Håck ma's 2024, Schloss in Ottenschlag
2024-08-30

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

Karolin Varner, Benjamin Lipp, and **Lisa Schmidt**
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:
rosenpass.eu/docs/ presentations/hackmas-2024/

Watch the presentation at:
media.ccc.de/v/how-to-build-post-quantum-cryptographic-protocols-and-why-wall-clocks-are-not-to

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

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.

Attacks from Quantum Computers: Shor’s algorithm

With Jargon: Solves a couple of mathematical problems that most modern cryptography is based upon.

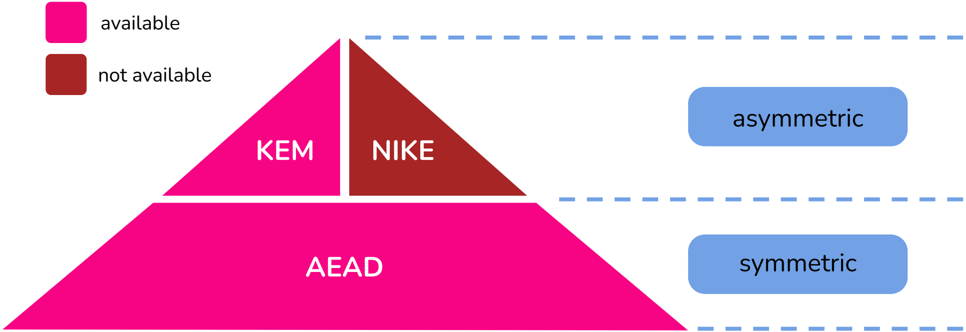
- RSA, “Rivest-Shamir-Adleman”, based on the problem of factorizing prime numbers
- DH, “Diffie-Hellmann”, based on the discrete logarithm problem
- ECDH, “Elliptic Curve Diffie-Hellmann”, based on elliptic curve discrete logarithm problem

Less Jargon: Breaks most modern, asymmetric cryptography.

Munch now decrypt later

- Post-Quantum Cryptography was just standardized [MK-KEM]
- Attackers can store important data and decrypt it once quantum computers are available

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!”*

* Forward Secrecy – 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

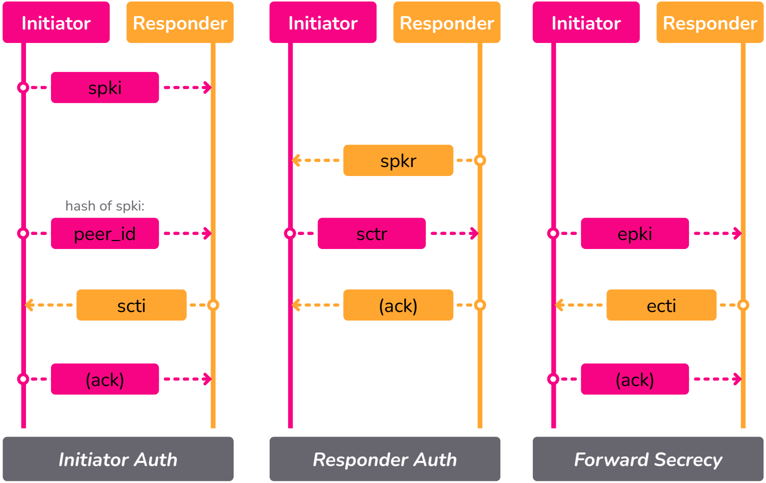
Key Encapsulation Method

```
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);
}
```

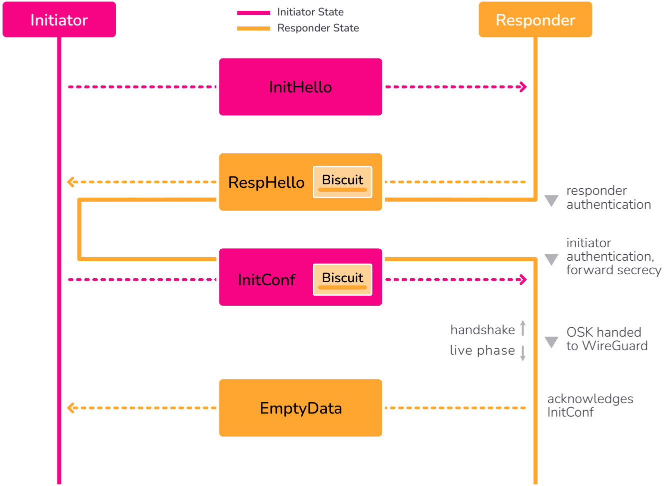
Non-Interactive Key Exchange

```
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

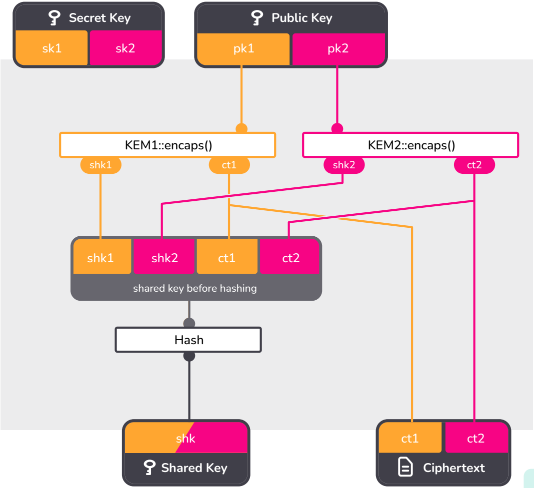


- authenticated key exchange
- three KEM operations interleaved to achieve mutual authentication and forward secrecy
- no use of signatures
- first package (InitHello) is unauthenticated
- stateless responder to avoid disruption attacks

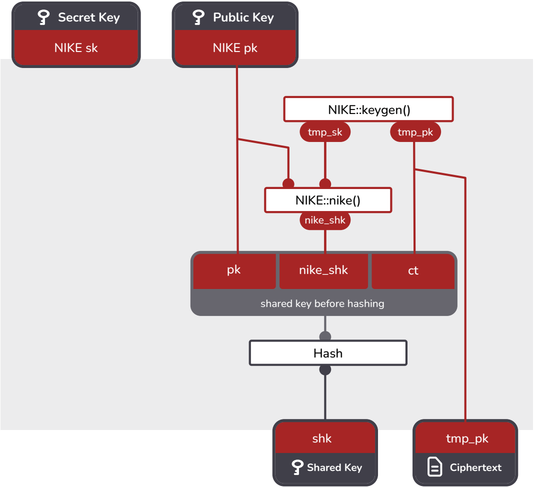
Hybridization

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



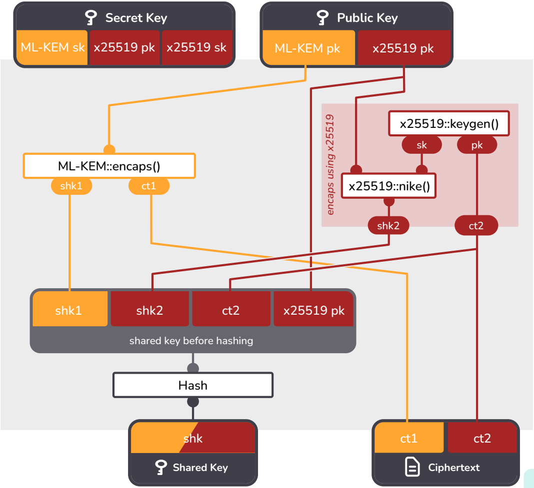
Turning a NIKE into a KEM



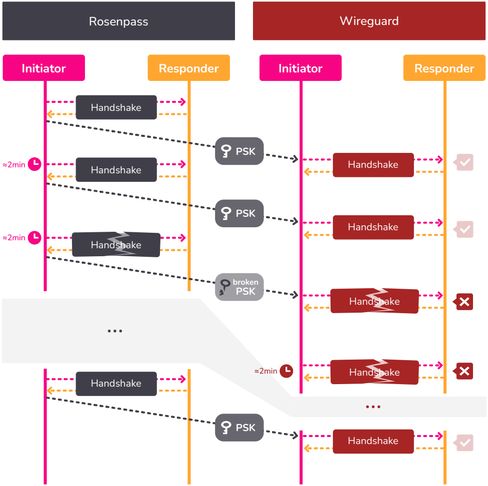
- from the HPKE RFC [HPKE]
- *remote* keypair is static keypair
- *local* keypair is temporary keypair
- local keypair public key is treated as ciphertext
- for proof-related reasons, ciphertext and public key are included in hash
- RFC work by Barnes, Bhargavan, Lipp, Wood supported by analysis work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

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

Initiator Code		Responder Code		Comments
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.

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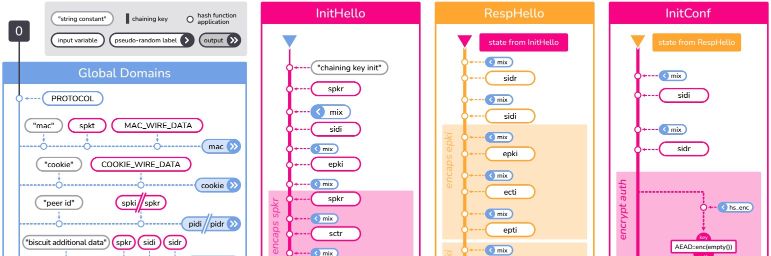

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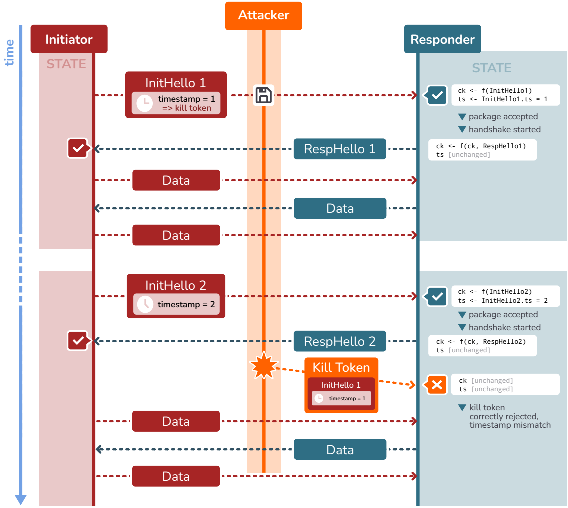
Trials ~ Attacks found

ChronoTrigger

Retransmission Protection in WireGuard



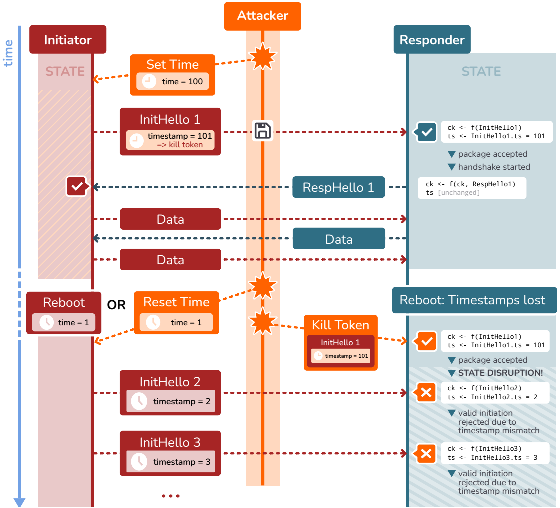
- replay attacks thwarted by counter
- counter is based on real-time clock
- responder is semi-stateful (one retransmission at program start may be accepted, but this does not affect protocol security)

⇒ 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

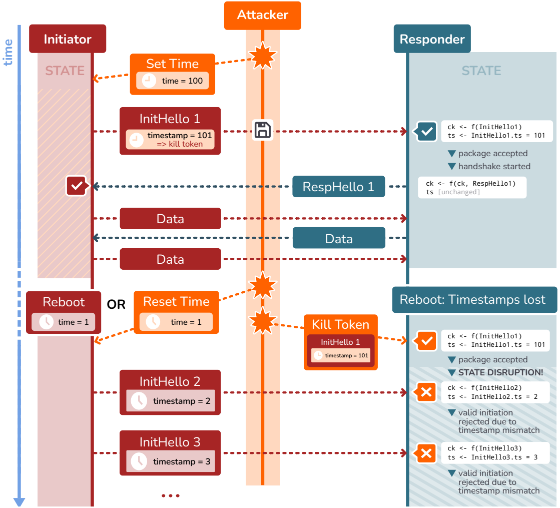
... both peers are being reset ...

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

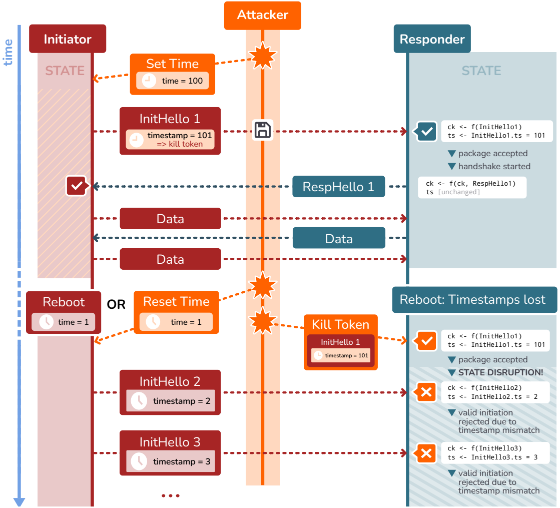


Gaining access to system time:

- 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:

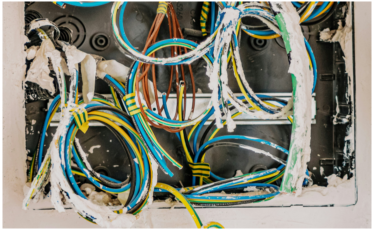
- eavesdropping of initiator packets
- access to system time

Delayed execution, attacker needs:

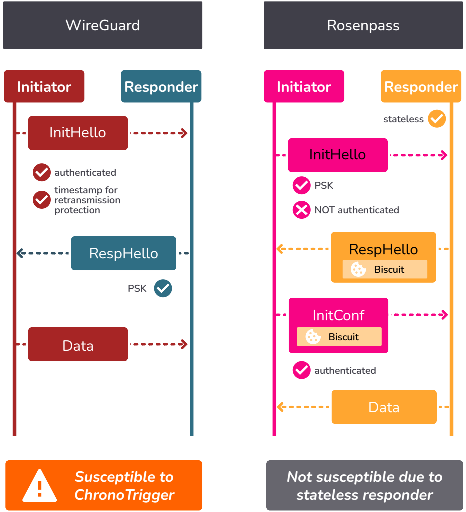
- no access beyond message transmission to responder

What are State Disruption Attacks?

Protocol-level DoS



ChronoTrigger: Changes in Rosenpass



WireGuard

Initiator **Responder**

InitHello

✓ authenticated

✓ timestamp for retransmission protection

RespHello

PSK ✓

Data

⚠ ***Susceptible to ChronoTrigger***

Rosenpass

Initiator **Responder**

stateless ✓

InitHello

✓ PSK

☒ NOT authenticated

RespHello
Biscuit

InitConf
Biscuit

✓ authenticated

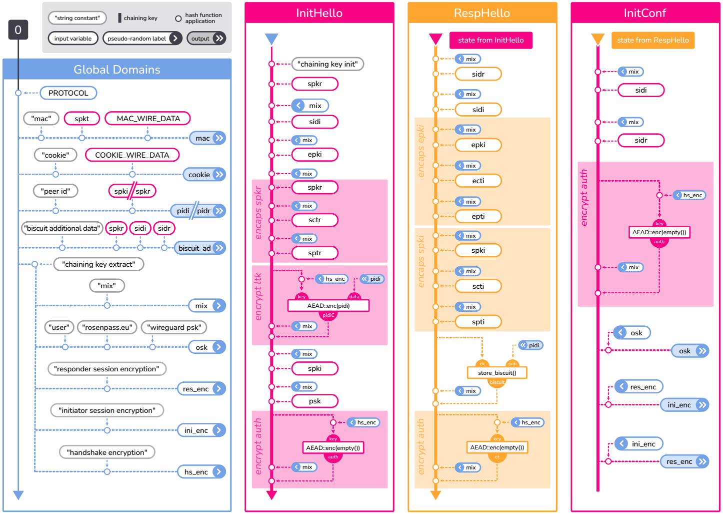
Data

Not susceptible due to stateless responder

- 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



"string constant"
chaining key
hash function application
input variable
pseudo-random label
output

0

Global Domains

PROTOCOL

"mac" spkt MAC_WIRE_DATA
mac

"cookie" COOKIE_WIRE_DATA
cookie

"peer id" spki/spkr
pidi/pidr

"biscuit additional data" spkr sidi sidr
biscuit_ad

"chaining key extract"

"mix"
mix

"user" "rosenpass.eu" "wireguard psk"
osk

"responder session encryption"
res_enc

"initiator session encryption"
ini_enc

"handshake encryption"
hs_enc

InitHello

"chaining key init"
spkr
mix
sidi
mix
epki
mix

encaps spkr
spkr
mix
sctr
mix
sptr

encrypt ltk
hs_enc
pidi
key
data
AEAD::enc(pidi)
pidiC
mix

mix
spki
mix
psk

encrypt auth
hs_enc
key
AEAD::enc(empty())
auth
mix

RespHello

state from InitHello
mix
sidr
mix
sidi

encaps epki
mix
epki
mix
ecti
mix
epti

encaps spki
mix
spki
mix
scti
mix
spti

pidi
ck
pidi
store_biscuit()
biscuit
mix

encrypt auth
hs_enc
key
AEAD::enc(empty())
ct
mix

InitConf

state from RespHello
mix
sidi
mix
sidr

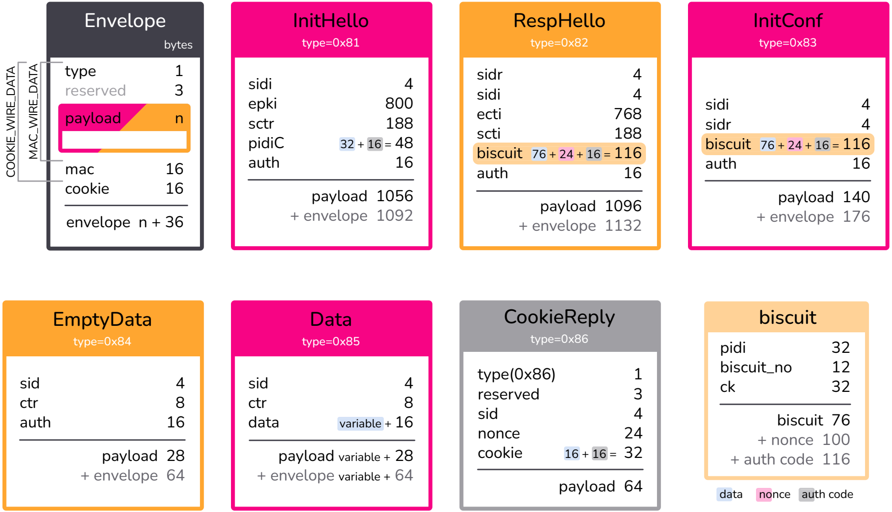
encrypt auth
hs_enc
key
AEAD::enc(empty())
auth
mix

osk
osk

res_enc
ini_enc

ini_enc
res_enc

Rosenpass Protocol Messages: Spot the Biscuit



Envelope

	bytes
type	1
reserved	3
payload	n
mac	16
cookie	16
envelope	n + 36

InitHello

type=0x81

sidi	4
epki	800
sctr	188
pidiC	32 + 16 = 48
auth	16
payload	1056
+ envelope	1092

RespHello

type=0x82

sidr	4
sidi	4
ecti	768
scti	188
biscuit	76 + 24 + 16 = 116
auth	16
payload	1096
+ envelope	1132

InitConf

type=0x83

sidi	4
sidr	4
biscuit	76 + 24 + 16 = 116
auth	16
payload	140
+ envelope	176

EmptyData

type=0x84

sid	4
ctr	8
auth	16
payload	28
+ envelope	64

Data

type=0x85

sid	4
ctr	8
data	variable + 16
payload	variable + 28
+ envelope	variable + 64

CookieReply

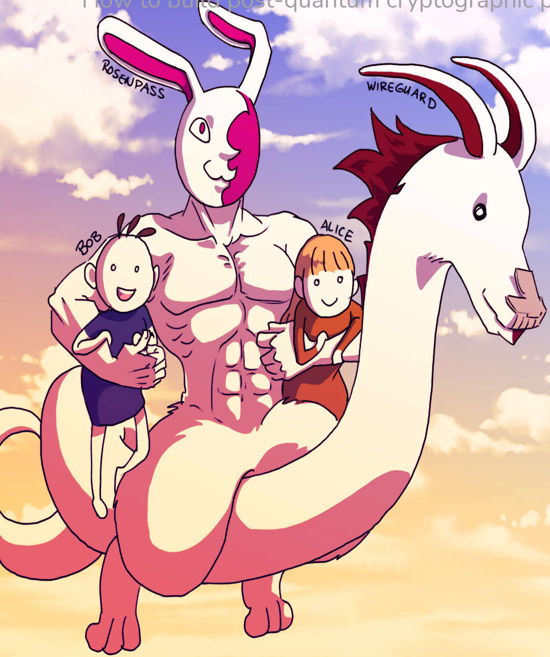
type=0x86

type(0x86)	1
reserved	3
sid	4
nonce	24
cookie	16 + 16 = 32
payload	64

biscuit

pidi	32
biscuit_no	12
ck	32
biscuit	76
+ nonce	100
+ auth code	116

data nonce auth code



Tribulations ~ Tooling

Oh These Proof Tools

Vive la Révolution! Against the

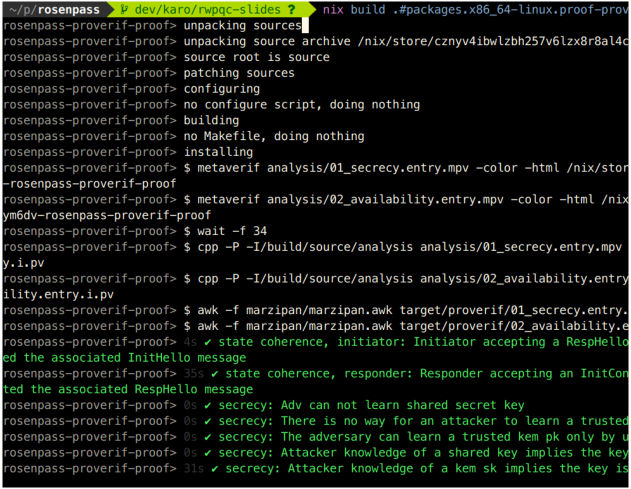
Bourgeoisie of Proof Assistants!

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”

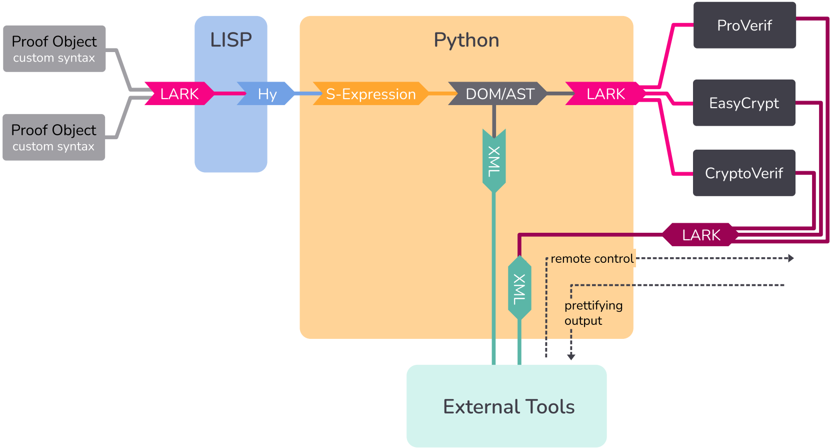
Symbolic Modeling of Rosenpass



```
~/p/rosenpass  dev/karo/rwpqc-slides ?  nix build .#packages.x86_64-linux.proof-prov
rosenpass-proverif-proof> unpacking sources
rosenpass-proverif-proof> unpacking source archive /nix/store/cznyv4ibwlzbh257v6lzx8r8al4c
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 /nix/stor
-rosenpass-proverif-proof
rosenpass-proverif-proof> $ metaverif analysis/02_availability.entry.mpv -color -html /nix
ym6dv-rosenpass-proverif-proof
rosenpass-proverif-proof> $ wait -f 34
rosenpass-proverif-proof> $ cpp -P -I/build/source/analysis analysis/01_secrecy.entry.mpv
y.i.pv
rosenpass-proverif-proof> $ cpp -P -I/build/source/analysis analysis/02_availability.entry
ility.entry.i.pv
rosenpass-proverif-proof> $ awk -f marzipan/marzipan.awk target/proverif/01_secrecy.entry.
rosenpass-proverif-proof> $ awk -f marzipan/marzipan.awk target/proverif/02_availability.e
rosenpass-proverif-proof> 4s ✔ state coherence, initiator: Initiator accepting a RespHello
ed the associated InitHello message
rosenpass-proverif-proof> 35s ✔ state coherence, responder: Responder accepting an InitCon
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 a trusted
rosenpass-proverif-proof> 0s ✔ secrecy: The adversary can learn a trusted kem pk only by u
rosenpass-proverif-proof> 0s ✔ secrecy: Attacker knowledge of a shared key implies the key
rosenpass-proverif-proof> 31s ✔ secrecy: Attacker knowledge of a kem sk implies the key is
```

- 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

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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://noiseprotocol.org/noise.html

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

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

[MK-KEM]: https://csrc.nist.gov/pubs/fips/203/final

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