Who Am I?

- Jason Donenfeld, also known as zx2c4, no academic affiliation.
- Background in exploitation, kernel vulnerabilities, crypto vulnerabilities, though quite a bit of development experience too.
- Motivated to make a VPN that avoids the problems in both crypto and implementation that I’ve found in numerous other projects.
What is WireGuard?

- Layer 3 secure network tunnel for IPv4 and IPv6.
  - Opinionated.

- Lives in the Linux kernel, but cross platform implementations are in the works.

- UDP-based. Punches through firewalls.

- Modern conservative cryptographic principles.

- Emphasis on simplicity and auditability.

- Authentication model similar to SSH’s authenticated_keys.

- Replacement for OpenVPN and IPsec.
Easily Auditable

<table>
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<tr>
<th></th>
<th>OpenVPN</th>
<th>Linux XFRM</th>
<th>StrongSwan</th>
<th>SoftEther</th>
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<tr>
<td>LoC</td>
<td>116,730</td>
<td>13,898</td>
<td>405,894</td>
<td>329,853</td>
<td>3,904</td>
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<tr>
<td>Plus</td>
<td>OpenSSL!</td>
<td>Plus StrongSwan!</td>
<td>Plus XFRM!</td>
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Less is more.
Easily Auditable

- **IPsec (XFRM+StrongSwan)**
  - 419,792 LoC

- **SoftEther**
  - 329,853 LoC

- **OpenVPN**
  - 116,730 LoC

**WireGuard**
- 3,904 LoC
Simplicity of Interface

- WireGuard presents a normal network interface:

  ```
  # ip link add wg0 type wireguard
  # ip address add 192.168.3.2/24 dev wg0
  # ip route add default via wg0
  # ifconfig wg0 ...
  # iptables -A INPUT -i wg0 ...
  
  /etc/hosts.{allow,deny}, bind(), ...
  ```

- Everything that ordinarily builds on top of network interfaces – like eth0 or wlan0 – can build on top of wg0.
Blasphemy!

- WireGuard is blasphemous!
- We break several layering assumptions of 90s networking technologies like IPsec.
  - IPsec involves a “transform table” for outgoing packets, which is managed by a user space daemon, which does key exchange and updates the transform table.
- With WireGuard, we start from a very basic building block – the network interface – and build up from there.
- Lacks the academically pristine layering, but through clever organization we arrive at something more coherent.
Simplicity of Interface

- The interface *appears* stateless to the system administrator.
- Add an interface – wg0, wg1, wg2, … – configure its peers, and immediately packets can be sent.
- Endpoints roam, like in mosh.
- Identities are just the static public keys, just like SSH.
- Everything else, like session state, connections, and so forth, is invisible to admin.
The fundamental concept of any VPN is an association between public keys of peers and the IP addresses that those peers are allowed to use.

A WireGuard interface has:
- A private key
- A listening UDP port
- A list of peers

A peer:
- Is identified by its public key
- Has a list of associated tunnel IPs
- Optionally has an endpoint IP and port
Cryptokey Routing

PUBLIC KEY :: IP ADDRESS
Cryptokey Routing

- Makes system administration very simple.

- If it comes from interface wg0 and is from Yoshi’s tunnel IP address of 192.168.5.17, then the packet *definitely came from Yoshi*.

- The iptables rules are plain and clear.
Timers: A Stateless Interface for a Stateful Protocol

- As mentioned prior, WireGuard appears “stateless” to user space; you set up your peers, and then it just works.
- A series of timers manages session state internally, invisible to the user.
- Every transition of the state machine has been accounted for, so there are no undefined states or transitions.
- Event based.
Timers

- **User space sends packet.** If no session has been established for 120 seconds, send handshake initiation.
- **No handshake response after 5 seconds.** Resend handshake initiation.
- **Successful authentication of incoming packet.** Send an encrypted empty packet after 10 seconds, if we don’t have anything else to send during that time.
- **No successfully authenticated incoming packets after 15 seconds.** Send handshake initiation.
Static Allocations, Guarded State, and Fixed Length Headers

- All state required for WireGuard to work is allocated during config.
- No memory is dynamically allocated in response to received packets.
  - Eliminates entire classes of vulnerabilities.
- All packet headers have fixed width fields, so no parsing is necessary.
  - Eliminates another entire class of vulnerabilities.
- No state is modified in response to unauthenticated packets.
  - Eliminates yet another entire class of vulnerabilities.
Stealth

- Some aspects of WireGuard grew out of an earlier kernel rootkit project.
- Should not respond to any unauthenticated packets.
- Hinder scanners and service discovery.
- Service only responds to packets with correct crypto.
- Not chatty at all.
  - When there’s no data to be exchanged, both peers become silent.
Crypto

- We make use of Trevor Perrin’s Noise Protocol Framework – noiseprotocol.org
  - Developed with much feedback from the WireGuard development.
  - Custom written very specific implementation of NoiselK for the kernel.
- The usual list of modern desirable properties you’d want from an authenticated key exchange
  - Modern primitives: Curve25519, Blake2s, ChaCha20, Poly1305, SipHash2-4
- Lack of cipher agility!
Crypto

- Key secrecy
  - Perfect forward secrecy – new key every 2 minutes
- Key agreement
  - Authenticity
  - KCL-resistance
- Identity hiding
- Replay-attack prevention, while allowing for network packet reordering
- Working on formal verification via Tamarin with Kevin Milner
The Key Exchange

Initiator

Responder

Handshake Initiation Message

Handshake Response Message

Both Sides Calculate Symmetric Session Keys

Transport Data

Transport Data
The Key Exchange

- In order for two peers to exchange data, they must first derive ephemeral symmetric crypto session keys from their static public keys.

- The key exchange designed to keep our principles static allocations, guarded state, fixed length headers, and stealthiness.

- Either side can reinitiate the handshake to derive new session keys.
  - So initiator and responder can “swap” roles.

- Invalid handshake messages are ignored, maintaining stealth.
The Key Exchange: NoiseIK

▪ One peer is the initiator; the other is the responder.
▪ Each peer has their static identity – their long term static keypair.
▪ For each new handshake, each peer generates an ephemeral keypair.
▪ The security properties we want are achieved by computing ECDH() on the combinations of two ephemeral keypairs and two static keypairs.
▪ Session keys = Noise( ECDH(ephemeral, static), ECDH(static, ephemeral), ECDH(ephemeral, ephemeral), ECDH(static, static) )
▪ The first three ECDH() make up the “triple DH”, and the last one allows for authentication in the first message, for 1-RTT.
Key Agreement and Correctness

- Key agreement is achieved even in multiple compromise situations:
  - Both ephemeral keys compromised
  - Initiator static compromised $\rightarrow$ Initiator still has key agreement with responder
    - (KCI resistance)
  - Responder static compromised $\rightarrow$ Responder still has key agreement with initiator
    - (KCI resistance)
  - Combinations of a static key and an ephemeral key compromised
Key Secrecy

- Dependent on key agreement.
- Key secrecy is achieved even in these compromise situations:
  - Both ephemeral keys compromised
  - Both static keys compromised
    - Implies forward secrecy
  - One static key and one ephemeral key
Session Uniqueness

- Different sessions should always have different unique keys
- When both ephemerals are fresh, this is achieved
- Also, when only one ephemeral is fresh, it is achieved
Identity Hiding

- Initiator achieves identity hiding when no keys are compromised.
- Initiator also achieves identity hiding when the responder’s ephemeral key is compromised.
- Initiator does not achieve identity hiding when the responder’s static key is compromised.
  - Lack of forward secrecy for identity hiding
  - A necessity of a 1-RTT handshake
Formal Symbolic Verification

- Ongoing work with Kevin Milner from Oxford to formally prove.
- The Tamarin model works!
The Key Exchange: NoiselK – Initiator → Responder

- The initiator begins by knowing the long term static public key of the responder.
- The initiator sends to the responder:
  - A cleartext ephemeral public key.
  - The initiator’s public key, authenticated-encrypted using a key that is an (indirect) result of:
    \[ \text{ECDH}(E_i, S_r) = \text{ECDH}(S_r, E_i) \]
    - After decrypting this, the responder knows the initiator’s public key.
    - Only the responder can decrypt this, because it requires control of the responder’s static private key.
  - A monotonically increasing counter (usually just a timestamp in TAI64N) that is authenticated-encrypted using a key that is an (indirect) result of the above calculation as well as:
    \[ \text{ECDH}(S_i, S_r) = \text{ECDH}(S_r, S_i) \]
    - This counter prevents against replay DoS.
    - Authenticating it verifies the initiator controls its private key.
    - Authentication in the first message – static-static ECDH().
The Key Exchange: NoiselK – Responder → Initiator

- The responder at this point has learned the initiator’s static public key from the prior first message, as well as the initiator’s ephemeral public key.

- The responder sends to the initiator:
  - A cleartext ephemeral public key.
  - An empty buffer, authenticated-encrypted using a key that is an (indirect) result of the calculations in the prior message as well as:

\[
\text{ECDH}(\text{Er}, \text{Ei}) =\text{ECDH}(\text{Ei}, \text{Er})
\]

and

\[
\text{ECDH}(\text{Er}, \text{Si}) =\text{ECDH}(\text{Si}, \text{Er})
\]

- Authenticating it verifies the responder controls its private key.
The Key Exchange: Session Derivation

- After the previous two messages (initiator → responder and responder → initiator), both initiator and responder have something bound to these ECDH() calculations:
  - $\text{ECDH}(E_i, S_r) = \text{ECDH}(S_r, E_i)$
  - $\text{ECDH}(S_i, S_r) = \text{ECDH}(S_r, S_i)$
  - $\text{ECDH}(E_i, E_r) = \text{ECDH}(E_r, E_i)$
  - $\text{ECDH}(S_i, E_r) = \text{ECDH}(E_r, S_i)$

- From this they can derive symmetric authenticated-encryption session keys – one for sending and one for receiving.

- When the initiator sends its first data message using these session keys, the responder receives *confirmation* that the initiator has understood its response message, and can then send data to the initiator.
The Key Exchange

▪ Just 1-RTT.

▪ *Extremely* simple to implement in practice, and doesn’t lead to the type of complicated messes we see in OpenSSL and StrongSwan.

▪ No certificates, X.509, or ASN.1: both sides exchange very short (32 bytes) base64-encoded public keys, just as with SSH.
Poor-man’s PQ Resistance

- Optionally, two peers can have a pre-shared key, which gets “mixed” into the handshake.

- Grover’s algorithm – 256-bit symmetric key, brute forced with $2^{128}$ iterations.
  - This speed-up is optimal.

- Pre-shared keys are easy to steal, especially when shared amongst lots of parties.
  - But simply augments the ordinary handshake, not replaces it.

- By the time adversary can decrypt past traffic, hopefully all those PSKs have been forgotten by various hard drives anyway.
Denial of Service Resistance

- Hashing and symmetric crypto is fast, but pubkey crypto is slow.

- We use Curve25519 for elliptic curve Diffie-Hellman (ECDH), which is one of the fastest curves, but still is slower than the network.

- Overwhelm a machine asking it to compute ECDH().
  - Vulnerability in OpenVPN!

- UDP makes this difficult.

- WireGuard uses “cookies” to solve this.
Cookies: TCP-like

- Dialog:
  - Initiator: Compute this ECDH().
  - Responder: Your magic word is “snail”. Ask me again with the magic word.
  - Initiator: My magic word is “Yorkshire pudding”. Compute this ECDH().
- Proves IP ownership, but cannot rate limit IP address without storing state.
  - Violates security design principle, no dynamic allocations!
- Always responds to message.
  - Violates security design principle, stealth!
- Magic word can be intercepted.
Cookies: DTLS-like and IKEv2-like

- Dialog:
  - Initiator: Compute this ECDH().
  - Responder: Your magic word is “cbdd7c...bb71d9c0”. Ask me again with the magic word.
  - Initiator: My magic word is “cbdd7c...bb71d9c0”. Compute this ECDH().
  - “cbdd7c...bb71d9c0” == MAC(key=responder_secret, initiator_ip_address)
    Where responder_secret changes every few minutes.

- Proves IP ownership without storing state.
- Always responds to message.
  - Violates security design principle, stealth!
- Magic word can be intercepted.
- Initiator can be DoS’d by flooding it with fake magic words.
Cookies: HIPv2-like and Bitcoin-like

- Dialog:
  - Initiator: Compute this ECDH( ).
  - Responder: Mine a Bitcoin first, then ask me!
  - Initiator: I toiled away and found a Bitcoin. Compute this ECDH( ).

- Proof of work.

- Robust for combating DoS if the puzzle is harder than ECDH( ).

- However, it means that a responder can DoS an initiator, and that initiator and responder cannot symmetrically change roles without incurring CPU overhead.
  - Imagine a server having to do proofs of work for each of its clients.
Cookies: The WireGuard Variant

- Each handshake message (initiation and response) has two macs: `mac1` and `mac2`.
- `mac1` is calculated as: \( \text{HASH(responder\_public\_key || handshake\_message)} \)
  - If this mac is invalid or missing, the message will be ignored.
  - Ensures that initiator must know the identity key of the responder in order to elicit a response.
    - Ensures stealthiness – security design principle.
- \( \text{MAC(psk, responder\_public\_key || handshake\_message)} \) when PSK is in use
  - If the responder is not under load (not under DoS attack), it proceeds normally.
  - If the responder is under load (experiencing a DoS attack), …
Cookies: The WireGuard Variant

- If the responder is under load (experiencing a DoS attack), it replies with a cookie computed as:
  \[
  \text{XAEAD(}
  \quad \text{key=HASH(responder\_public\_key),}
  \quad \text{additional\_data=handshake\_message,}
  \quad \text{MAC(key=responder\_secret, initiator\_ip\_address)}
  \text{)}
  \]

- key=MAC(psk, responder\_public\_key) when PSK is in use

- mac2 is then calculated as:
  \[
  \text{MAC(key=cookie, handshake\_message)}
  \]

- If it’s valid, the message is processed even under load.
Cookies: The WireGuard Variant

- Once IP address is attributed, ordinary token bucket rate limiting can be applied.
- Maintains stealthiness.
- Cookies cannot be intercepted by somebody who couldn’t already initiate the same exchange.
- Initiator cannot be DoS’d, since the encrypted cookie uses the original handshake message as the “additional data” parameter.
  - An attacker would have to already have a MITM position, which would make DoS achievable by other means, anyway.
Performance

- Being in kernel space means that it is *fast* and low latency.
  - No need to copy packets twice between user space and kernel space.

- ChaCha20Poly1305 is extremely fast on nearly all hardware, and safe.
  - AES-NI is fast too, obviously, but as Intel and ARM vector instructions become wider and wider, ChaCha is handedly able to compete with AES-NI, and even perform better in some cases.
  - AES is exceedingly difficult to implement performantly and safely (no cache-timing attacks) without specialized hardware.
  - ChaCha20 can be implemented efficiently on nearly all general purpose processors.

- Simple design of WireGuard means less overhead, and thus better performance.
  - Less code → Faster program? Not always, but in this case, certainly.
Performance: Measurements

Bandwidth

- OpenVPN (AES): 257 Mbits/s
- IPSec (ChaPoly): 825 Mbits/s
- IPSec (AES): 881 Mbits/s
- WireGuard: 1011 Mbits/s

Ping Time

- OpenVPN (AES): 1.541 ms
- IPSec (ChaPoly): 0.508 ms
- IPSec (AES): 0.501 ms
- WireGuard: 0.403 ms
Simple, Fast, and Secure

- Less than 4,000 lines of code.
- Easily implemented with basic data structures.
- Design of WireGuard lends itself to coding patterns that are secure in practice.
- Minimal state kept, no dynamic allocations.
- Stealthy and minimal attack surface.

- Handshake based on NoiseIK
- Fundamental property of a secure tunnel: association between a peer and a peer’s IPs.
- Extremely performant – best in class.
- Simple standard interface via an ordinary network device.
- Opinionated.
WireGuard

- Real production code, not just an “academic” proof of concept
- Open source
- $ git clone https://git.zx2c4.com/WireGuard
- Mailing list: lists.zx2c4.com/mailman/listinfo/wireguard wireguard@lists.zx2c4.com

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