A Mechanised Cryptographic Proof of the WireGuard Virtual Private Network Protocol

Benjamin Lipp, Bruno Blanchet, Karthik Bhargavan (INRIA Paris, Prosecco)

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Protocol and implementation in progress since 2015

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- works directly over UDP
- only a few thousand lines of code
- ongoing integration into the Linux kernel
- aims to replace OpenVPN and IPsec
- VPN providers are starting to adopt it

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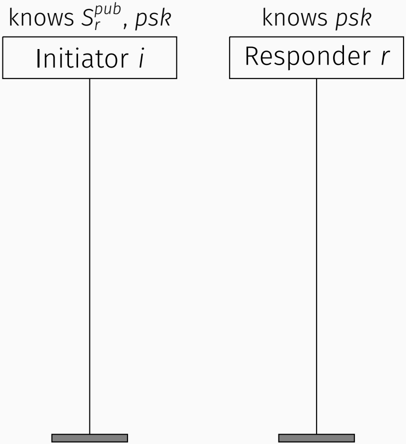
WireGuard’s Main Protocol: Noise IKpsk2 (simplified)



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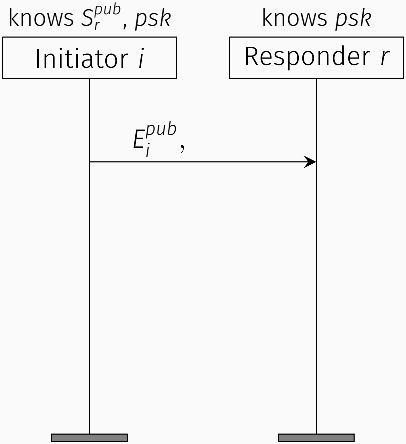

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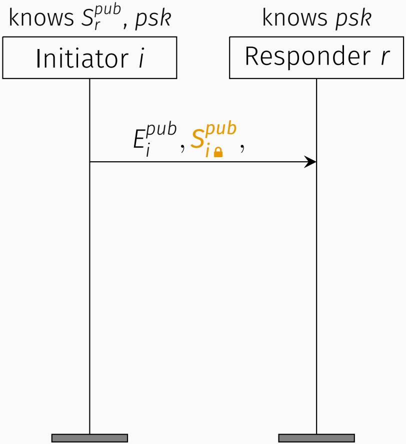

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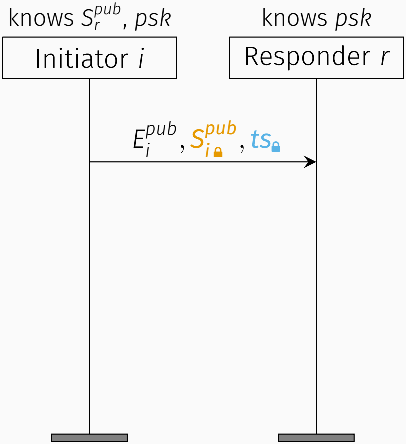

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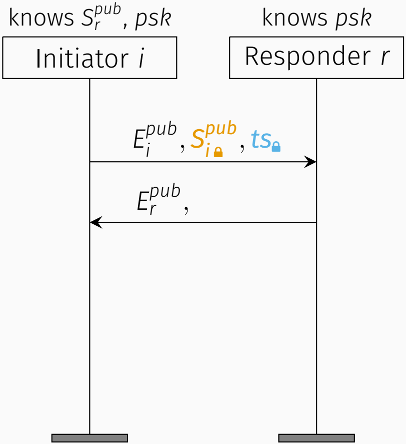

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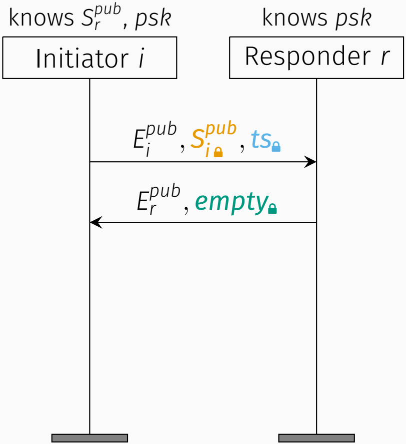

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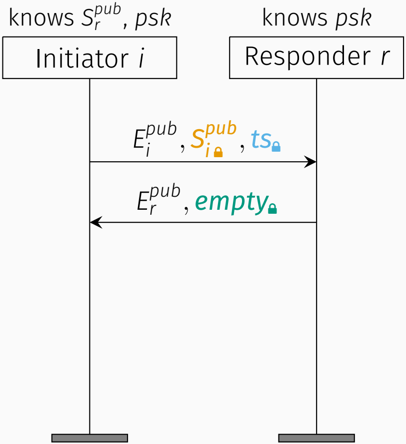

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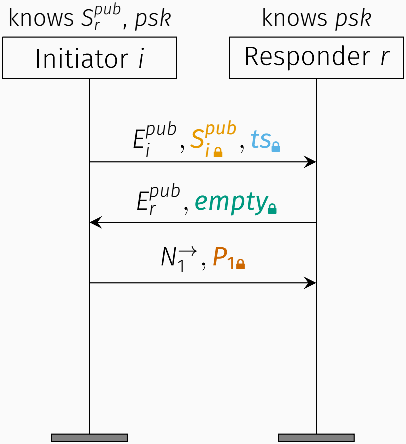

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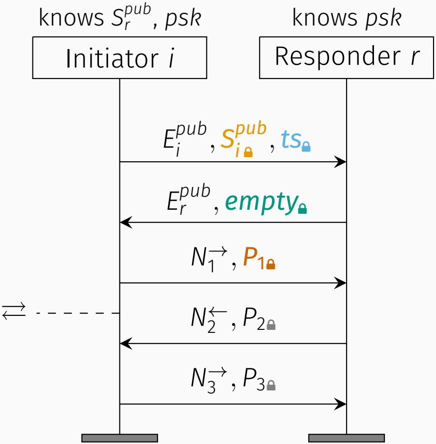

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WireGuard's DoS Protection During Handshake (simplified)

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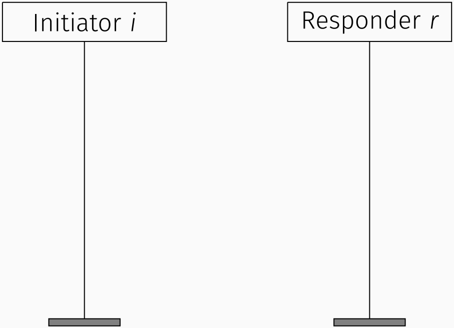

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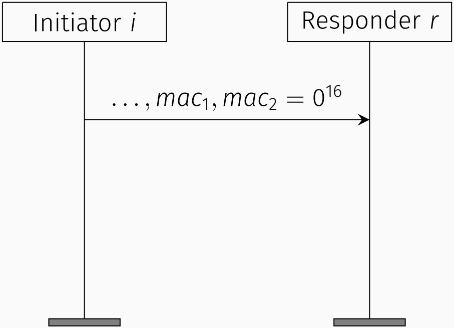

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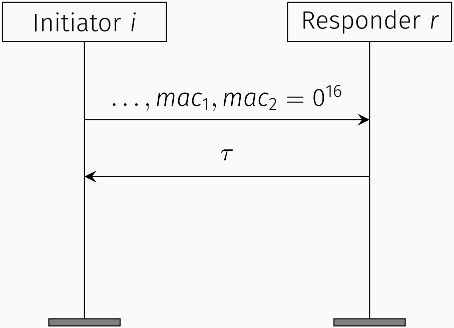

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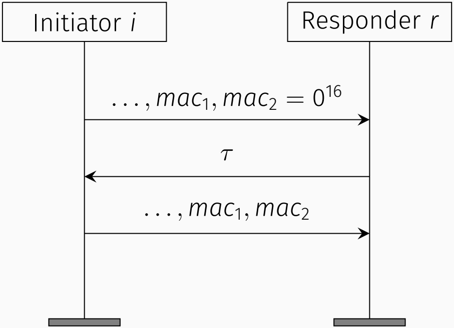

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3) Non-zero mac_2 in response to cookie messages:

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Security Goals of WireGuard's Secure Channel Protocol

Classic key exchange and secure channel properties

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Additional properties in WireGuard

- Resistance against denial of service
- Identity hiding

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Mechanised cryptographic proof of WireGuard using CryptoVerif, analysing:

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Related work: DowlingPaterson'18, DonenfeldMilner'18 on WireGuard
KobeissiNicolasBhargavan'19, Suter-Dörig'18, Girol'19 on IKpsk2

The CryptoVerif Automatic Protocol Prover

Proof assistant for game-based cryptographic proofs

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- successful termination ⇒ asymptotic security
- exact security given by probability bound

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  - a session is clean if it's not trivially broken
    i. e. if *not all* secrets of one party are compromised

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$\Rightarrow$ CryptoVerif creates nested branches for hkdf inputs

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(remember: 8 *dependent* random oracle calls with inputs $v_0, \ldots, v_7$)

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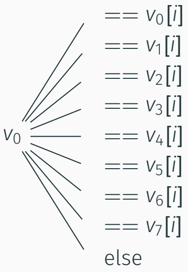

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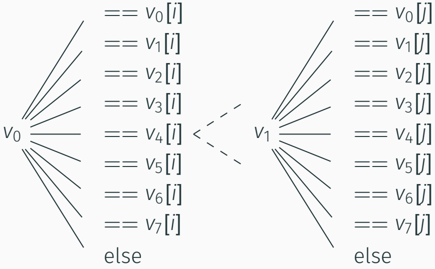

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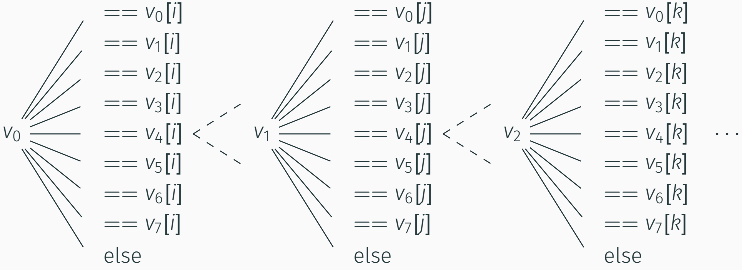

Simplification of the Key Derivation's HKDF Chain

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C \| \pi \| k_3 &\leftarrow \mathrm{hkdf}(C, v_6) \\
T^{\rightarrow} \| T^{\leftarrow} &\leftarrow \mathrm{hkdf}(C, \epsilon)
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C &\leftarrow \mathrm{hkdf}(C, v_5) \\
C \| \pi \| k_3 &\leftarrow \mathrm{hkdf}(C, v_6) \\
T^{\rightarrow} \| T^{\leftarrow} &\leftarrow \mathrm{hkdf}(C, \epsilon)
\end{aligned}
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3 independent calls to
3 *independent* random oracles.

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k_1 &\leftarrow \mathrm{chain}_1(v_0, v_1) \\
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Simplification of the Key Derivation's HKDF Chain

8 chained calls to
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Idea: extract only whenever the protocol needs a key

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Indifferentiable in any context:
(manually proved, some lemmas with CryptoVerif)

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A Theoretical Attack leading to Identity Mis-Binding

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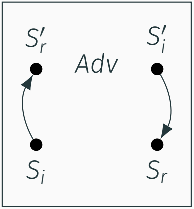

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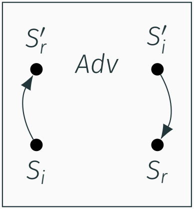

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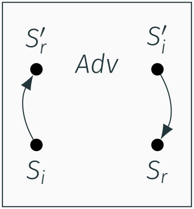

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Mitigation: include static public keys S_i^{pub} and S_r^{pub} into key derivation

Identity Hiding: Known Weaknesses

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$\Rightarrow$ the MACs weaken identity hiding properties

- $S_{i🔒}^{pub}$ not forward secret, would require a round-trip more

Identity Hiding: Our Contribution on Noise IKpsk2

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$$S_{i\,🔒}^{pub} \leftarrow \mathrm{aenc}(k_1, 0, S_i^{pub}, H_2)$$

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$$H_2 \leftarrow \text{hash}(\text{hash}(\text{const}_H \| S_r^{pub}) \| E_i^{pub})$$
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    - public key S_{A1}^{pub} initiating sessions with S_{B1}^{pub}
    - public key S_{A2}^{pub} initiating sessions with S_{B2}^{pub}

Metrics

Numbers based on the largest variant of our model:

- approx. 1300 lines of model code
- 36 proof instructions
- 168 games produced by CryptoVerif
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- CryptoVerif formally encodes many small steps, separately

Results Compared to Goals

Classic key exchange and secure channel properties:

Secrecy	• Secrecy (by proving message indistinguishability) • Forward secrecy
Agreement	• Mutual authentication (as of 2nd message) • Session uniqueness • Channel binding • Resistance against key compromise impersonation (KCI) • Resistance against identity mis-binding (except theoretical attack)

Additional properties in WireGuard:

- Resistance against denial of service
  (no replay of 1st msg, cookie enforces round-trip)
- Identity hiding (weak)

Conclusion and Main Take-Aways

- WireGuard *protocol* is cryptographically safe
  - weak identity hiding
- more context in key derivation prevents theoretical attack
  - (teaser: and makes proofs easier)
- chains of random oracle calls can be reduced to fewer calls
- precise model for Curve25519 and Curve448

- detailed comparison to other analyses of WireGuard in our paper's related work section
- the long version and our models with an updated version of Curve25519 are available at: `https://cryptoverif.inria.fr/WireGuard`