Advanced Computer Networking (ACN)

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Tunnel Protocols

Tunnel Protocols

Introduction
Tunneling
Definition

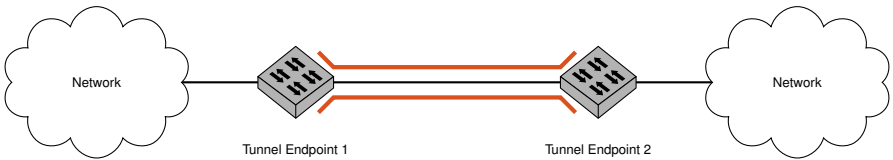
- Tunneling encapsulates one datagram within another datagram.
- The outer packet and its headers are regarded for switching / routing purposes of the underlay network.
- The inner packet is opaque to the underlay network.
- The overlay network handles the inner packet, including switching and routing.
- May be used at any layer of the ISO OSI model.

Possible benefits

- Build overlay structure
- Deal with heterogeneous protocols
- Protect traffic
- Isolate customers (data center)

But ...

- More overhead
- Configuration effort
- MUCH room for misconfiguration



Introduction
Possible Tunneling Use Cases

What can be achieved with a tunnel?

- Force packet to reach specific node in the network (different path than from regular routing), e.g. using IP-in-IP tunnel - RFC 2003
- Traverse incompatible nodes, e.g. IPv6 tunnel over IPv4 only nodes
- Provide secure connection between different nodes, e.g. using IPsec

Which considerations when using tunneling?

- Performance
  - Processing overhead
  - Packet length overhead: reduced MTU, possible fragmentation, limited visibility to end systems
- Security
  - Correct configuration and tunnel setup not trivial
  - Inner and outer headers need to be verified
  - Tunnels may circumvent security policies (e.g. bypassing filters / firewalls)

Representative Tunneling Technologies

- Traffic management and isolation
  - VLAN
  - MPLS
  - VXLAN
- Secure tunnels
  - IPsec
  - TLS, DTLS
  - Wireguard
  - ssh
  - TOR - Onion Routing Overlay
- Protocol innovation; incremental protocol deployment
  - IP multicast overlays, e.g. “Mbone” (“multicast backbone”)
  - various IPv6 transition technologies
  - Peer-to-Peer overlays

Introduction
Virtual Private Network (VPN)

What is a VPN?

- In general, just another tunneling protocol
- VPNs are usually encrypted
- Provide secured connections between different nodes

Use cases:

- Securely connect different offices to HQ
- Build secure connection from a laptop to a company network
- Anonymization

What does TUM/LRZ use?

- LRZ offers eduVPN
  - part of the GÉANT project (co-funded by the EU)
  - very easy to configure
  - supports OpenVPN and WireGuard
  - supports split and full tunnel
- Other VPNs LRZ used to offer in the past:
  - Cisco AnyConnect
    - TLS-based signalling
    - DTLS transport of tunneled VPN traffic
    - fallback to TLS-based transport where UDP is blocked
  - Cisco IPsec-based VPN
    - with IKEv1 signalling protocol

Tunnel Protocols

TLS/SSL-based VPNs
OpenVPN [1]

Overview

- Key exchange is based on TLS/SSL
- Can be used on top of UDP or TCP (Why is TCP a bad idea?)
- Traffic encryption uses custom scheme
- Good NAT traversal properties
- Easy to use
- Not an industry standard
- Not very “professional”, but hacker community likes it
- Open Source

Use case:

- Road warriors (laptops connecting to the office)
- Students etc. building a cheap VPN

TLS/SSL-based VPNs
Cisco AnyConnect [2][3]

Overview

- Proprietary Cisco software
- Supports several protocols:
  - (Mostly) SSL/TLS based
  - Can use Datagram TLS (DTLS), DTLS uses UDP instead of TCP
  - Can run on port 443 (HTTPS) $\rightarrow$ usually no problem with firewalls
- No problems with NAT

Use cases:

- Big corporations supporting mobile endpoints (laptops)
- Corporations with existing Cisco infrastructure
- Academic compute centers (e.g. LRZ) deployed Cisco AnyConnect

Tunnel Protocols

- Layer 3 secure network tunnel for IPv4 and IPv6
- Implemented in the Linux kernel since version 5.6
- UDP based, easy firewall holepunching
- Modern cryptographic algorithms
- Emphasis on simplicity and auditability
- Authentication model similar to `ssh authorized_keys`
- Replacement for OpenVPN and IPsec

The following slides contain content from Jason A. Donenfeld (wireguard.com)

Easily auditable

- openvpn: **116,730** LoC + OpenSSL!
- Linux IPSec: XFRM (119,363 LoC) + StrongSwan: **405,894** LoC!
- SoftEther: **329,853** LoC
- WireGuard: **4,561** LoC

Easy to set up

- Just a network interface
- `ip link add wg0 type wireguard`
- Endpoint roaming like in `mosh`/`tinc`
- Identities are static public keys like in `ssh`

Packet flow

- Userspace: `send(data)`
- Standard Kernel: Standard routing decision for `wg0`
- WireGuard: Destination IP selects peer
- WireGuard: `encrypt(data)`
- Standard Kernel: `send(encrypted)`
- ... Internet ...
- Standard Kernel: `receive(encrypted)`
- WireGuard: `decrypt(packet)` & determine peer
- WireGuard: Check source IP against allowed peer IPs
- Standard Kernel: further packet processing

Further design ideas

- Fixed width header fields, **no parsing needed**.
- **No State allocation** during work, only during config
- **No Memory allocation** when handling received packets
  - requires the crypto to work with finite amount of preallocated memory
- No state is modified when handling unauthenticated packets
- WireGuard grew out of kernel rootkit project
  - Does not respond to any unauthenticated packets
  - No keepalives

Modern Crypto Primitives

- `ChaCha20` for symmetric encryption
- authenticated with `Poly1305`
- using `RFC7539`'s `AEAD` construction
- `Curve25519` for ECDH
- `BLAKE2s` for hashing and keyed hashing described in `RFC7693`
- `SipHash24` for hashtable keys
- `HKDF` for key derivation, as described in `RFC5869`
- `Noise_IKpsk2` key exchange protocol

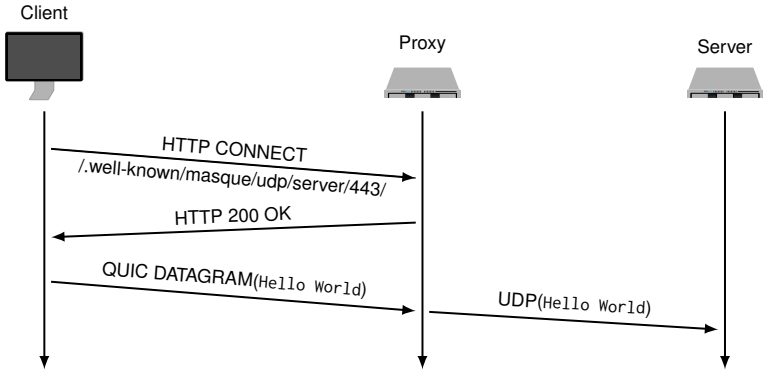
Tunnel Protocols

MASQUE

- A set of protocols for proxying over HTTP
- Under active development
- Standardized by the IETF:
  - proxying of IP traffic (`CONNECT-IP`, RFC 9484)
  - proxying of UDP traffic (`CONNECT-UDP`, RFC 9298)
- Under development by the IETF:
  - proxying of L2 traffic (`CONNECT-Ethernet`)
  - QUIC-aware proxying
- Benefits from using mainly QUIC as transport
- MASQUE traffic is hard to distinguish from HTTP
  - therefore hard to block

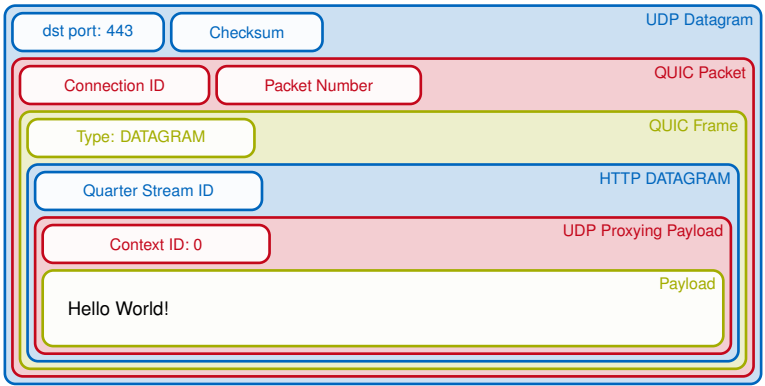
MASQUE

CONNECT-UDP



- Client signals destination and data type via URL scheme
- Proxy acknowledges connection setup with HTTP status code 200
- Client sends application data in DATAGRAM frames, proxy forwards data in UDP packets

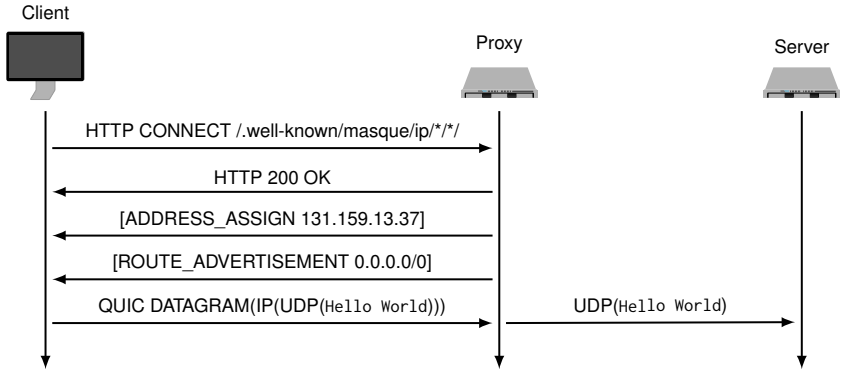
MASQUE
Packet format between client and proxy



- MASQUE uses QUIC DATAGRAMS, which provide unreliable transport (no retransmissions, but CC)
- Context ID is always set to zero (so far) indicating UDP transport
- Payload is arbitrary bytes (could be DNS, HTTP/3 or nested MASQUE)

MASQUE

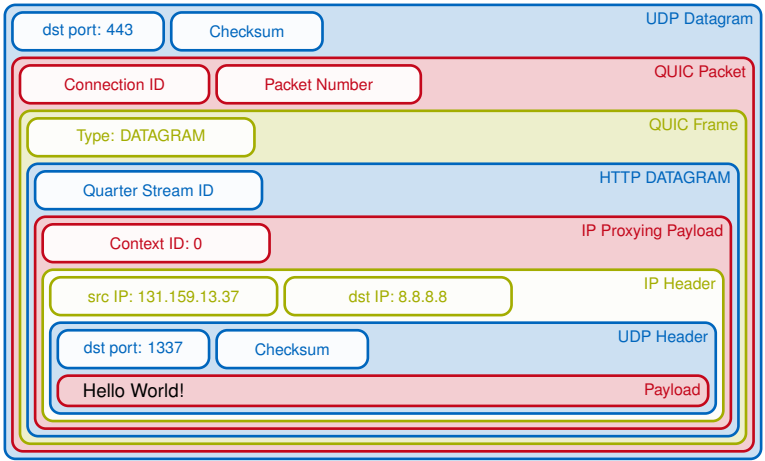
CONNECT-IP



- Client requests tunnel anywhere using a URL scheme
- Proxy acknowledges connection setup with HTTP status code 200
- Proxy can optionally signal a source IP for the client to use and allowed destination subnets
- IP assignment is useful for VPN use cases
- Client sends complete IP packets in DATAGRAM frames, proxy sends them out

MASQUE

Packet format between client and proxy



- Payload includes a full IP packet
- The source address of the encapsulated IP packet is routed to the proxy
- The IP packet can be decapsulated and forwarded without modification

Use cases differ between MASQUE protocols!

CONNECT-UDP

- Ability to transport UDP enables transport of QUIC, in turn enables a HTTP/3 proxy
- Proxying of HTTP/1 or /2 is enabled by CONNECT protocol of HTTP for TCP
- Increase of data being transported via HTTP(/3) demands HTTP/3 proxy

CONNECT-IP

- Enables Layer-3-VPN
- Capsules enable signalling of additional info
- Alternative to Wireguard/IPSec/OpenVPN

MASQUE
iCloud Private Relay

- A privacy service from Apple using MASQUE
- Available for iCloud+ subscribers
- Enabled by default on. . .
  - . . . iOS 15 and later
  - . . . macOS Monterey (12) and later
- Uses Privacy Partitioning principle

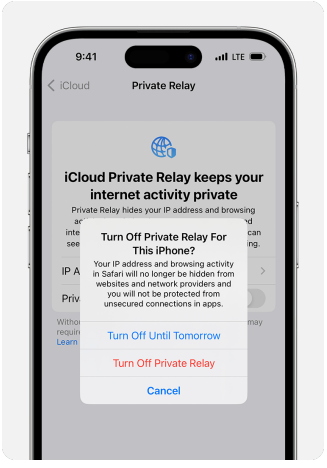


Image taken from https://support.apple.com/en-us/102022

MASQUE
iCloud Private Relay - Privacy Partitioning

- Two nested MASQUE connections
- Data is sent to the ingress proxy
  - operated by Apple
  - Knows client's IP address
  - Does not know content or destination IP address
- Data is forwarded to the egress proxy
  - operated by "third-party content provider"
    - a CDN like Akamai or Cloudflare
  - Knows destination IP address
  - Does not know the client's IP address . . .
  - . . . and the content, depending on the protocol used

Can access	Client	Ingress	Egress	Server
Data	✓	×	○	✓
Client IP	✓	✓	×	×
Destination	✓	×	✓	✓

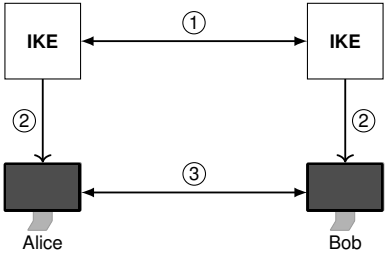
Figure 1: Data flow from client to server with Apple iCloud Private Relay. Illustration taken from https://support.apple.com/en-us/102602.

Tunnel Protocols

IPsec
Overview

- Standardized by a number of RFCs (most important RFC 4301 [4])
- 2 modes of operation
  - Tunnel Mode: (a) Subnet to Subnet, Endpoints are called Security Gateways, or (b) Host to Security Gateway
  - Transport Mode: Host to Host
- 2 phases of operation
  - Handshake: Establish one or more Security Associations (SA), IPsec signalling protocols that establish SAs: IKEv1 (old), IKEv2
  - Data transfer: Use SAs to send encrypted and/or integrity protected traffic, Protocols used: Encapsulated Security Payload (ESP), Authentication Header (AH)
- Implementations
  - Commercial implementations by major hardware vendors (Cisco, Juniper, Arista, ...)
  - Open Source implementations (IKEv1 / IKEv2 / ESP / AH)
    - IKEv1 (deprecated - don't use it) - implementations include: vpnc
    - IKEv2 (State-of-the-art) - implementations include: strongSwan, libreswan
    - ESP / AH: Linux / FreeBSD kernel
- Usage scenarios
  - Connections between different sites (e.g. branch office to HQ)
  - Connection of client into enterprise network (road warrior scenario)

How does IPsec work?



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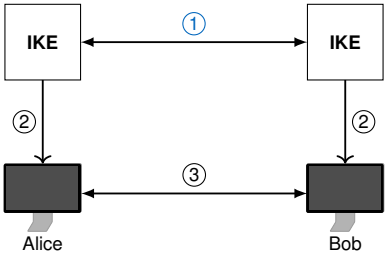

① Authentication, key establishment and negotiation of crypto algorithms

- Possible protocols: ISAKMP, Internet Key Exchange (IKE), IKEv2

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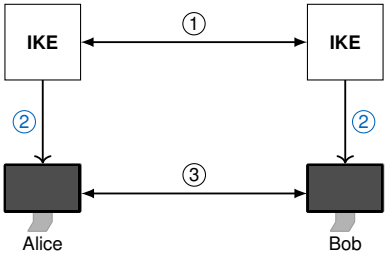

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② Set keys and cryptographic algorithms

IPsec

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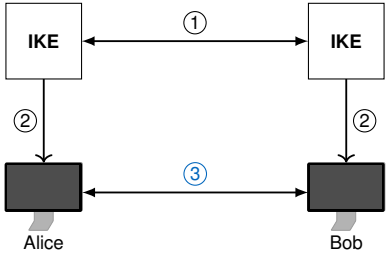
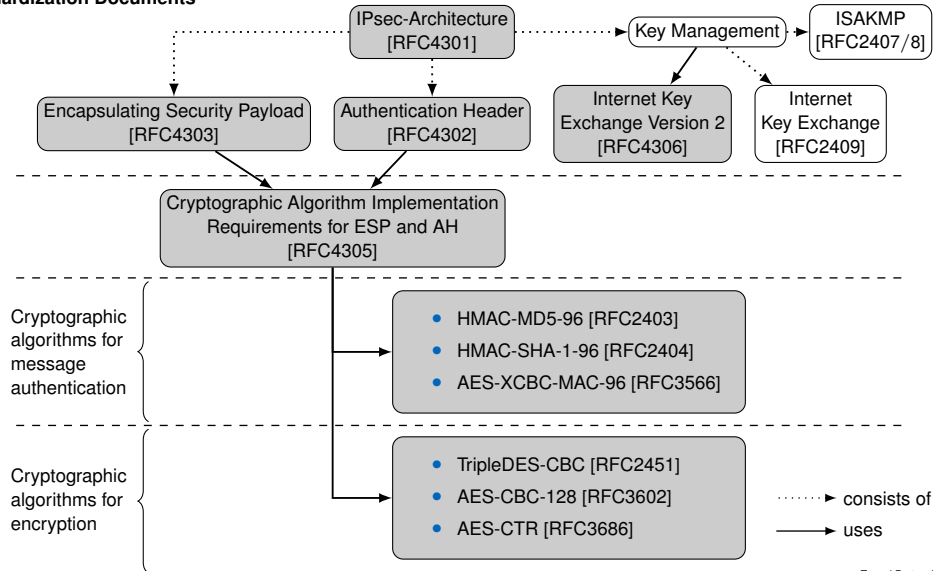


1. Authentication, key establishment and negotiation of crypto algorithms
   - Possible protocols: ISAKMP, Internet Key Exchange (IKE), IKEv2
2. Set keys and cryptographic algorithms
3. Secure channel which provides
   - Data Integrity via Authentication Header (AH) or Encapsulating Security Payload (ESP)
   - Confidentiality using ESP

Note: ESP can provide both data integrity and encryption while AH only provides data integrity

IPsec Standardization Documents



IPsec

RFC 4301 defines the basic architecture of IPsec:

- Concepts
  - Security Association (SA) and Security Association Database (SAD)
  - Security Policy (SP) and Security Policy Database (SPD)
- Fundamental Protocols
  - Authentication Header (AH)
  - Encapsulation Security Payload (ESP)
- Protocol Modes
  - Transport Mode
  - Tunnel Mode
- Key Management Protocols
  - ISAKMP, IKE, IKEv2

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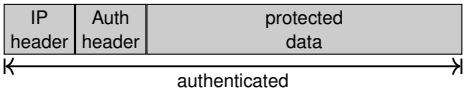
List of IPsec related RFCs: https://datatracker.ietf.org/wg/IPsec/documents/

- Most RFCs updated in 2005 after several years of revision
- Support for integration of new crypto primitives for encryption and integrity
- Reduced complexity and better protocol design

Available Protocols

Authentication Header (AH):

- Data origin authentication and replay protection
- Inserted between the IP header and the data to be protected



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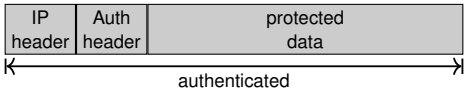
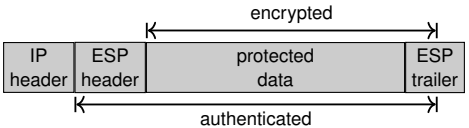


Encapsulating Security Payload (ESP):

- Data origin authentication, confidentiality and replay protection
- A header and a trailer encapsulating the data to be protected



Key management and setup of Security Associations (SA)

Internet Security Association Key Management Protocol (ISAKMP)

- Defines generic framework for authentication, key exchange and SA parameters [RFC2408]
- Does not define a specific authentication protocol but defines
  - Packet formats
  - Retransmission formats
  - Message construction requirements
- Use of ISAKMP for IPsec is further described in [RFC2407]

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Internet Key Exchange Version 2 [RFC4306]

- Defines an authentication and key exchange protocol
- Reduced complexity by better protocol design and by omitting unnecessary features

IPsec
IPsec Replay Protection

AH- and ESP-protected packets carry a sequence number

- On setup of a Security Association (SA) this sequence number is initialized to zero
- The sequence number is increased with every IP packet sent
- The sequence number is 32-bit long and a new session key is needed before a wrap-around occurs
- The receiver checks if the sequence number is contained in a window of acceptable numbers

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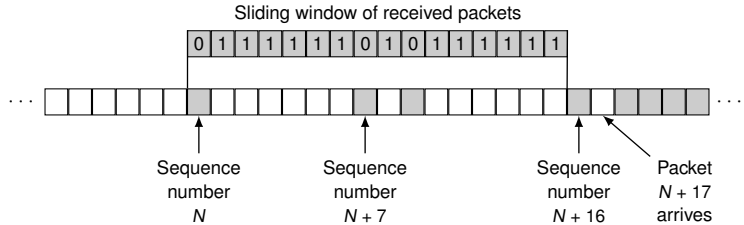

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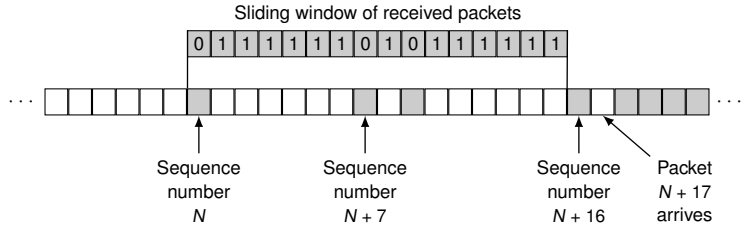

- Packet with sequence number *N* can still be accepted
- Window size has to be at least 32 in practice

IPsec
IPsec Replay Protection

If a received packet has a sequence number which

- is left of the current window $\Rightarrow$ the receiver rejects the packet
- is inside the current window $\Rightarrow$ the receiver accepts the packet and advances the window
- is right of the current window $\Rightarrow$ the receiver accepts the packet and advances the window

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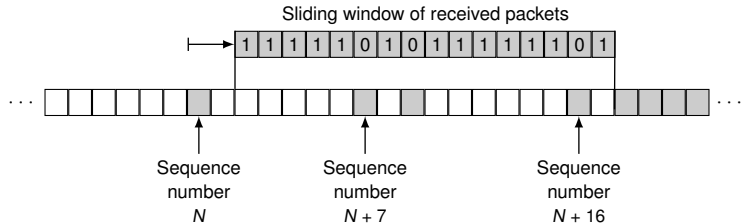

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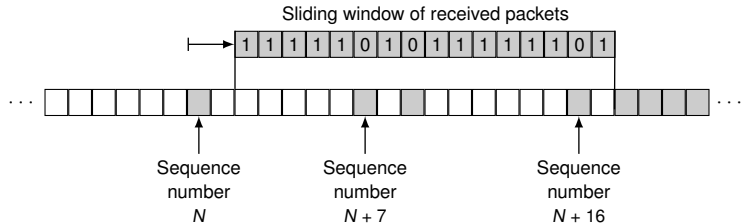

- Packet with sequence number *N* can no longer be accepted
- IP packets are only accepted after successful authentication verification
- The window is never advance before this verification

Transport Mode

- Only usable between communication endpoints
  - Host ↔ Host
  - Host ↔ Gateway (e.g. Gateway is end-point for network management)
- Adds a security specific header (+ trailer if ESP is employed)

IPsec Security Protocol Modes

Transport Mode

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Tunnel Mode

- Usable with arbitrary peers
- Encapsulates IP packets

- Allows for e.g. a gateway, protecting traffic on behalf of hosts in subnetwork

Transport Mode

- Used when the *cryptographic endpoints* are also the *communication endpoints* of the secured packets
  - Cryptographic Endpoints: Entities that process IPsec headers
  - Communication Endpoints: Source and destination of an IP packet

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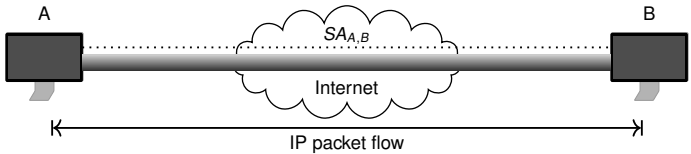

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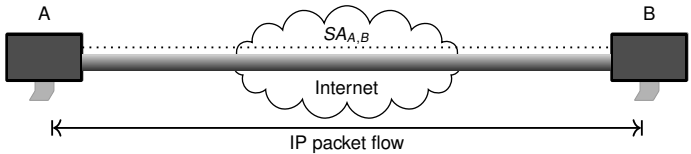

- In most cases, *communication endpoints* are hosts
- But not always the case (e.g. Gateway being managed by SNMP)

IPsec Security Protocol Modes

Tunnel Mode

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- This allows for gateways securing IP traffic on behalf of other entities

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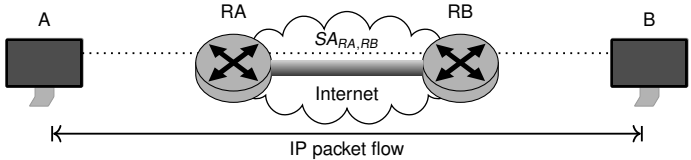

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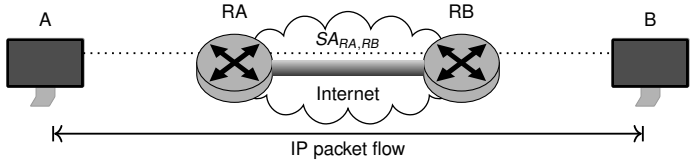

What if only one cryptographic endpoint is a communication endpoint?

Tunnel Mode

- Used when at least one *cryptographic endpoint* is not a *communication endpoint*.
- Example: Security gateway, ensuring authentication and/or confidentiality between subnetwork and host

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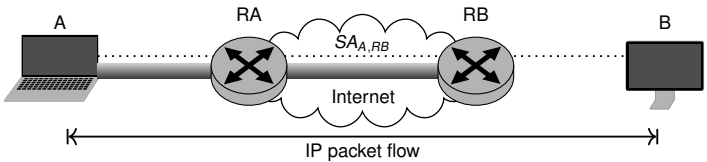

Traffic Selectors

A Traffic Selector (TS) is a set of properties used to characterize IP packets. Each TS may contain:

- IP source address
  - Specific host, network prefix, address range or wildcard
- IP destination address
  - Specific host, network prefix, address range or wildcard
  - In case of incoming tunneled packets the inner header is evaluated
- Name
  - DNS name, X.500 name or other name types
- Protocol
  - Protocol identifier of the transport protocol for this packet (e.g. TCP/UDP)
  - This may not be accessible when a packet is secured with ESP

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  - In case of incoming tunneled packets the inner header is evaluated
- Name
  - DNS name, X.500 name or other name types
- Protocol
  - Protocol identifier of the transport protocol for this packet (e.g. TCP/UDP)
  - This may not be accessible when a packet is secured with ESP

Traffic Selectors are used to define Security Policies!

IPsec
Security Policies

Definition

A Security Policy (SP) specifies which and how security services should be provided to IP packets.

This includes

- Selectors that identify specific IP flows
- Required security attributes for each flow
  - Security protocol (AH / ESP)
  - Protocol Mode (Transport / Tunnel)
  - Other parameters (e.g. policy lifetime, port number, ...)
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Security Policies are stored in the Security Policy Database (SPD)

IPsec
Security Associations

Definition

A Security Association (SA) is a simplex channel that describes the way how packets need to be processed

As such

- An SA defines employed encryption / authentication algorithms and keys
- An SA is associated with either AH or ESP but not both
- Bidirectional communication requires two security associations
- SAs can be setup as
  - Host $\leftrightarrow$ Host
  - Host $\leftrightarrow$ Gateway
  - Gateway $\leftrightarrow$ Gateway

Security Associations are stored in the Security Association Database (SAD)

IPsec
Security Associations

In the Security Association Database (SAD)

- an entry (SA) is uniquely identified by a Security Parameter Index (SPI)
- the SPI value is specified by the receiving side during SA negotiation
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An SA entry in the SAD includes

- Security Parameter Index (SPI)
- IP source / destination address
- A security protocol identified (AH / ESP)
- Current sequence number counter (replay protection)
- Protocol algorithms, modes, IVs and keys for authentication and encryption
- Security Association Lifetime
- IPsec protocol mode (tunnel / transport)
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IPsec
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Now, how does this work in practice?

Outgoing Traffic

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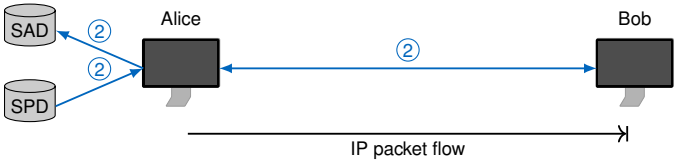
Processing of IPsec Traffic

Outgoing Traffic



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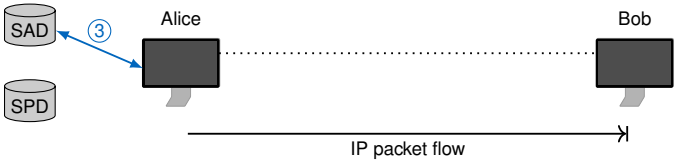
Processing of IPsec Traffic

Outgoing Traffic



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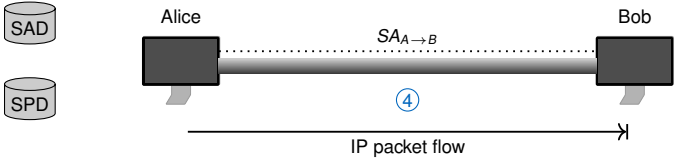
Outgoing Traffic



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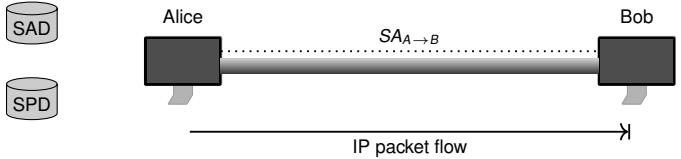

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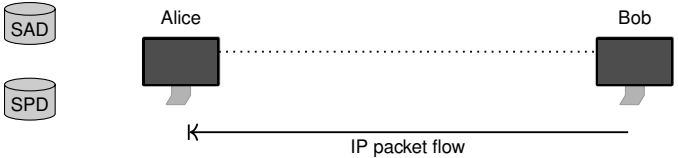
Incoming Traffic



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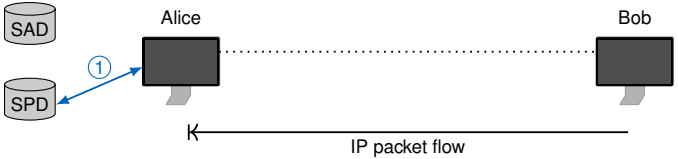

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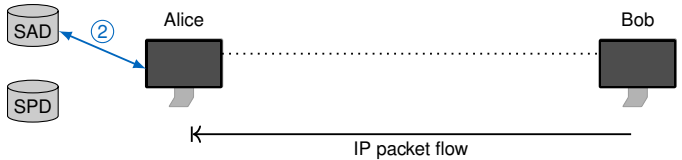
Processing of IPsec Traffic

Incoming Traffic



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Processing of IPsec Traffic

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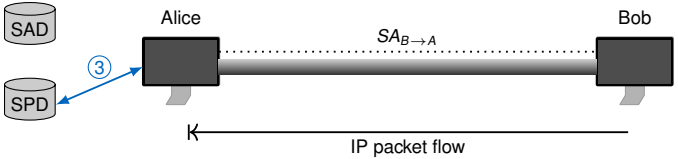

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Processing of IPsec Traffic

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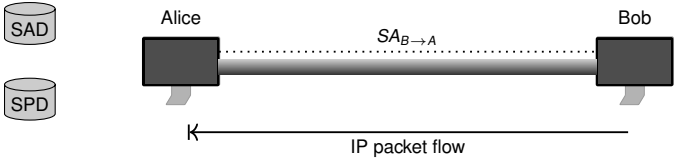

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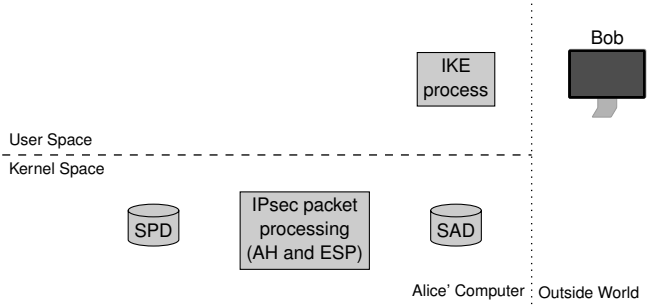
4. Deliver to the appropriate protocol entity (e.g. network / transport layer)

IPsec
Processing of IPsec Traffic

Architecture View



IPsec
Processing of IPsec Traffic

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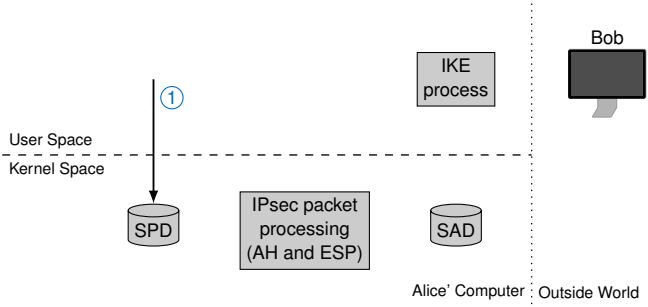

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IPsec
Processing of IPsec Traffic

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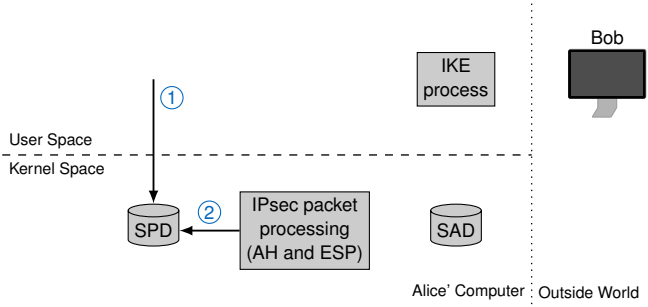

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IPsec
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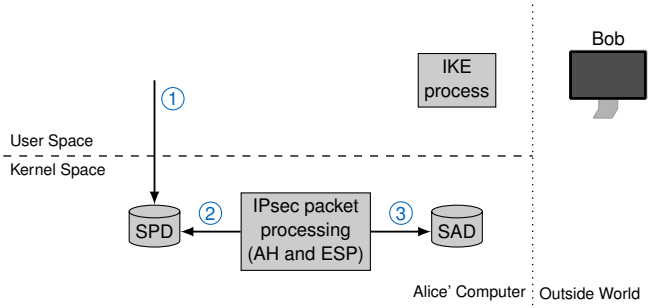

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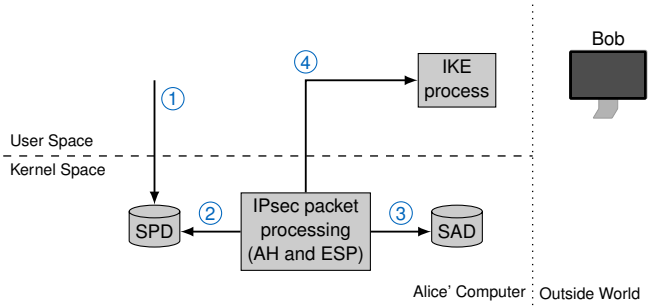

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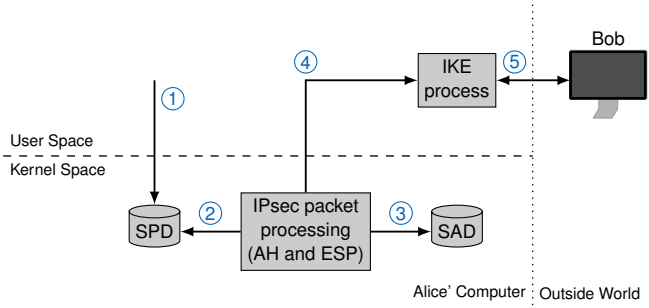

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IPsec
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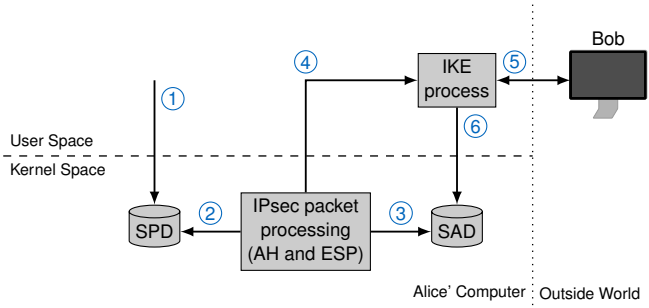

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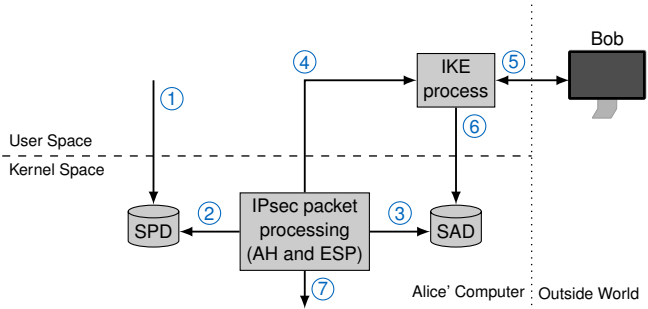

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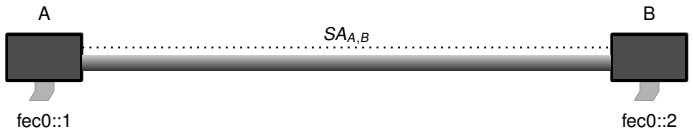
7. The IPsec module can now send a packet with applied IPsec

Example:
IPv6 connection with *ESP* and *Transport Mode*



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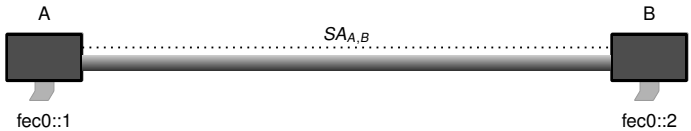

Configuration at Host A

- `spdadd fec0::1 fec0::2 any -P out IPsec esp/transport//require;`
- `spdadd fec0::2 fec0::1 any -P in IPsec esp/transport//require;`

where

- First IP corresponds to source in the IP header
- Second IP corresponds to destination in the IP header
- `any` defines the upper-layer protocol (e.g. ip4, ...)
- `out` defines the policy to hold for outgoing packets
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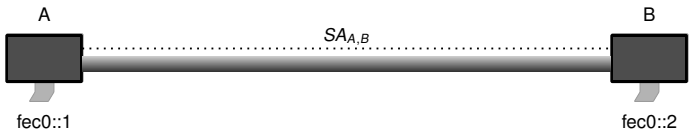

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⇓

Configuration at Host B

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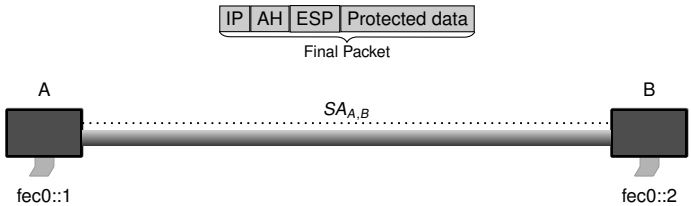
Setup of IPsec Security Policies

Example:

IPv6 connection with *ESP/Transport* applied first and *AH/Transport* applied next:



Setup of IPsec Security Policies

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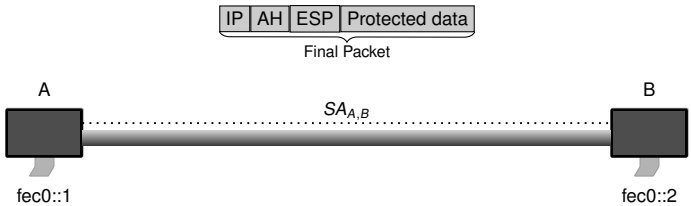

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Setup of IPsec Security Policies

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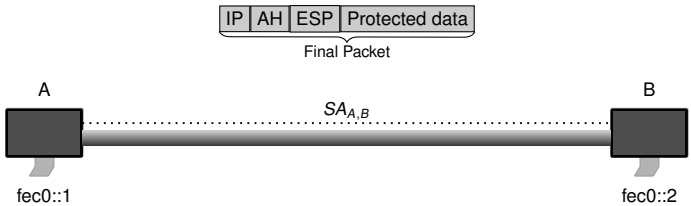

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⇓

Configuration at Host B:

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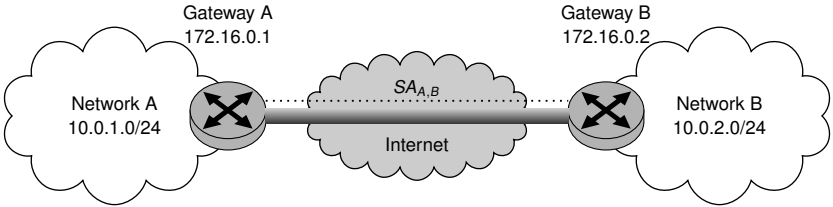
- `spdadd fec0::1 fec0::2 any -P in IPsec esp/transport//require ah/transport//require;`

Example:
ESP Tunnel for VPN



IPsec
Setup of IPsec Security Policies

Example:
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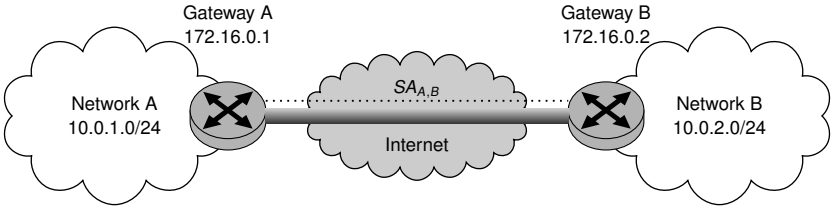

Configuration at Gateway A

- `spdadd 10.0.1.0/24 10.0.2.0/24 any -P out IPsec esp/tunnel/172.16.0.1-172.16.0.2/require;`
- `spdadd 10.0.2.0/24 10.0.1.0/24 any -P in IPsec esp/tunnel/172.16.0.2-172.16.0.1/require;`

Setup of IPsec Security Policies

Example:
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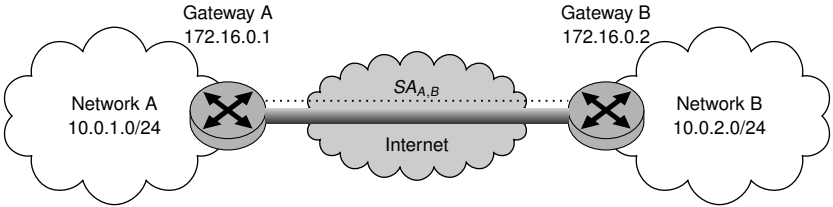

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⇓

Configuration at Gateway B:

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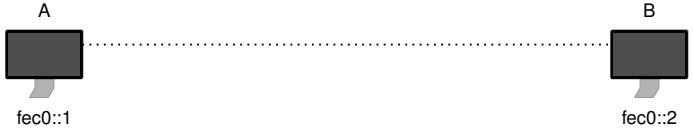
- `spdadd 10.0.1.0/24 10.0.2.0/24 any -P in IPsec esp/tunnel/172.16.0.1-172.16.0.2/require;`

Setup of IPsec Security Associations



Example:
Manually setting up an *AH SA*:

```
# add src dst proto spi -A authalgo key;
add fec0::1 fec0::2 ah 700 -A hmac-md5 0xbf9a081e7ebdd4fa824c822ed94f5226;
add fec0::2 fec0::1 ah 800 -A hmac-md5 0xbf9a081e7ebdd4fa824c822ed94f5226;
```

Manually setting up an *ESP SA*:

```
# add src dst proto spi -E encalgo key;
add fec0::1 fec0::2 esp 701 -E 3des-cbc 0xdafb418410b2ca6a2ba144561fab354640080e5b7a;
add fec0::2 fec0::1 esp 801 -E 3des-cbc 0xdafb418410b2ca6a2ba144561fab354640080e5b7a;
```

WARNING: Setting up an SA manually is error prone!

- The administrator might choose insecure keys
- The set of SAs might be inconsistent
- It is better to rely on an IKE daemon for setting up SAs

Tunnel Protocols

Other protocols

Other well-known tunneling protocols

- Point-to-Point Tunneling Protocol (PPTP, RFC 2637)
- Layer 2 Tunneling Protocol (L2TP, RFC 3355)
- Generic Routing Encapsulation (GRE)
- SSH tunnel (port forwarding)
- IP-over-IP (RFC 2003)
- HTTP tunnel
- ICMP tunnel
- DNS tunnel
- ...

Tunnel Protocols

Summary

Different protocols for different use-cases

- Simplifying L2 networks administration and separation: VLAN, VXLAN
- Connect remote workers to company resources over the Internet: IPsec, SSL-based VPNs
- Evade some firewalls: MASQUE, IP-over-(HTTP/DNS/ICMP), ...

Different protocols for different features

- Encryption and authentication
- Easier addressing
- Performance (e.g. TCP-over-TCP)

Different protocols for different software support

- Some tunneling protocols are directly supported by operating systems

Tunnel Protocols

Tunnel Protocols

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