Tor's Circuit-Layer Cryptography

Attacks, Hacks, and Improvements

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Why should you care about privacy?

"There is an entire genre of YouTube videos devoted to an experience which I'm certain that everyone in this room has had. It entails an individual, who, thinking they're alone, engages in some expressive behaviour – wild singing, girating dancing, some mild sexual activity – only to discover that, in fact, they are not alone, that there's a person watching and lurking, the discovery of which causes them to immediately cease what they're doing in horror. The sense of shame and humiliation in their face is palpable: it's the sense of 'this is something I'm willing to do only if no one else is watching.' This is the crux of the work on which I have been singularly focused for the sixteen months: the question of why privacy matters."

—Glenn Greenwald, TED Talk, October 2014

Introduction to Tor

Background: Anonymising proxies

- Typically application-specific proxies, e.g. HTTP proxies, or generic request-based proxies, e.g. SOCKS proxies
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Designs like anonymising proxies which place ultimate trust in any single node in the network cannot provide any strong guarantees to anonymity, because these single points-of-failure can be exploited—legally or otherwise—to deanonymise users.

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- Message shuffling in order to achieve unlinkability.

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  - To be fair, Chaum invented RSA blind signing two years later, in 1983.

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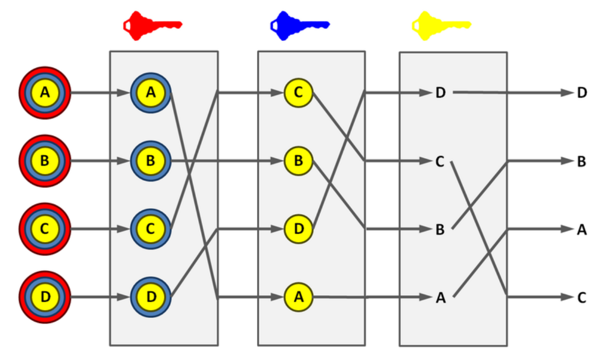
First proposed way to chain mixes together is called *cascade mixing*, and uses all nodes in the network, in a specific order (grey boxes), each of which shuffles the order of outgoing messages:



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- They illustrate a number of attacks to show that, if *only one* mix is honest in the network, the anonymity of the messages going through it can be compromised.
- These attacks rely on compromised mixes which exploit some knowledge of their position in the chain ...
- ... or multiple messages using the same sequence of mixes through the network.

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Onion Routing: Combine the advantages of each system

- Use (non-cascading) mix (called a Tor *circuit*) of proxies, which are called Tor *relays* or Tor *nodes*
- Use asymmetric cryptography for establishing an (one-way) authenticated, encrypted channel, then use fast symmetric cryptography.

What is Tor?

Tor is an anonymity network, which uses onion routing to encapsulate client traffic in a manner such that each node in the client's chosen path only knows the destinations before and after it.

How Tor Works: Directory Authorities and Consensus Protocol

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- Despite the misleading name, “consensus” documents are created by majority vote.

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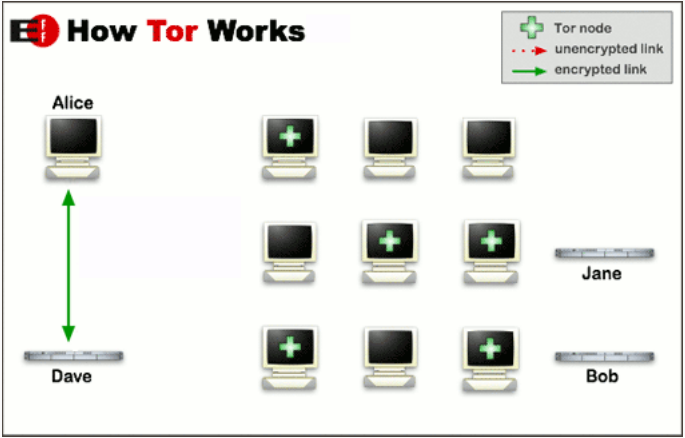
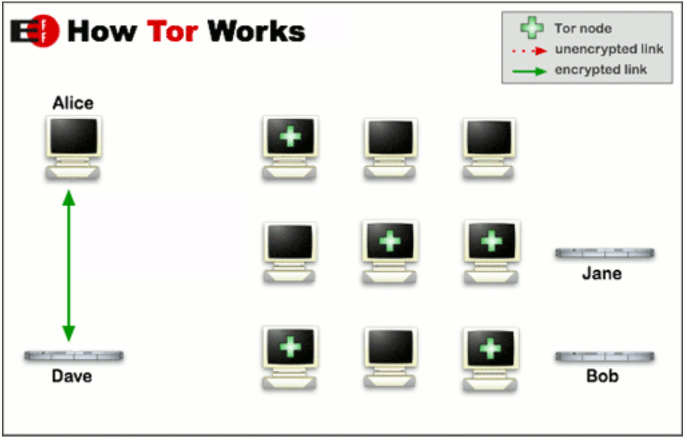
We currently require that all clients know about all valid nodes in the Tor network, in order to safeguard against *partitioning attacks* where an adversary uses a client's partial knowledge of the network topology in some manner to gain some advantage (usually to increase feasibility of further attacks, e.g. a correlation attack).

When a new *stream* is created (e.g. some data to be transmitted over Tor has arrived), a circuit is either chosen from a list of pre-constructed circuits, or a new circuit is created as needed. Using the same bandwidth-weighted list (as before), the Client selects a *Middle* relay and an *Exit* relay for the new circuit.

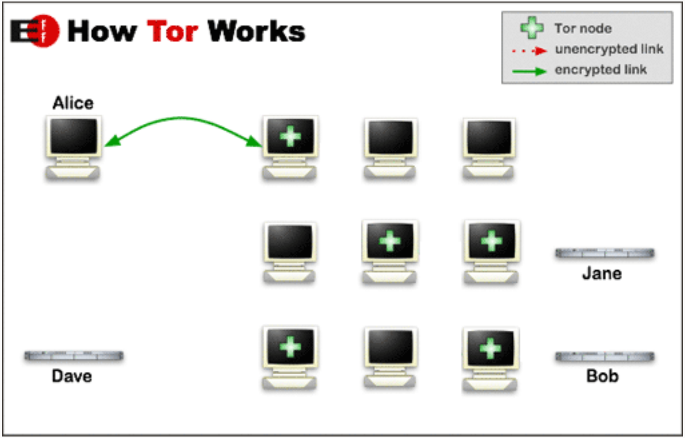
Establishing a Circuit



Request consensus from Directory Authorities (DirAuths)



Pick entry, middle, and exit node; obtain their public keys from directory mirror (DirServ)



Exchange symmetric key with entry node (Diffie-Hellman)

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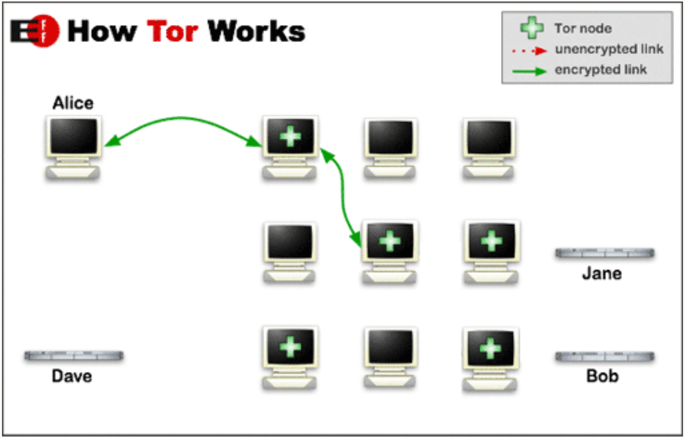

Exchange key with middle node (tunnelled through entry node)

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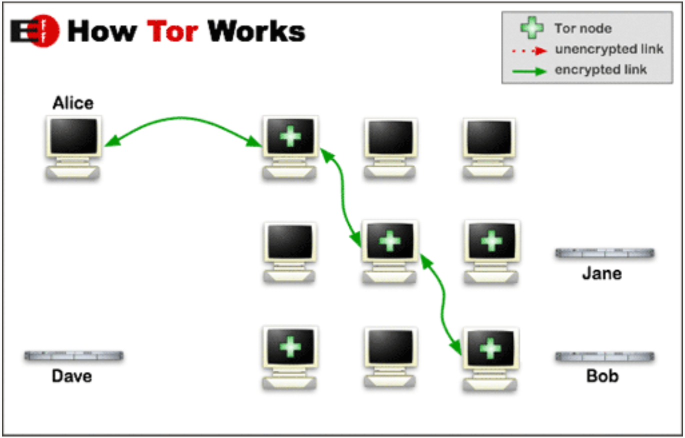
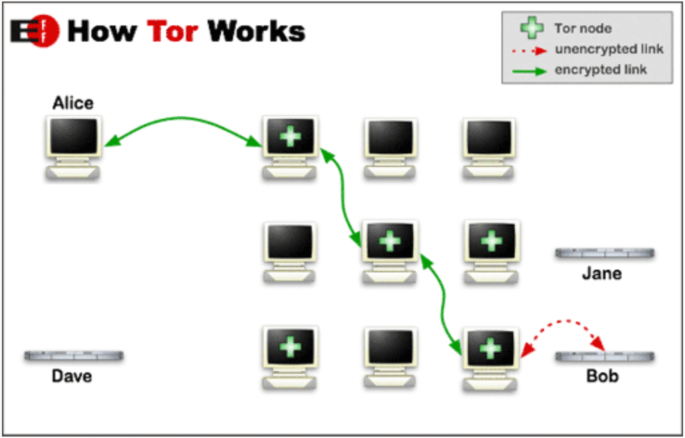


Exchange key with exit node (tunnelled through middle node, tunnelled through entry node)



Communicate with Bob

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- The Client next creates a **RELAY EXTEND** cell to extend the circuit to the Middle relay ($\mathbf{R_2}$) which contains the first stage of the circuit-level handshake with $\mathbf{R_2}$. It encrypts this relay cell with $\mathbf{KF_{R_1}}$ and sends it forward to $\mathbf{R_1}$, who decrypts with $\mathbf{KF_{R_1}}$ and packages the content into a **RELAY CREATE** cell, which is sent over a newly established TLS connection between R_1 and R_2, TLS_{R_2} who sends its half of the circuit handshake in response, packaged in a **RELAY CREATE** cell and reverse encrypted (with the corresponding $\mathbf{KB_i}$ keys) down the reverse path.

Circuit Extension to the Exit Relay

- After the Client's handshake with the Middle relay (R_2) completes, the Client creates another **RELAY EXTEND** cell to extend the circuit to the Exit relay, R_3. This is then tunneled over $\mathbf{TLS_{R_2}}$ (which is tunneled through $\mathbf{TLS_{R_1}}$). The cell itself is super-encrypted with $Enc(\mathbf{KF_{R_2}}, Enc(\mathbf{KF_{R_1}}, \mathbf{CELL}))$.

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- The Exit relay R_3 receives this **RELAY CREATE** cell, does $Dec(\mathbf{KF_{R_3}}, \mathbf{CELL})$ and receives the traffic the client had intended to proxy (which is hopefully further encrypted with some application-layer encryption, e.g. TLS, SSH, etc).

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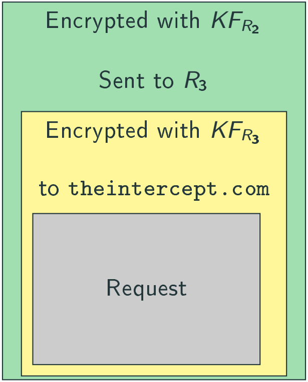

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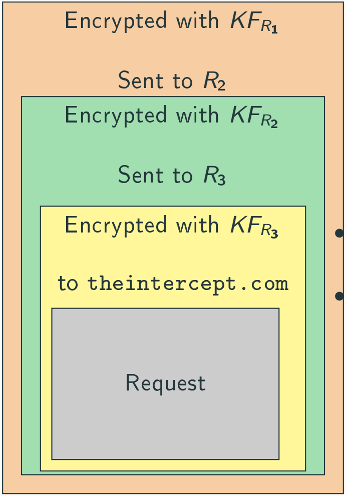

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  - Entry relay R_1 (keys KB_{R_1}, KF_{R_1})
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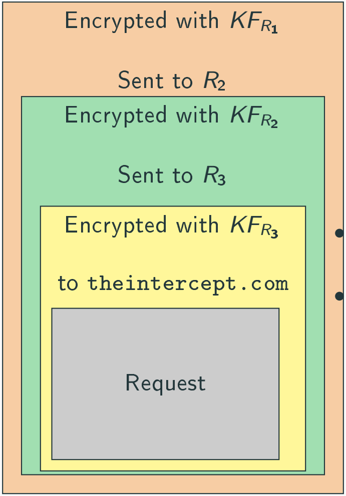
How Tor Works: Relay Cells on the Forward Path



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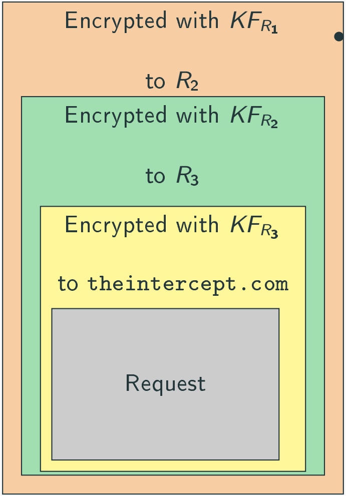

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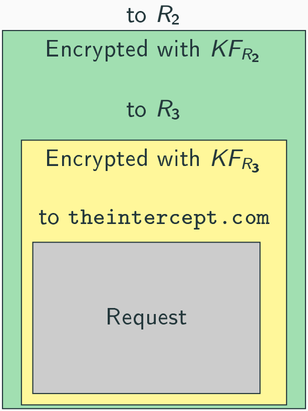

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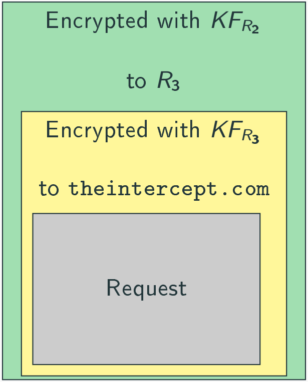

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- R_3 receives response from `theintercept.com`.
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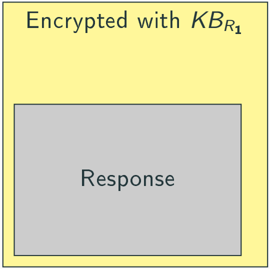

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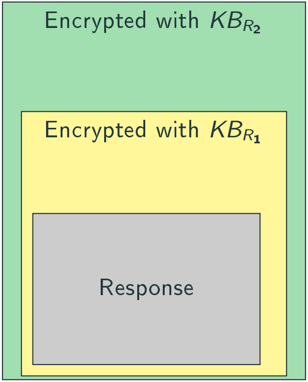

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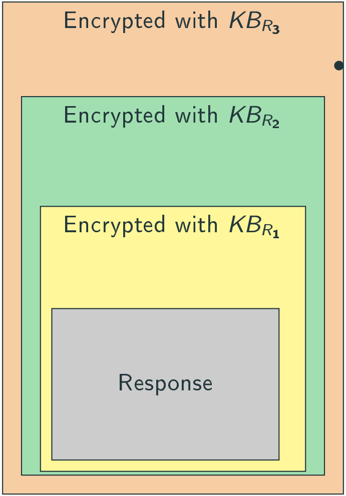

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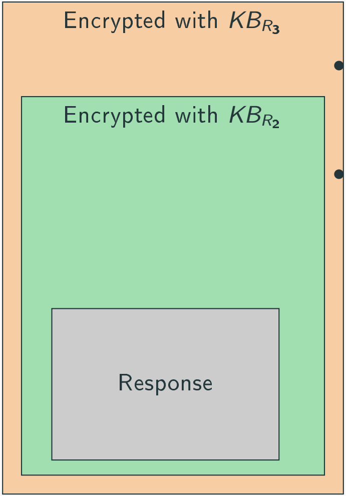

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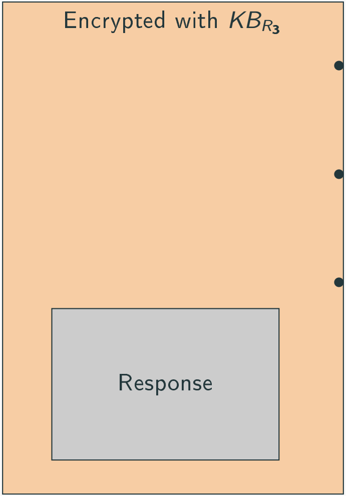

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- The Tor Client decrypts with $\mathbf{KB_{R_1}}$ and thus receives the response.

Tor as Censorship Circumvention Mechanism

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- Can also use Tor to circumvent country filters:
  - Need an IP address that isn't in Germany (e.g. because of GEMA restrictions on YouTube): can use Tor access YouTube from a non-German IP address.

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Since 2010, various nation state adversaries have been conducting active probing and enumeration attacks to attempt to collect all of Tor's bridges. Since then, an arms race to distribute the bridge addresses to honest clients without these adversaries obtaining them has ensued.

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In 2012, Ethiopia began blocking all TLS (and hence blocking all Tor) traffic by looking for the client HELLO. Any packet with the string **TLS_DHE_RSA_WITH_AES_256_CBC_SHA** in it is dropped. If you pick **TLS_DHE_RSA_WITH_AES_128_CBC_SHA** instead, or fragment the ciphersuite list, it works anyway.

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Solution: Tor's Pluggable Transports

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Yawning has recently created a newer PT, called "basket2" which uses a hybrid handshake between Ed448 Goldilocks and NewHope.

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While there’s probably not any remaining research problems in Pluggable Transports for producing academic papers, writing new PTs is an incredibly fun project (suitable for Master’s, or sufficiently-motivated Bachelor’s, students) because you get to be super #yolo and use experimental new crypto.

While Pluggable Transports effectively obfuscate the link between a Client and a Bridge—and modern Pluggable Transports make the traffic data look uniformly indistinguishable from random—this turns out to be insufficient to prevent Bridge *enumeration attacks*.

Bridge Enumeration Attacks, Part II

While Pluggable Transports effectively obfuscate the link between a Client and a Bridge—and modern Pluggable Transports make the traffic data look uniformly indistinguishable from random—this turns out to be insufficient to prevent Bridge *enumeration attacks*.

Another possibility is to simply automate obtaining Bridges in the same manner an honest client would.

The proposed solution uses attribute-based credentials to record honest users' good behaviour (i.e. the bridges not being censored/blocked), which also serves to effectively lock censoring adversaries out of the distribution system.

A Social Protocol for Bridge Distribution

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Wang, Q., Lin, Z., Borisov, N., & Hopper, N. (2013, February). rBridge: User Reputation based Tor Bridge Distribution with Privacy Preservation. In NDSS.

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Currently, I'm redesigning the protocol and implementing the scheme using an anonymous credential based on algebraic MACs.

The best game a censor can play against the rBridge scheme is to exhibit good behaviour in order to slowly amass brownie points, trading them in for new Bridges and invite tickets. Using an *Event-Driven Blocking Strategy*, that is, waiting until some important event, e.g. a political protest, and blocking all known Bridges en masse, is the most effective.

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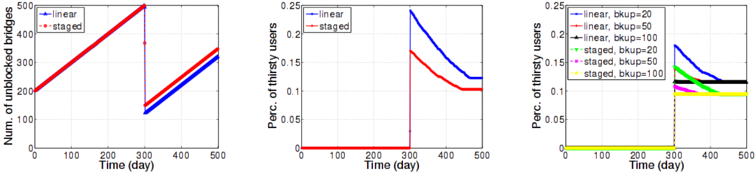

(a) Unblocked bridges (b) Thirsty users (c) Thirsty users with backup bridges

Figure 4: Event-driven blocking ($f = 5\%$)

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- These researchers claim to have run this attack on the live Tor network in 2011, enumerating 2369 Bridges in just 14 days.

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We can exploit this unintended feature to give Bridges *their own* Guards, unbeknownst to the client, thus protecting Bridges from malicious Middle relays.

Future Improvements to Tor's Circuit-Level Cryptography

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Due to using CTR mode and re-MACing at each hop, a tagging attacks is possible.

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- The adversary may repeat this attack until a colluding Exit relay is chosen by the client.

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Other potential (non-cryptographic) improvements to Tor's circuit protocol: There's not really any reasons we haven't considered disparate forward and reverse paths. Nothing in the crypto or protocol is technically preventing it. It would be an interesting area of research to see the changes (and, hopefully, improvements to anonymity guarantees) which might be derived from disjoint path selection.

Tor Relay Handshake

Tor's Relay Handshake Protocol: NTor

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In the event of a quantum-capable adversary in the future, who is currently recording Tor handshakes now, we need a post-quantum handshake.

Proposed Post-Quantum Hybrid Handshakes for Tor

A Modular Hybrid Handshake

Tor proposal #269: Transitionally secure hybrid handshakes
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John Schanck currently has a branch which integrates NTRU, and I'm currently working on an expirmental branch which implements the modular hybrid handshake (#269) and adds a plugin to implement the NewHope version (#270).

Questions & Contact

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