our AST as XML
 - XML is just a convenient grammar for trees
 - We do not need to support the full complexity of XML including XML style sheets and such things