Network Security HS20

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Contents

1 Crypto Refresher

Secrecy Keep data hidden from unintended receivers.
Confidentiality Keep *somone else's* data secret.
Privacy Keep data *about a person* secret.
Anonymity Keep identity of a protocol participant secret.
Data integrity Prevents unauthorized or improper changes to data.
Entity Authentication / Identification Verify the identity of another protocol participant.
Data Authentication Ensure data originates from claimed sender
Semantic Security If adversary had to guess value of a single plaintext bit, can guess at best at random.

1.1 Symmetric Crypto

Use same key k for encryption and decryption:

- **Stream Ciphers**:
  - One-time pad: Use unique random keystream for each message (secure if we dont reuse keystream, else we can xor two ciperhtexts and key cancels out)
  - Practical Stream Ciphers: Use PRG to generate keystream from seed, send ciphertext and IV (initialization vector = seed)
  - Examples: AES in CTR mode, ChaCha Stream Cipher.
  - Vulnerabilities
- **Block Ciphers**: Pseudo random permutation (PRP), each key defines a one-to-one mapping of input block to output block. Need to encrypt each block seperately for that use a mode of operation.
  - Modes of Operation: CTR (Counter Mode), CBC (Cipher block chaining), GCM (Galois Counter Mode -> Encryption and Authentication in single pass).
  - Examples: DES, AES
- **Message Authentication Codes (MAC)**: Cryptographic checksum with a symmetric key for authentication/ integrity.
  - Hash-based MAC (HMAC)
  - Block-cipher based MAC (CMAC)

1.2 Asymmetric Crypto

A public key pk for encryption and secret key sk for decryption.

- Diffie-Hellman Key Generation: slide 25.
  - Discrete Logarithm Problem: $g^a mod p = x$, given x, g and p find a is assumed to be very hard.
  - Problem: Man-in-the-Middle Attack
- RSA public, secret keypair generation: slide 29.
- Encrypted Key Exchange (EKE) DH Protocol: slide 31.
- Signature: encrypt a message with your secret key, others can decrypt it using your public key and thus know it comes from you. Authentication enables the receiver to verify origin, signature additionally can convince third party of origin as well.

Asymmetric vs Symmetric Crypto:

Asymmetric Crypto	Symmetric Crypto
Need shared secret key	Need authentic public-key infastructure (PKI)
128 bit key for high security	3072 bit key (RSA), 384 bit key (EC) for high security
fast	slower
hardware speedup	limited HW speedup

1.3 Hash Functions:

Maps arbitrary length input into finite length output and fulfills following properties (Examples: MD5, SHA3):

- **One-way**: Given $y = H(x)$ cannot find x' s.t. $H(x') = y$
- **Weak collision resistance**: Given x, cannot find x' s.t. $H(x) = H(x')$
- **Strong collision resistance**: Cannot find $x \neq x'$ s.t. $H(x) = H(x')$

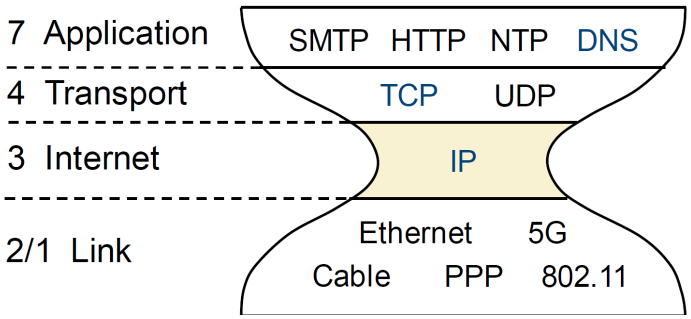
2 Networking Refresher

Component	Function	Example
application, or app, user	uses the network	Skype, iTunes, Firefox
host, or end-system, edge device, node, source, sink	supports apps	laptop, mobile, desktop
router, or switch, node, hub, intermediate system	relays messages between links	access point, cable/DSL modem, Internet router
link, or channel	connects nodes	wires, wireless

- **Autonomous System (AS):** Internet is a network of networks. ASes only exchange information at edges, internal topology hidden. (Advantages: internal infrastructure and protocols are independent, more efficient routing)
  - Internet service providers (ISP)
  - Global backbone networks (CenturyLink, Verizon)
  - Universities, large companies (Google, Cloudflare)

2.1 Layering / Encapsulation

- **Protocols and Layers**: main structuring method used to divide up network functionality
  - Each instance of a protocol uses only the services of the lower layer but should not look at data from higher protocols (violated in e.g. NAT)
- **Encapsulation**: mechanism used to effect protocol layering. Lower layer ("envelope") wraps higher layer ("letter") content. Each layer adds its own header.
  - Advantages: Higher layers do not need to worry about low-level details. Possibility to connect different systems.
  - Disadvantages: Some optimization potential is lost. Often Layering not strictly followed.



- **Physical/Link Layer**: less relevant for this lecture.
- **Internet Layer**:
  - ***Internet Protocol***: Internet Layer, IPv4/IPv6 64/128 bit addresses
    - End hosts specify source and destination.
    - No control over paths.
    - Internet Control Message Protocol (ICMP) for error messages.
    - Allocation and Ownership of IP addresses handled by Authorities (IANA)
  - ***Border Gateway Protocol (BGP)***: Internet Layer
    - Border Gateway Protocol (BGP) for global routing (interdomain) and IP for intradomain routing. Glues the internet together.
    - Business relationships shape topology: An AS only forwards traffic where it can earn money from someone.
  - **Reminder: NAT** (Network Address Translation) connects an internal network to an external network. Many internal hosts are connected to same external IP address. NAT keeps track of which internal host is connected to which of the NATs external ports.
- **Transport Layer**:
  - ***Transmission Control Protocol (TCP)***:
    - Deliver data to correct application
    - Split data into packets (segmentation), reassemble at destination (reassembly)
    - Make sure data is unchanged and arrives in order (ACK's, checksums, sequence nrs)
    - Do not overload receiver (flow control with sliding window sl. 66)
    - Do not overload the network (congestion control sl 68.)
    - TCP Three-way handshake and connection release (sl. 62)
  - ***User Datagram Protocol (UDP)***
    - Only delivers packets to correct application.
    - Checksum for error detection
    - No segmentation, no retransmission, no flow control, no congestion control.
    - No connection establishment, very little overhead but no reliability.
- **Application Layer**:
  - **Domain Name System**:
    - Translates between human-readable host names and IP addresses.
    - Hierarchical name space
    - Distributed operation
    - Recursive Resolvers: Resolve the domain name recursively and make extensive use of caching at every step.

2.2 Routing / Forwarding

- **Routing**: (part of Control Plane) is the process of discovering best routes in network. (network-wide, expensive, performed ahead of time)
- **Forwarding**: (Data Plane) is the process of sending packet on its way (local computation for node, very fast)
- **Rules of Routing Algorithms**:
  - All nodes are alike; no controller.
  - Node can exchange messages concurrently with neighbors to gain knowledge of topology.
  - There may be node/link failures
- ***Distance-Vector (DV) Routing***:
  - Simple early routing approach
  - Distributed version of Bellman-Ford algorithm
  - Works but very slow convergence after some failures.
- ***Link-State (LS) Routing***:
  - 1. Nodes flood topology in the form of link-state packets
  - 2. Each node computes its own forwarding table (Dijkstra's alg.)
  - Faster convergence, supports multipath, but more state and computation required.
- ***Path-Vector (PV) Routing***:
  - Extenstion of DV routing, where full paths are included. Overcomes issues of DV routing.
  - E.g: BGP

2.3 Reliability and Security

- **Reliability**: Checksums and error-correcting codes can detect accidental errors. Can be corrected through error correction or retransmission.
- **Security**: Additional mechanism are necessary to prevent malicious modifications (MACs, Signatures). Most original networking protocols only had reliability but not security.

3 Public Key Infrastructure (PKI)

3.1 Overview

Main challenge of public-key systems is key authentication, as keys need to be distributed via authentic channels. PKI's provide a way to validate public keys.

CA Certification Authority

Public-key certificate is signed and binds a name to a public key

Trust anchor self-signed certificates of public keys that are allowed to sign other certificates

X.509 standard format of digital certificate

3.1.1 X.509

- Two sections: data and signature section
- A CA assigns a unique name to each user and issues a signed certificate
- Often name is the domain or Email address

3.2 Problems of PKI

- If the private key of a root of trust is obtained, the adversary can issue any certificates he wants.
- **Content Delivery Network**:
  - distributed network of servers for hosting websites for domains
  - CDN's only need one single certificate for multiple domains. E.g. Incapsula.com is hosting a banking website and the Chick-fil-a website, so they have the same certificate, lol.
  - **Problem**: one website could impersonate another website on the CDN-Server and access the website
- **Compelled certificates**:
  - public/private key pair for law enforcement (MitM-attacks on TLS) with a CA certificate enabling private key to sign additional certificates
  - Pre-made MitM-Boxes with a compelled certificate exist (for government use)
  - **Problem**: If box is obtained by adversary, it can be hacked and the compelled certificate keys can be used to sign fake certificates.
- **Statistics**:
  - 300 roots of trust (root CA's)
  - 1200 intermediate keys users don't see in the browser, but are still trusted

3.3 Two approaches for trust roots:

- **Monopoly model**: single root of trust
  - E.g. DNSSEC
  - **Problem**: world cannot agree on who controls root of trust
- **Oligarchy model**: numerous roots of trust
  - E.g. SSL/TLS PKI (over 1000 trusted root CA certificates)
  - **Problems**:
    - Weakest-link security: single compromised entity enables MitM-attack
    - Not trusting one trust roots result in unverifiable entities

3.4 Improve TLS

3.4.1 Let's Encrypt

Goal provide free certificates based on automated domain validation, issuance and renewal

- Non-profit, no company behind (sponsored by many companies tho)
- More than 100 million certificates issued until 2017
- short-lived certificates: 90 days
- Based on ACME (Automated Certificate Management Environment). Communications protocol for automating interactions between certificate authorities and their users' web servers, allowing the automated deployment of public key infrastructure at very low cost. (Wikipedia)

3.4.2 Extended validation entities

Levels of trust:

- **No SSL/TLS**
- **Domain Validation (DV)** Automated system like ACME
- **Organization Validation (OV)** Almost indistinguishable from DV
- **Extended Validation (EV)** Entities (companies) are being validated, maybe physically, costs over 1000 CHF

Problem with EV: If PKI is compromised and someone issues a DV for an EV domain, normally, people don't realize it, so-called "downgrade attack"

3.4.3 HTTP Strict Transport Security (HSTS)

Goal allows servers to declare that clients should only use HTTPS

- Prevents some "downgrade", "SSL stripping" and "session hijacking" attacks
- Browsers should automatically redirect to HTTPS or display a warning message

3.4.4 HTTP Public-Key Pinning (HPKP)

Goal the server sends a set of publik keys to client. Only those are valid for connection to this domain.

Problem Public key is cached in browser. If domain has new public key, user cannot access website anymore.

3.4.5 Certificate revocation list

Mechanism to invalidate certificates

Goal CA periodically publishes Certificate Revocation List

Problem If adversary controls the network, the can block the revocation list. This blocks the access to the website.

Possible solution would be the OSCP.

3.4.6 Online Certificate Status Protocol (OCSP):

Goal ensure certificate is valid and has not been revoked

- **Problems**:
  - OCSP servers can be slow
  - Some browsers ignore OCSP errors as fatal (Do not want to lose users)

OCSP stapling web servers can directly provice OCSP information, so no latency for accessing the OCSP server. **BUT**: multi-stapling needed for intermediate CAs

3.5 Certificate Transparency (CT)

Goal make all public end-entity TLS certificates public knowledge, hold CAs publicly accountable for all certificates they issue

- A CT log is an append-only list of certificates.
- Merkle hash tree is used to implement log
- Entry of tree = certificate
- Periodically append new entries and sig the root

When the log receives a certificate chain from domain or CA, it verifies the certificate and issues a Signed Certificate Timestamp (SCT).

3.5.1 Security of CT

- **How CT improves security**:
  - Browser would require SCT for opening connection
  - Browser contacts log server to ensure that certificate is listed in log
  - A fake attack certificate would have to be listed in public log
  - Attacks become publicly known
- **Advantages**:
  - CT is fully operational today
  - No change to domain's web server required
- **Disadvantages**:
  - MitM attacks still possible (but public)
  - Browser still has to contact Log to verify that certificate is listed
  - Malicious Log server can add dumb certificate

4 TLS

4.1 High level goals

Entity authentication

- Server side of the channel is **always** (only in TLS 1.3) authenticated
- Client side is **optionally** authenticated
- Via asymmetric crypto (e.g. signatures) or a symmetric pre-shared key

Confidentiality

- Data sent over the channel is only visible to the endpoints
- TLS does not hide the length of the data it transmits (but allows padding)

Integrity

- Data sent over the channel cannot be modified without detection
- Integrity guarantees also cover reordering, insertion, deletion of data (packets)

TLS aims for security even if the attacker has complete control over the network. Only requires reliable, in-order data stream (TCP).

4.1.1 Secondary goals

- Efficiency
- Flexibility (choices of algorithms and authentication methods)
- Self-negotiation
- Protection of negotiations (Prevent MitM attacker from performing version and cipher suite downgrade attacks)

4.2 Why TLS 1.3

- Lot of attacks in older versions found
- Increasing importance of protocol
- Older versions are too slow (3 RTT to set up secure channel)

4.3 Record Protocol

Records Protocol data units in TLS (fragment of data stream)
Ctype field Single byte indicating whether conten is handshake message, alert message or application data
AED nonce Constructed from 64-bit sequence number(SQN) and IV (pseudorandom value derived from secrets in TLS Handshake Protocol)
Record Header Contains dummy type field, to imitate TLS 1.2 and length of AEAD ciphertext.
SQN sequence nr that is maintained as a counter at each endpoint, but not included in the record header.

4.3.1 Cryptographic protections in TLD Record Protocol

- Data origin authentication, integrity for records using a MAC
- Confidentiality for records using a symmetric encryption algorithm
- Prevention of replay, reordering, deletion of records using per record sequence number protected by the MAC (include sequence number in the computation of the MAC, on the other end, use shallow copy of sequence number to verify MAC)
- Prevention of reflection attacks by key separation (different symmetric keys in different directions, but see Selfie attack)
- AEAD is obligatory in TLS 1.3, while earlier versions of TLS also supported MAC-encode-encrypt (MEE), which is vulnerable to several attacks.

4.3.2 Padding

- Optional feature that can be used to hide true lengths of fragments
- Removed after integrity chek, so no padding oracle issues arise

4.3.3 Attacks not prevented by TLS 1.3 Record Protocol

- Truncation attacks on the stream of records.
- Application layer confusion: record boundaries APDU boundaries.
- Timing attacks on the padding scheme (recognised in RFC).

4.4 Handshake Protocol

1. Client includes DH share(s) in its first message, along with `ClientHello`, anticipating group(s) that server will accept
2. Server responds with single DH share in its ServerKeyShare response.

- If this works, a forward secure key is established after 1 round trip (1 RTT). If server does not like DH group(s) offered by client, it sends a `HelloRetryRequest` and a group description back to client, in this case handshake will be 2-RTT. (It is recommended to use ECDHE because of its efficiency also)
- Provides authentication of server (usually) and client (rarely), using public key cryptography supported by digital certificates or pre-shared key (less common, used in IoT).
- Protects negotiation of all cryptographic parameters. SSL/TLS version number, encryption and hash algorithms, authentication and key establishment methods. This prevents version rollback and cipher suite downgrade attacks.
- When using static DH instead of ephemeral i.e. when the server always uses the same DH share, we loose perfect forward secrecy. Also when DH shares are generated with bad Pseudo Random Number Generators (PRNG), we might loose perfect forward secrecy or even all security guarantees (if DH share can be predicted by an attacker for both the server and client)

4.4.1 Efficiency

- **full handshake in 1 RTT** Achieved via feature reduction (we always do (EC)DHE in one of a short list of groups). Client speculatively sends severl DH share in supported groups. Server picks on, replies with its share, and can already derive Record Protocol keys.
- **o-RTT handshake** when resuming a previously established connection, client + server keep share state enabling them to derive a PSK (pre-shared-key). But o-RTT sacrifices perfect forward secrecy.

4.4.2 Privacy

TLS 1.3. encrypts almost all handshake messages. This provides security against passive/active attackers.

4.4.3 Continuity

The handshake messages imitate the ones of TLS 1.2, so middleboxes do not block the protocol.

4.4.4 Cipher Suits and Version Negotiation

- Client proposes list of cipher suites and list of (EC)DHE groups in `ClientHello` message.
- Values selected by server and incorporated into signatures and Finished messages as part of transcript.
- Assures that both sides have same view of what was proposed and what was accepted.

4.4.5 Session Resumption and PSKs

Lightweight handshake protocol, exchange of nonces and new key derivation based on existing mastersecret. Reduces latency and server load, since clients return frequently to same servers.

- Achieves 1 RTT, no public key crypto. O-RTT improves this by enabling the client to send secure application data in its first flow in the Resumption Handshake, but without perfect forward secrecy. For this an `early_traffic_secret` derived from the stored PSK is used.
- Client and server are assumed to have already established Pre Shared Keys (PSK) using `NewSessionTicket` handshake messages (or via out of band method in pure PSK mode).
- These messages are sent under the protection of existing Record Protocol.
- Each PSK has an identity a unique string identifying it at client and server.
- 0 RTT data cannot be replayed within a connection, and cannot be confused with 1 RTT data (by key separation). However, 0 RTT data can be vulnerable to replay attacks across connections, especially in distributed server environments.

5 VPNs

A VPN creates a secure channel between two networks over an untrusted network (the Internet). VPNs and end-to-end security (TLS) complement each other. Many different VPN protocols and applications exist. (IPsec, Strongswan, OpenVPN, WireGuard, ...)

- **Set-up phae:** Tunnel endpoints authenticate each other and set up keys (similar to TLS handshake
- **Tunneling phase:** Packets are encapsulated at the first endpoint and decapsulated at the second. The original packet is (often) encrypted and authenticated with a MAC.

Typical properties of VPN tunnels:

- Similar security properties as the TLS record protocol:
  - Authentication of the source, integrity (MACs)
  - Confidentiality (symmetric encryption)
  - Replay suppression (sequence numbers)
- Some tunneling protocols do not provide encryption or authentication

Typical VPN setups:

- site-to-site: secure connection between two physically separated networks.
- host-to-site: secure connection of a remote host to company/university network. Private IP addresses can be accessed without port forwarding. Services do not need to be exposed to the internet. All traffic between Host and private network is secure.
- VPN as a “secure” proxy (avoid tracking, spoof location, circumvent censorship)

VPN does not provide anonymity:

- Local network and ISP do not see which websites you access.
- VPN server can monitor and record all traffic.

Why do we need VPNs when we have TLS?

- If we only want to operate on layer 3 (e.g. company printer network) and still be secure
- When only using TLS: we still leak metadata
- HTTPS doesn't hide layer 3 information (srcIP, dstIP)
- VPNs protect all traffic (’blanket’ security): DNS requests, accessing webservers without TLS
- VPNs can give access to services in private networks or behind firewalls
- VPNs allow to spoof your location

Why do we need TLS when we have VPNs?

- With VPNs, data is only secure inside the tunnel. But the data needs to somehow get to and from the tunnel. VPNs provide no security outside the tunnel
- VPN server can see all unencrypted traffic. TLS is still necessary.
- With a VPN it is not possible to authenticate a webserver, only the tunnel endpoint.
- VPNs need initial credential setup, TLS can be setup without knowing each other

There are many different VPN protocols but only one TLS. Why? Because TLS is universal, everybody should be able to access webservers securely through TLS. We thus need a globally universal standard. VPNs are setup by companies, universities, private person etc. and it only affects their clients, employees etc.. For VPNs, we can thus use whatever we want.

	TLS	VPN
Secured layer	**Transport layer** (L4)	**Link/network layer** (L2/3)
Protection	End-to-end	Tunnel
Client authentication	Not authenticated	Authenticated
Diversity	One / very few globally accepted standards	Many different protocols

Availability/Performance of VPNs:
- VPNs can negatively impact performance (potential detours, limited bandwidth at VPN server, additional crypto)
- Generally VPNs do not provide higher availability (no DDoS defence)
- VPNs can defend against targeted packet filtering (Routers can recognize VPN packets but not content

VPN vs VLAN
- VPN: connects two different networks
- VLAN: set up multiple isolated virtual networks on a single physical infrastructure.

Look at schema example of VPN routing on slide 21

5.1 IPsec

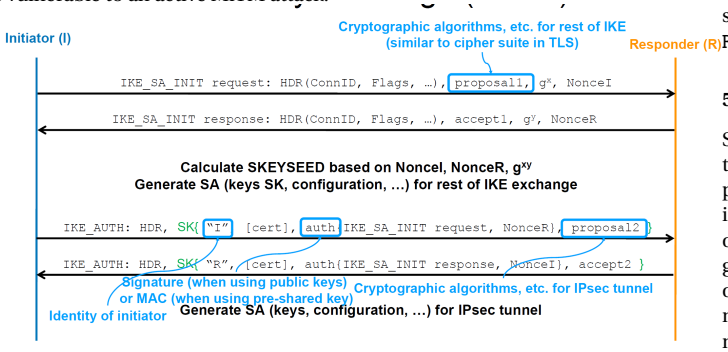
1. Set up a security association (SA) via IKE
2. Encapsulate packets and tunnel them between SA endpoints

IPsec is a very large and complicated protocol. The tunnel is setup at layer 3 (network). In IPsec, we also use sequence numbers (like in TLS) *but* they are included in the packets (while TLS doesn't include sequence numbers in the packet). That's because IPsec runs on top of IP and IP is best-effort transport. The ordering of packets can thus be off at the receiver. That's why sequence numbers need to be in the packets. What if we are tunneling UDP traffic? The numbers are also there to avoid replay attacks. Each party has a sliding window so that it can detect if a packet is replayed by inspecting the sequence number. IPsec and IKE have many options and modes

Problems with IPsec
- Configuration is difficult and error-prone due to many options.
- Some options do not provide any security

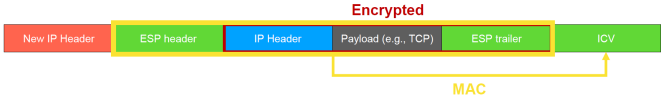
5.1.1 Internet key exchange (IKEv2)

IKE is used to setup a security association (SA). In IKE, we have an anonymous DH exchange. This provides forward security and does not leak identities (as e.g. TLS does) since no authentication data is sent in plaintext. The disadvantage is that anonymous DH is vulnerable to an active MiTM attack.



5.1.2 IPsec session

After an SA was setup using IKE, we encapsulate packets and tunnel them between SA endpoints. Encapsulation works as follows:
- Add ESP trailer: Padding, type encapsulated (original) packet
- Encrypt packet and trailer
- Add ESP header: SA identification, sequence number
- Create Integrity Check Value (ICV): MAC over original packet, ESP header, ESP trailer
- Add new IP header



Similarly, decapsulation:
- Strip off outer IP header
- Look up keys and configuration using information in ESP header
- Check MAC
- Strip off authentication tag and ESP header
- Decrypt original packet
- Remove ESP trailer
- Forward original packet

	TLS	IPsec
Key exchange	TLS handshake	Additional protocol: Internet Key Exchange (IKE)
Authentication	Typically only server Typically using RSA certificate	Server and client Many different authentication mechanisms
Underlying transport	Reliable (runs on top of TCP)	Best-effort (runs on top of IP)

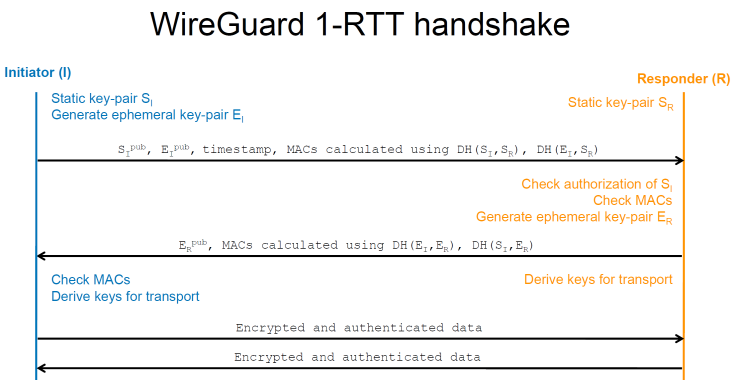
5.2 Wireguard

WireGuard is a modern lightweight VPN that only has roughly 4000 LOC (opposed to OpenVPN with 600'000 LOC!).
WireGuard relies on simple configuration and no cryptographic agility. It only uses state-of-the-art primitives: Curve25519 (signatures), ChaCha20 (encryption), Poly1305 (authentication). The small codebase provides minimal attack surface and is formally verifiable. Wireguard is faster than IPsec or OpenVPN.

5.2.1 Authentication and keys

Each peer has a static key pair. Initiator: S_I^{pub}, S_I^{priv}, Responder: S_R^{pub}, S_R^{priv}. Peers specify in configuration which public keys are authorized. WireGuard uses a 1-RTT handshake during which each peer generates an ephemeral key pair: Initiator: E_I^{pub}, E_I^{priv}, Responder: E_R^{pub}, E_R^{priv}. Symmetric keys are then derived from four DH combinations:

$$\{DH(S_I, S_R), DH(S_I, E_R), DH(E_I, S_R), DH(E_I, E_R)\}$$



The WireGuard protocol is connectionless. A series of timers, both based on message counts and time, are used to steer key renegotiation, handshakes and session termination. The strict key rotation timers (`REKEY_AFTER_MESSAGES`, `REKEY_AFTER_TIME`) and the ephemeral ECDH session key exchange guarantee PFS.

5.2.2 DoS protection

Since VPN servers need to do expensive crypto, they are susceptible to (D)DoS attacks. A WireGuard implementation can choose to respond with a cookie instead of processing the handshake: the initiator will then use this cookie as a key for computing HMACs of their message. The cookie mechanism of IKEv2 is very similar to the one just described. However, an important difference between the two is that Wireguard requires an additional MAC on the handshake message — using the public key of the responder as HMAC key. This allows the responder to stay completely silent — not responding even with a cookie — unless the initiator knows its public key. (Remember that "public" key do not need to be publicly accessible, often they are not).

6 Anonymous communication systems

Why are VPNs and TLS not enough? VPN server still sees metadata such as srcIP, dstIP, ports, metadata etc. We need something stronger for anonymous communication. TLS does not hide src and dest address.

6.1 Terminology: "anonymity"

- **Sender anonymity:** adversary knows/is receiver, may learn message, sender is unknown. The sender anonymity set is the set of all possible senders, which can be used as a (rough) metric. A small set means little anonymity. Return address is a token provided by original sender.
- **Receiver anonymity:** Adversary knows sender, may learn message, receiver is unknown. The sender needs a return address: the receiver provides a token (since the sender doesn't know the receiver) and the token will be used to direct the message. Receiver anonymity set is the set of all possible receivers.
- **(Sender-receiver) unlinkability:** Adversary knows senders, knows receivers, link between senders and receivers is unknown. Multiple users need to communicate at the same time. Anonymity –> Unlinkability
- **Unobservability:** Adversary cannot tell whether any communication is taking place.

- **Plausible Deniability:** Adversary cannot prove that any particular individual was responsible for a message (or other action). Anonymity –> plausible deniability

The following holds: $Unobservability \rightarrow Anonymity \rightarrow Unlinkability$

Threat Model:

- Degree of control: Local or global
- Type of Control: network or compromised infrastructure
- Types of Behavior: passive or active
- Often quite unspecified attacker model –> unclear guarantees

6.2 Basics of Anonymous Communication

What Mechanisms can we use?

- **Broadcast:** Receiver anonymity is guaranteed, sender can be de-anonymized (localization through triangulation)!.
- **Hijacked Connection:** burner phone, hacked WiFi, network ID != personal sender ID.
- **Proxy or VPN with layered encryption:** Proxy can see metadata (src, dest)

–> **Cascade of multiple proxies** Each proxy only sees addresses of two neighbors, due to layered encryption. Works as long as message passes one honest proxy.

–> However the attacker may link in and outgoing messages through timing.

6.3 Mixnets

Batching and Mixing: Collect a number of messages before forwarding (Batching), change the order of the messages (Mixing), also we need to padd messages to a fixed length.
An adversary can still mount an **intersection attack:** Often, users only communicate with a small subset of other users. Every time a message is seen by the target, register the sets of destinations.

Cover traffic for unobservability: To achieve full unobservability, use **cover traffic**, both for sending and receiving. Now we are fully anonymous, as long as one mix is honest.
How do we handle return addresses? Alice prepares a return address and encloses it in her first message. That address contains layered information.

6.4 Circuit-based systems (AKA onion-routing system)

Mix-nets are very secure but very slow. We want a system that can support web browsing.
Circuit-based anonymous communication systems, commonly known as Onion Routing Systems. The nodes are called relays (also nodes or routers), there are usually 3 of them Entry guard, Middle relay and Exit relay. The virtual circuit is also called tunnel.

- Main ideas: use layered encryption, no batching and mixing, no cover traffic.
- Flow-based: establish a virtual circuit (keys) once per flow, reuse it for all packets in the flow using only symmetric key crypto.
- The threat model is constrained: only a local adversary (e.g. ISP) which cannot launch confirmation attacks.

Circuit setup

- Initially, sender knows long-term public keys of relays.
- The sender negotiates shared keys with all relays on the path (this requires expensive asymmetric key cryptography)
- The relays store the necessary state.

Direct circuit setup: a packet is sent through the whole system and returned and at each step the state is generated. The encryption keys of data are only based on public keys of relays. Thus (immediate) Forward Security does not hold since no ephemeral information is used. We can achieve eventual forward security by changing public keys of the relays regularly
Telescopic circuit setup: Keys are negotiated one relay at a time. The circuit is "extended" by one hop at a time (that's why it is called telescopic). Ephemeral session keys are negotiated before the circuit is extended. This setup is slower... but it offers immediate forward secrecy: As soon as the circuit is closed, the session keys are deleted.

Data forwarding The sender has established a circuit (keys and per-link IDs). A data packet is encrypted as usual (layered encryption). The ID of the next relay is added in clear text. To protect against network adversaries, links can be encrypted (TLS).

Circuit tear-down Can be initiated both by sender and by intermediate relays. The sender communicates the tear-down to one relay at a time, starting from the furthest away. The exit relay may tear down the circuit if a corrupt packet is detected, or some other attack. Circuits have a limited lifetime, so they will eventually be destroyed.

Comparison of mix-nets and onion routing

	Mix-net	Onion routing
Forwarding system	Message-based	Circuit-based
Layered encryption	✔ (asymmetric)	✔ (symmetric)
Mixing and batching	✔	✘
Cover traffic	✔ (optional)	✘
Forward security	✘	✔ (telescopic setup)
Latency	High	Low/medium

6.5 Attacks on circuit-based anonymous-communication systems

Many attacks have been proposed, however for many it is unclear if they fit the standard threat model. Some of them are practical, requiring limited resources. Others are only achievable by state-level adversaries (Five Eyes).

Traffic Analysis:

- Passive traffic analysis: The adversary observes the edges of the network, recording traffic patterns. Real-time detection is challenging, alternative is store and compare later.
- Active traffic analysis:
  - The adversary actively modifies packet timings: Inter-packet timings (delaying/reordering packets), packet drops also possible but detectable
  - Flow watermarking: inject one bit of information (marked or not)
  - Flow fingerprinting: inject multiple bits (e.g., sender IP address!)
- Website fingerprinting: Many websites have a distinct pattern of traffic they receive and send. Adversary can keep a database of patterns and compare traffic recorded from a single observation point (ISP, WiFi users,...)

Denfence against Traffic Analysis:

- Cover traffic and mixing: significant overhead, scalability becomes an issue. Only suitable for few applications (VoIP) with low bandwidth.

In order to prevent traffic analysis, you should omit *everything* that makes you stand out: don't install any plugins, never use TOR in fullscreen mode (gives away your screen resolution), don't type inside the browser, type inside a text-editor and copy-paste messages into webforms, etc.

6.5.1 Higher-layer attacks

- OS Network stack fingerprinting: Compromised adversary can probe TCP stack, solution would be per-hop TCP. Still TLS or HTTP layer may be identifiable.
- Most deanonymization is still done through other means: Trick user into downloading malware, trick user into downloading file that will access the Internet directly, analyze user behavior like texts.

To achieve anonymity, all layers need to be anonymized: Any gap will break anonymity!

6.6 Tor

Tor basics:

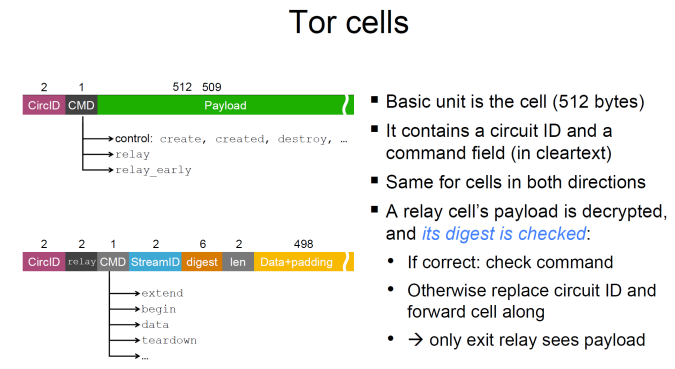
- Circuits established over 3 relays
- Telescopic setup (forward secrecy!)
- Per-hop TCP, established on the fly to avoid TCP stack fingerprinting
- Per-hop TLS (except on the last hop). Multiple circuits over same TLS connection. End-to-end HTTPS is possible.
- Main tool: Tor browser (Firefox)

Tor additional features:

- Exit policies (exit can restrict the destinations they connect to)
- Multiple streams per circuit (helps with performance, weakens anonymity)
- Censorship resistance (bridges)
- Hidden services: Provide receiver anonymity, use .onion URL (not in DNS). The name is the hash of the HS's public key.

6.6.1 Cells

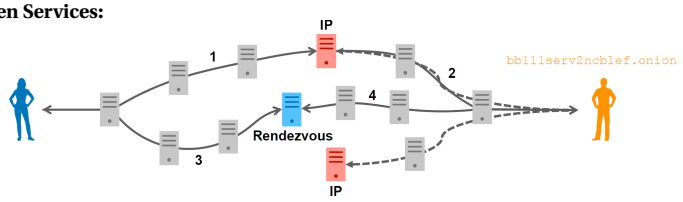
Basic unit in Tor. If a relay obtains a cell: it looks up keying material from circuit id and will decrypt the payload which contains sets of fields. The relay then checks the digest and if it matches it looks at the cmd.



Circuit extension with relay_early:

- Path of arbitrary length can be used for very cheap DoS: Simply create a circuit that goes through all honest nodes, dozens of times: incredibly large amplification factor.
- Solution: Tor extend cells can only be contained in relay early cells

Hidden Services:



- The hash of Bob's public key is the identifier of his hidden service
- Bob has connections to a set of *introduction points* (IP)
- To communicate, Alice connects to an IP and suggests a *rendezvous*
- Bob can connect to the rendezvous and start the communication

6.6.2 Directory authorities

- How do the clients know what relays there are? 10 directory authorities (servers) running a consensus algorithm.
- The authorities track the state of relays, store their public keys.
- Client software (Tor browser) comes with a list of the authorities' keys (If an adversary can supply the list, de-anonymization is trivial!). A client accepts a consensus document if signed by ≥ 50%.
- The centralized authorities are an important weakness of Tor. An adversary compromising 5 authorities can compromise Tor.
- Every relay periodically reports a signed statement (state, stats.)
- DAs also act as bandwidth authorities: verify bandwidth of nodes.
- Sybil protection: DAs limit the number of relays per IP subnet

6.6.3 Censorship resistance in Tor

- Problem: relay nodes are publicly listed and can be blocked.
- The Tor network contains a number of bridge relays (or bridges). Not (all) publicly listed, instead distributed through friends networks. This is used to circumvent censors which black-list Tor relays.
- Problem: deep packet inspection allows detection of Tor traffic
- Solution: obfuscate the traffic (pluggable transports)

6.6.4 Circuit setup

Who is authenticated on the first hop? Alice is *not*. The entry guard is since Alice encrypted her ephemeral DH value g^{x_1} with the entry guard's pubKey. The entry guard then sends back g^{y_1} and a hash of $g^{x_1 y_1}$ which it can only do if it was able to decrypt g^{x_1} which it can only do if it has the privKey.

7 Border Gateway Protocol (BGP) Security

Why should we care about BGP security when we have secure connections (TLS, VPN, DNSSEC, etc.)? The one that controls BGP controls routing.

- Obtain fake TLS certs: use BGP route hijacking in combination with automatic certificate issuance (ACME) to obtain fake TLS certs. BGP allows to reroute HTTP challenge traffic from CA to illegitimate IP.
- deanonymize TOR users: reroute TOR exit node traffic and use it for correlation attacks.
- hijack DNS requests: hijack routes to DNS servers (e.g. MyEtherwallet hack)
- Not all traffic is enrypted/authenticated: DNS, HTTP
- Even encrypted traffic leaks timing information (fingerprinting)

The problem with BGP is that endusers can't protect themselves. Solving these issues is only possible with ISP cooperation.

7.1 IP Addresses, Autonomous Systems & the Border Gateway Protocol

IP addresses: are globally assigned by ICANN (global authority). ICANN assigns certain IP regions to certain parts of the world. Regional Internet Registries (RIRs) are then responsible to further assign IPs. As of 25th November 2019 15:35 UTC+1, we have officially run out of IPv4 addresses.
IP addresses are assigned in prefixes (e.g. /16 prefix has $2^{32-16} - 2 = 65534$) IPs).

Internet: The Internet is a network of networks (autonomous systems). Autonomous systems can be ISPs (e.g. DT, Swisscom), global backbone network (e.g. Verizon), universities and large companies (e.g. ETH, Google).

BGP: BGP "glues" the internet together: routing protocol between ASes, disseminates information about location and paths for IP prefixes. BGP is a path-vector protocol and follows typical business relationships.
BGP speaker sends and receives messages from peers over TCP connections on port 179. Messages sent include: `OPEN, UPDATE, KEEPALIVE, NOTIFICATION`. Route information is disseminated through `UPDATE` message using attributes: `Withdraw, path attributes, network layer reachability information`.

BGP Policies: ASes have different business relationships with each other: provider, peer, customer. Each AS implements peering policies. These decide routes are accepted and advertised based on policies. Policies are configured in the BGP daemons of the AS. Policies can be used to implement filters to prevent route leaks (= falsely announced prefixes), or for business reasons.

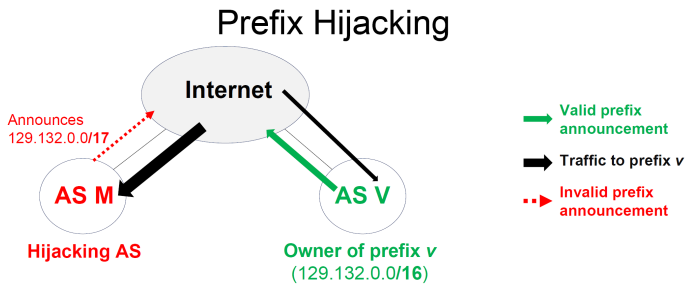
- Input policy: which paths to keep/ discard
- Export policy: which paths do I advertise to neighbors

How to create your own ISP:

1. Register an autonomous system number to be able to connect via BGP to other networks
2. Request Internet number resources from your regional network coordination center (get assigned IPv4 and IPv6 prefixes which can be announced over BGP)
3. Find other networks to connect to and exchange traffic with
4. Deploy hardware to the peering location an announce IP prefixes

7.2 BGP Hijacking

BGP vs. OSPF: BGP is used as an inter Autonomous System protocol, while OSPF is used to establish routes inside an AS. Also, OSPF is a link-state protocol: routers exchange what they know about the network until all routers have a complete map of the network; then the routers compute the routing tables independently. In BGP, we have a path-vector mechanism: every AS announces the prefixes it owns and all the paths that go through it to neighboring ASes.



Stronger Variation: Sub-Prefix Hijacking

- AS M originates a longer (more specific) prefix for the victim's address space (up to /24 is allowed)
- Traffic follows the **longest (most specific)** matching prefix
- Why can't V announce more specific prefixes by default?

Also a less strong attack could be done, where attacker announces same size prefix and only a fraction of traffic to prefix is hijacked. Number of affected sources depends on business relationships, topology, policies.

7.2.1 Problem 1: BGP does not validate the origin of advertisements!

IP prefix origination into BGP: Prefix advertised by the AS who owns the prefix or by upstream providers on its behalf.

IP prefix hijacking: A malicious or misconfigured AS originates a prefix it does not own, as there is no proper verification in place.

How to perform BGP interception:

- Selective announcement of hijacked prefix only to some neighbors (problem: neighbors may still learn hijacked routes from their peers)
- Use BGP poisoning, only select neighbors that use hijacked route.
- Use BGP communities to explicitly state to which ASes a particular advertisement should be advertised. Can tell an AS not to forward announcement to specific other ASes using the NoExportSelect action.

BGP hijacking in 3 steps:

1. Set up an AS and border router or compromise someone else's router.
2. Configure router to originate the target (sub-)prefix
3. Get other ASes to accept the wrong route (Many ASes do not discard wrong routes)

BGP hijacking is not as easy as it sounds (you can't just announce route from your home router). You need access to a BGP router (your own AS or compromised AS).

7.2.2 Problem 2: BGP does not validate the content of advertisements

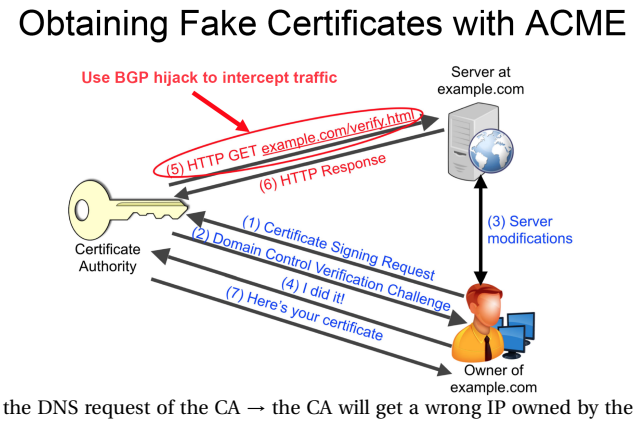
After a BGP message has been announced, the content of the advertisement is not validated! ASes that receive the advertisement can modify it!

ASes can modify the BGP path:

- Remove ASes from the AS path:
  Legitimate AS Path: [AS 701, AS 6939, AS 88]. Remove AS 6939: [AS 701, AS 88]
  Motivation:
  – Attract traffic by making path look shorter, attract sources that try to avoid AS 6939.
  Only AS 701 can tell that the AS path is wrong!
- Add ASes to the AS path:
  Legitimate AS Path: [AS 701, AS 88]. Add 6939 in-between: [AS 701, AS 6939, AS 88]
  Motivation:
  – Trigger loop detection in AS 6939 (AS sees itself on the AS path and drops the advertisement to avoid routing loops) → DoS attack on AS 6939, "BGP poisoning".
  – Make your AS look like it has richer connectivity
  AS 701 can detect the AS path is wrong (but may not care), AS 6939 could detect but may not see the route.

7.3 Attacks on BGP: Obtaining fake certificates

When using ACME (Automated Certificate Management Environment), a domain is validated through either a HTTP challenge or a DNS challenge to prove that you actually own the domain. By using BGP hijacking, an attacker can:



- hijack the DNS request of the CA → the CA will get a wrong IP owned by the attacker.
- hijack the connection to the correct IP and route it to an IP she owns.

7.4 Other attacks on BGP

- Denial-of-service attacks: overload links between BGP routers, send bogus TCP packets (FIN/RST to close session, TCP SYN flood)
  A possible solution to bogus TCP RST is to only accept TCP RST with TTL=255, i.e. only TCP RST from direct neighbor router.
- Eavesdrop or tamper messages by tapping the link
- Most such attacks are easy to defend against and are no longer a large concern

7.5 Countermeasures

What properties do we want?

1. Only an AS that owns an IP prefix is allowed to announce it (can be proven cryptographically)
2. Routing messages are authenticated by all ASes on the path (AS cannot add or remove other ASes in BGP announcements)

7.5.1 Best Current Practices (BCPs)

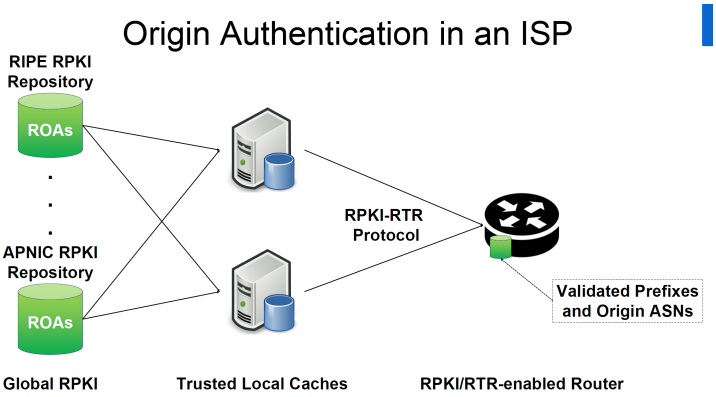
- Securing the BGP peering session between routers (authentication, prioritize BGP traffic)
- Filtering routes by prefix and AS path
- Filters to block unexpected control traffic (e.g. ignore TCP RST for BGP if it comes from the inside, implement TTL=255 policy)
- Enter prefixes into Internet Routing Registries (IRRs) and filter based on these entries
  None of these actually have strong security properties (no crypto).

7.5.2 Solution to Problem 1: Origin Authentication (OA)

- Required: Ability to prove ownership of resources.
- Resource Public-Key Infrastructure (RPKI): A secure database to map Internet number resources to a trust anchor. A digital certificate proves that an AS is the current holder of a specific resource. Each regional Internet registry (RIR) is a root of trust.
- Enables issuance of Route Origination Authorizations (ROAs): States which AS is authorized to announce certain IP prefixes. Can determine the max length of the prefix that the AS is allowed to advertise (avoid sub-prefix hijacking). Certificate follow same delegation as IP addresses from RIRs
- Requires no actual modification to BGP (out-of-band checking)
- Trusted local caches collect information from RPKI servers and whitelists are periodically pushed to routers: the verification of signatures is therefore performed offline.

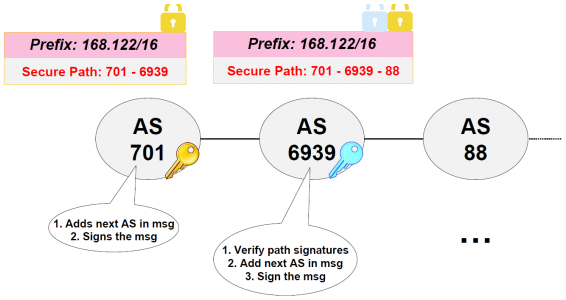
If AS M now tries to hijack AS V's prefix v, routers will check against ROAs in RPKI for prefix v and see that the announcement is invalid and thus drop it.

However OA is not enough: AS M can announce that it has a path to AS V by appending itself on the path *after* the entry for AS V. BGP routers in other ASes check against ROAs in RPKI for prefix v, and find a valid ROA for prefix v. AS M manages to attract a fraction of traffic for AS V.



7.5.3 Solution to Problem 2: BGPsec

In order to prevent the problem of ASes illegitimately appending themselves to AS paths, we need to secure the AS-path attribute, which prevents crafting a valid origin on path and path poisoning. BGPsec is trying to achieve this through Origin authentication and cryptographic signatures.
BGPsec signs received update message to prove that path was correctly updated and includes the next AS in the signature. This way, BGPsec can validate that the AS path indicates the order ASes were traversed and that no intermediate ASes were added or removed. RPKI is used to verify AS key material (as in origin authentication).



Example: AS 701 send out advertisement and signs msg with its privatekey. AS 6939 can verify the signature (pubKey of AS 701) and add the next AS to the path and again sign the message. ASes always need include the next AS on the path and then sign - otherwise there would be no link between ASes and only individual ASes are secured but not the linking between them.

Problems with BGPsec:

- Insecure ASes use legacy BGP, and secure ASes must accept legacy insecure routes → *protocol downgrade attacks*: If operators don't prioritize security, an attacker can just use legacy BGP to announce bogus routes to BGPsec neighbors.
- Routing policies can interact in ways that can cause BGP wedgies.
- *Performance degradation*: Prefix aggregation no longer possible, since you can't sign a prefix owned by someone else. Real-time signature and validation. Slower convergence.
  → *BGPsec does not scale*

Other Approaches: Extensive Monitoring

- Monitoring BGP update messages and use past history.
- Out-of-band detection mechanism

7.5.4 Path-End Validation: Deployable Routing Security

Important observation: AS paths today are very short! Average AS-level path length is only 3-4 hops. The basic idea is to have something between origin authentication and BGPsec. Path-End Validation tries to reduce overhead of BGPsec.

- Origin Authentication with RPKI secures only the announced prefix. This way, no AS can announce a prefix it does not own.
- Path-end Validation secures the first hop from originator to its provider. This way, no AS can simply append itself after the first AS on the AS path. Why does this work: you can still append yourself after two ASes. *But* this makes the AS path rather long and thus less attractive.

This has several advantages over full BGPsec: Lower overhead, requires no cooperation from other ASes, no full deployment necessary, stronger incentive for early adopters.

8 DDoS Attacks and Defenses

Denial of Service (DoS) attack: attempt to consume resources which are then not available to legitimate users. Possible target resources: network links, servers, processing, storage, etc. Distributed Denial of Service (DDoS) attack is a coordinated DoS with many attackers. DDoS attacks pose a significant threat and are often used to extort companies!

8.1 Attack types

What are attack targets?

	Network links	Network devices / networking stack	Applications
Description	Volumetric attack	Protocol attack	Application-layer attack
Unit of measurement	Bits per second (bps)	Packets per second (pps)	Requests per second (rps)
Used mechanisms / examples	• Reflection and amplification • Shrew attack	• Reflection • State exhaustion • SYN/ACK floods • Fragmentation	• Computational complexity • Hash collisions • Slowloris
Defenses	• Filtering, traffic scrubbing • Black-hole filtering	• Cookies • Rate-limiting	• Randomized/keyed hash functions

8.2 (IoT) Botnets

Botnet
- A set of compromised machines connected to the Internet.
- Execute malicious code and can be controlled via command and control (CC) systems.
- Often geographically distributed

IoT devices are perfect for constructing botnets
- Many devices with uniform configuration
- Often very poorly secured, hardcoded credentials.
- Often no security updates after few years.
- Often connected to internet without bandwidth limitations

Possible Mitigations:
- Patch: automatic security updates, provide patches for full life-time of devices.
- Credentials: No hardcoded credentials, force users to change default passwords.
- Monitoring: ISPs should actively monitor their network for suspicious traffic.

8.3 Reflection and Amplification

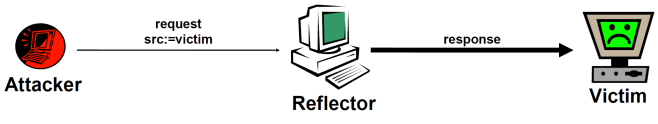
Address Spoofing: Source address in IP header can be set by sender. In a connectionless protocol (UDP), server cannot confirm actual sender.

Defenses against address spoofing:
- Address filtering by ISPs: ensure hosts use their own addresses. Needs to be globally deployed. Poor incentives for ISP to deploy it (only other ISPs profit)
- Use connection-based protocols (TCP). Additional latency, potentially additional DoS attack vector (state exhaustion).
- Cryptographic source authentication: Additional DoS attack vector if built on expensive asymmetric crypto. Requires symmetric key distribution or PKIs

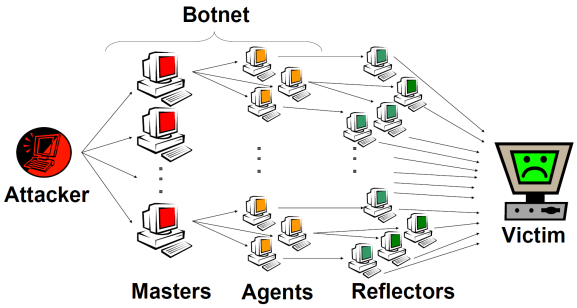
Reflection and Amplification:
- Requirements:
  - Ability to spoof source address
  - Publicly accessible servers
  - Ideally response is (much) larger than request -> amplification
- Typical reflectors:
  - DNS (up to 180)
  - NTP (up to 500) vulnerability was closed.
  - Memcached (up to 50000) UDP disabled by default in version 1.5.6

How reflection and amplification works

1. Choose open service (e.g., open DNS resolver) as reflector
2. Craft request that triggers (much) larger response
3. Send packet where source address is set to victim's address
4. Reflector sends reply to victim



Distributed DoS with Reflectors



Reflection Mitigations:
- Prevent address spoofing
- Perform access control (DNS servers deployed within an organization or ISP should only serve clients from this organization.
- Implement response rate limiting RRL (limit the nr of responses to a client)
- Ensure small amplifications factors (ideally < 1)

8.4 Specific Attack Examples

8.4.1 Volumetric Attack: Shrew Attack

Conventional bandwidth-based DoS requires sending high-rate attack traffic (like an elephant). Can we achieve the same effect by sending low-rate attack traffic (like a fierce shrew)? YES!

Shrew DoS Attack: Exploits TCP congestion control feature. Researchers discovered that if you send traffic during very short but specific amounts of time, you can completely disrupt TCP. This is due to TCP congestion control resending packets at multiple whole seconds granularity (1s, 2s, 4s, 8s, ...). By only creating congestion during these time periods the attacker forces TCP flows to repeatedly enter a retransmission timeout state by sending high-rate but short-duration bursts! We deny the bandwidth of legitimate TCP flows as it makes TCP believe there is a long-term congestion.

Retransmission Timeout in TCP Congestion Control
- Exponential bakcoff timeout: If packet dropped retransmit in 1s, then 2s, then 4s...

Temporal lensing: "multiple rounds simultaneous impact". Use time as an additional amplification factor. Different paths have different transmission delays. An attacker can send packets at different times s.t. they *all* arrive at the target *at the same time*. So that a low-bandwidth source can also perform a shrew attack.

8.4.2 Volumetric Attack: Coremelt and Crossfire

Both of these attacks haven't been seen in the wild yet but are theoretically possible.

Coremelt attack
- Adversary controls many bots distributed across the Internet.
- Bots send traffic *between each other*, thus all traffic they produce is legit traffic desired by the destination (destinations are bots). Traffic is not sent to a victim as in regular DDoS attacks. Thus, all defense methods discussed before do not work here.
- Adversary can exhaust bandwidth on victim link.
- As a result, the attack traffic exhausts bandwidth in per-flow fair sharing systems.

Crossfire attack
- Adversary controls distributed bot army
- Observation: due to rout optimization, few links are actually used to connect a target region to rest of internet.
- Adversary can contact selected servers near/in target region to overload target links.
- Result: disconnect target region from remainder of Internet.
- Hard to stop since only connection establish packet (TCP SYN) are sent.

8.4.3 Protocol Attack: DNS FLooding

NXDOMAIN Attack
- Goal: overwhelm victim's authoritative name servers.
- Idea: query many non-existent subdomains of victim domain.
- Resolver queries all authoritative name serverss in turn
- Can use multiple DNS resolvers
- Can be sent from distributed botnet and via many different DNS resolvers.
- Result: name server can no longer reply to legitimate requests.

Why is this a problem?
- Most internet-based services rely on DNS to map domain names to IP addresses.
- If a domain name cannot be resolved, the service does not work.
- A DoS attack on the DNS system makes many additional systems unavailable.

8.4.4 Protocol Attack: Session State Exhaustion

Session State Exhaustion In a two way communication, each channel between peers needs a unique session number. This session number has to be known at the server to match requests to the right session/ channel. Keep in mind that servers have limited memory.
Attack: Exhaust the session table of the server.
Result: Server can no longer accept new connections, existing connections are dropped, maybe the server/service crashes.

SYN Flood Attack TCP uses a three-way handshake to establish a connection. The client initiates the handshake by sending a SYN packet. The server stores a new state for the received SYN packet.
Attack: The attacker can send lots of TCP SYN packets with spoofed srcIP. The server tries to keep state for every single packet. Eventually, the state table overflows and the server is unable to accept new legit connections. For each second where the packet is in buffer, its TTL is decreased by 1. It thus takes 255 seconds until the state is dropped.
Mitigation: SYN Cookies - no state table needed. Server doesn't create session state for TCP SYN packet. Instead, the server replies with SYN+ACK and a cookie (sequence number) $B = F(time, IP, port, ...)$. On the next reply, the server then checks if the client sent $B+1$ along. Attacker can just send the cookie too...? No! Since the srcIP is typically spoofed, the attacker won't receive the cookie. The attacker could try to spoof the cookie (if she knows the function F...). The server should use cryptographic hashes or salted hashing such that the attacker can only guess B.

Generic Mitigations
- Attack: The attacker aims to exhaust session state of a protocol/application at server.
- Countermeasures:
  - Encode state in a unique but determined way that allows the server to validate the state in the reply.
  - No need to store session state at the server.
  - Ensure the encoding cannot be tampered (use crypto-hashes, unique data known to server only)
  - Server generates B = Hash(salt, A) where salt is known to server only and changes over time
  - Server only needs to store a few salt values to validate replies.

8.4.5 IP spoofing defense

- Ingress Filtering: at network edge, outgoing packets with incorrect srcIPs are filtered (e.g. ETH filters packets whose srcIP is not within the ETH prefix). All ISPs should do this (in reality only 30% do).
- iTrace: One in 20,000 packets "triggers" a router to send a special packet with route information sent to both src and dst. DDoS victim could reconstruct attack paths. But extra packets waste bandwidth.
- Packet Marking: Routers mark 16-bit IP ID field with information that enables reconstruction of IP address. This has no overhead but probabilistic marking often requires ca. 1000 packets.

8.4.6 Application-Layer Attack: Algorithmic Complexity Attack

Algorithms often have good average case running times but bad worst case running times (for certain inputs) (e.g. quicksort or hashtable lookup).
An attacker can exploit this by sending special inputs that trigger worst-case running times of algorithms.

Hash table lookup: Countermeasures
- Universal Hashing: Hash functions guarantee 0 or low collision for any input
- Hash randomization: Harder for attacker to find out the worst-case input. E.g. use a secret hash function for each hash table.

8.4.7 Regular Expression Denial of Service (ReDoS)

There are "malicious" inputs to certain regular expressions that take a very long time to evaluate. A server could become unresponsive when facing such a regex.
Example: input aaaaaa!@gmail.com to:
`([a-zA-Z0-9])(([.]+)?([a-zA-Z0-9]+))*(@)1[a-z0-9]+[.]1(([a-z]2,3)|([a-z]2,3[.]1[a-z]2,3))`

8.4.8 Application-Layer Attack: Slowloris

Slowloris allows a single machine to take down another machine's web server with minimal bandwidth and side effects on unrelated services and ports.
Basic idea: Slowloris tries to keep many connections to the target web server open and hold them open as long as possible. Periodically, it will send subsequent HTTP headers, adding to - but never completing - the request. This will fill the maximum concurrent session pool of the server, eventually denying additional connection attempts from clients.

Mitigation:
- increase the maximum number of clients the webserver will allow
- limit the number of connection per srcIP
- put a lower bound on the transfer speed (might lose some customers with very slow internet), but this forces the attacker to spend at least some resources
- put an upper bound on the connection time (again, might lose some legitimate customers)
- setup reverse proxies, firewalls, load balancers or content switches

8.5 DDoS Defense Mechansims

- Ingress filtering: Removes packet with illegiimate source IPs
- Computational puzzles: Slows down attacks, achieves per-computation fairness
- Cloud- or ISP-based filtering
- Network capabilities: Allows victim to block unwanted traffic closer to the src
- IP traceback: Reveals the real source IPs of packets.
- No single point of failure, more than two geographically diverse locations, more than two independent Internet connections
- Long term monitoring: to assess periodicity and peak periods/loads.
- Over Provisioning: Plan bandwidth and resources to cover the majority of extreme peak loads

8.6 In-network and Cloud-based DDoS Mitigation Services

8.6.1 Cloud-based DDoS Mitigation Service

Cloud/CDN providers such as Akamai or Cloudflare offer DDoS mitigation. By changing BGP or DNS of web server, the traffic is redirected to the provider as a middle-man (e.g. use BGP anycast to have the same IP address at different places). Some provide Content Delivery Network (CDN) service to achieve diversion of traffic. This is today's state of the art.

8.6.2 ISP-based DDoS Mitigation Service

Upon detecting a DDoS attack, ISP redirects *entire* traffic destined to victim to the scrubbing center, then send good traffic back to the destination. Scrubbing center keeps state for each connection (lots of machines) and uses Deep packet inspection (DPI) and connection pattern to filter malicious traffic. Parts of the detection algorithm is signature based (needs frequent updates).

8.6.3 Discussion: Cloud- or ISP-based Filtering

- Cloud-based security provider can be easily bypassed: Because most cloud use DNS to redirect traffic, attackers can easily bypass the proxies if the victim's IP is exposed.
- Privacy violation: E.g., Radware decrypts HTTPS and injects CAPTCHAs to client. An untrusted or compromised cloud could expose users' sensitive data.
- Very limited destination traffic control
- High cost for small-, medium-size organizations
- Requires continuous subscription for fetching attack signatures

8.7 Remotely Triggered Black Hole Filtering (RTBH)

RTBH is a generic technique that can be used to mitigate volumetric DoS attacks - the offending traffic is simply dropped (black-holed) at the border routers of an AS. RTBH comes in two flavors, source-based and target-based.
- source-based RTBH: All traffic from attacker's subnet is dropped by target's ISP
- destination-based RTBH: All traffic to the target's subnets is dropped by the target's ISP

RTBH will drop traffic at the border routers, so that the traffic does not even enter the AS. The main solution is to sink all traffic that is destined to a particular placeholder IP address, chosen among an unused subnet. The subnet usually chosen is 192.0.2.0/24, technically reserved for testing purposes. Let's say that we want all traffic destined to 192.0.2.1 to be dropped: we will then create the following static route. `ip route 192.0.2.1 255.255.255.255 null0`.
The RTBH will be triggered by an admin that will insert route updates that route traffic destined to the attacked IP to the placeholder IP, 192.0.2.1 . These routes will then be propagated via iBGP to the edge routers, effectively making them send all the attack traffic to `null0`.

9 Firewalls, Intrusion Detection & Evasion

9.1 Firewalls

A firewall is a system used to protect or separate a trusted network from an untrusted network, while allowing authorized communications to pass from one side to the other.
- **Network Firewall:** Network firewalls are a software appliance running on specific hardware or as virtual instance that filter traffic between two or more networks. Protect different network segments.
- **Host Firewall:** Host-based firewalls provide a layer of software on one host that controls network traffic in and out of that single machine. Protect single machine

Hostbased vs Network: Host based firewalls have context, know exactly what is running on a host. This allows for more fine-grained decisions. Host based firewalls are good for mobile devices (e.g. phones). Network firewalls are good if you e.g. can't install a firewall on a device (e.g. printer).

Filtering Rule: Firewall rules are processed in order: the first rule that matches is picked. Thus, ordering of rules is very important.
- Ingress: Filter incoming traffic (from low security to high security)
- Egress: Filter outgoing traffic (often gets forgotten)
- Default Policy: Define what to do when no rule matches (default accept vs. default reject)
- Deny Access: Tehniques to deny access: DROP silently drop packet (port scanner think its open), REJECT drop packet and inform sender (ICMP message).

Firewall State:
- **Stateless Firewall:** look at each packet on the network layer individually, no state maintained. Decisions based on packet header information. This is fast, scalable and simple but very limited.
- **Stateful Firewall:** keep also track of the state of the network connections, decision also based on session state. This is more powerful but: state explosion, inconsistencies, state for UDP? The problem with state explosion: an attacker can exhaust the memory of a firewall. Then, the default rule matches: if default accept: all traffic is allowed. If default deny: server is DoSed.

Evolution of Firewalls: The legacy firewall technology is effectively blinded by the evolution:
- Firewalls can't block all malicious traffic, many ports must be kept open for legitimate applications.
- Users unwittingly download dangerous applications or other forms of malicious code
- Peer-to-peer and instant messaging have introduced new infection vectors.
- Web 2.0 trends push critical business applications through firewall ports that were previously reserved for a single function (e.g. HTTP)

Next Generation Firewall (NGFW) **Functionality:** deep packet (content) inspection, take application and protocol state into account for security decision. This allows for even more powerful rules, protocol and application awareness but requires support for many (badly documented) protocols, has performance and scalability issues and introduces inconsistencies between host/app and FW.

Web Application Firewall (WAF) Protect web-based applications from malicious requests. Request filtering: request pattern, SQL injection, XSS, buffer overflow attempts, etc. Often implemented as a reverse proxy. Static or dynamic blacklisting/whitelisting. False positive problem. WAF's are often implemented as a reverse proxy to protect public facing web applications. Reverse Proxy: client accesses reverse proxy without knowing internal network. Reverse proxy then manages resources from internal network for client.

Organizational Challenges Managing and maintaining firewall rules in a company is challenging. Firewall rules are complex and if the employee that created them leaves, someone else has to understand the monster. Further, security and network operation teams have opposing interests: security team wants to provide secure access, network team wants to provide high availability.

Firewall Attack Methods
- IP Source Spoofing: spoofing src addr to bypass filters
- Artificial Fragmentation: of packets to bypass rules (firewall needs to reassemble to understand content), also out of sequence sending of fragments.
- Denial of Service: Firewall state explosion, whats fallback policy?
- Encodings: Different encodings and addition of noise (different obfuscation techniques). Undefined or border cases are very effective for detection evasion.
- Vulnerabilities: Firewalls are complex software, which are riddled by vulnerabilities as any other software product.

9.2 Intrusion Detection & Prevention

Protecting a large number of hosts, end-points, or network segments is not trivial.
- Reactive: system can only detect already known attacks
- Proactive: system can detect known and yet unknown attacks
- Deterministic: system always performs the same given the same input (blacklist, signatures)
- Non Deterministic: system detection is fuzzy (heuristics, machine learning, sandboxing) and depends on current state of the world. The reason for alert is typically not known.

Detection Techniques
- Protocol Analysis: Analysis and decoding of protocols. Reassembly and normalization of traffic
- Signature based systems (static): Promptly identify and label threat. But I can only identify threats that I've already seen before. For each new threat, a unique signature or signature artifact is created by a skilled engineer or security researcher. Frequent updates to signature database or online lookups.
  - One-Dimensional: blacklist/ whitelist (e.g based on MD5 hashes). This is fast and low rate of false positives. But it's reactive and needs frequent updates.
  - Two-Dimensional: classic regular-expression functions and string matching. This is more flexible and has low FPR and low/medium resource requirements. More flexibility but it's still reactive and needs frequent updates.
  - Multi-Dimensional: instead of triggering on a single signature, a multi-dimensional signature was created. More efficient and effective than single approach. hybrid of two above methods
- Sandboxing: Run (potential) malware in a VM and examine its behavior. This is proactive and doesn't need signature updates but is resource intensive and difficult to scale. Malware can further evade sandboxing (e.g. malware could wait for 3 days before becoming malicious).
- Machine Learning: Apply supervised and unsupervised machine learning algorithms to detect malicious traffic, malware, etc. Problem with SL models: training data *needs* to be clean (no unknown attacks), otherwise the SL model learns something wrong. With USL models, interpretability is an issue (also with SL).

Decision Making This faces many challenges: encrypted traffic (can't inspect content, only headers and statistical analysis), high number of false positives, high link speeds, induced latency, application level attacks (JavaScript, ..), etc.
Accurate = right direction, on target. Precise = clustered values with low scatter.

"It is better to be roughly right than precisely wrong."

- **0% FNR:** Always predict 'Attack!'
- **0% FPR:** Always predict 'No attack!

The difficulty: Build a detector with optimal balance between FP and FN. FNR and FPR should never be considered in isolation. Ideally, consider a joint detection metric such as the F1 score.
Accurate detection is very challenging when rate of attacks is very low. If we have lots of traffic but very few attacks, we'll have lots of false positives, which lowers trust in the detector.

Detection Evasion

Malware Development Lifecycle
1. Develop new malware with desired functionality
2. Automatically create numerous permutated samples of the initial malware at massive scale:
3. Protect samples from analysis:
   - Use *crypter* to encrypt malware s.t. detection systems and static analysis processes are ineffectual.
   - Upon execution only decrypt sections of code that are in the process of being executed on the victim's computer.
   - Use *packers* to make binary files smaller (faster infection), make it more difficult for AV to detect malicious payload. Advanced packers employ polymorphic output capabilities (restructure malware binary everytime it's executed)
4. Make samples aware of sandboxing/detection technologies
   - Use *protector* to add anti-debugging features to malware that prevent security researchers and automated sandbox analysis technologies from dissecting samples.
   - "protector" technology was originally designed as a DRM protection technology
   - Protectors detect the use of debuggers or virtualization techniques if seen, the malware then causes different operations
5. Quality Assurance: Test samples against all current anti-malware solutions before deployment (if sample is detected by antivirus: `goto 2`):
   - Check if the malware is detected by common AV software. Only testing services that do not submit malware samples to antivirus vendor are used (otherwise the malware would already be known).

The malware used in a targeted attack will not be detected by anti-malware tools at the time of attack because it was tested beforehand.

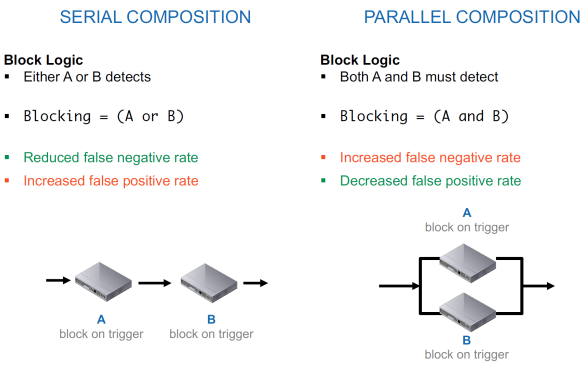
Polymorphism Techniques Mutate code while keeping the original algorithm intact. Swapping equivalent code constructs, changing the order of code, insert noise, compiler modulation. Also swapping of registers, reordering of instructions and defining functions in a different order.

Binders: Binders are used by malware authors to "embed" and Trojan other software packages (e.g. add trojan to Adobe Photoshop torrent). This helps to propagate malware, trick users into downloading and executing seemingly legit software.

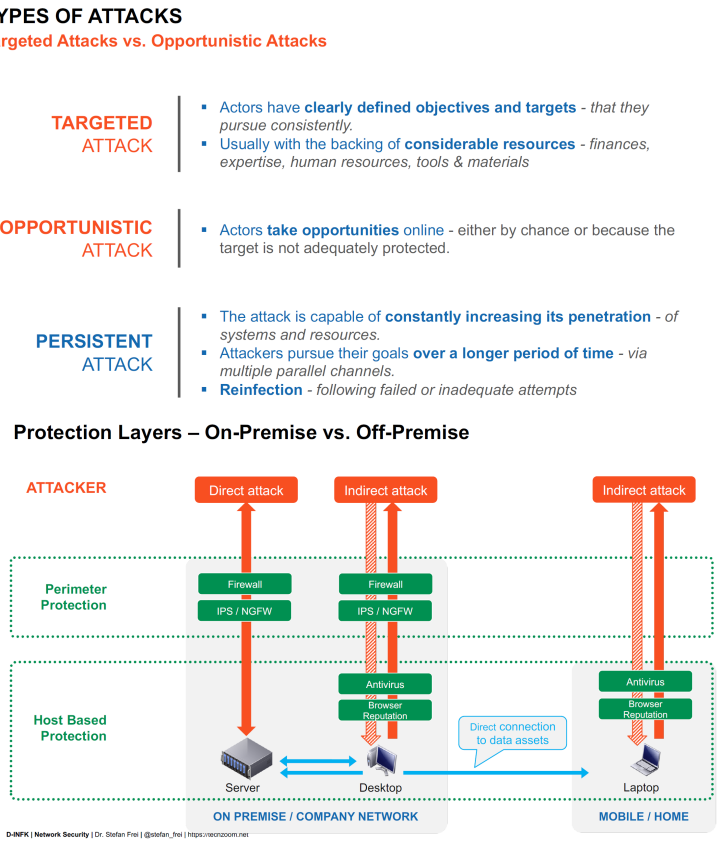
Attack Detection & Defense Effectiveness
- Unable to inspect encrypted traffic
- High number of false positives
- Latency introduced by inspection engine
- Application level attacks (JavaScript,...)
- Policy/signature management

Multiple Detectors

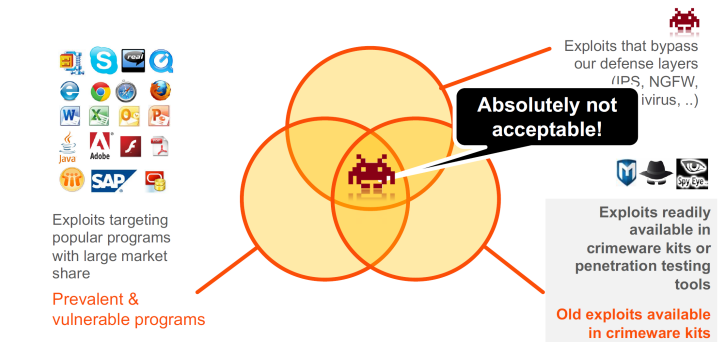
Combining two independent detectors, do we get a better detector?



9.3 Layered Security Filtering and Protection:



- Direct attack: "server-side" exploits, the threat/exploit is executed remotely by the attacker against a vulnerable application and/or operating system
- Indirect attack: the threat/exploit is initiated by the vulnerable target. The attacker has little or no control over when the target user executes the threat.



9.4 Botnets

Basic components:

- Bots: devices under control of the attackers – often vulnerable hosts that have been infected with a malware.
- Command and Control infrastructure: often owned by the attackers, is it used to push commands to the bots.

9.4.1 Mirai botnet

Mirai mainly targeted IoT devices. IoT devices are a very interesting attack vector since there are lots of IoT devices (ca. 10 billion for 2019), they are configure-and-forget (owners don't update them and don't realize when they're compromised) and security is often lacking in IoT devices.
Mirai has been used mainly for Distributed Denial of Service attacks. DDoS is much harder to track and take down than a regular DoS. This allows the attacker to hide his identity behind the botnet. Additionally, a DDoS enables the attacker to have a virtually unlimited bandwidth for flood attacks.
Mirai infection technique:

1. Scan: infected device scans network for open Telnet ports (send TCP SYN packets to random IPv4 addresses)
2. Brute force: the bot tries to log in using 10 random user/pass combinations taken from a hardcoded list of 62. These represent default credentials of existing devices.
3. Report: upon login success, the bot reports the target to a Report Server. It lists IP address, type of device (if available) and successful credentials.
4. Infection: a Loader program gets a detail of the target from the Report Server, connects to Telnet and uploads the correct malware binary to the machine.

Mirai is non-persistent: the binary is loaded into memory and immediately deleted from disk. Rebooting will remove the malware, but the device can still be reinfected. This makes detection and forensic analysis more difficult, especially for IoT devices.
Mirai infected devices were fingerprinted by the fact that Mirai generated probe packets had their sequence number equal to the IP of the scanned device. Probability of this happening is $\frac{1}{2^{32}}$.

9.5 Stuxnet

Stuxnet is the first (publicly know) cyberweapon - a complex malware, widely believed to have targeted uranium enrichment infrastructure in Iran. Stuxnet used various infection vectors such as WinCC machines, network shares, print spooler zero-day, removable drives (to jump airgaps). Stuxnet installed a driver, signed with a legitimate Realtek certificate. This driver intercepts I/O requests, making the files installed by the malware invisible. It also registers as a boot start service, acting as load point at reboots. This driver behaves very much like a legitimate Windows driver: this, and its legitimate Realtek signature, make it very hard to detect even for an experienced sysadmin. Stuxnet would survive manual inspection, OS updates and antivirus scans. This required legitimate certificates. Using fake certificates would have also been possible but surviving system updates would become harder. Hiding in plain sight is often a winning strategy. Stuxnet often injected itself into the privileged antivirus process to ease the infection. Depending on the antivirus, it alternatively ignored it and injected itself in a Windows system process.

10 Internet of Things (IoT)

10.1 Common Ground

- Safety = protection against accidents (environment doesn't adapt to bypass safety measures).
- Security = protection against targeted attacks (adaptive attacker).

The biggest challenge in cyber security is the misconception of risk. Humans perceive fire as risky. (Most) humans don't perceive their smart toaster as a risk, although it is. People need highly visible incidents before they act. We no longer live in a complicated system but in a complex adaptive system **CAS**:

10.2 IoT (and IIOT, ICS, SCADA, OT&IT)

- **Information Technology (IT):** The entire spectrum of technologies for information processing, including software, hardware, communications technologies and related services. Generally does not include embedded devices.
- **Operational Technology (OT):** Hardware and software that detects or causes a change through the direct monitoring and/or control of physical devices, processes and events in the enterprise.
- **Industrial Control Systems (ICS):** Systems that are used to monitor and control industrial processes focused on automation, computerized monitoring and control of physical industrial processes (e.g. oil refining). Typically considered to be mission-critical applications with a high-availability requirement.
- **Internet of Things (IOT):** High level concept of a global network of "smart" physical objects of various kinds (wearables, smart toaster,...)
- **Industrial Internet of Things (IIOT):** Subset of IoT specific to industry (e.g. advanced field sensors)
- **Critical Infrastructure (CI):** Critical infrastructure refers to processes, facilities, technologies, networks and systems (including IIOT and ICS) that control and manage essential services. Disruptions of critical infrastructure could result in catastrophic consequences.

Our world is quickly changing in an irreversible move towards IT/OT convergence. Extending security models to include the OT domain introduces many challenges: conventional IT security thinking hasn't reached (I)OT industry yet, OT devices must not be assumed to be 'just another end point'.

Key Differences between IT and OT: **OT: availability & integrity**

- at edge of the network
- long life cycle
- slow response to threats
- Limited data capacity and computing power
- Safety Operations is critical

IT: Confidentiality (integrity, availability):

- at the center of the network (consumer at edge)
- short life cycle
- rapid response to threats
- High data capacity and computing power
- Few safety critical operations

10.3 IOT Attack Surface

Example 1: STRAVA - the nr. 1 app for runners and cyclists Data about exercise routes shared online by soldiers can be used to pinpoint overseas facilities, and individuals. Location of military bases and individual identities exposed

Example 2: Ingoring Known Security Best Practice Hacked jeep

Example 3: Modern Airplanes - Legacy Communications

Attack Surface IOT connects innumerable everyday devices and systems. Previously closed systems are opened up to remote access and control. This opens up a large attack surface:

- Device: insecure software, lacking update mechanism
- Communication: insecure communication, weak or no cryptography, lack of authentication
- Backend services: Central control, erosion of privacy, data breaches

Further, user perception of risks in cyber security is usually wrong: most users perceive their PC as exposed to malware and fear getting malware but think their smart TV, smart toaster, smart everything are great and don't pose any risks. In reality, the opposite is the case: PC security is rather sophisticated (hardened over 20 years) and we have frequent security updates (e.g.finding a vulnerability in Win10 is hard). But IoT devices ran in isolation for years and only recently became connected. They are designed for high availability and safety, *not* security. Further, IoT devices rarely get security updates. However, the threat environment only gets worse over time, thus we rapidly create a huge future liability with devices lacking an automated and robust protection functionality.
To make matters worse:

Attacking Embedded Devices:

- OSINT: Open source intelligence, retrieve firmware from vendor website. Get devices from e-bay.
- Access Debug Interfaces: Retrieve firmware, configurations, secrets.
- IoT devices are mass produced, if an attack is built for one of these devices it can be replicated across all same devices.
- Root Access to the device through default accounts or secrets, certificates, device fleet passwords.
- We rapidly create a huge future liability with devices lacking automated and robust update functionality.
- IoT devices typically have a much longer lifetime (1-20+ years) than phones/PCs. That's a long time: vendor could go bankrupt. Solutions: Code escrow (copy source code at trusted third party), open source software
- Certification vs. Security: operation critical devices (e.g. flight management system) need certification. However, digital products constantly require security updates which invalidates the certificate. Thus, we need to re-certificate after every patch. BUT: Certification timeline is outpaced by cyber security.

You're doomed if you patch - you're doomed if you don't.

10.4 Possible approaches to make things better

IOT security is part of a complex and evolving ecosystem of diverse domains. Technology based security solutions have to complement other domains to achieve the desired security level.

- **enforce some minimal security standards and testing for IoT devices**
- Design systems with redundancy and resiliency.
- Active management of vulnerabilities (coordinated disclosure, bug bounty)
- Robust and scalable process to deploy security updates timely and efficiently - on any connected device
- Industry-wide systematic security and integrity testing of all critical components

10.5 TRENDnet Security Breach

IP cameras by Trendnet had vulnerability that allowed attackers to view live video stream of any camera. The root directory of the camera's server had, next to the management directory, another script called mjpg.cgi This script, accessible at `https://IP_ADDR/anony/mjpg.cgi`, streamed the captured video in real-time without the need of any authentication. Shodan (https://www.shodan.io/shodan.io) was used by attackers to find IPs with that camera behind.

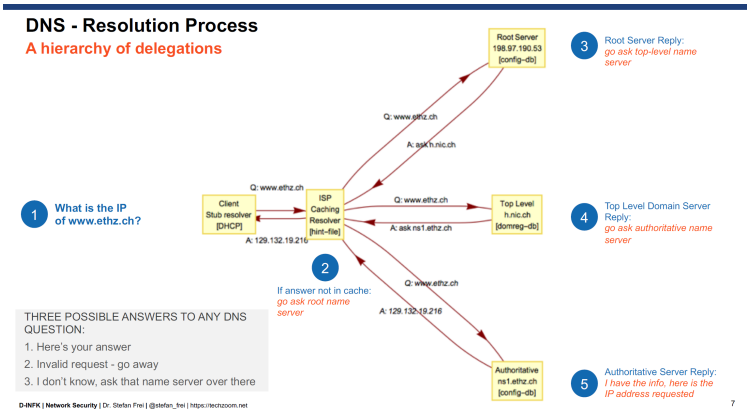
11 DNS Security

The Internet is a critical infrastructure, yet its operation depends on the fundamentally insecure DNS. DNS provides a mapping of names to resources of several types. However, DNS, as a robust key protocol of the Internet, is also a formidable attack vector for cyber criminals:

- Manipulating the DNS mapping allows an attacker to redirect connections to malicious server, facilitate MitM attacks and launch DoS attacks.
- DNS helps building hidden channels (tunneling)
- is abused for powerful denial of service attacks
- is abused for various impersonation attacks
- used to setup services that are hard to hunt-down or shut-down (Botnets, Fast-Domain Flux)

11.1 Domain Name System (DNS)

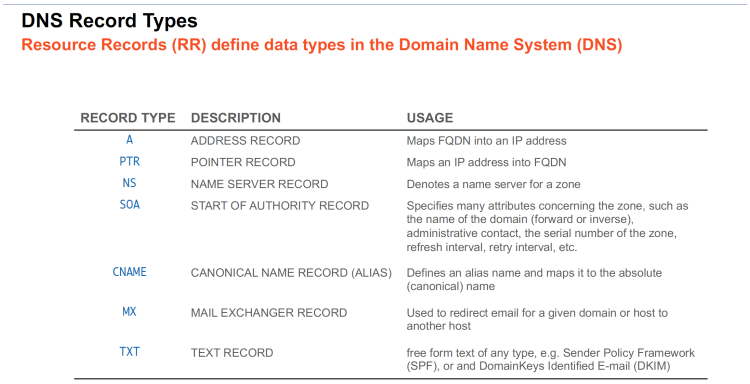
DNS is a globally distributed, loosely coupled, scalable, reliable and dynamic database. DNS data is maintained locally and retrievable globally, no single computer has all DNS data. DNS uses hierarchical namespaces to scale: tree structure down from root level ".", to top-level domains (TLD, e.g. .com) to second-level domains (SLD, e.g. google.com). A fully qualified domain name (FQDN) for example is mail.ethz.ch. The hierarchy descends from right to left. Domains are namespaces: everything below .com is the *com* domain, everything below .ibm.com. is the *ibm.com* domain.



11.2 DNS Protocol Features

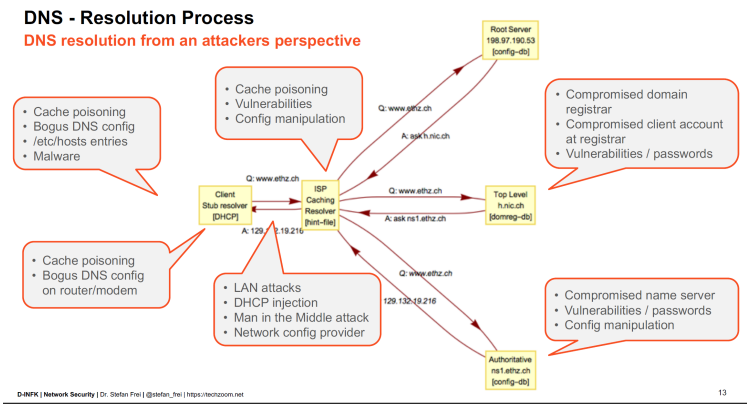
The DNS protocol was designed with a mechanism to protect against forged responses. The first two bytes in the message form a transaction ID (txid) that must be the same in the query and response.

- Protocol: simple client-server protocol, operating on TCP/UDP port 53. No encryption, authentication nor integrity built into original protocol.
- Name server: Servers that map names to objects (= resource records RR). Authoritative: server is authoritative for a specific zone. Caching/Resolver: server resolves domains recursively, caches results.
- Client sends query and random txid, dnsserver responds with query, txid, response.
- Resolver: Client side of DNS resolution, responsible for initiating and sequencing the queries that ultimately lead to a full resolution. Stub resolver: piece of software running on a client that sends recursive DNS requests to a recursive resolver. Recursive resolver: processes DNS resolution iteratively to provide full answer: it contacts all the different servers at the different domain levels to get the final answer.



DNS Caching: We want to decrease lookup latency and network traffic. Each DNS response has a TTL. Caching resolvers will redo a recursive lookup once the TTL for a cached response has expired. A shorter TTL leads to shorter living cache entries, leading to faster refreshes for end users in case of an update. However, this means that there will be more load on the DNS servers for doing the recursive lookup again.

Attack Patterns: Insert tampered information into DNS server or resolution process. Control DNS of all clients served by name server/resolver



LOCAL HOST NETWORK	▪ Manipulate DNS entries and conversation on local host or network ▪ Impact: impersonation of services
CACHE POISONING	▪ Inject manipulated information into DNS cache of resolver ▪ Impact: impersonation of services
DNS TUNNELING	▪ Uses DNS as a covert communication channel to bypass firewalls ▪ Impact: Data exfiltration and hidden communication
DNS HIJACKING	▪ Modify DNS record settings (most often at the domain registrar) to point to a rogue DNS server or domain ▪ Impact: impersonation of services
DISTRIBUTED REFLECTION	▪ Abuse large number of DNS servers to combine reflection and amplification of queries. ▪ Impact: DDoS on victim

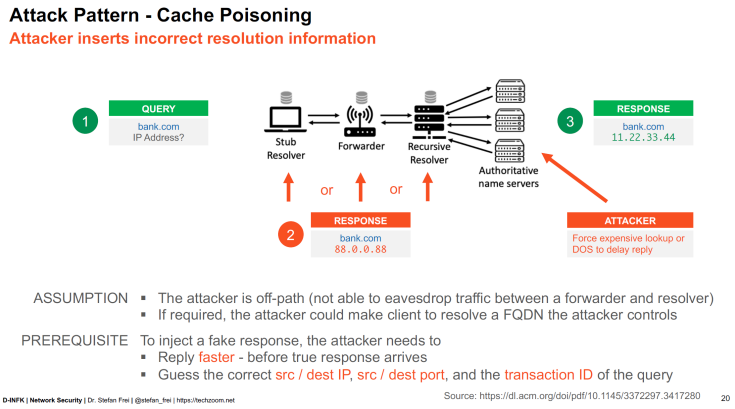
11.2.1 Root servers

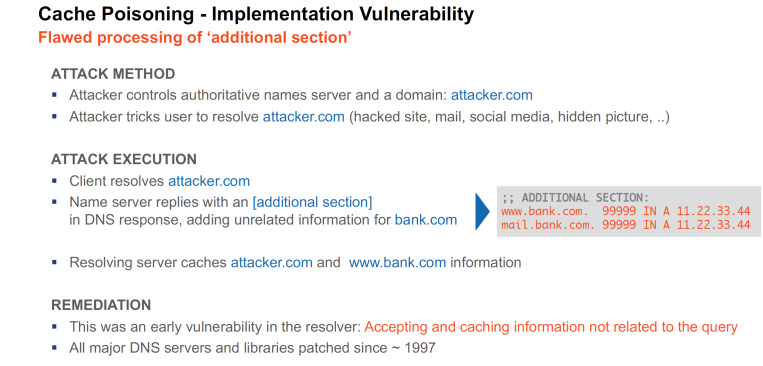
DNS Root Zone: DNS root name servers are the key to the Internet kingdom: the DNS root zone is served by 13 root server clusters which are authoritative for queries for the top level domains. Every name resolution in the Internet either starts with a query to a root server, or, uses information that was once obtained from a root server. DNS root name servers have the official names a.root-servers.net to m.root-servers.net. They only resolve the IP addresses for the top-level name servers (TLD). The bandwidth available at RSS (Root Server System) is significant but no immune to DoS. Try to vary hardware in RSS to limit effects of a vulnerability.

Top-Level name servers A domain name registrar is an organization that manages the reservation of second-level Internet domain names (SLD) below a given top-level domain (TLD). A domain name registrar must be accredited by a top-level domain registry and/or a country code top-level domain (ccTLD) registry. Based on the domain registration database, the top-level name server points resolvers to the authoritative name server of the SLD.

Authoritative Domain Server The authoritative name server for a second-level domain is managed by private entities or on behalf of private entities that have registered a domain name. The authoritative name server has all records for a zone configured and can provide the final / authoritative information.

11.3 Cache Poisoning





Cache Poisoning - Guessing Game

- Attacker sends DNS query to a resolver for a nonexisting subdomain of banking.com, then sends forged response(s) as soon as the resolver queries the name server. If the injected response gets accepted the attacker has successfully injected a fake ip address for banking.com.
- Only knowing the txid and source port prevent the attacker to insert his own information.
- At best attacker can guess: port and txid entropy (at max): $2^{16}x2^{16} = 65'536^2$ bad odds! However, this is theory and we live in the real world.
- Attacker needs to wait until next race if his response is late or wrong - the correct info is cached until TTL expires.

Kaminsky Attack: Use some tricks to make the odds turn:

- Attacker can force a server to look sth up: client-server request & response round-trip takes time. It takes attacker no time to immediately send face response.
- Try lots of random txid and send a reply for each of them simultaneously.
- Lookup [1-100].www.bank.com -> attacker gets 100 races
- When found correct combination of txid and src port send additional section in reply similar to previous attack.
- This attack was mitigated by randomizing src port.

SADDNS Attack:

- When a DNS server issues a query, its source port effectively becomes open to the public.
- Trigger the DNS server to send a query on target server (src port becomes open to public)
- Mute victim Name Server to delay response (buy time for attacker)
- Scan port range with UDP to identify open source port.
- Once the source port nr is known, the attacker simply injects a large number of spoofed DNS replies bruteforcing the txid.
- **Mitigations:** DNSSEC, Disable ICMP port unreachable to disallow portscanning, Randomize ICMP global rate limit.

Learned Lessons

- Source port randomness is not everywhere truly random.
- Txid has insufficient randomness and entropy (only 16 bit).
- Birthday Paradox: Multiple outstanding requests for the same resource records.

11.4 Compromised Configuration

Attack Domain Registrar Top Level Domains are controlled by specific domain registrars (selected by IANA). Compromise Domain Registrar, Second level domains (SLD) are registered with one of the domain registrars of the TLD.

- The DNS information is as secure as the Web App, Registration Processes, or the Passwords of the registrar and the domain owner.
- Hack the Web App of the domain registrar, Brute-force users password.
- Then change registration entries directly at the registrar. Lock owner out of his account.

Attack Network & Local Configuration: Insecure provisioning of DNS setting Manipulate DNS configuration settings on internal network or local host. Have target point to attackers name server.

- WAN Network: Scan ISP networks, identify vulnerable routers or weak/default passwords. Attack poorly protected client router of Internet Service Providers (ISP)
- LAN Network: Attack client router or DHCP server directly. Attack DHCP exchange in local network (Cache poisoning against DHCP: attacker replies faster than DHCP)
- Local Host: Manipulate DNS local hosts settings on compromised machine. Malware changes local DNS configuration (e.g. the file for static mapping of names to IPs `/etc/hosts` for linux, disable Antivirus updates by changing the mapping from download-site, or mapping of name server). Possible exploits are ad manipulation (Google ads), phishing (credit cards, online banking) or selling software (fake iTunes shops).

Name Server Roles Recursive name servers that resolve queries for anybody are a security problem: Can be abused to launch powerful DDoS attacks from anywhere. DNS queries are typically transmitted over UDP - they are fire and forget. The source IP can be spoofed and the receiver has no way of determining its veracity before responding. The attacker will spoof the srcIP to the victim's IP - the response will thus be reflected to the victim and overload his servers. DNS also is capable of generating a much larger response than query (e.g. `dig ANY isc.org @x.x.x.x` query is 64 bytes, the response is 3,223 bytes). There are many powerful and well connected DNS servers, which can be abused to redirect large DNS responses to any target. The key to this attack are *open* DNS resolvers (recursive resolver that replies to any DNS query, coming from any device on the Internet).

- Authoritative Server: responds to queries from any source. Non recursive queries. Only with data it is authoritative about.
- Cache/Recursive Resolver: Respond to local network only. Recursive queries. Should attempt to resolve any legitimate request

Mitigation: Source IP verification (reject packets with source addresses not reachable via the actual packet's path), disable recursion on authoritative name servers, limit recursion to authorized clients, Response Rate Limiting (RRL).
However, the main mitigation is hosting a service on different locations in the internet, s.t. it gets harder for an attacker to target all possible locations. Using BGP anycast, the same IP address is advertised on different locations on the internet.
A user is directed to the nearest service location. This helps to distribute the load on different sites. There are CDN services like Akamai or CloudFlare that offer this as a service.
On TCP, this attack would not work as is since the second message after the TCP SYN is not the DNS response but the TCP SYN ACK. The TCP ACK would go to the victim (due to the srcIP spoofing). The DNS response would be the second message sent by the server. However, the attacker could reply with the third handshake message + payload after intercepting the replies and dropping them. If the attacker is not Dolev-Yao, which is often the case, the attack would become tricky to perform.

11.5 Domain Name System Security Extensions (DNSSEC)

DNSSEC attempts to add security, while maintaining backward compatibility to the existing DNS. DNSSEC is a set of extensions to DNS to provide resolvers:
- origin authentication of DNS data
- authenticated denial of existence
- integrity
- But not availability or confidentiality.

DNSSEC Key Features:
- DNSSEC zone data is digitally signed using a private key for that zone. A DNS server receiving DNSSEC signed zone data can verify the origin and integrity of the data by checking the signature using the public key for that zone.
- DNSSEC can protect any data published in the DNS

Protection Process:
1. Each DNS zone signs its data using a private key (recommended to do offline).
2. A query for a particular record returns: The requested resource record set, a signature (SIG) of the requested resource record set.
3. The resolver authenticates response using public key.

DDNSSEC Resource Records: List of added RR in dnssec

DNSSEC Resource Records

DNSSEC adds new types of DNS records

RECORD TYPE	DESCRIPTION	USAGE
RRSIG	RESOURCE RECORD SIGNATURE	DNSSEC signature for a record set. Resolvers verify the signature with a public key, stored in a DNSKEY-record.
DNSKEY	PUBLIC KEY RECORD	Contains the public key that a resolver uses to verify DNSSEC signatures in RRSIG-records
DS	DELEGATION SIGNER RECORD	Holds the name of a delegated zone. DS record is placed in the parent zone along with the delegating NS-records. References a DNSKEY-record in the sub-delegated zone.
NSEC	NEXT SECURE RECORD	Contains a link to the next record name in the zone and lists the record types that exist for the record's name. DNS Resolvers use NSEC records to verify the non-existence of a record name and type as part of DNSSEC validation.

CLIENT	SERVER
Indicates DNSSEC support	Include RRSIG signature if DNSSEC is supported

The DS record contains a hash of the KSK (key signing key) belonging to the child zone. Once the DNS resolver knows the contents of DS, it can retrieve the KSK and ZSK (zone signing key) belonging to the child zone. KSK is checked against DS. ZSK is validated using the KSK. Finally, if the child zone is the actual target of the query, the answer can be checked by using the ZSK.

DNSSEC Pros and Cons: Advantages and disadvantages of dnssec

DNSSEC ADVANTAGES	DNSSEC DISADVANTAGES
▪ Origin authentication ▪ Integrity protection ▪ Stops DNS spoofing attacks	▪ High Complexity ▪ Performance ▪ No confidentiality protection ▪ Adversary can gradually learn all host names ("zone walking") ▪ Large response messages *(DNS amplification, TCP)* ▪ Still no browser support ▪ Slow adoption
▪ DNSSEC now deployed at key zones including net, com, gov, and edu	▪ Against the initial design principles of DNS: autonomy of individual zones

11.6 DNS over HTTPS (DoH) or TLS (DoT)

DoT users service specific port 853, which might be filtered by firewall/attacker. DoH users standard HTTPS port (443), usually no filtering, easy integration. Problems:
- DNS messages are not protected from eavesdropping (even with DNSSEC)
- DNS request are an easy way of tracking users (by the ISP or intelligence services)

DOH would solve some attacks on DNS such as DNS spoofing, mass-logging of DNS requests, DNS amplification/reflection, cache poisoning, etc. However, there are disadvantages. With DOH, local caches are no longer possible – each query needs to reach the remote DoH resolver. In the case of large providers, load and latency are not a problem: anycast is used to respond to the queries in a geographically distributed way. However, this concentrates even more power in the hands of a few companies (Google, Cloudflare, etc.); the internet gets even more centralized.

12 SCION (Secure Multipath Interdomain Routing Architecture)

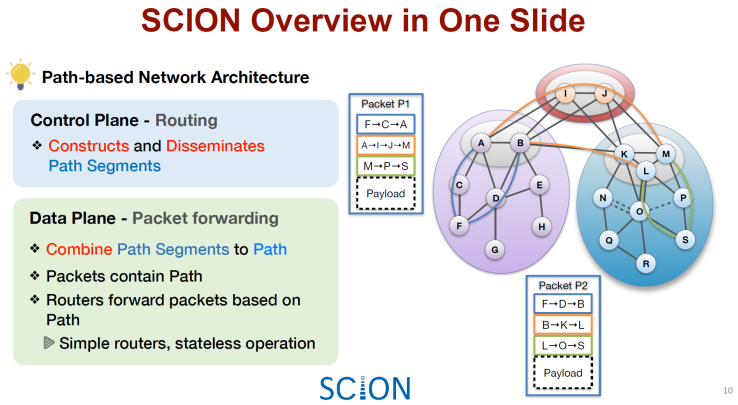
BGP security issues have been going on for years. Instead of trying to fix and patch BGP, why not just develop a completely new inter-AS protocol with modern requirements as features.

Goals of SCION: High availability, Secure entity authentication, Flexible trust, Transparent operation, Balanced control, Scalability, efficiency

SCION Architecture Principles
- Stateless packet forwarding (no inconsistent forwarding state)
- "Instant convergence" routing
- Path-aware networking
- Multi-path communication
- High security through design and formal verification (This is necessary, fromal verifications from the beginning avoids "difficult-to-verify" components
- Sovereignity and transparency for trust roots

12.1 Approach for Scalability: Isolation Domain (ISD)

The architecture of SCION mandates that the Internet is partitioned into *Isolation Domains (ISDs)*, that are independently organized groupings of ASes. In each ISD, part of the ASes form the *ISD core*, which is responsible for managing the whole ISD and has some special functions (e.g. Swisscom, Sunrise would be core ASes). An ISD usually represents an area of common trust or of common legislation (e.g. countries, multinational federations). ISDs are SCION's approach for scalability and they are a virtual concept: ASes can be in different ISDs and can have different roles in different ISDs.



12.1.1 Intra-ISD Path Exploration: Beaconing

Beaconing is am asynchronous process through which paths are found in SCION. The Core ASes in an ISD (Isolation Domain) periodically flood the ISD with PCBs, by sending them in an anycast fashion (dubbed service anycast in SCION). Any AS receiving this packet will send it to its beacon server, which will add the current AS info and send the PCB to the ASes downstream. When beacons reach leaf nodes in the AS graph, the process is completed. Each AS receives multiple PCBs representing path segments to a core AS.

Each AS deploys one or multiple beacon servers. SCION border routers receive PCB and select one beacon server to forward it to. Beacon servers coordinate to resend PCBs periodically to downstream ASes (currently every 5 seconds). ASes can choose to which customers and peers to forward which beacons, but in the end it is the sources that determine the final path.

PCB contents: PCB contains an info field with: PCB creation time. Each AS on path adds: AS name, Hop field for data-plane forwarding (Link identifiers, Expiration time, Message Authentication Code (MAC)), AS signature.
Link identifier: ASes have multiple interface numbers. The hop field has an `IN` and `OUT` link identifier, they say where traffic enters/ leaves the AS.
MAC: highly efficient (verified in a few ns) but needs symmetric keys (only known inside the AS). This allows the AS to verify its own forwarding information.

Up-Path and Down-Path Segments: PCBs contain path segments that can be used as communication paths. A path segment is any contiguous subsequence of ASes contained in a PCB, provided that at least one of the extremes is a core AS. They owe their name to the fact that they represent different segments of a whole path. Each path is comprised of an **up-path segment** (from source AS to a core AS) plus a **core-path segment** (from core AS to core AS, possibly on a different ISD), plus a **down-path segment** (from core to destination AS).

12.1.2 Core Beaconing for Inter-ISD Path Exploration

Beaconing that happens inside ISDs also happens across ISDs → core ASes beacon among each other. Beacon info looks similar as for intra ISD beaconing. With Core Beaconing for Inter-ISD Path Exploration, there is *no* convergence process! Connecting the whole internet would only take a few seconds. However, finding the best and multiple paths takes longer.
But: scalability of inter-ISD beaconing is actually **worse** than in BGP because we send lots of inter-ISD beacons and we also want to discover multiple paths. However, it still scales since the number of core ASes is highly limited (few tier 1 Ases).

12.1.3 Path server infrastructure

Every AS has its own path server. Non-core AS's path server contains up-path segments to reach the core ASes. Core AS's path server contains down-path segments and core-path segments. Caches along the way cache paths at various levels.
Up-Path Segment Registration: AS selects path segments to announce as up-path segments for local hosts. Up-path segments are registered at local path servers.
Down-Path Segment Registration: AS selects path segments to announce as down-path segments for others to use to communicate with AS. Down-path segments are uploaded to core path server in core AS.

12.2 Data plane: How to send packets

In IP, the router looks up a routing table and (usually based on the destination of the packet) makes a routing decision, forwarding the packet to the appropriate interface. In SCION none of that happens: the packet already contains the forwarding information (full AS path), so a router only needs to check the next hop information in the SCION header. As a consequence, SCION packets need larger headers compared to IP.

12.2.1 Path lookup

Disadvantage of SCION over today's internet: we need to look up paths. In today's internet, we just lookup an IP, send a packet and pray.

Steps of a host to obtain path segments:

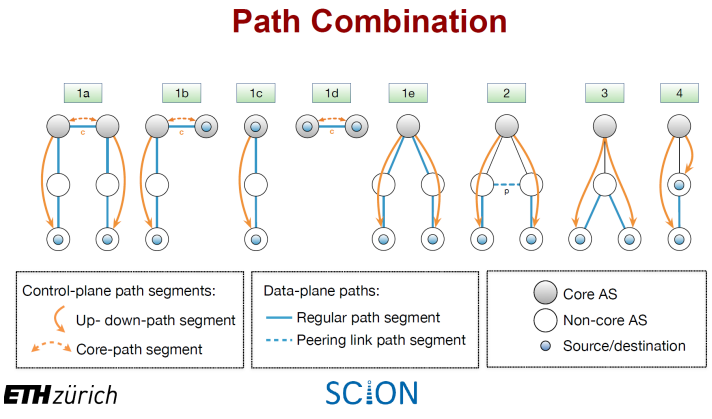
1. Host contacts RAINS server with a name: H → RAINS
   RAINS → H: ISD X, AS Y, local address Z
2. Host contacts local path server to query path segments H →→ PS: ISD X, AS Y
   PS → H: up-path (to local ISD core ASes), core-path (connect up-path and down-path segments), down-path segments (from core AS to ISD X)
3. Host combines path segments to obtain end-to-end paths, which are added to packets

Path lookup: local ISD
In step 2, client requests path segments from local path server. If down-path segments are not cached, local path server sends request to core path server.

Path Lookup: remote ISD
In step 2, client requests path segments from local path server. If down-path segments are not cached, local path server send request to core path server. If core path server does not have path segments cached, it will contact remote core path server.

Path segments are valid for several hours and cached locally. Otherwise the whole process would take too much time for each time we want to send. SCION's path combination of up-path, core-path, and down-path segments reflect current Internet routing.

Problem: Economic incentives are not all prevailed in SCION: customer could choose to use a very costly link (path) since we have multiple paths available. This would be bad for the provider. *But:* this could be solved by the provider by setting BW limits or just making customers pay more if they use more expensive links.

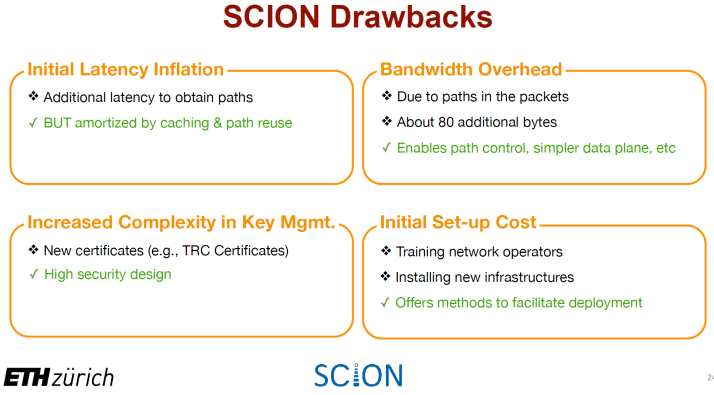


12.2.2 SCION Packet Header

A SCION packet has multiple headers:

- SCION common header
- SCION source and destination address
- Info field provides information about a path segment
- Path segment consists of one or multiple hop fields

SCION does not look at srcIP & dstIP in the network! Only when the packet gets to the destination AS will IPs be considered. **This allows for communication between private address spaces!** E.g. 192.168.0.1 in AS X could communicate with 192.168.0.1 in AS Y. Also, this would solve IPv4 address exhaustion (although IPv6 already solved it).



12.2.3 Ingress and Egress Interface Identifiers

Each AS assigns a unique integer identifier to each interface that connects to a neighboring A. The interface identifiers identify ingress/egress links for traversing AS. ASes use internal routing protocol to find route from ingress SCION border router to egress SCION border router

12.2.4 Path Encoding in Packet

In order to send a packet back (destination to source), we don't need to do another path lookup! The dst just needs to do some parsing to reverse the path. Forward and return paths are the same (one could also lookup a new path).

12.2.5 Hop Field MAC Verification

Message Authentication Code (MAC) computation and verification of Hop Field MAC value based on local AS secret key (not shared with any external entity).
Computation: $MAC_K(Timestamp, Flags'_{HF}, ExpTime, Ingress, Egress, HF')$, with HF the hop field of the previous AS.
With AESni HW crypto, only 30 cycles are needed to compute MAC!

12.3 Deployment and use cases

ISP deployment: Core ASes have to adapt quite a lot and need to do quite a bit of work for SCION. For regular ASes, most of this work is not needed. Integration of SCION limits to additional infrastructure such as beacon server, path server, RAINS, certificate, SIBRA and time servers.

12.3.1 Use Case: Low-Latency Connectivity

Generally, two paths exist between Europe and Southeast Asia:
- western route (Europe-US-SEA): High latency, high bandwidth
- eastern route (Europe, Suez canal, SEA): Low latency, low bandwidth

BGP is a "money routing protocol", traffic follows cheapest path, typically highest bandwidth path. Thus, Europe-SEA traffic generally takes the western route. There is no wrong path (both have advantages and disadvantages) but the wrong thing to do is to only advertise one single path (as BGP does).

12.3.2 Use Case: Low Earth Orbit Satellite Networks

Speed of light in fibres is a lot slower than speed of light in free space. New Low Earth Orbit (LEO) satellite networks only require around 5ms propagation latency between earth and satellite. Inter-Satellite Laser (ISL) links enable global communication. However, LEO has frequent outages/ short time windows of availability due to changing weather conditions - BGP convergence is too slow to support. SCION however can optimally integrate LEO network into Internet fabric.

13 Probabilistic Traffic Monitoring

Network traffic monitoring is crucial in today's internet. Applications of traffic monitoring are broad: anomaly detection (detect DoS attack or port scans, enforce QoS), network management (accounting (often deterministic monitoring), usage-based pricing, traffic engineering). Without network management, we have no idea what's happening inside the network.
Large content providers such as Google, Akamai, Cloudflare constantly monitor their network to detect large traffic loads and (D)DoS attacks.
Why do we want probabilistic monitoring? It's more efficient. Why do we want deterministic monitoring for accounting? Accounting happens at the edge of the network there we have enough compute power to store all states.

Traffic monitoring can be done at different granularities:
- Per-flow basis: *(srcIP, dstIP, srcPort, dstPort, protocol)*, or IPv6 flow label (20 bit)
- Can also monitor on a subset of the flow 5-tuple: DDos detection: *(*, dstIP, *, *, *)*, source bandwidth monitoring for usage-based pricing: *(srcIP, *, *, *, *)*

Traffic monitoring is difficult:
- Core routers in the Internet forward multiple terabit of traffic per second
- Empirical evidence: 20 million different flows on a 1 Tbps router
- On a 1Tbps router we have one packet every *10ns*! (1KB packets)
- Monitoring is especially important when something goes wrong (e.g. attacks). Exactly then it's even more challenging since we have more traffic.

- Attackers can craft traffic to target monitoring system (send from various ports, spoof srcIP), e.g. to exhaust state of monitoring system

13.1 Basic Concepts of Probabilistic Traffic Monitoring

Intuition: trade accuracy/precision for efficiency. Deterministic monitoring is not possible for core internet. Challenge: Measure with limited memory/processing. Output an "accurate" estimate with high probability.

General concept of probabilistic monitoring: (1) Router summarizes traffic into a compact dataset. (2) Router periodically reports the dataset to a server. (3) Server estimates certain statistics based on multiple datasets.
(2) & (3) are optional and not done by all systems.

13.2 General-Purpose Measurements (NetFlow)

Sample every packet (standard Netflow) or sample every k-th packet (sampled Netflow). Keep flow entry $\{C_{pkt}, C_{byte}\}$ for each flow, counting the number of sampled packets and bytes.
Estimate the number of packets and bytes with $\tilde{n}_{pkt} = k * C_{pkt}$, $\tilde{n}_{byte} = k * C_{byte}$.

Advantages: simple and efficient.
Disadvantages: Memory overhead (one entry per flow in worst case), imprecise estimate, especially for short-lived flows (we have both FP and FN), attacker could exploit by only sending large traffic in between sampling (solution: sample with probability $\frac{1}{k}$)

General-purpose flow measurement is either imprecise or infeasible. Solution: focus on specific traffic information (large flows, number of flows, flow distribution, ...).

13.3 Large-Flow (Elephant) Detectors

Large flows are flows that consume more than a given threshold of link capacity during a given measurement interval, e.g. flows that take more than 1% of link capacity. There is evidence that less than 1% of flows account for more than 90% of traffic volume. It thus makes sense to look at large flows and ignore small ones.
It is possible to efficiently identify large flows without keeping per-flow state on routers because #large flows << #flows in total.

13.3.1 Sample and Hold (Sampling based)

This is essentially a variant of Netflow.
Sample: We sample each byte with probability p. Practically, samples a packet of size s with probability p_s, $p_s = 1 - (1-p)^s \approx p * s$ (when p is small).
Hold: updates a flow entry for all subsequent packets once it is created. Requires flow-table lookup for every incoming packet. Flow-table stores $\{C_{pkt}, C_{byte}\}$.

A problem with sample-and-hold is that for large flows we need to look at all packets. Once we've seen all flows, we might need to keep track of a lot of flows.

13.3.2 Multistage Filter (Sketch based)

Use a CountMin sketch to estimate the number of packets of a flow.
Reminder: CountMin sketches use k different hash function and an array. We hash the flow-tuple with each hash function and increase all counters at the positions indicated by the hash functions. The count estimate is the minimum value of all counters.
Properties: fixed memory resources, no FNs (we can't undercount), low FPs (overcount due to hash collisions). However, we need to look at all packets, but we can keep fewer counters.

13.3.3 EARDet Algorithm (Frequent item finding)

Goal: : F ind all items that appear in a stream of m items more than k times with no false negatives
Space: n = m/k - 1 counters
Algorithm: We have k counters. For each new packet $p \in f$ (flow f), we increase the corresponding counter for f by the packet size. If no counter tracks f, we start tracking it. If all counters are used, we decrease *all* counters by the packet size. If one counter reaches zero while decreasing, we add the current flow with the remaining packet size.
Virtual traffic: Use "virtual flows" for each idle period. Each virtual flow is at most equal to a low-bandwidth threshold (Th_L).

Properties of EARDet: no FN for large flows, no FP for small flows, FN & FP possible for medium flows, deterministic (keep performance regardless of input traffic or attack pattern), relatively small storage cost (but many counters are needed) **Disadvantage**: per-packet counter update is an expensive operation

EARDet is an adaption of the MG-algorithm, instead of increasing counters by number of packets, we increase counters by packet size.

13.4 Finding Duplicates: Bloom Filters

Problem: identify if an element is a duplicate
Challenge: cannot store all previous elements
Solution: Bloom filter provides probabilistic data structure for set membership testing

Bloom filters are a more memory-efficient approach for insertions and membership queries. Bloom filters consist of a fixed size table `bf` with M 1-bit cells and K hash functions and we write a 1 at each position indicate by each hash function.

13.4.1 Dimension your bloom filter

N elements, M cells, K hash functions, FP false positive rate.
- probability that one hash function returns the index of a particular cell: $\frac{1}{M}$
- probability that one hash function does not return the index of a particular cell: $1 - \frac{1}{M}$
- probability of a cell to be 0: $(1 - \frac{1}{M})^{KN}$
- false positive rate P(FP): $(1 - (1 - \frac{1}{M})^{KN})^K$
- false negative rate: 0

For an approximation, use: $p := P(FP) = (1 - (1 - \frac{1}{M})^{KN})^K \approxeq (1 - e^{-KN/M})^K$.

There's a global minimum when $K = \ln(2) * \frac{M}{N} \approx 0.7 * \frac{M}{N}$ found by taking derivative of $P(FP)$.
For that choice of K, resulting $p := P(FP) = 2^{-K} \approx 0.6185^{M/N}$.
Given optimal K, choice of optimal $M = -\frac{N \ln p}{(\ln 2)^2} \rightarrow O(N)$ space.

In practice: if we use the Bloom filter for a long time, it's going to fill up, which leads to more false positives (a full bloom filter we just conclude that every packet is in the filter). We thus need to reset the Bloom filter periodically. Simply resetting the whole Bloom filter leads to false negatives (all cells are back to 0 after reset).
In practice, we use *two* same-sized Bloom filters and alternate them. We only put values into one single BF at a time and switch after a reset. *BUT* for membership queries, we always check both filters! However, for very old packets we can still get FNs. Solution: use timestamps on packets and remove tracking for old packets. This gives us the FN guarantee.

13.5 Probabilistic Counting: Estimating the Number of Flows

Simple probabilistic counting: Hash flow ID to generate a value in [0,1). Keep the flow ID associated with the smallest hash value.
Expectation value of smallest value is 1 / (number of flows + 1).
Estimate the number of flows by the smallest value v seen so far: $\tilde{n} \approx 1/v - 1$.

Problems:
- minimum has large variance → not very robust
- An attacker controlling only 1 input can bias the estimation. Solution: use private hash function or salted hashing.

Proposal by Bar-Yossef et al. (2002):
- Keep track of the k smallest hash values
- Expectation value of k-th smallest value is $k/(n+1)$, variance is smaller
- Estimate the number of flows by the k-th smallest value v_k that has been seen so far: $\tilde{n} \approx k/v_k - 1$

13.6 Traffic Monitoring vs. Intrusion Detection

Both can detect malicious activities such as DoS attacks & port scans at selected network vantage points.
Intrusion detection: Typically deployed at network edges, destination-based diagnosis, can analyze detailed payload data as well.
Traffic monitoring: Can be deployed at high-speed backbone routers, diagnoses network-wide anomalies, analyzes packet headers only.