IP, IPsec, and IKEv2

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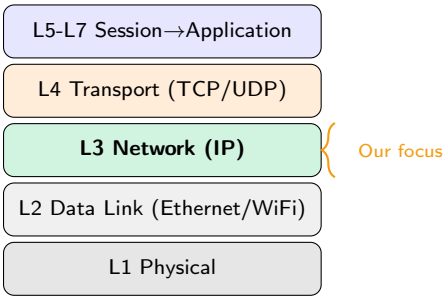
Outline

1. IP Fundamentals
2. IPv6 and MTU Considerations
3. IP Security Problems
4. IPsec
5. IKEv2 (Internet Key Exchange)

IP Fundamentals

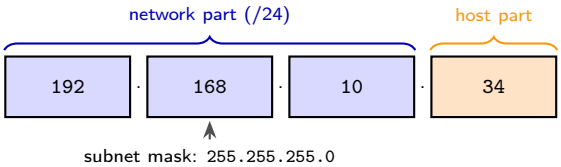
The IP Layer in the ISO/OSI Stack

- IP operates at **Layer 3 (Network layer)**.
- Main role: logical addressing and packet forwarding across multiple networks.
- IP is **connectionless**:
  - no built-in delivery guarantee
  - no built-in ordering guarantee
  - no built-in confidentiality/integrity
- Transport protocols (TCP, UDP, QUIC) run above IP.



Reading an IPv4 Address

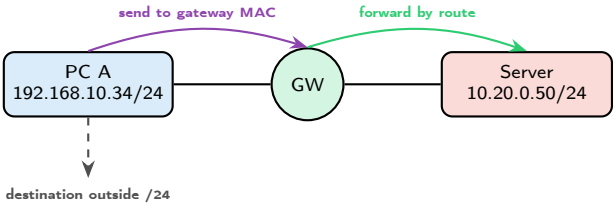
- Example IPv4 address: **192.168.10.34/24**
- Dots split the address into **4 octets** (8 bits each): total **32 bits**.
- Prefix **/24** means:
  - first 24 bits = network part
  - last 8 bits = host part



Result: this host is number 34 in network `192.168.10.0/24`.

Addressing Basics: Network, Host, and Gateway

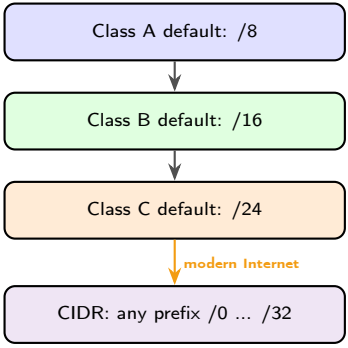
- Every host needs:
  - an IP address
  - a subnet mask/prefix
  - a default gateway
- Same subnet: direct delivery at Layer 2.
- Different subnet: send to default gateway.



IP Classes vs CIDR

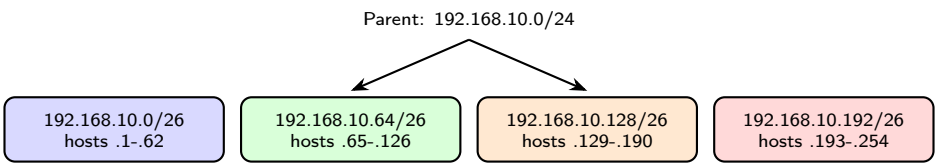
Class	First octet	Default mask	Default prefix
A	1–126	255.0.0.0	/8
B	128–191	255.255.0.0	/16
C	192–223	255.255.255.0	/24

- Classful addressing was rigid and wasted space.
- **CIDR** is classless: choose any prefix length (for example /20, /27, /31).



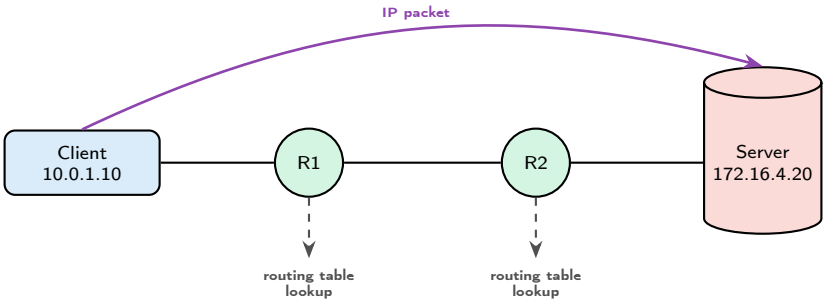
Subnetting with CIDR: Example

- Start with network `192.168.10.0/24` (256 total addresses).
- Split into four /26 subnets: each has 64 addresses.
- Host bits in /26: $32 - 26 = 6$ so total addresses are $2^6 = 64$.
- Usable hosts per /26: $2^{(32-26)} - 2 = 62$.
- Why -2? One address is the subnet ID (all host bits 0) and one is broadcast (all host bits 1).

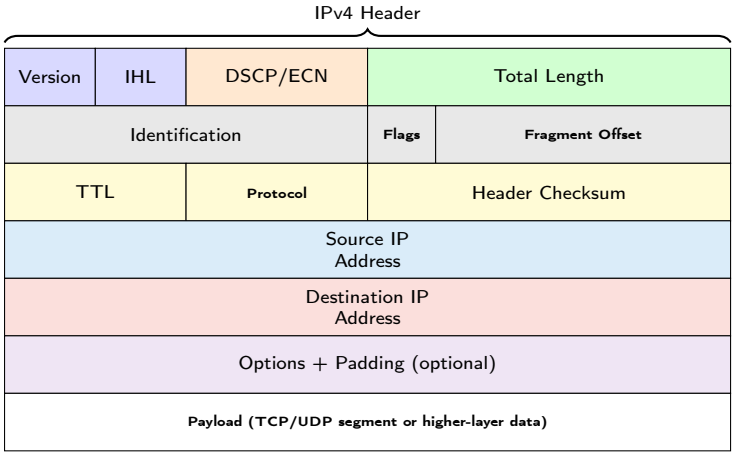


IP Addressing and Forwarding Logic

- Hosts use **source IP** and **destination IP** in each packet.
- Each router makes forwarding decisions based on destination IP and routing table.
- Forwarding path is hop-by-hop until packet reaches destination network.
- Default gateway is used when destination is outside local subnet.

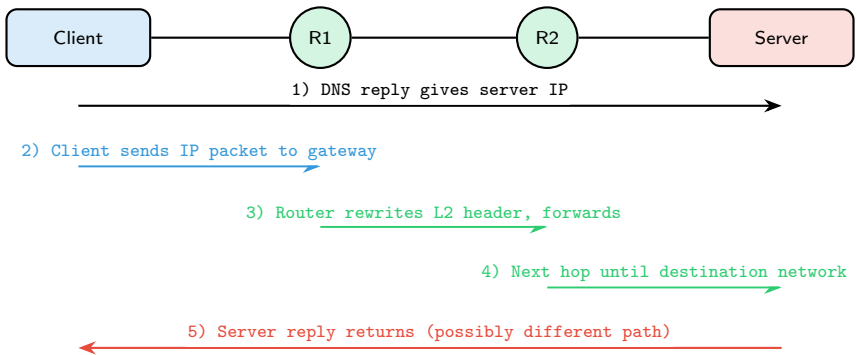


IPv4 Packet Format



- **TTL** limits loop duration; each router decrements it.
- **Protocol** identifies next layer (TCP=6, UDP=17, ESP=50, AH=51).
- **Fragmentation** may occur when packet exceeds MTU (Maximum Transmission Unit).

How IP Exchanges Work

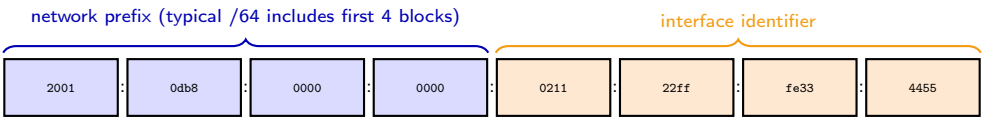


IP itself does not create a session state like TCP; it forwards independent packets.

IPv6 and MTU Considerations

Reading an IPv6 Address

- IPv6 has **128 bits**, written as 8 groups of 16-bit hex blocks.
- Example full form: `2001:0db8:0000:0000:0211:22ff:fe33:4455`
- Compression rules:
  - drop leading zeros in each block
  - use `::` once for one contiguous run of zero blocks



compressed: `2001:db8::211:22ff:fe33:4455`

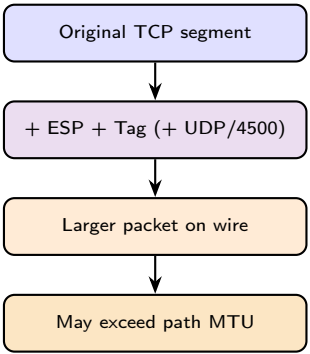
IPv4 vs IPv6

	IPv4	**IPv6**
Header size	Variable (20–60 bytes)	Fixed 40 bytes + extension headers
Checksum in IP header	Yes	No (removed for efficiency)
Fragmentation	Routers and hosts may fragment	Only source host fragments
Address space	32-bit	128-bit
NAT dependency	Frequent in enterprise/home	Less architectural pressure for NAT
IPsec support	Optional	Designed with native support mindset

- Security consequence: IPv6 extension headers must be monitored in filtering policies.
- In real deployments, policy consistency across dual stack is often harder than protocol mechanics.

MTU, Fragmentation, and VPN Overhead

- IPsec adds overhead (ESP header, IV/nonce, tag, optional UDP encapsulation).
- Effective MTU decreases inside tunnels.
- Without proper MSS clamping or PMTUD, symptoms include:
  - stalled HTTPS sessions
  - large-file transfer instability
  - intermittent application failures



Rule: always validate MTU/MSS during VPN rollout and after topology changes.

IP Security Problems

Why Plain IP Is Not Enough for Security

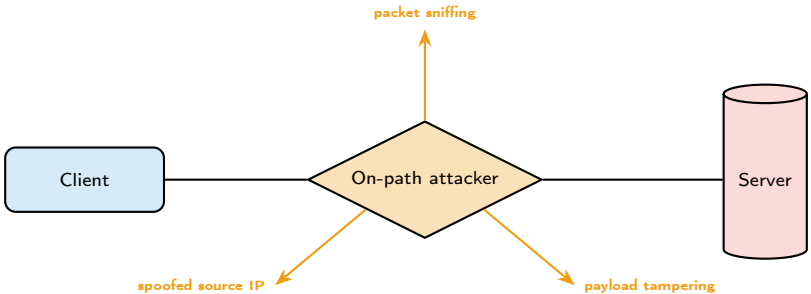
- **No origin authentication**: source addresses can be spoofed.
- **No integrity protection**: on-path modification is possible.
- **No confidentiality**: payload visible to network observers.
- **No anti-replay**: old packets can be resent in some scenarios.
- **Metadata leakage**: addresses, timing, size, and flow patterns remain visible.

These weaknesses motivate security at/around Layer 3: **IPsec**.

IP Threat Taxonomy and Typical Defenses

Threat	Example attacks	Common defenses
Spoofing	Source-IP spoofed packets, reflection	Ingress/egress filtering, ACLs
Tampering	On-path payload/header modification	End-to-end integrity (ESP AEAD, TLS)
Eavesdropping	Passive traffic capture	Encryption (IPsec, TLS, QUIC)
Replay	Re-injection of valid captured packets	Sequence numbers + anti-replay windows
Control-plane abuse	Route hijack, policy manipulation	Authenticated routing, monitoring, anomaly detection

Threat Examples on IP Networks



- Typical scenarios: MITM, route hijack segments, rogue middleboxes, hostile ISP path.
- Goal: protect traffic even when transit networks are untrusted.

IPsec

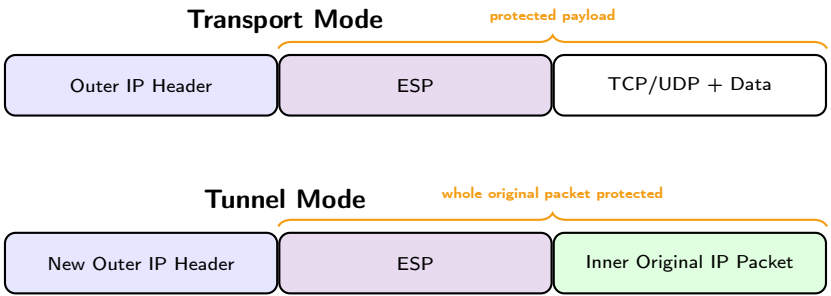
IPsec Overview

- IPsec is a suite of protocols for securing IP at Layer 3.
- Main security services:
  - confidentiality (encryption)
  - integrity and origin authentication
  - anti-replay protection
- Core protocol components:
  - **AH (Authentication Header)**
  - **ESP (Encapsulating Security Payload)**
- Key management is usually done via **IKEv2**.

AH vs ESP

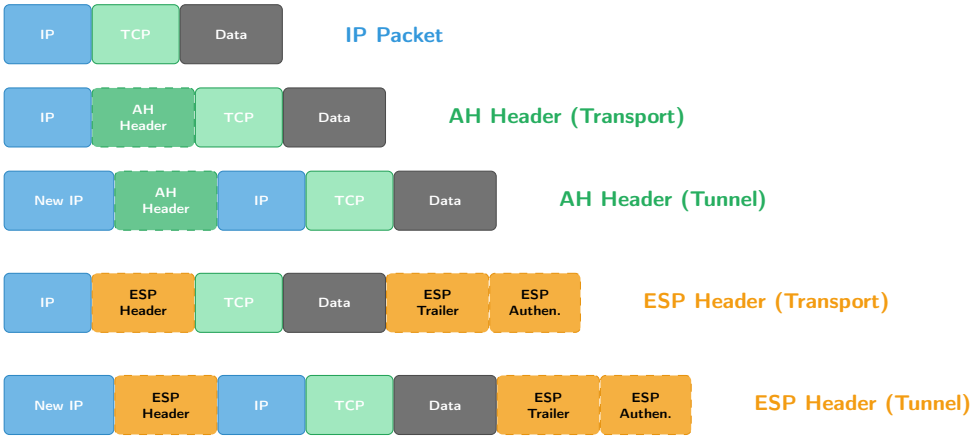
Feature	AH	ESP
IP protocol number	51	50
Confidentiality	No	Yes (encryption)
Integrity/authentication	Yes	Yes (with AEAD or auth option)
Protects IP header fields	Parts of immutable fields	Mainly payload (and inner packet in tunnel mode)
NAT compatibility	Poor	Better (with NAT-T/UDP encapsulation)
Deployment	Rare today	Dominant in practice

Transport Mode vs Tunnel Mode

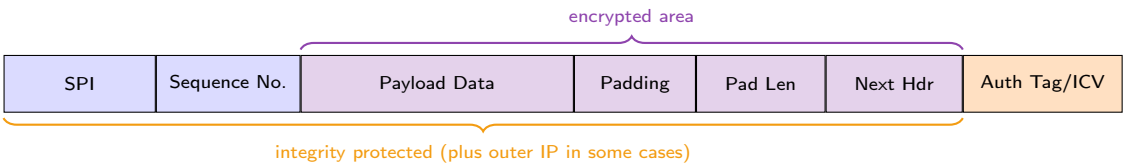


- **Transport mode**: host-to-host protection.
- **Tunnel mode**: gateway-to-gateway or remote-access VPN (most common).

AH and ESP Placement (Transport vs Tunnel)



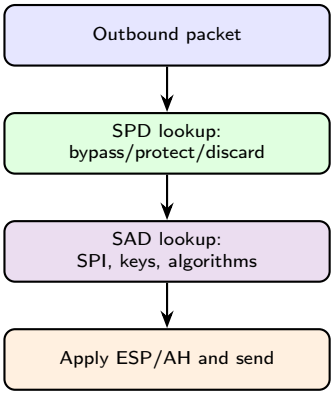
ESP Packet Format



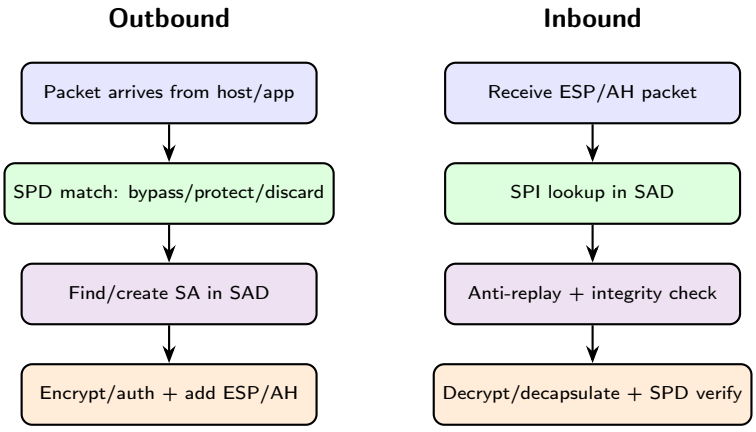
- **SPI** (Security Parameter Index) identifies the Security Association (SA).
- Sequence number supports anti-replay with sliding window checks.

Security Associations, SPD, and SAD

- A **Security Association (SA)** is a one-way logical channel (like a state) with:
  - algorithms and keys
  - SPI for identification
  - lifetime and anti-replay state
- **SPD** (Security Policy Database):
  - policies that match traffic selectors (src/dst IP, port, protocol)
  - rules that say bypass/protect/discard
- **SAD** (Security Association Database):
  - each row corresponds to an active SA
  - indexed by SPI for inbound processing
  - contains all crypto parameters and state for active SAs

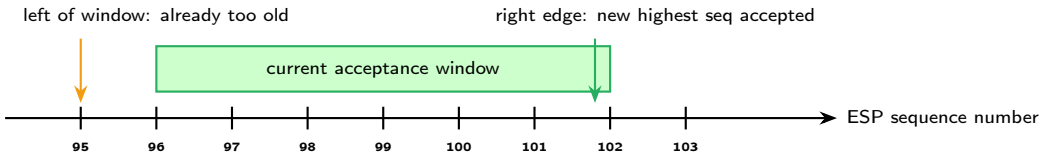


IPsec Processing Pipeline (Outbound and Inbound)



Drops commonly happen at SPD mismatch, replay window failure, or authentication-tag verification.

Anti-Replay Window (Overview)



- Duplicate packets inside the window are dropped.
- Packets older than the window are dropped.
- Window advances as higher valid sequence numbers arrive.

Cryptography Recap for IPsec

- **Symmetric encryption**: protects confidentiality.
- **Integrity/authentication**: MACs or AEAD authentication tags.
- **AEAD** (e.g., AES-GCM, ChaCha20-Poly1305): combine encryption and integrity.
- **Anti-replay**: uses monotonically increasing sequence numbers and replay windows.

Example with AEAD:

$$\text{ciphertext}, \text{tag} = \text{AEAD-Encrypt}(K, \textit{nonce}, \textit{plaintext}, \textit{AAD})$$

$$\text{valid?} = \text{AEAD-Verify}(K, \textit{nonce}, \textit{ciphertext}, \textit{tag}, \textit{AAD})$$

AAD may include selected headers that must be authenticated but not encrypted.

Algorithm Choices and Policy Baseline

Component	Recommended baseline	Notes
ESP encryption/integrity	AES-GCM-128/256 or ChaCha20-Poly1305	Prefer AEAD suites
PRF in IKEv2	HMAC-SHA2 family	Avoid SHA-1 (deprecated)
Diffie-Hellman group	Elliptic Curve groups	
Authentication	Usually via Certificates or EAP methods	PSK (Pre-Shared Key) only with strong secrets
SA lifetime	Time/volume based re-key policy	Balance security and operational stability

IPsec Deployment Patterns

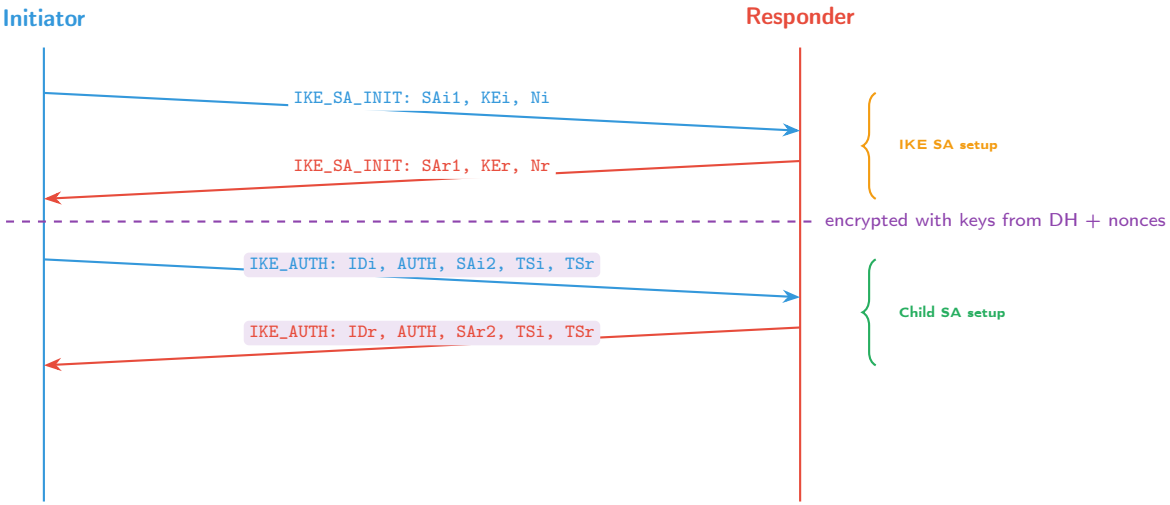
- Site-to-site
- Host-to-site

IKEv2 (Internet Key Exchange)

Why IKE Is Needed

- IPsec needs fresh keys, algorithms, and lifetimes to build SAs.
- Manual key configuration does not scale and is error-prone.
- **IKEv2** automates:
  - peer authentication
  - Diffie-Hellman key agreement
  - SA negotiation and rekeying
  - liveness checks and mobility support

IKEv2 High-Level Exchange



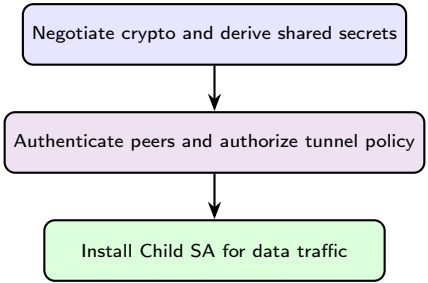
IKEv2 Messages

IKE_SA_INIT

- SA proposals (algorithms)
- DH public values (KEi/KEr)
- nonces (Ni/Nr)

IKE_AUTH

- peer identities (IDi/IDr)
- authentication proofs (AUTH)
- first Child SA proposals
- traffic selectors (TSi/TSr): define what traffic the Child SA will protect



IKEv2 Cryptography Recap

- **Diffie-Hellman (DH)**: peers derive a shared secret over an untrusted network.
- **Nonces**: random values that ensure freshness and key separation.
- **PRF** (pseudo-random function): derives multiple session keys from shared material.
- **Authentication**: certificates (RSA/ECDSA), raw public keys, or EAP methods.

Example key derivation from DH Shared Key and Nonces:

$$SKEYSEED = \text{prf}(N_i \| N_r,\ g^{ir})$$

$$\{K_1, K_2, \ldots\} = \text{prf+}(SKEYSEED,\ \text{context})$$

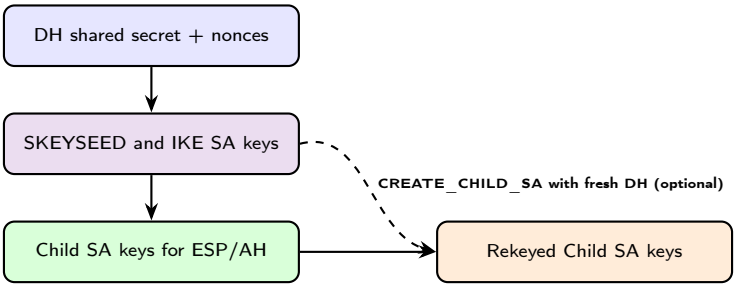
These keys protect IKE messages and IPsec Child SAs. What is g^{ir}?

Authentication Methods in IKEv2

Method	Typical usage	Strengths / Caveats
Pre-Shared Key (PSK)	Small controlled environments	Simple, but weak secrets and reuse are risky
X.509 certificates	Site-to-site and enterprise VPN	Strong identity model with PKI management overhead
EAP-based auth	Remote access (users/devices)	Flexible integration with AAA systems

- AAA stands for Authentication, Authorization, and Accounting, often used in enterprise environments for user/device management.

IKEv2 Key Hierarchy and Perfect Forward Secrecy



- With fresh DH during rekey, compromise of one key epoch does not expose past sessions (**Perfect Forward Secrecy**).

Rekey, Mobility, and Operational Notes

- **CREATE_CHILD_SA**: rekey existing IPsec SAs without full re-authentication.
- **INFORMATIONAL**: delete SAs, report errors, liveness checks.
- **MOBIKE** extension: supports client IP changes (e.g., WiFi to LTE) with tunnel continuity.
- NAT traversal typically encapsulates ESP in UDP/4500.

Stable VPNs need correct timers, MTU/MSS tuning, and clean certificate lifecycle handling.

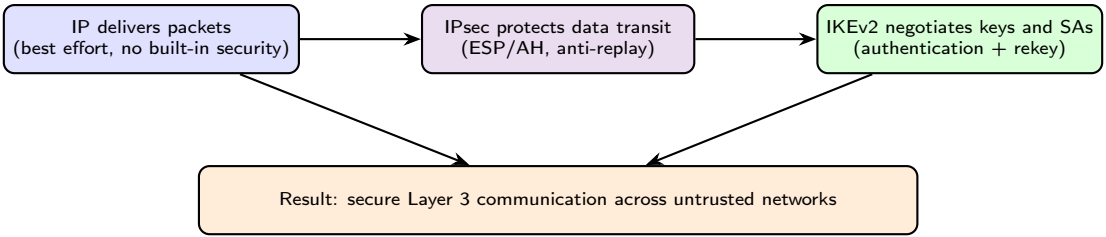
Common Deployment Issues

- **Proposal mismatch**: peers share no common algorithm set.
- **Identity mismatch**: certificate does not match expected ID.
- **Selector mismatch**: traffic selectors are different or too narrow.
- **NAT-T issues**: UDP/4500 filtered or fragmented packets dropped.
- **Clock skew**: certificate validation failures and re-key instability.

Diagnostic:

1. Is Phase 1/IKE SA established?
2. Is Child SA installed?
3. Do policy selectors match expected subnets?
4. Are ESP packets and replay counters increasing?

Secure Layer 3



CLI Example

- Inspect routes and interfaces:
  - `ip route`
  - `ip addr`
- Observe IPsec SAs and policies (Linux with strongSwan):
  - `ip xfrm state`
  - `ip xfrm policy`
  - `swanctl -list-sas`
- Capture IKE/IPsec traffic:
  - `sudo tcpdump -ni <iface> 'udp port 500 or udp port 4500 or proto 50'`

Only run in authorized lab or enterprise environments.

CLI Example (Cont'd)

1) Verify IKE and Child SAs:

```
swanctl --list-sas
```

2) Verify kernel xfrm states and policies:

```
ip xfrm state
ip xfrm policy
```

3) Capture control and data traffic:

```
sudo tcpdump -ni <iface> 'udp port 500 or udp port 4500 or proto 50'
```

References (Selected)

- RFC 791: Internet Protocol (IPv4).
- RFC 8200: Internet Protocol, Version 6 (IPv6).
- RFC 4301: Security Architecture for IP.
- RFC 4303: IP Encapsulating Security Payload (ESP).
- RFC 7296: Internet Key Exchange Protocol Version 2 (IKEv2).
- RFC 8247: Algorithm implementation requirements for IKEv2.

Questions?