WireGuard

FAST, MODERN, SECURE VPN TUNNEL

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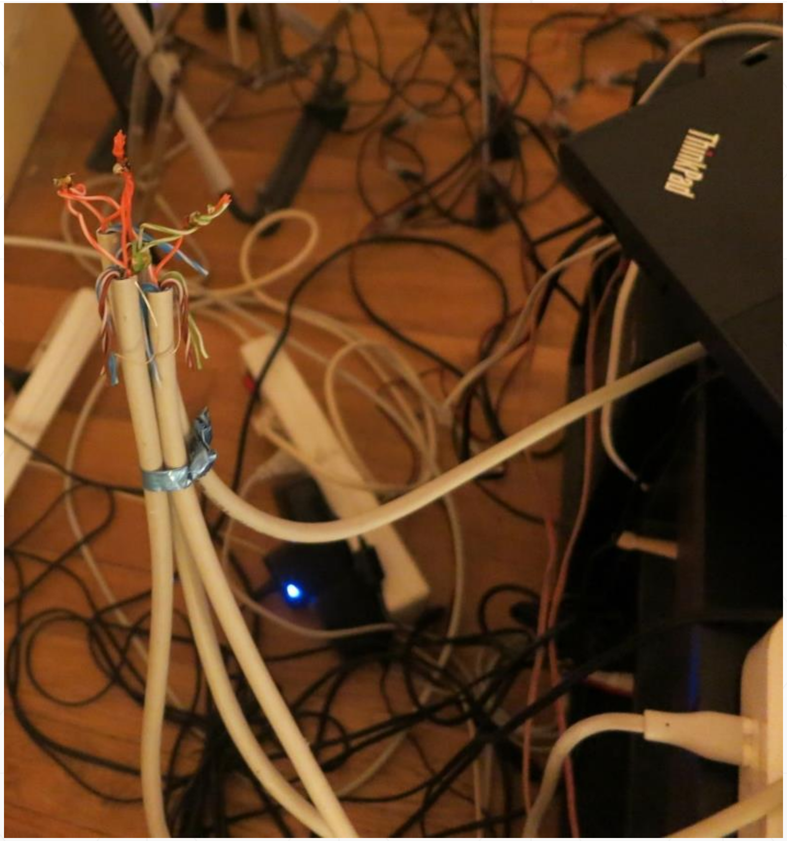
Who Am I?

- Jason Donenfeld, also known as **zx2c4**.
- Background in exploitation, kernel vulnerabilities, crypto vulnerabilities, and been doing kernel-related development for a long time.
- 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. Only layer 3!
- *Designed* for the Linux kernel
  - Slower cross platform implementations also.
- 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.
- Grew out of offensive research.
  - Techniques desired for stealth are equally as useful for tunnel defensive measures.

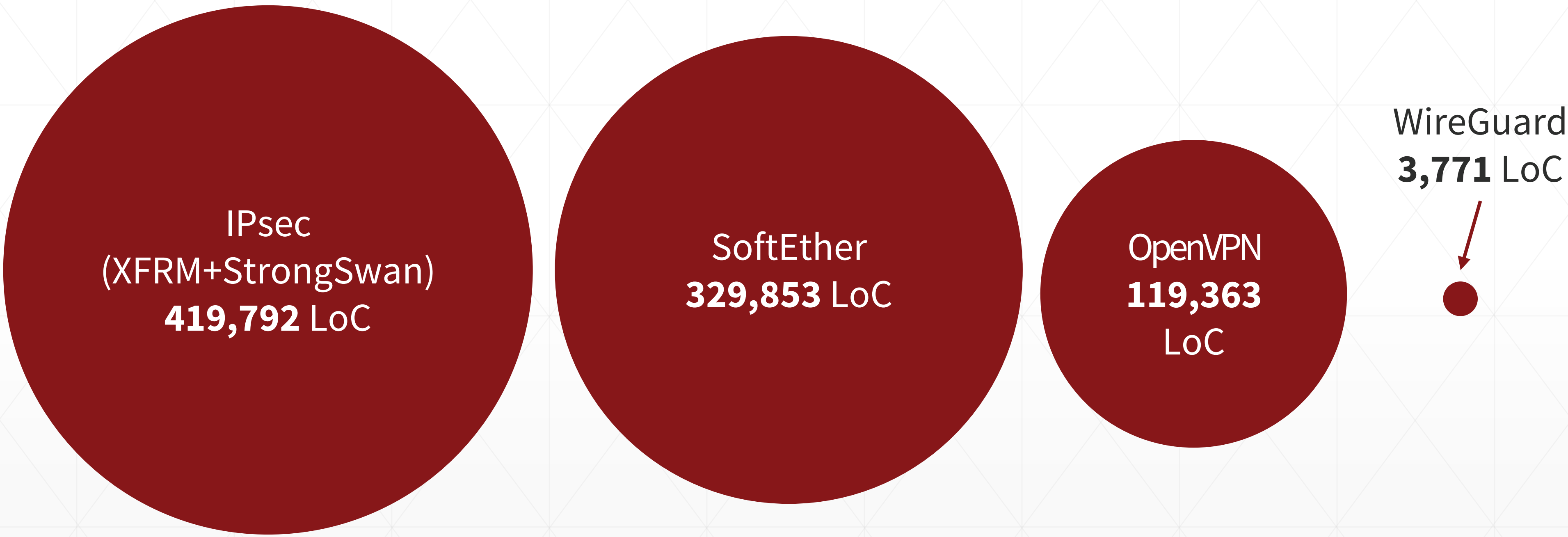


Easily Auditable

OpenVPN	Linux XFRM	StrongSwan	SoftEther	WireGuard
116,730 LoC Plus OpenSSL!	119,363 LoC Plus StrongSwan!	405,894 LoC Plus XFRM!	329,853 LoC	**3,771 LoC**

Less is more.

Easily Auditable



WIREGUARD

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.

Cryptokey Routing

- **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

Server Config

```
[Interface]
PrivateKey =
yAnz5TF+lXXJte14tji3zlMNq+hd2rYU
IgJBgB3fBmk=
ListenPort = 41414

[Peer]
PublicKey =
xTIBA5rboUvnH4htodjb6e697QjLERt1
NAB4mZqp8Dg=
AllowedIPs =
10.192.122.3/32,10.192.124.1/24

[Peer]
PublicKey =
TrMvSoP4jYQlY6RIzBgbssQqY3vxI2Pi
+y71lOWWXX0=
AllowedIPs =
10.192.122.4/32,192.168.0.0/16
```

Client Config

```
[Interface]
PrivateKey =
gI6EdUSYvn8ugXOt8QQD6Yc+JyiZxIhp
3GInSWRfWGE=
ListenPort = 21841

[Peer]
PublicKey =
HIgo9xNzJMWLKASShiTqIybxZ0U3wGLi
UeJ1PKf8ykw=
Endpoint = 192.95.5.69:41414
AllowedIPs = 0.0.0.0/0
```

Cryptokey Routing

Userspace:
`send(packet)`

→

Linux kernel:
Ordinary routing table
→ wg0

→

WireGuard:
Destination IP address
→ which *peer*

→

WireGuard:
`encrypt(packet)`
`send(encrypted)`
→ *peer*'s endpoint

WireGuard:
`recv(encrypted)`

→

WireGuard:
`decrypt(packet)`
→ which *peer*

→

WireGuard:
Source IP address
←→ *peer's* allowed IPs

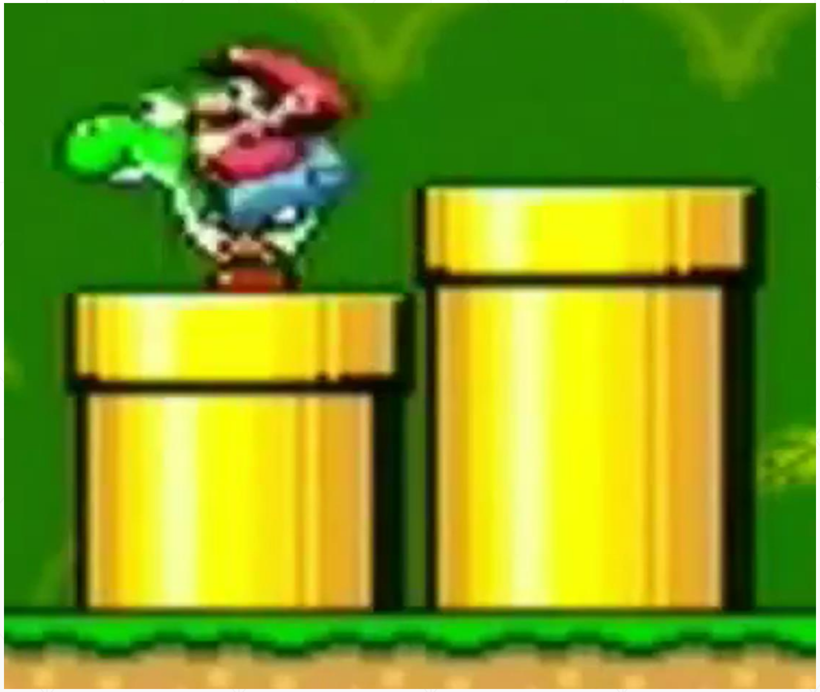
→

Linux:
Hand packet to networking stack

WIREGUARD

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.



Simplicity of Interface

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- Endpoints roam, like in mosh.
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Demo

Simple Composable Tools

- Since `wg(8)` is a very simple tool, that works with `ip(8)`, other more complicated tools can be built on top.
- Integration into various network managers:
  - OpenWRT
  - OpenRC netifrc
  - NixOS
  - systemd-networkd
  - LinuxKit
  - Ubiquiti's EdgeOS
  - NetworkManager (WIP)
  - …

Simple Composable Tools: `wg-quick`

- Simple shell script
- ```
  # wg-quick up vpn0
  # wg-quick down vpn0
  ```
- /etc/wireguard/vpn0.conf:

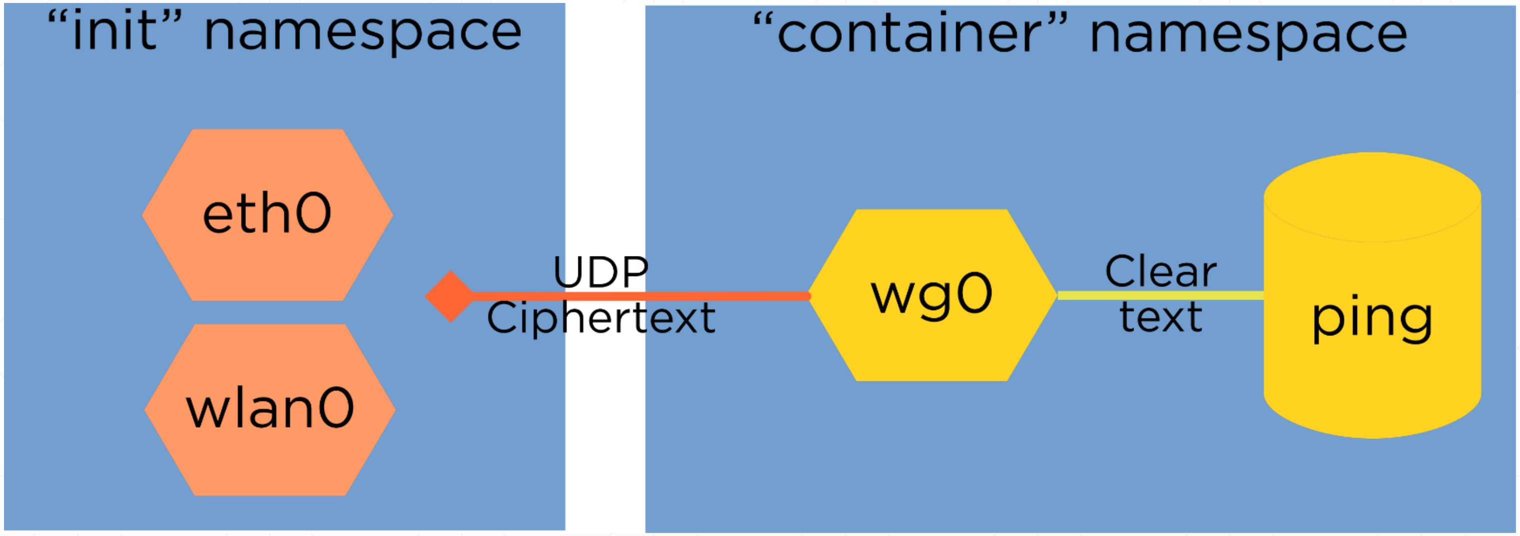
```
[Interface]
Address = 10.200.100.2
DNS = 10.200.100.1
PostDown = resolvconf -d %i
PrivateKey = uDmW0qECQZWPv4K83yg26b3L4r93HvLRcal997IGlEE=

[Peer]
PublicKey = +LRS63OXvyCoVDs1zmWRO/6gVkfQ/pTKEZvZ+CehO1E=
AllowedIPs = 0.0.0.0/0
Endpoint = demo.wireguard.io:51820
```
```

Network Namespace Tricks

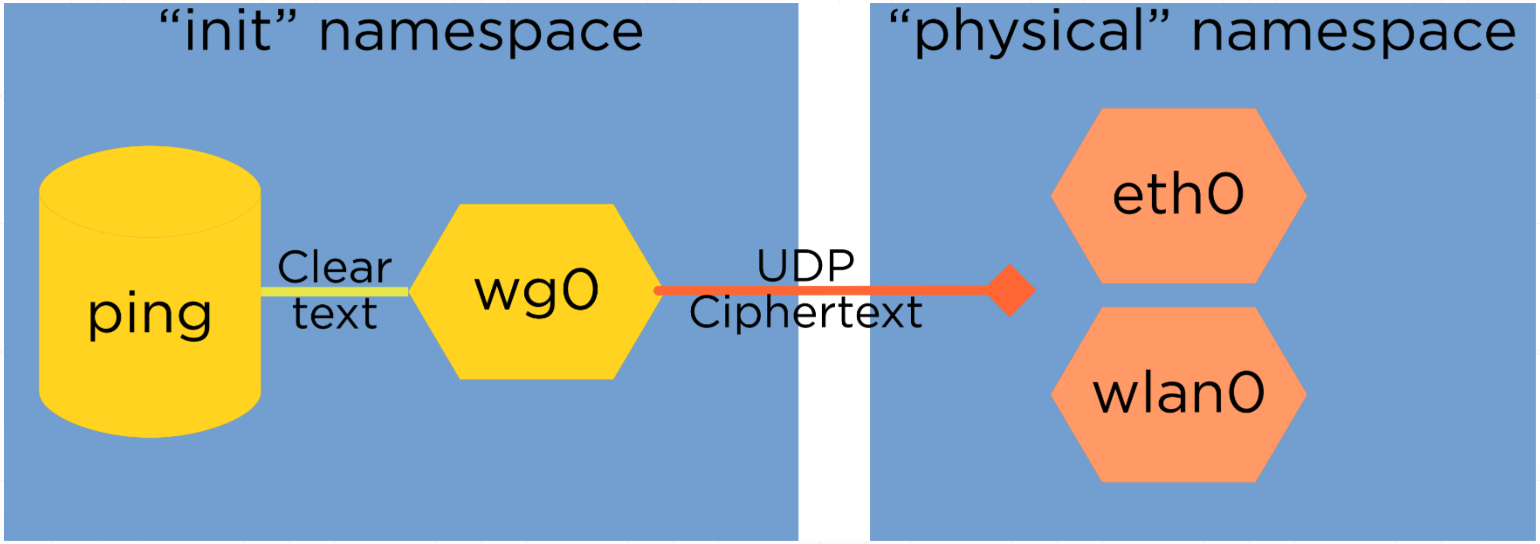
- The WireGuard interface can live in one namespace, and the physical interface can live in another.
- Only let a Docker container connect via WireGuard.
- Only let your DHCP client touch physical interfaces, and only let your web browser see WireGuard interfaces.
- Nice alternative to routing table hacks.

Namespaces: Containers




```
# ip addr
1: lo: <LOOPBACK,UP,LOWER_UP>
    inet 127.0.0.1/8 scope host lo
17: wg0: <NOARP,UP,LOWER_UP>
    inet 192.168.4.33/32 scope global wg0
```

Namespaces: Personal VPN




```
# ip addr
1: lo: <LOOPBACK,UP,LOWER_UP>
    inet 127.0.0.1/8 scope host lo
17: wg0: <NOARP,UP,LOWER_UP>
    inet 192.168.4.33/32 scope global wg0
```

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

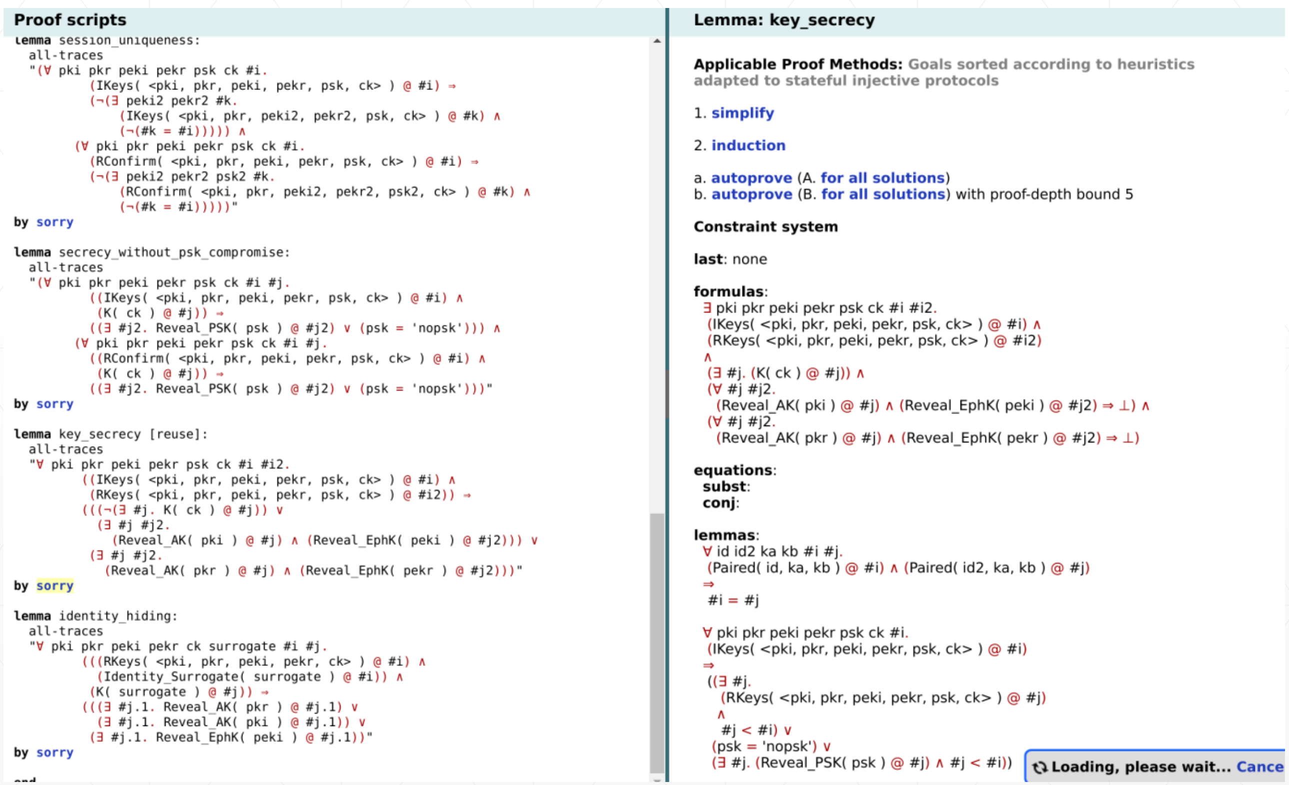
- We make use of Trevor Perrin's Noise Protocol Framework – noiseprotocol.org
  - Custom written very specific implementation of Noise_IKpsk2 for the kernel.
- The usual list of modern desirable properties you'd want from an authenticated key exchange
- Modern primitives: Curve25519, Blake2s, ChaCha20, Poly1305, SipHash2-4
- Lack of cipher agility!

Crypto

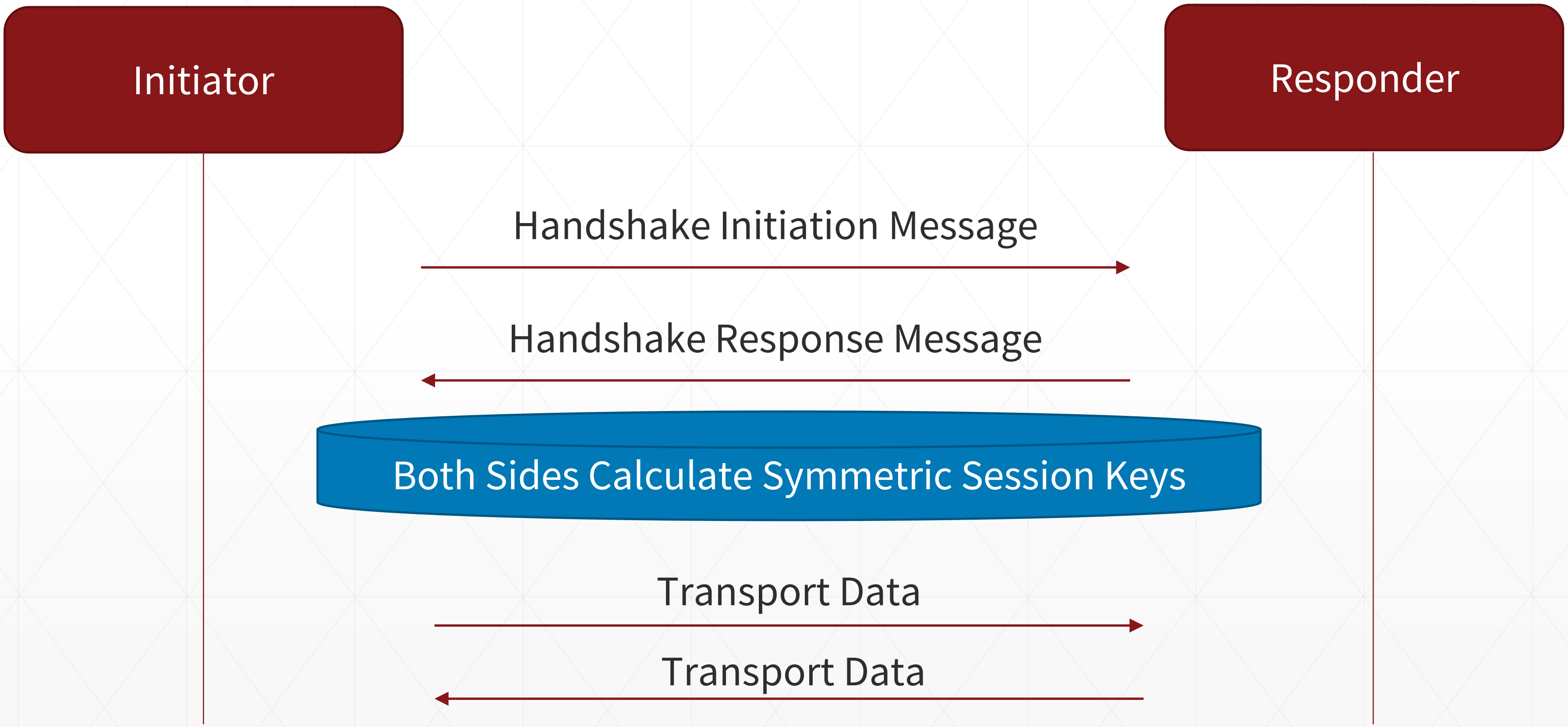
- Strong key agreement & authenticity
- Key-compromise impersonation resistance
- Unknown key-share attack resistance
- Key secrecy
- Forward secrecy
- Session uniqueness
- Identity hiding
- Replay-attack prevention, while allowing for network packet reordering

Formal Symbolic Verification

- The cryptographic protocol has been formally verified using Tamarin.



The Key Exchange



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: (Elliptic Curve) Diffie-Hellman Review

```
private A = random()
public A = derive_public(private A)
```

```
private B = random()
public B = derive_public(private B)
```

`ECDH(private A, public B) == ECDH(private B, public A)`

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.

The Key Exchange: NoiseIK

Alice	Bob
Static Private	Static Public
Ephemeral Private	Ephemeral Public

The Key Exchange: NoiseIK

Bob	Alice
Static Private	Static Public
Ephemeral Private	Ephemeral Public

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.

```
zx2c4@thinkpad WireGuard/src $ cloc noise.c
-------------------------------------------------------------------------------
Language      blank         comment         code
-------------------------------------------------------------------------------
C               87              39           441
-------------------------------------------------------------------------------
```

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} complexity.
  - 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.

Hybrid PQ Resistance

- Alternatively, do a post-quantum key exchange, *through*, the tunnel.
- PQ primitives not directly built-in because they are slow and new and likely to change.
- PSK design allows us to easily swap them in and out for experiments as we learn more.

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 “galette”. Ask me again with the magic word.
  - Initiator: My magic word is “galette”. 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(responder_secret, initator_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: `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.
- 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:

```
XAEAD(
  key=HASH(responder_public_key),
  additional_data=handshake_message,
  MAC(key: responder_secret, initiator_ip_address)
)
```

- `mac2` is then calculated as:

  ```
  MAC(key: cookie, handshake_message)
  ```

  - If it's valid, the message is processed even under load.

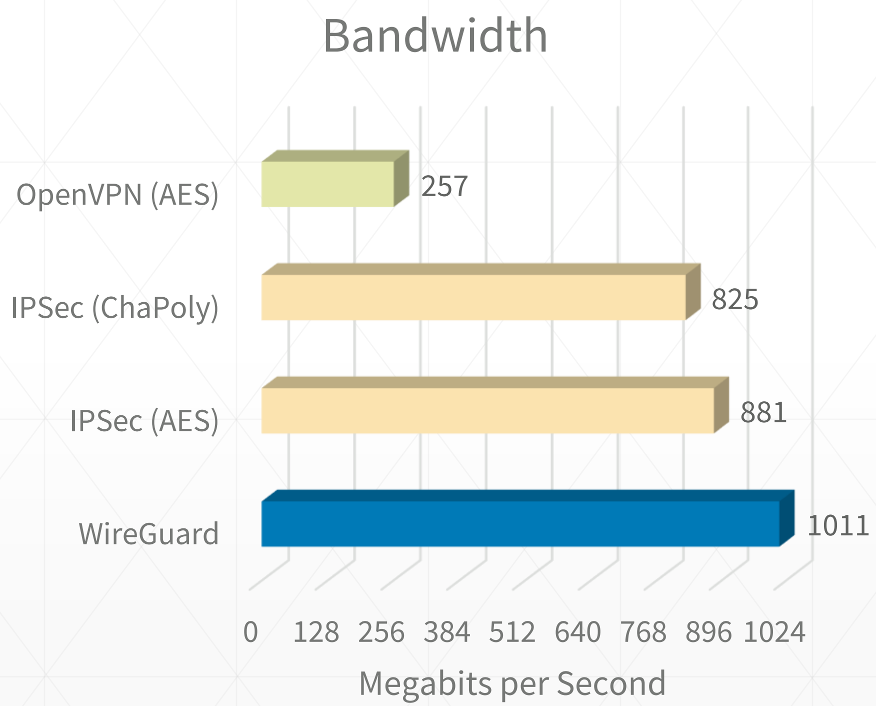
Cookies: The WireGuard Variant

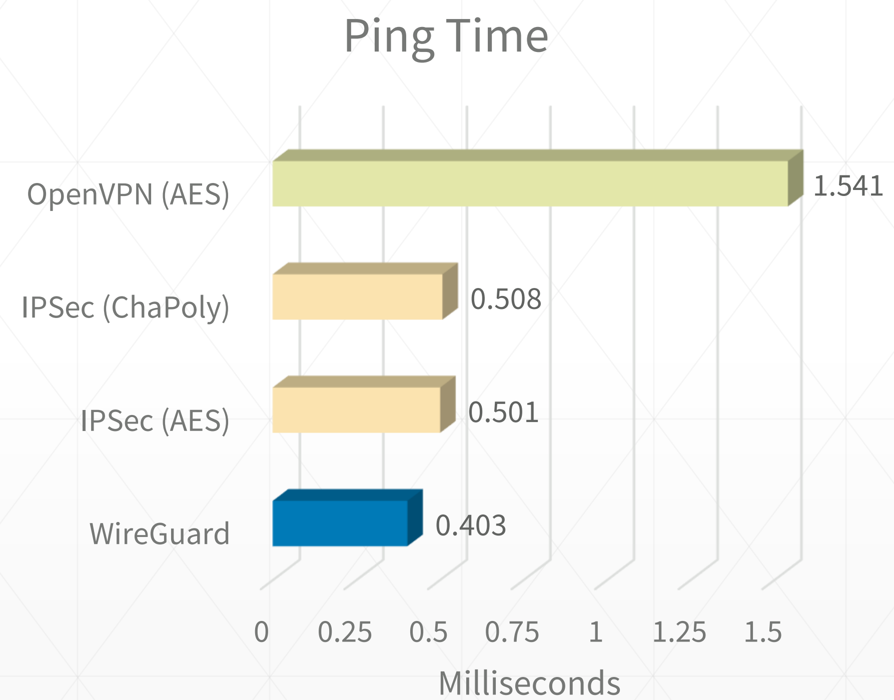
- Once IP address is attributed, ordinary token bucket rate limiting can be applied.
- Maintains stealthiness.
- Cookies cannot be intercepted by somebody who couldn't already initiate the same exchange.
- Initiator cannot be DoS'd, since the encrypted cookie uses the original handshake message as the "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





WireGuard

Multicore Cryptography

- Encryption and decryption of packets can be spread out to all cores in parallel.
- Nonce/sequence number checking, receiving, and transmission must be done in serial order.
- Requirement: fast for single flow traffic in addition to multiflow traffic.

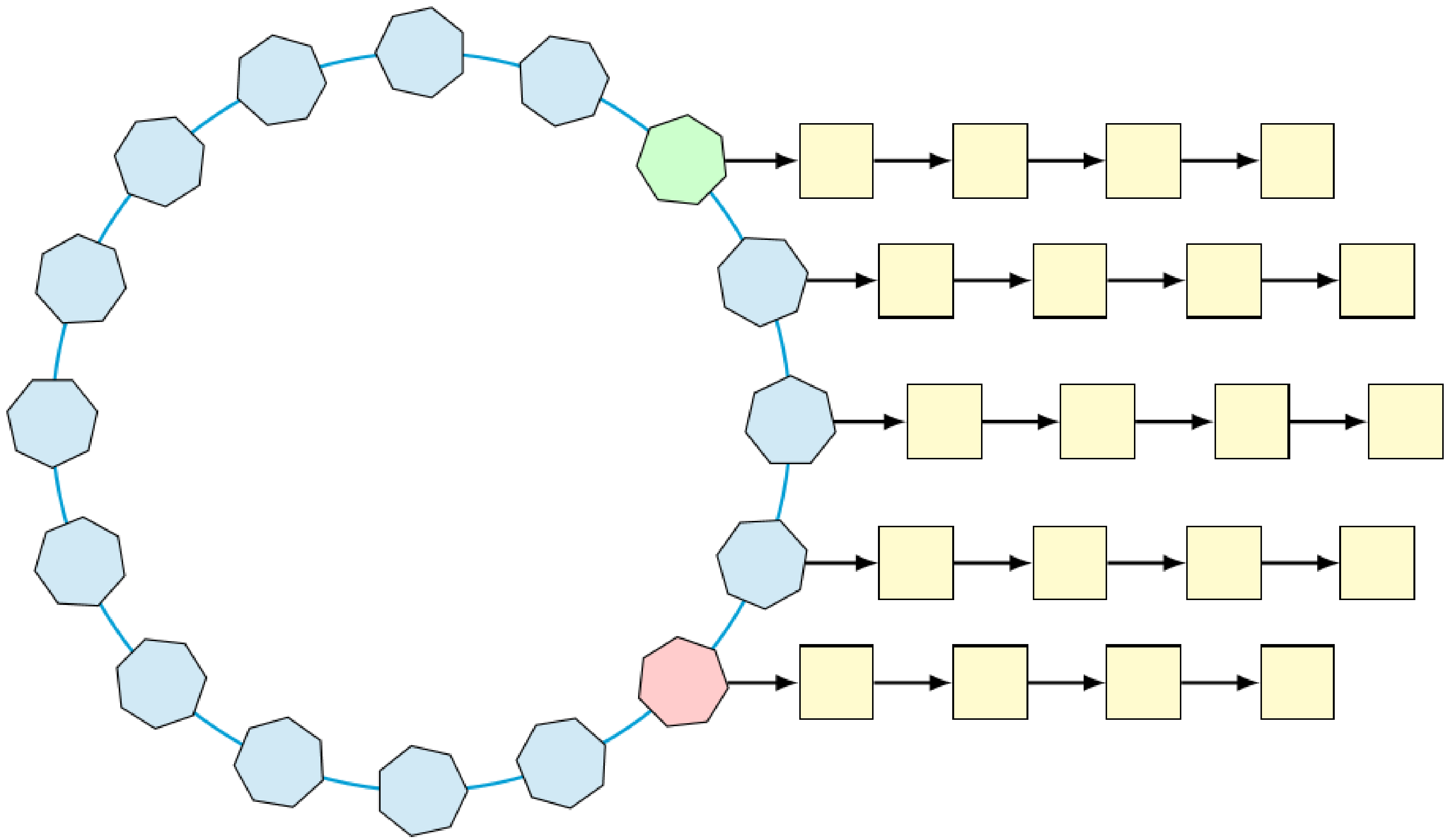
Multicore Cryptography

- Parallel encryption queue is multi-producer, multi-consumer
- Single queue, shared by all CPUs, rather than queue per CPU
  - No reliance on process scheduler, which tends to add latency when waiting for packets to complete
  - Serial transmission queue waits on ordered completion of parallel queue items
- Bunching bundles of packets together to be encrypted on one CPU results in high performance gains
  - How to choose the size of the bundle?

Generic Segmentation Offload

- By advertising that the `net_device` suppports GSO, WireGuard receives massive “super-packets” all at the same time.
- WireGuard can then split the super-packets by itself, and bundle these to be encrypted on a single CPU all at once.
- Each bundle is a linked list of skbs, which is added to the ring buffer queue.

Multicore Cryptography



Sticky Sockets

- WireGuard listens on all addresses, but manages to always reply using the right source address.
- Caching of destination address and interface of incoming packets, but ensures that this stickiness isn't too sticky.
- Does the right thing every time – interface disconnects, routes change, etc.
- Actually maps mostly nicely to possible semantics of `IP_PKTINFO`, so userspace implementations can do this too, sort of.

Continuous Integration

- Extensive test suite, trying all sorts of topologies and many strange behaviors and edge cases.
- Every commit is tested on every kernel.org kernel (and a few more), and built and run fresh in QEMU
- Tests on x86_64, ARM, AArch64, MIPS

build.wireguard.com

Linux 4.14-rc8 (aarch64)	Success
Linux 4.14-rc8 (arm)	Success

```
Show build details.

    WireGuard Test Suite on Linux 4.14.0-rc8 armv7l

[+] Mounting filesystems...
[+] Module self-tests:
 *  routing table self-tests: pass
 *  nonce counter self-tests: pass
 *  curve25519 self-tests: pass
 *  chacha20poly1305 self-tests: pass
 *  blake2s self-tests: pass
 *  ratelimiter self-tests: pass
[+] Enabling logging...
[+] Launching tests...
[+] ip netns add wg-test-44-0
[+] ip netns add wg-test-44-1
[+] ip netns add wg-test-44-2
```

Linux 4.14-rc8 (mips)	Success
Linux 4.13.11 (x86_64)	Success
Linux 4.9.60 (x86_64)	Success
Linux 4.4.96 (x86_64)	Success
Linux 4.1.45 (x86_64)	Success

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.

Jason Donenfeld

- Personal website: www.zx2c4.com
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- Available now for all major Linux distros, FreeBSD, OpenBSD, macOS, and Android: wireguard.com/install
- Paper published in NDSS 2017, available at: wireguard.com/papers/wireguard.pdf
- `$ git clone https://git.zx2c4.com/WireGuard`
- wireguard@lists.zx2c4.com
  lists.zx2c4.com/mailman/listinfo/wireguard
- `#wireguard` on Freenode
- **STICKERS FOR EVERYBODY**
- Plenty of work to be done: looking for interested devs.