DI-FCT-UNL
Segurança de Redes e Sistemas de Computadores
Network and Computer Systems Security

Mestrado Integrado em Engenharia Informática
MSc Course: Informatics Engineering
2º Semestre, 2018/2019

IPSec (IP Security)

"If a secret piece of news is divulged by a spy before the time is ripe, he must be put to death, together with the man to whom the secret was told."

—*The Art of War*, Sun Tzu

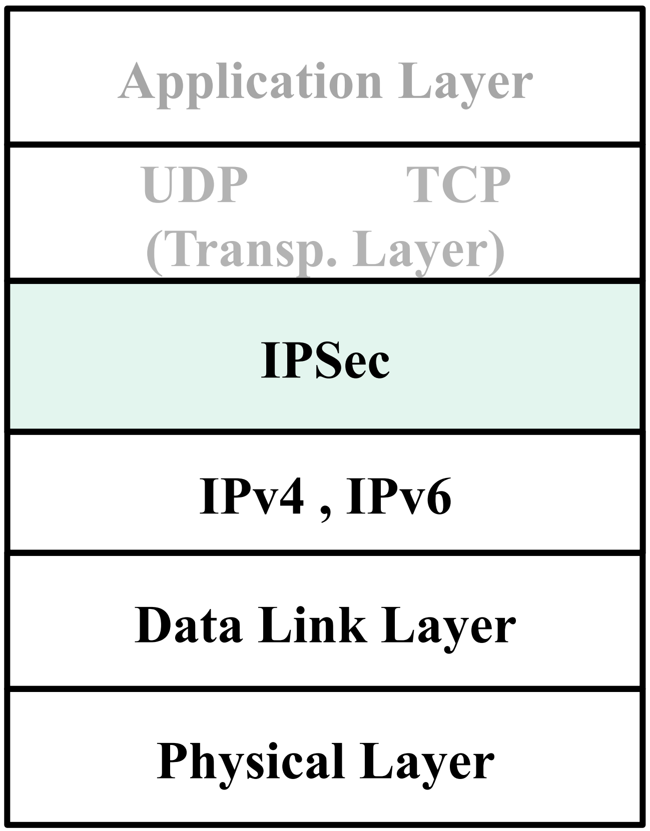
IP Security Level Approach

Security Approach at the Network Level (IP Traffic Protection)

- Initially addressed as answer to requirements and challenges in IAB (RFC 1636, Fev/1994)
- IPSec Architecture, AH and ESP Protocols (1st Approch): RFCs 1825, 1826, 1827 (Aug/1995)

IPSec is a Security Stack of Sub Protocols for IP Traffic Protection

Can be supported / added to current versions of IPV4 and IPV6 Protocols:



Other Possible IP Security Encapsulations

IPSec is a Security Stack of Sub Protocols for IP Traffic Protection

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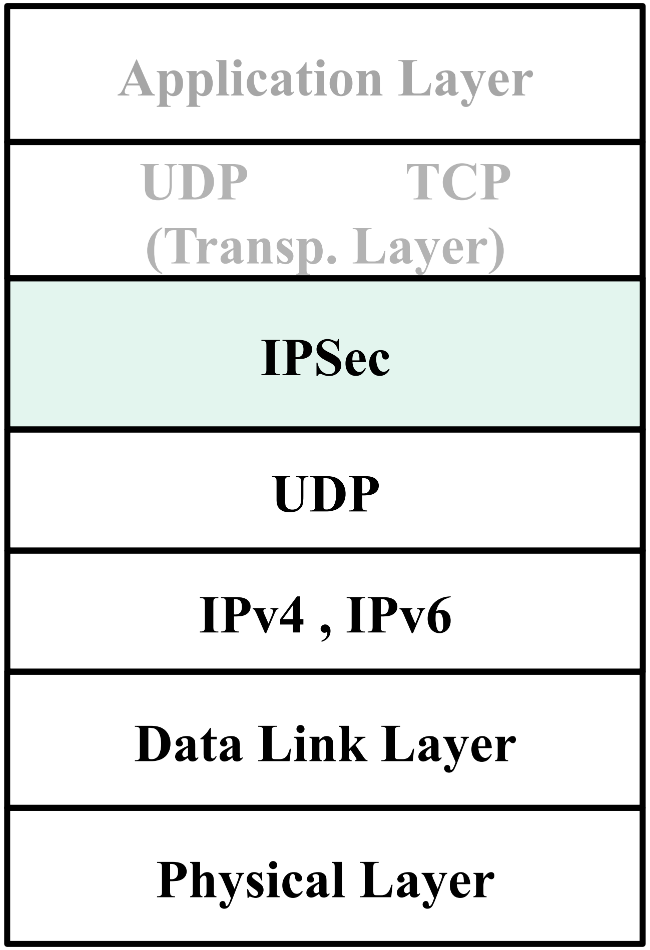

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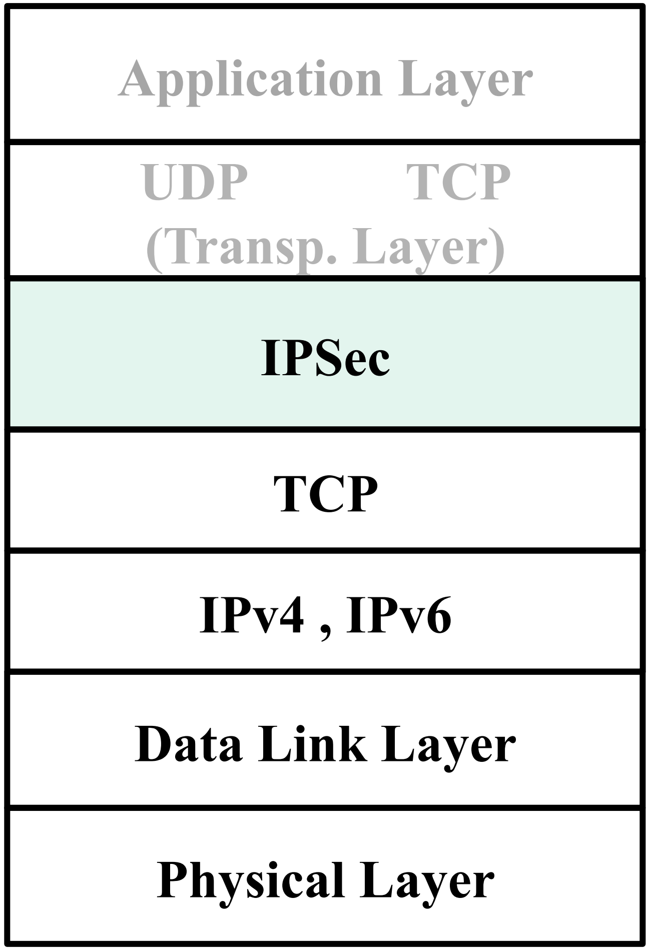

Other Possible IP Security Encapsulations

IPSec is a Security Stack of Sub Protocols for IP Traffic Protection

Can be supported / added to current versions of IPV4 and IPV6 Protocols:

Appl. Protocols
UDP, TCP
IPSec
HTTP
TCP (Transp. Layer)
UDP
IPv4 , IPv6
Data Link Layer
Physical Layer

Roadmap / Outline

- **IPSec (IP Security)**
  - IP Security Overview
  - IPsec uses and benefits
  - IPSec Standardization
  - IP Security Architecture (and IPSec Stack)
  - IPSec Modes: Transport vs. Tunneling
  - IPSec Security Associations
  - IPSec Security protocols and encapsulation
  - Anti-Replaying Service
  - Security and Flexibility: Combination of Security Associations
  - IPSec crypto-suite
  - Key Management Schemes

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IP Security Stack (Archit. amd Sub-Protocols)

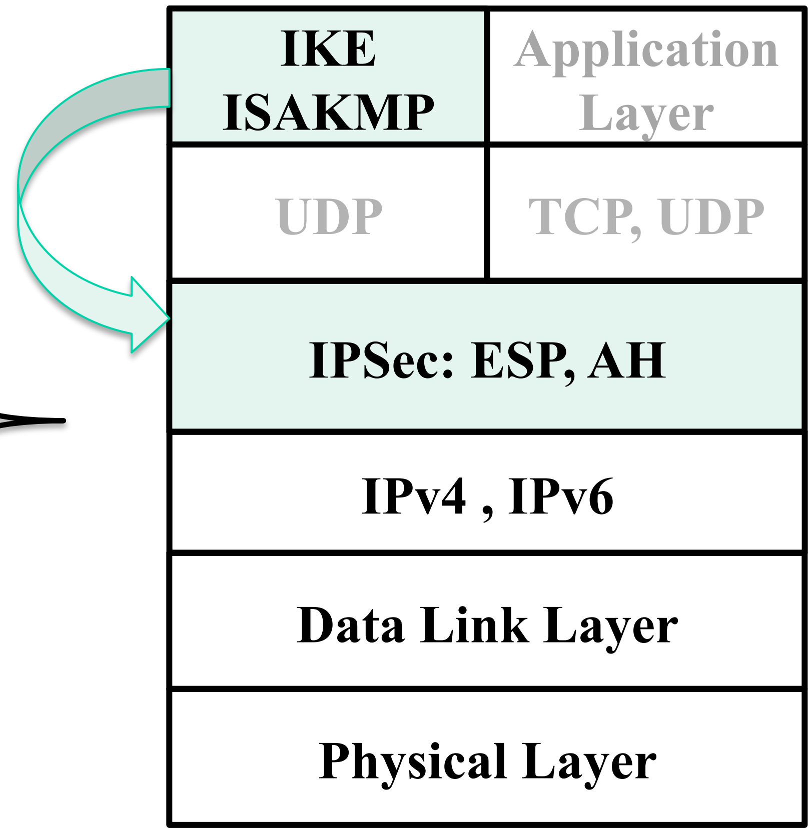
IPSec Architecture and vast related standardization effort
Ipsec Protocols Stack: IKE, ISAKMP, ESP and AH Protocols

IKE
Internet Key Exchange

ISAKMP
Internet Security Association and Key Management Protocol

ESP
Encapsulating Security Payload

AH
Authentication Header



IP Security Sub-Protocols

IPsec Stack: IKE, ISAKMP, ESP and AH Protocols

IKE
Internet Key Exchange

ISAKMP
Internet Security Association and Key Management Protocol

Authentication of IPSec Endpoints (IP Addresses)
Secure Establishment of Keys and SA Parameters

Access-Control Mechanism

ESP (ESP-A, ESP-AE)
Encapsulating Security Payload

Payload Data Origin Authentication
Connectionless-Integrity
Anti-Replaying
Connectionless-Confidentiality
Limited Traffic Flow Confidentiality

AH
Authentication Header

Payload Data Origin Authentication
Connectionless-Integrity
Anti-Replaying

IP Security Stack: Base security mechanisms

IPsec Stack: IKE, ISAKMP, ESP and AH Protocols

IKE
Internet Key Exchange

ISAKMP
Internet Security Association and Key Management Protocol

X509 Certification +
Authenticated Diffie-Hellman Agreement and other techniques

Security Message Format for IKE

ESP (ESP-A, ESP-AE)
Encapsulating Security Payload

ESP-Authentication Only:
(use of HMACs)

ESP-Authentication and Encryption:
(Use of HMACs + Symmetric Encryption)

AH
Authentication Header

Authentication Header
(Use of HMACs)

Summary of IPSec Services (Ref ESP, RFC 4301)

- Access control for IPsec packets
- Connectionless integrity
- Data origin authentication (IP Authentication) of delivered/ received IP packets (*)
- Anti-Replaying Protection: Rejection of replayed packets
  - a form of partial sequence integrity
- Confidentiality (encryption)
- Approach to traffic flow confidentiality protection (or limited traffic flow confidentiality)
- Key-Establishment Services (via IKE)

- Helps in securing routing, but no routing control: different routing attacks require other contra-measures complementarily to IPSec
  - Problem/Focus: Security in Routing Protocols (Ex., Secure BGP)

Protection in the IPSec protocol suite

Protection against communication attacks against IP Traffic
(remember ref. X.800 or RFC 2828)

	AH	ESP (E-Only)	ESP (A+E)
• Access control – AIP packet admission	X	X	X
• Connectionless integrity	X		X
• Authentication (IP origin) (authentication of the IP packet origin)	X		X
• Anti-*replay* (IP packet replay) *(Form of Sequential integrity)*	X	X	X
• Payload Data Confidentiality • Limited Traffic-Flow Confidentiality		X X	X X
• Availability (DoS, DDoS)	?	?	?
• Routing control (IP routing control)	?	?	?

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Use of IPSec

- Essentially, Protection w/ IPV4 and IPV6 Encapsulation
- Secure branch office connectivity over the Internet
- Secure remote access over the Internet
  - Ex., VPN Access (IP / IPSec)
- Establishing extranet and intranet connectivity with partners (secure internetworking between private intranets or secure extranets)
- Enhancing security for
  - Electronic commerce infrastructures
  - Critical infrastructures and related secure systems and applications

Benefits and Support of IPSec

- **Protection below transport layer (at the network level)**, hence transparent to transport and application level protocols
  - Secure IP Traffic between IP Sec Endpoints
- Can be **transparent providing security to transport protocols, applications end user**
- **IPSec is supported:**
  - **In routers or network firewalls**:
    - Provides strong security to all traffic crossing the perimeter (perimeter protection strategy)
    - Resistant to bypass
    - NAT supported

    Tunnel Mode
  - **In end-hosts**
    - Provides end-to-end (host-to-host) traffic
    - Resistant to bypass w/ local-enabled firewalls

    Transport Mode

Other benefits of IPSec

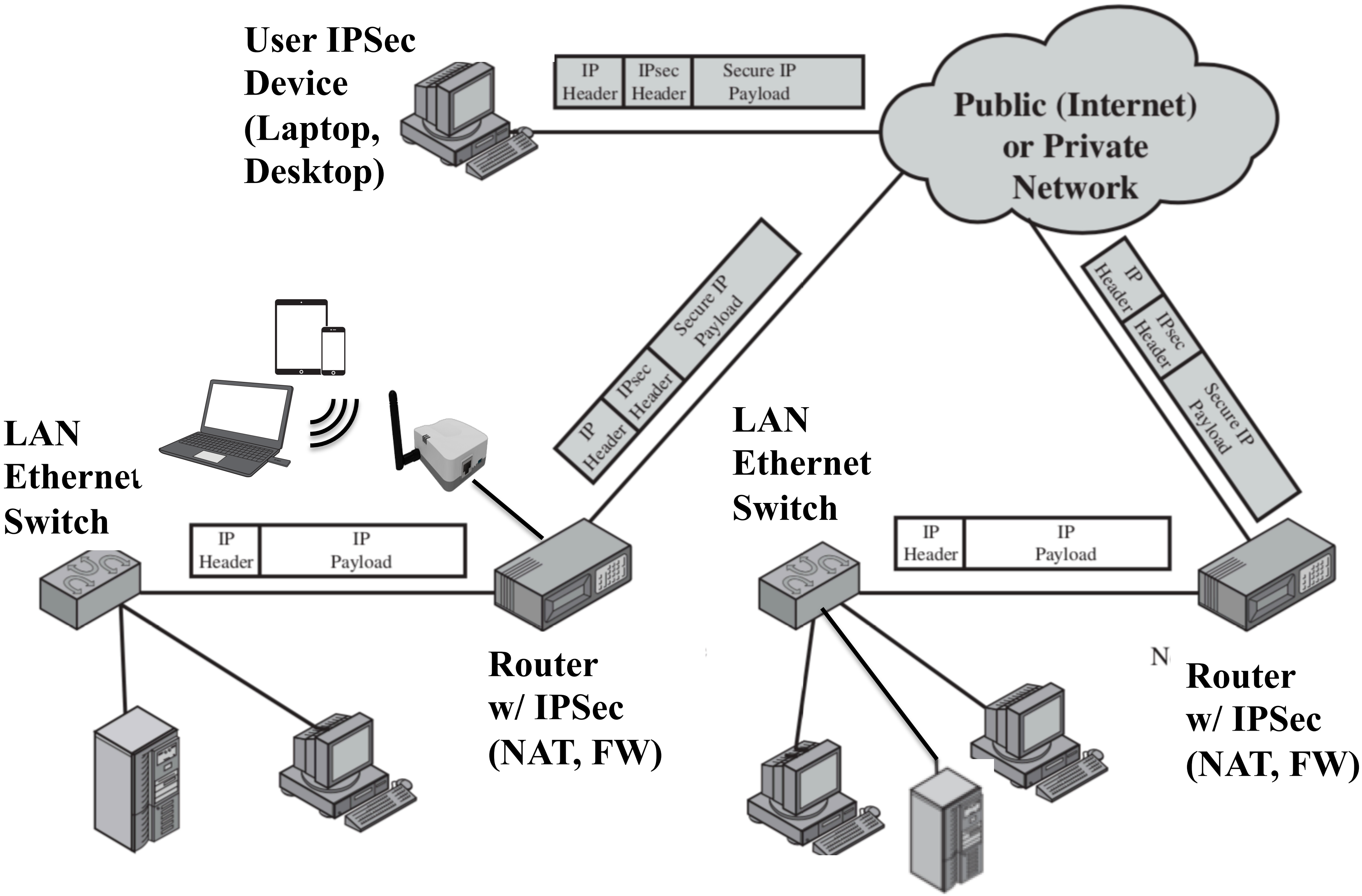
Helps in securing routing architecture (and other "control plane" management protocols)

- Base protection of router advertisements, authentication/ authorization of advertisements, control of authenticated/ authorized neighbors, authentication of redirections, contra-measures against forged update announcements
- Protection of routing protocols (VD-LS, OSPF)
  Note: BGPSpecProtocol (RFC 8205) when using IP (no sec)

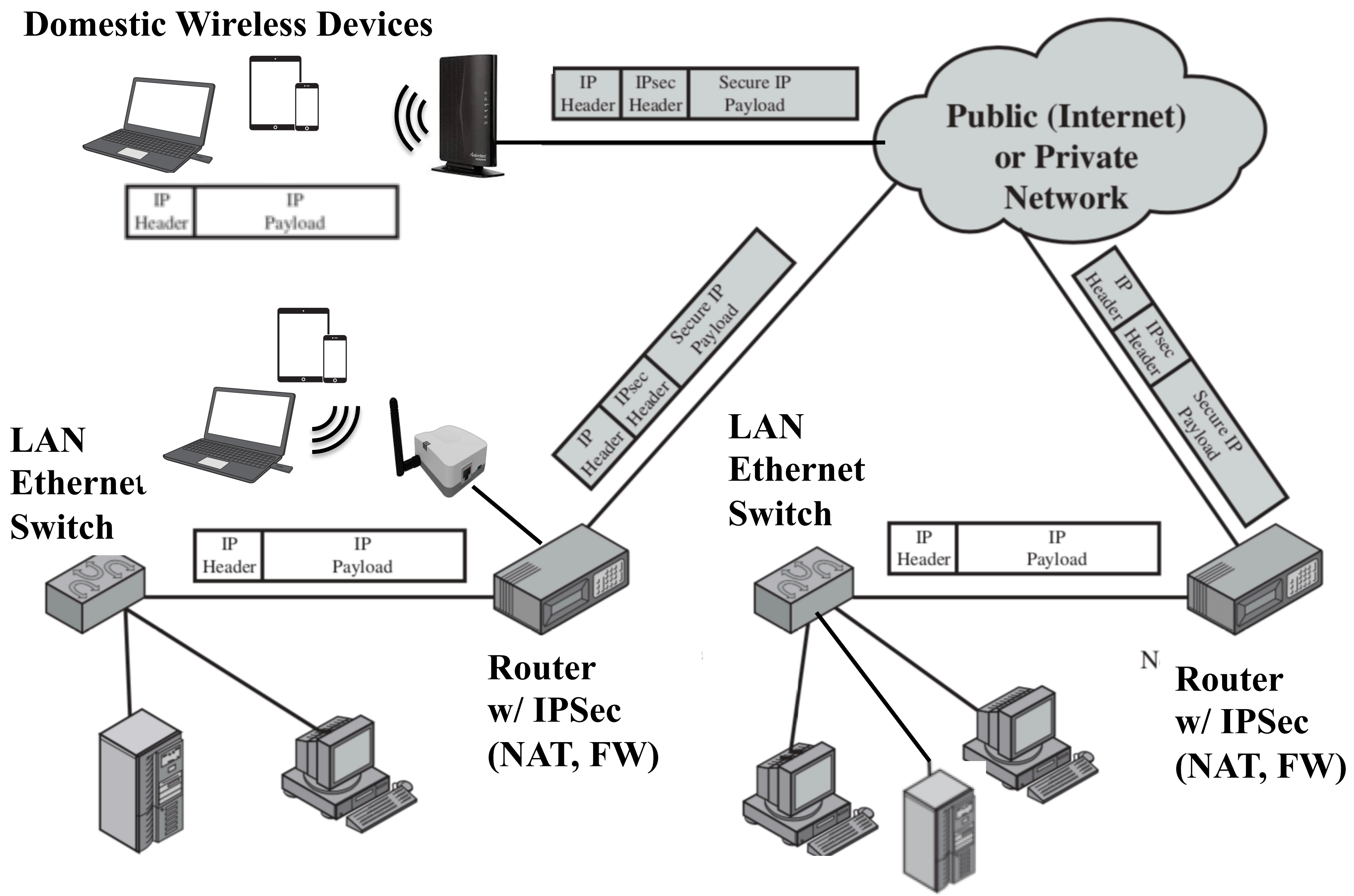
But there are some issues in playing well together:

- Performance penalties due to IP Sec rekeying (IKE sub protocol)
- Outages due to "missed or desync. keys and security associations"
- DoS / DDoS Issues due to overheads imposed by IPSec processing
- For example in general BGP routers have layered DoS protection that encapsulated IPSec BGP packets may weaken
  - Mitigation requires that routers must have access to the BGP packets
- Alternatives: Secure BGP without IPSec (S-BGP, BGPSec, RFC8205)

IPSec Internetworking scenario



IPSec Internetworking scenario



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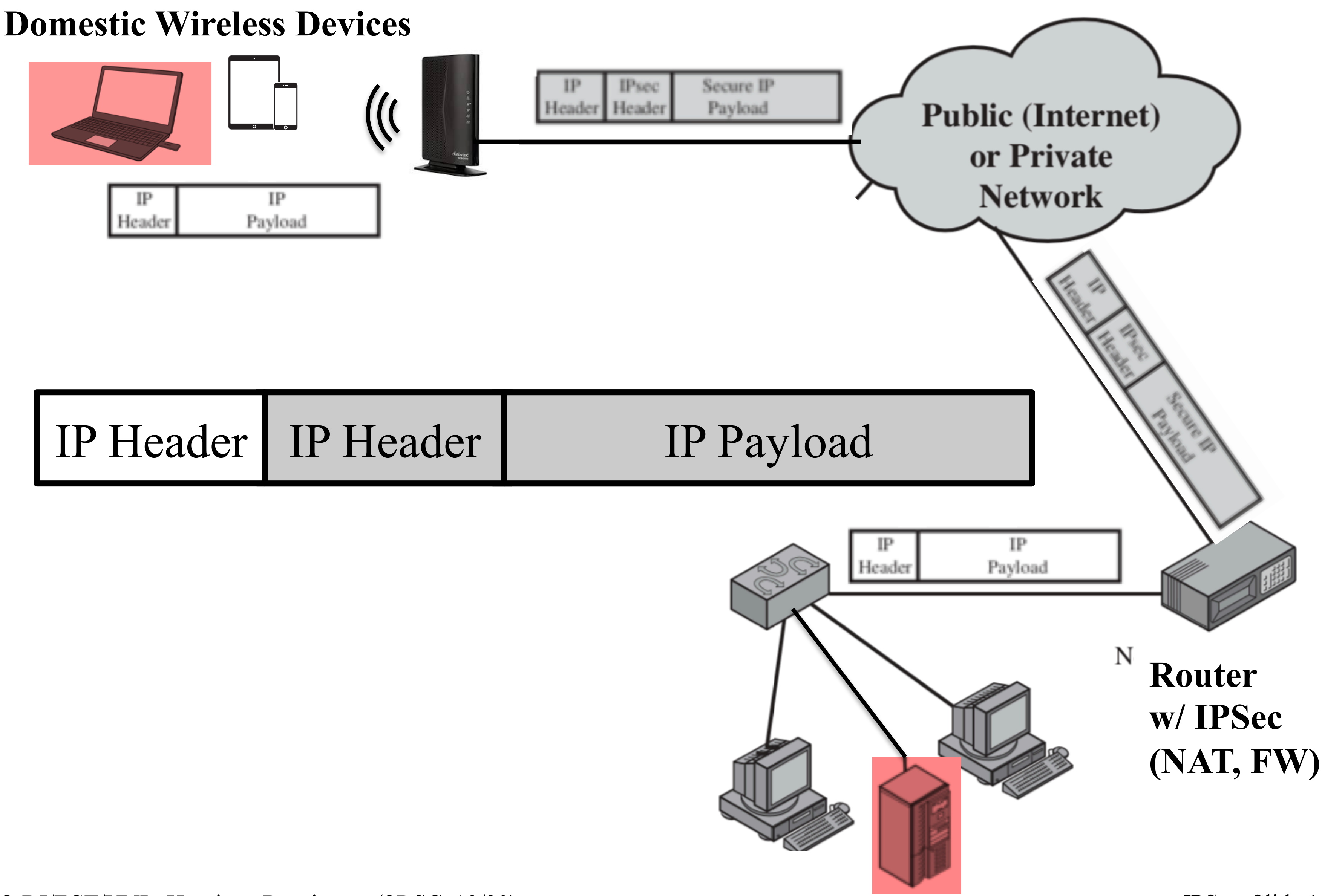
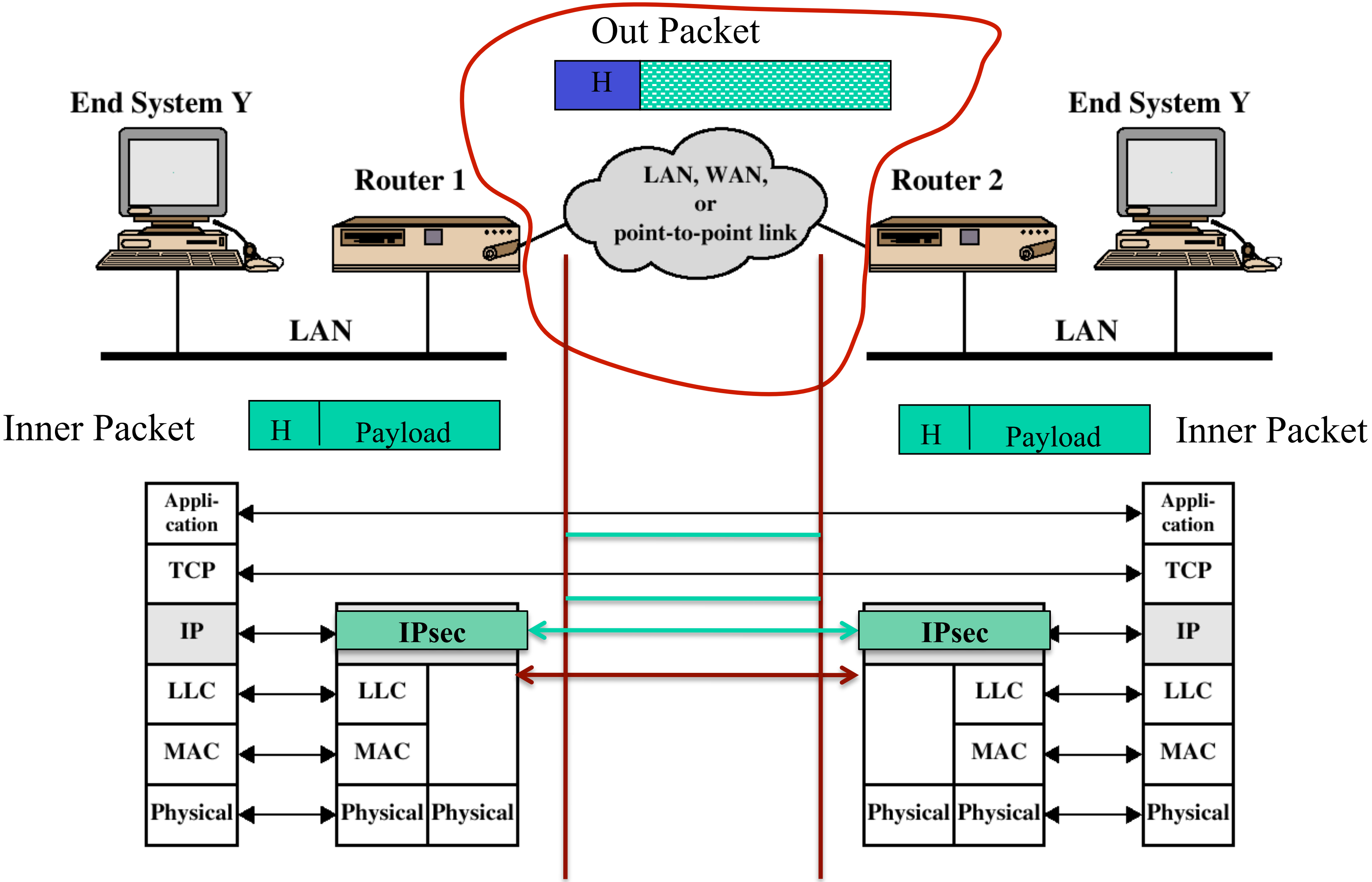
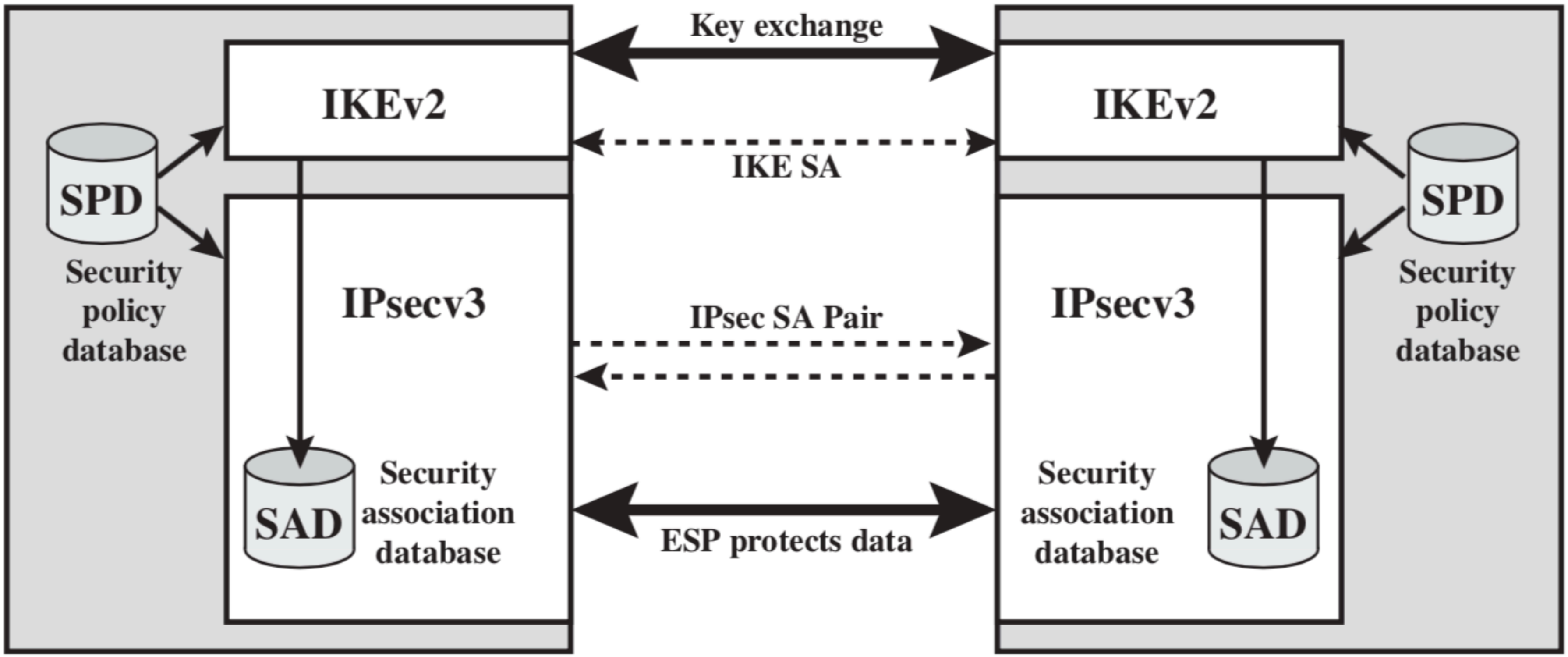


Secure LAN to LAN interoperability



IPSec operation overview



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IPSec Protection

- **Principals as Secure "IP endpoints":**
  - **IP Addresses (with peer-authenticity guarantees**
- Can use over LANs, across public & private WANs, & Internet

- **Current Ref. Standards** for the IPSec Protocol Suite:
  - **IKE** (currently v2, workdrafts for v3)

    Authentication and Establishment of Keys and Security Association Parameters

  - **IPSec** (currently v3)

    Main protocol suite: AH, ESP-E and ESP-AE Sub protocols and related encapsulations over IPV4 and IPV6

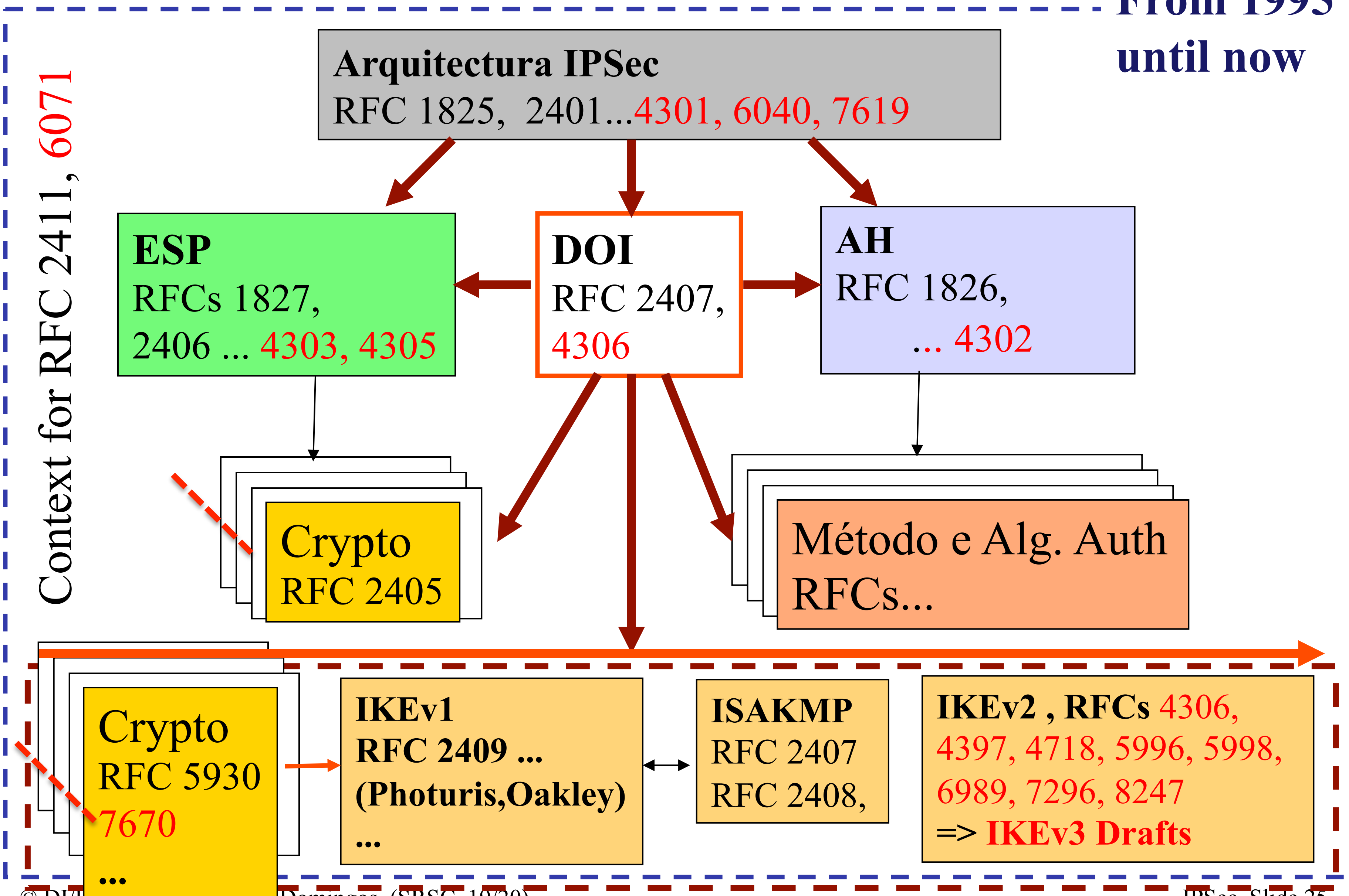
IPSec standardization

IPSec is a Security Suite with different dimensions involved and on-going standardization effort:

- **Conceptual bases**
  - IPSec Domain of Interpretation
  - IPSec Architecture Reference
- **Sub-protocols (IPSec protocol stack)**
  - ESP (ESP AE, ESP A only), AH
- **Configuration and Management Protocols**
  - IKE, ISAKMP and Management of SAs and SPDs
- **IPSec Standardized Cryptography and Techniques**
- **Adaptation and integration issues (TCP/IP stack)**
  - IPV4 and IPV6 Support and Encapsulation

IETF, IPSec standardization effort

On-Going From 1995 until now



IPSec suite: Architecture, AH and ESP

- **Architecture:** Covers the general concepts, security requirements, definitions, and mechanisms defining IPsec technology.

- **Authentication Header (AH Protocol):**
  - AH is an extension header to provide message authentication.
  - Because message authentication is also provided by ESP, the use of AH is now deprecated.
  - It is included in IPsecv3 for backward compatibility but should not be used in new applications. We do not discuss AH in this chapter.

- **Encapsulating Security Payload (ESP Protocol):**
  - ESP consists of an encapsulating header and trailer
  - Used to provide encryption (ESP-E) or combined encryption/ authentication (ESP-AE)

IPSec suite: IKE, Crypto and SA/SP Management

- **Internet Key Exchange (IKE):** This is a collection of documents describing the key management schemes for use with IPsec. The initial specification is RFC 4306, *Internet Key Exchange (IKEv2) Protocol*, but there are a number of related / evolved RFCs.
  - Evolution effort for **IKEv3**

- **Cryptographic algorithms:** This category encompasses a large set of docu- ments that define and describe cryptographic algorithms for encryption, mes- sage authentication, pseudorandom functions (PRFs), and cryptographic key exchange.

- **Others:** There are a variety of other IPsec-related RFCs, including those deal- ing with security policy and management information base (MIB) content.

IETF, IETF WorkGroups and OnGoing Work

- IETF
  - https://www.ietf.org
- IETF WG Charter .. See Active WGs
  https://datatracker.ietf.org/wg/
- IPSec, https://datatracker.ietf.org/wg/ipsec/about/
- IPSec Maintenance and Extensions (**ipsecme**)
  https://datatracker.ietf.org/wg/ipsecme/about/

Last and Ongoing Efforts (2009-2019 …)

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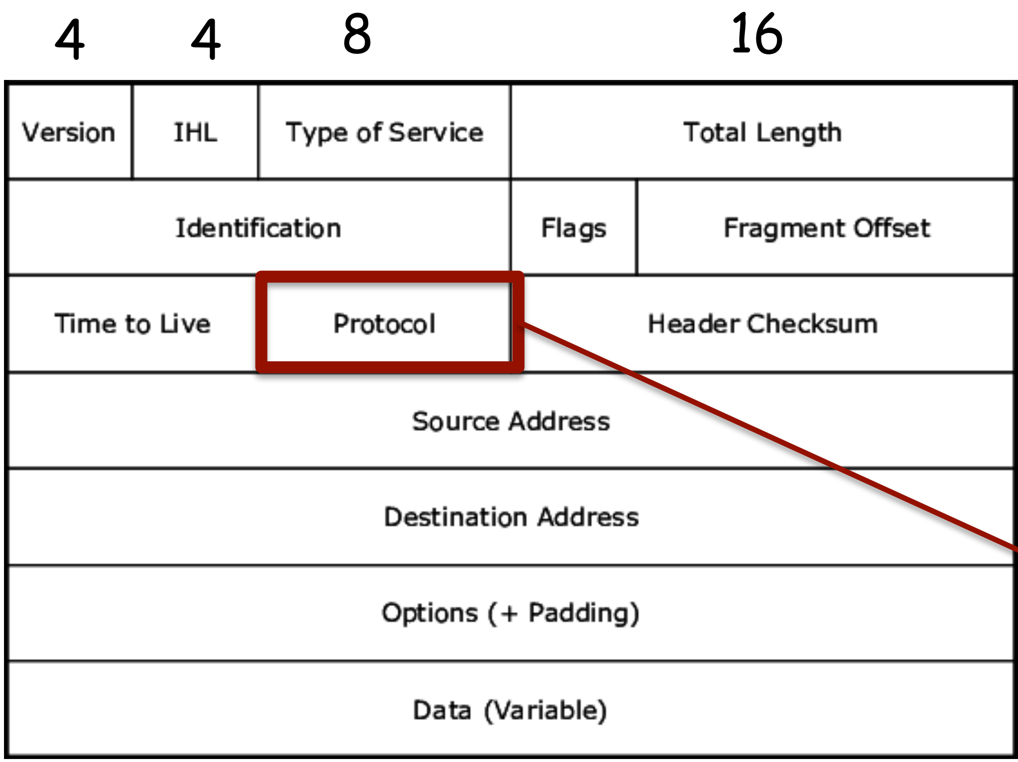
IPV4 Packet and IPSec Encapsulation

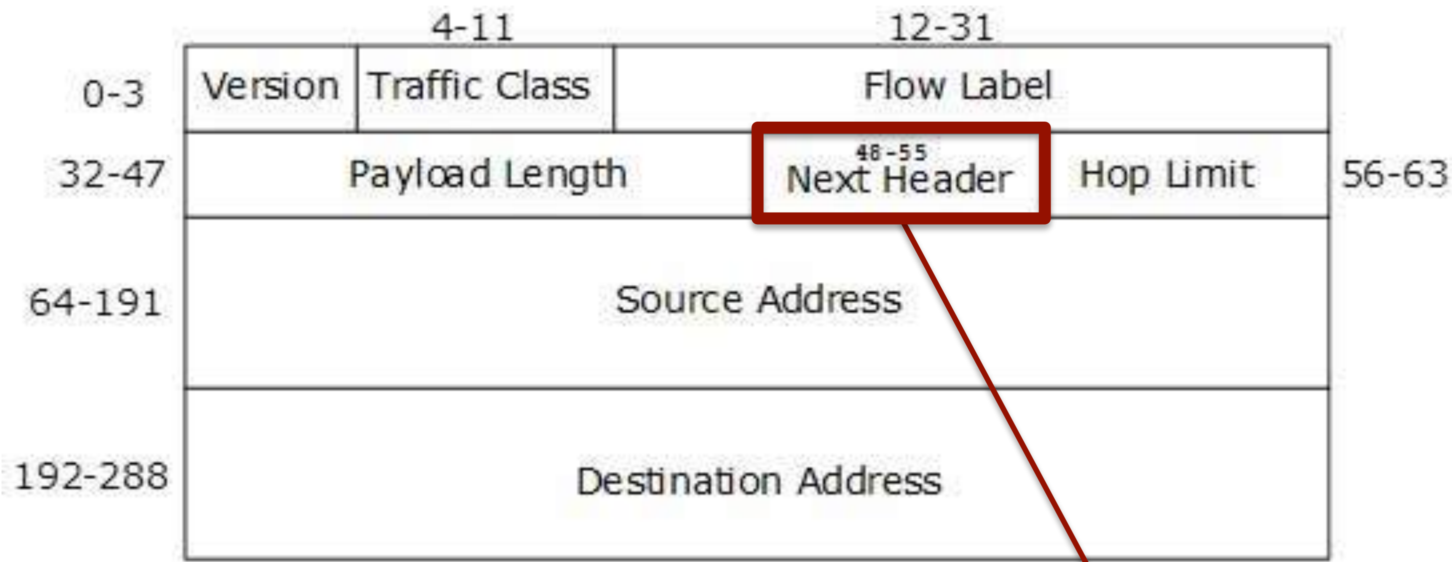


Protocol Codes, ex:
1 (ICMP Control Packet)
6 (TCP packet)
41 (IPV6 encapsulation), 4 (IPV4 encapsulation)
17 (UDP datagram packet ...
51 (AH Encapsulated Packet)
50 (ESP Encapsulated Packet)

https://www.iana.org/assignments/protocol-numbers/protocol-numbers.xhtml

IPV6 Packet and IPSec encapsulation

see https://en.wikipedia.org/wiki/IPv6_packet for details

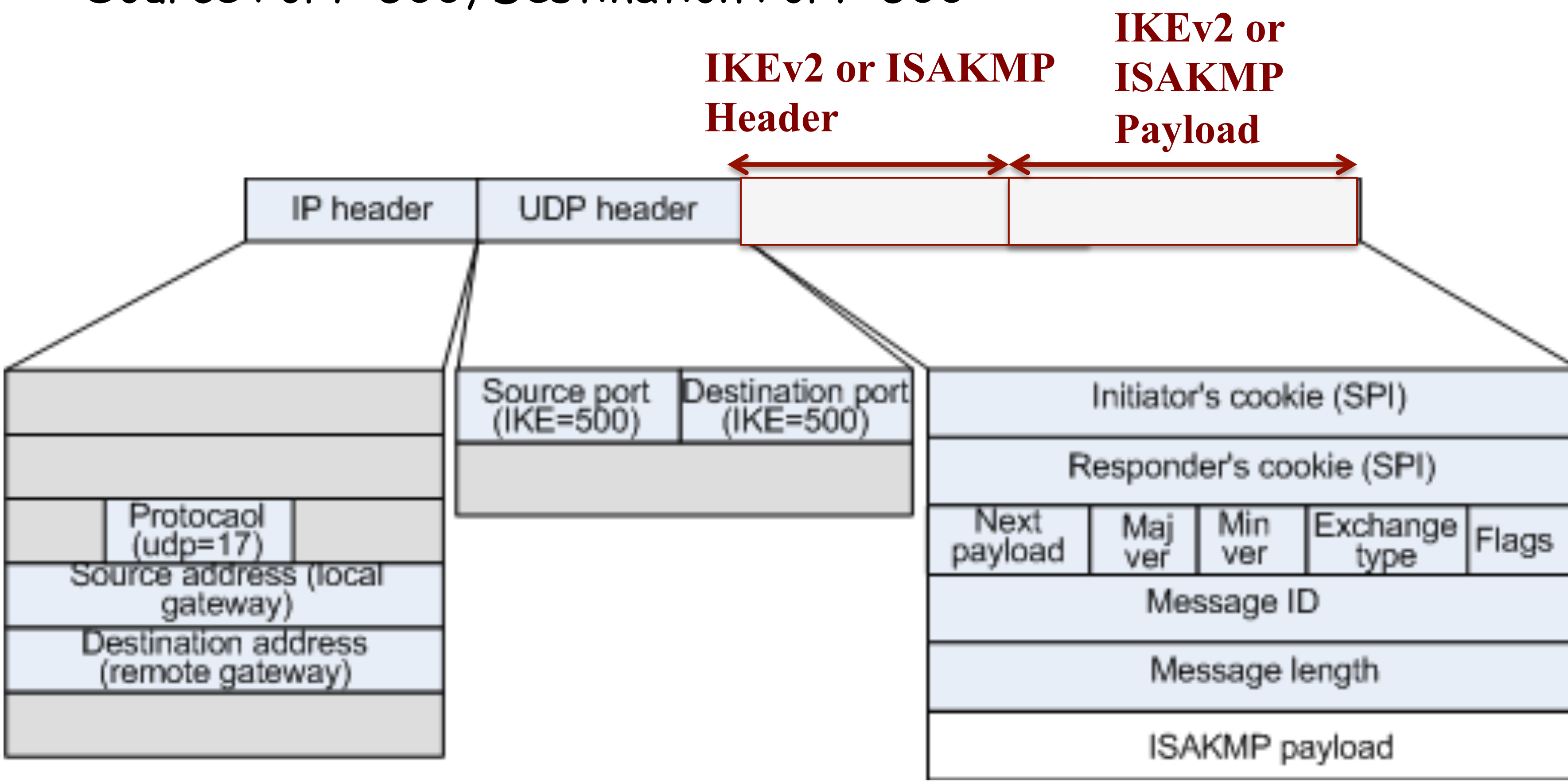


Next Header (encapsulated packet), ex:
1 (ICMP Control Packet)
6 (TCP packet)
41 (IPV6 encapsulation), 4 (IPV4 encapsulation)
17 (UDP datagram packet …
51 (AH Encapsulated Packet)
50 (ESP Encapsulated Packet)

IP (v4,v6) and IKE or ISAKMP encapsulation

IKE is usually encapsulated on UDP Packets
(On-going/recent RFC proposals on TCP and also HTTP encapsulation)

- Via IKEv2 or ISAKMP Headers
- Source Port: 500, Destination Port: 500



Other forms of encapsulation …

- Can have IPSec (ESP-E, ESP-AE or AH packets) encapsulated in other options
- Can also have IP (not necessarily IPSec) encapsulated in other stackable solutions for VPNs, ex:
  - VPN SSL/TLS
  - VPN IPSec
  - VPN PPPT
  - VPN L2PT
- Other IP Protection solutions by tunneling: STUNNEL (TLS tunnels), SSH Tunnels

Ex., Solutions (opensource):

- Stunnel https://www.stunnel.org
- OpenVPN https://openvpn.net

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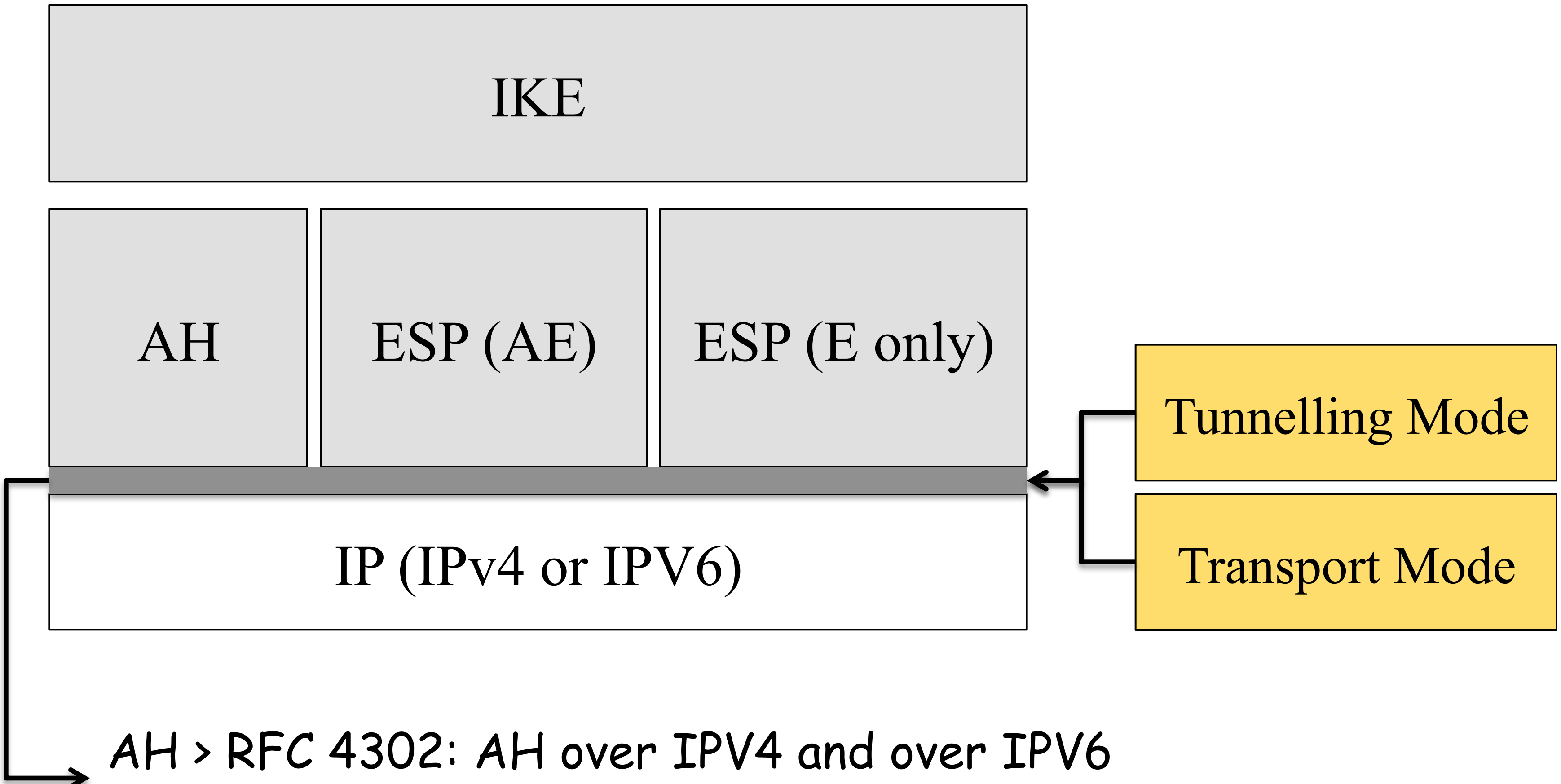
IP Security Stack (and Sub-Protocols)

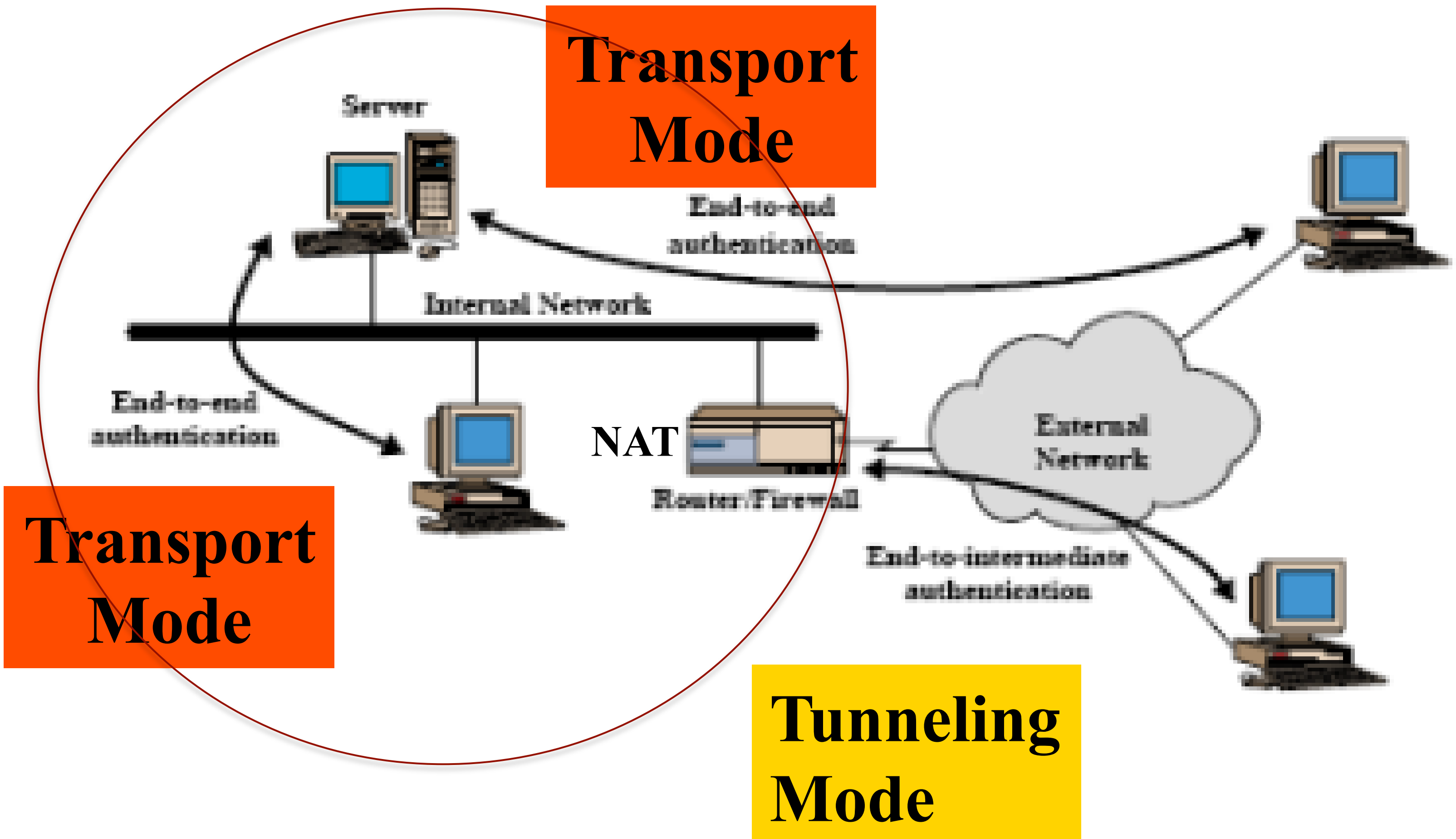
- Sub-Protocols and Modes + Encapsulation (IPV4 or IPV6), … as well as other (tunneling) encapsulation options



AH > RFC 4302: AH over IPV4 and over IPV6
ESP > RFCs 4303, 4305: ESP over IPV4 and IPV6

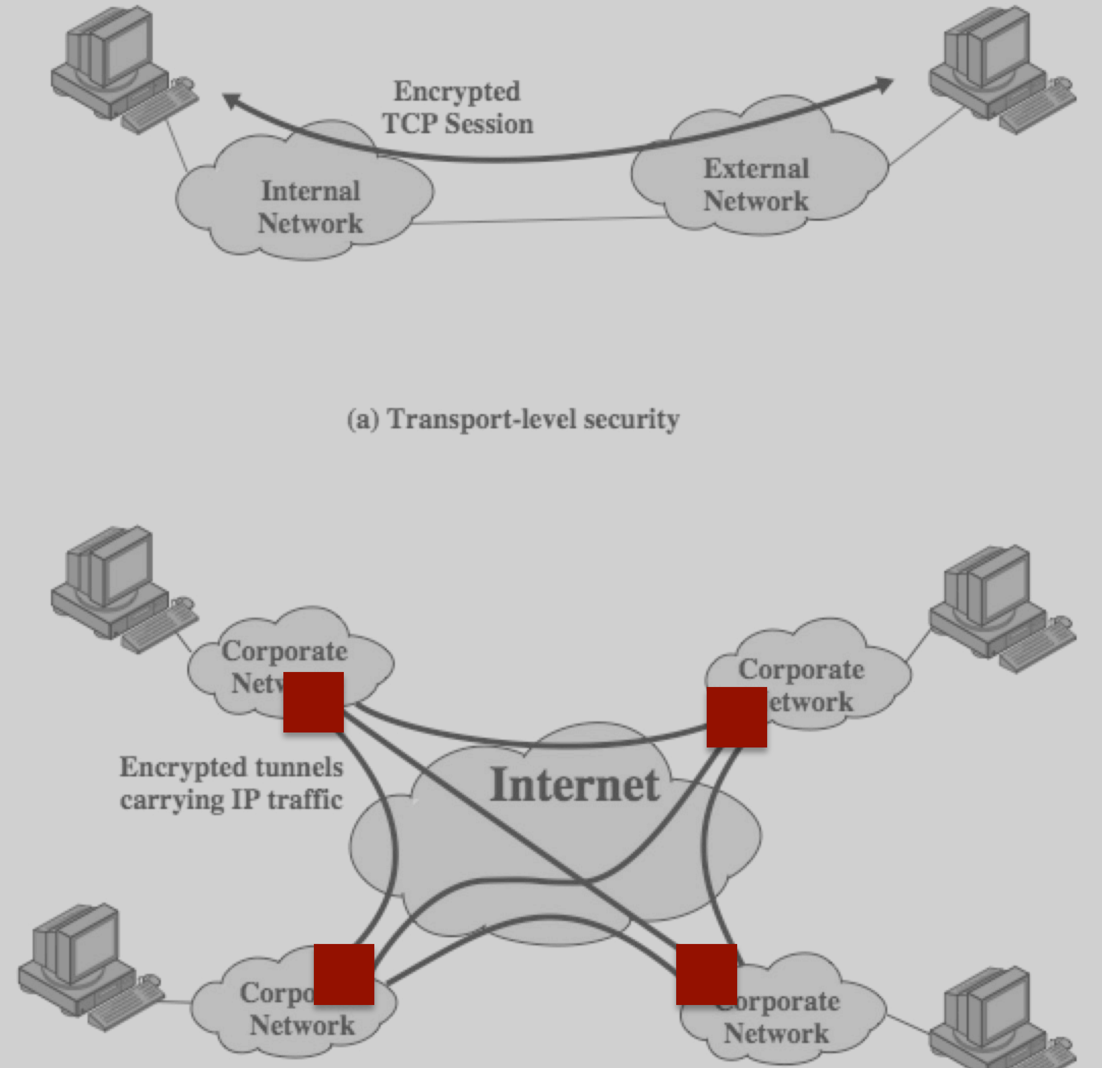
IPSec modes

Modes are considered for different IPSec uses



Transport and Tunnel Modes

- **Transport Mode:**
  - End-to-End Security
  - Host-to-Host
- **Tunnel Mode:**
  - Intermediary-Support
  - via Routers, Firewalls
  - NAT supported



(a) Transport-level security

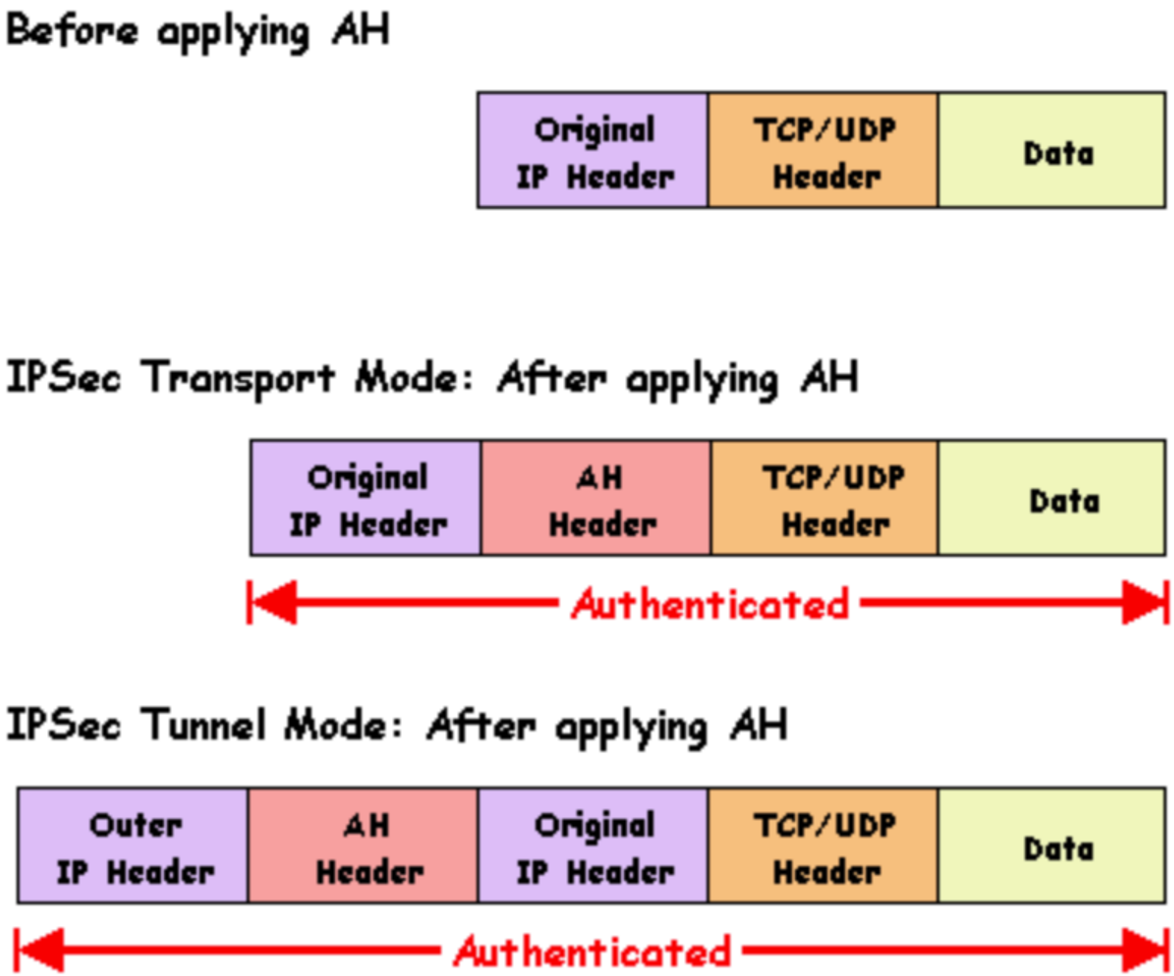
(b) A virtual private network via Tunnel Mode

Specific encapsulation of IPsec modes

- Depending on the IPSec modes, encapsulation of ESP and AH is done in a different way
- Combinations:
  - AH in Tansport mode
  - AH in Tunnel mode
  - ESP-Authentication Only in Transport mode
  - ESP-Authentication Only in Tunnel mode
  - ESP-Auth & Encryption in Transport mode
  - ESP-Auth & Encryption in Transport mode

- Combinations imply on different provided security properties:

AH/IP in Transport and Tunnel modes

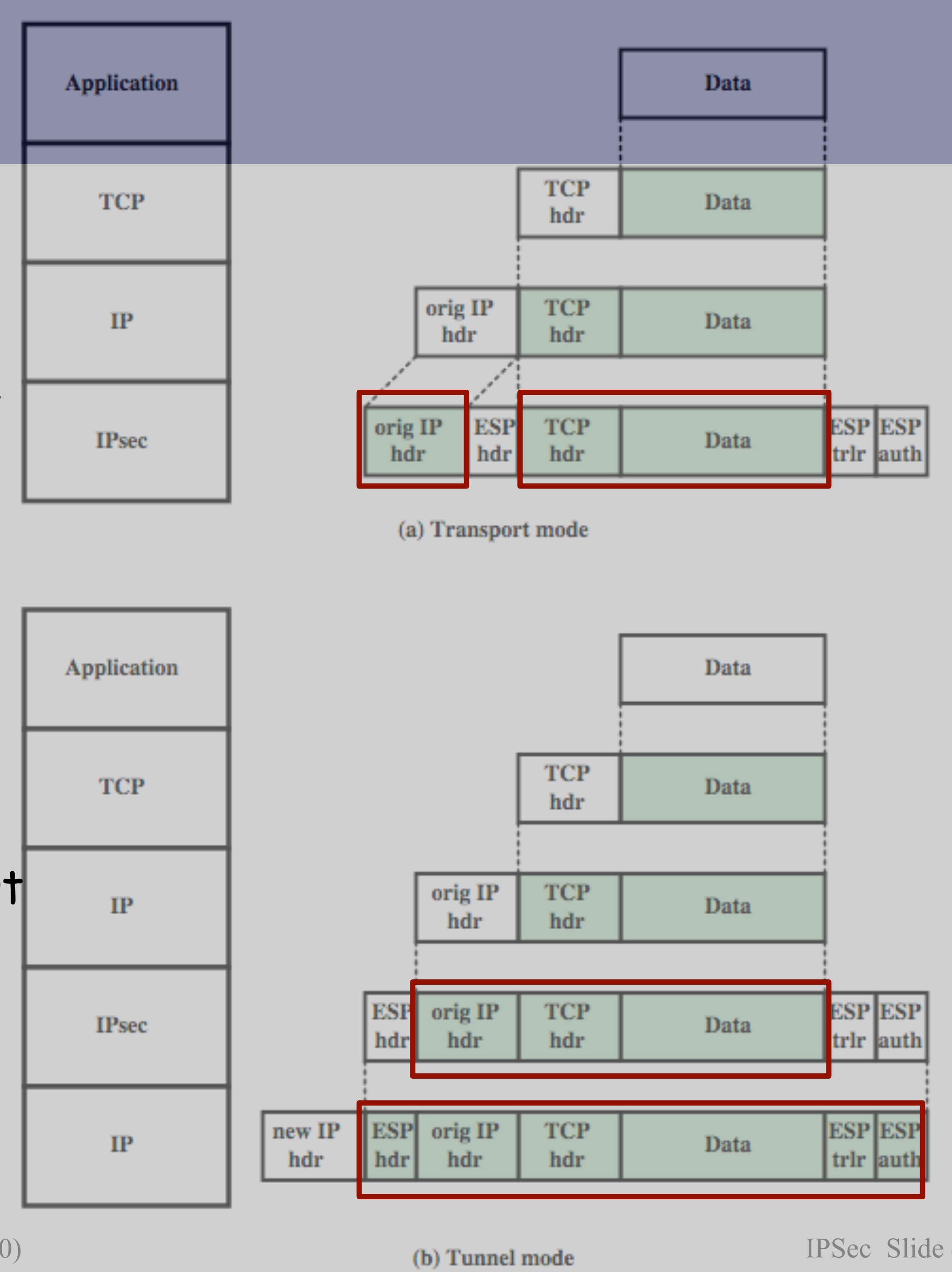


Transport Mode

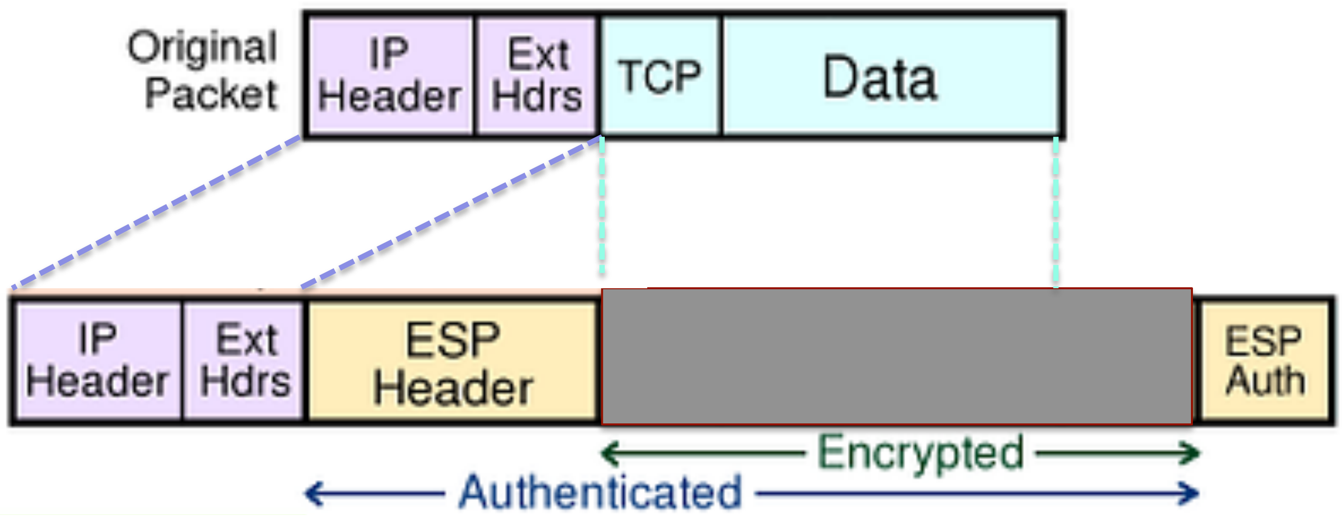
Tunnel Mode

ESP/IP encapsulation

- **Transport Mode:**
  - End-to-End Security
  - Host-to-Host
- **Tunnel Mode:**
  - Intermediary-Support
  - Routers, Firewalls



ESP Encapsulation: Transport Mode



Transport Mode

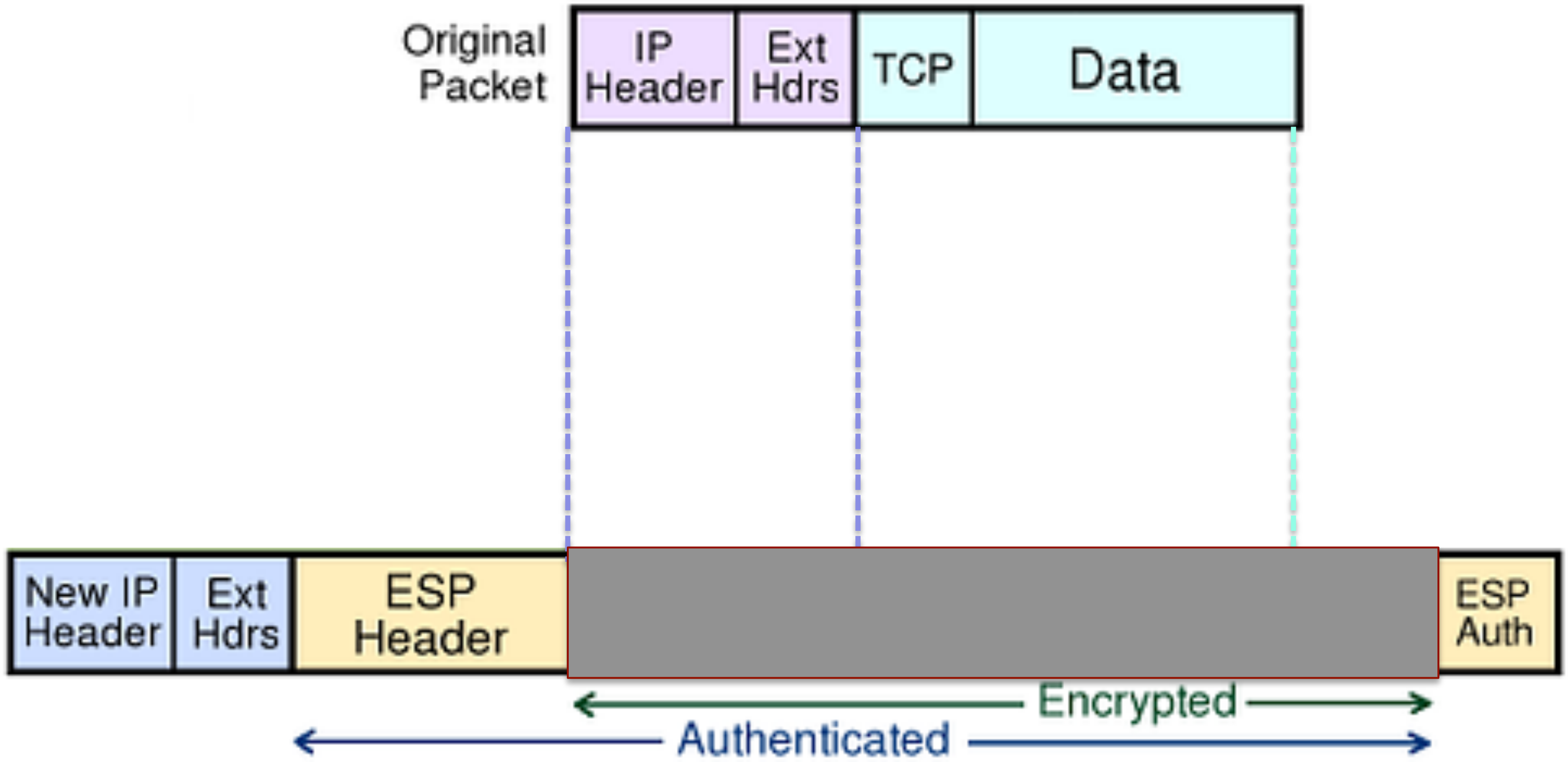
Encrypts & Optionally authenticates IP data

Can do traffic analysis … but it is efficient

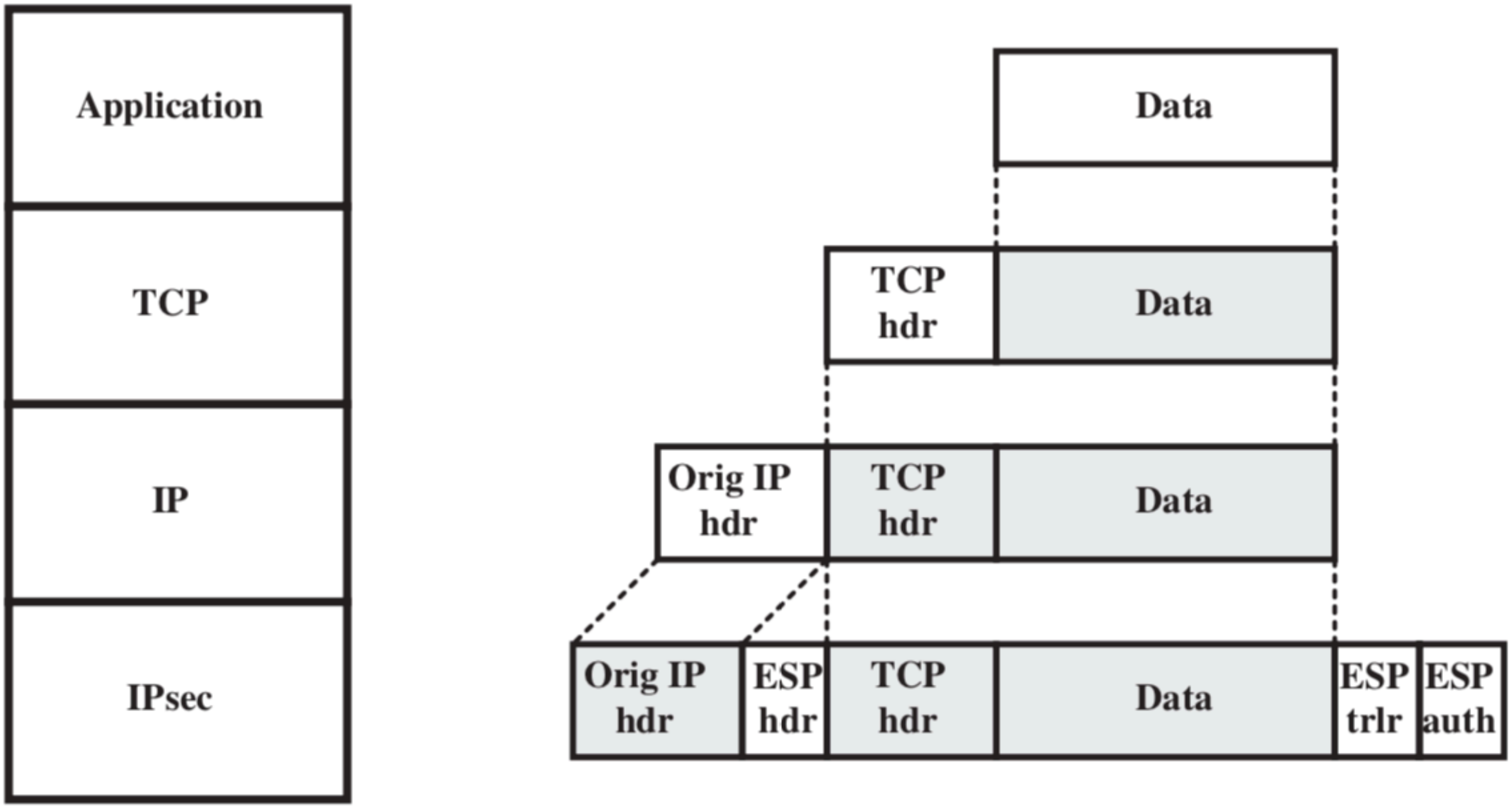
Good for ESP "host to host" traffic, end-to-end

Note: what about "covert channels" control, "non-controlled access for malicious software entry points, … etc ? Implications ?

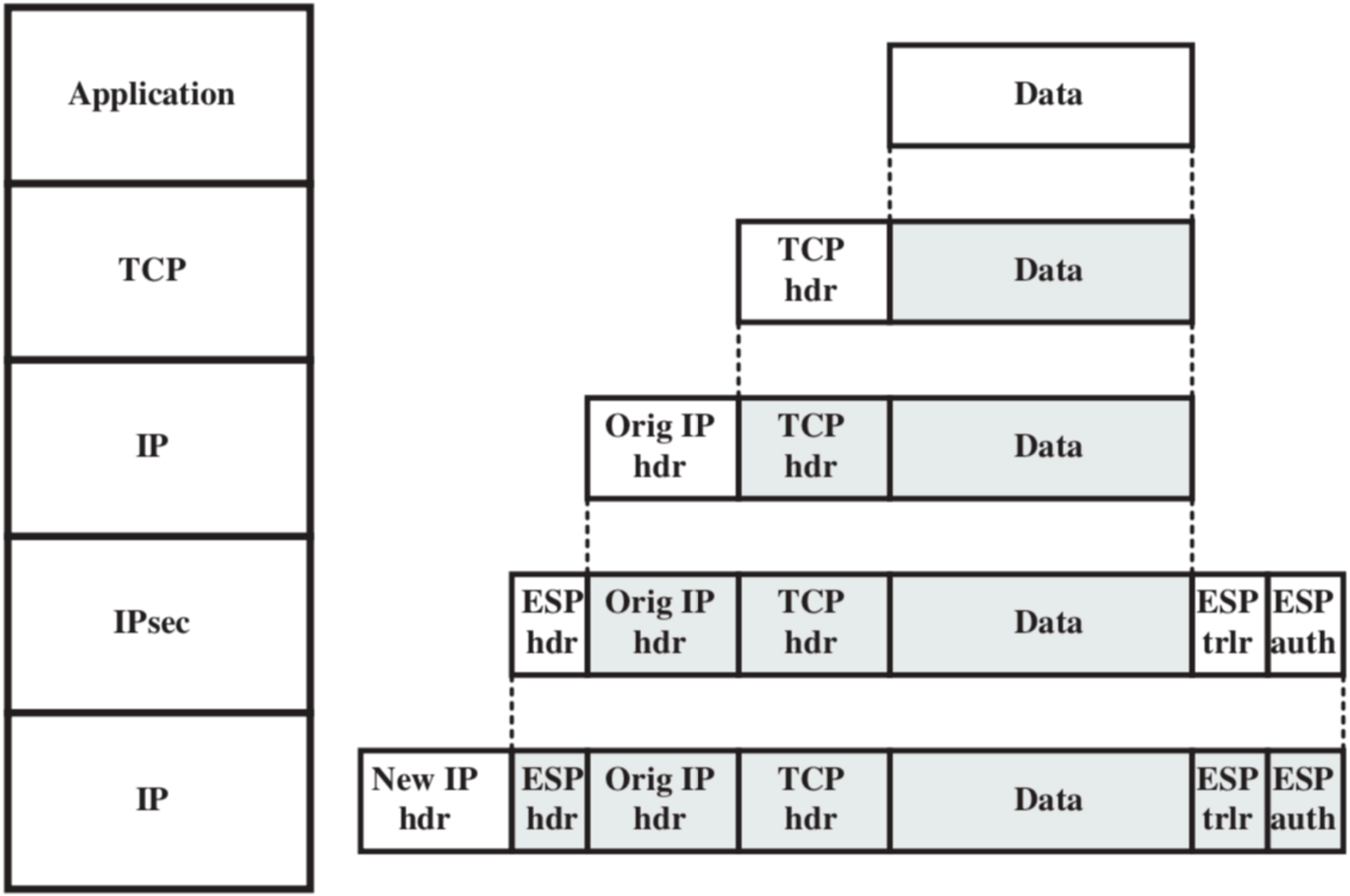
ESP Encapsulation: Tunnel Mode



ESP Processing: Transport Mode



ESP Processing: Tunnel Mode



IPSec Sub-Protocols and Modes

Support for six different protection behaviours and related SAs (IPSec Security Associations)

	Transport Mode SA	Tunnel Mode SA
AH	Authenticates IP payload and selected portions of IP header and IPv6 extension headers.	Authenticates entire inner IP packet (inner header plus IP payload) plus selected portions of outer IP header and outer IPv6 extension headers.
ESP	Encrypts IP payload and any IPv6 extension headers following the ESP header.	Encrypts entire inner IP packet.
ESP with Authentication	Encrypts IP payload and any IPv6 extension headers following the ESP header. Authenticates IP payload but not IP header.	Encrypts entire inner IP packet. Authenticates inner IP packet.

ESP A&E in Tunnel vs. Transport Mode

- **Transport modes (Host-Based, End-to-End)**
  - Encrypts entire IP packet
  - Limited Traffic Flow Protection. Why and How ?
  - End-to-End Protected Packets
  - No Switches nor LAN-to-LAN MiM on way can examine inner IP header and Payloads ! Issues ? How to address ?

- **Tunnel Mode (Router or FW Intermediation)**
  - Encrypts entire IP packet
  - Limited Traffic Flow Protection. Why and How ?
  - Add new header for "each" next hop
  - But no routers/firewalls on way can examine inner IP header and Payloads ! Issues ? How to address ?
  - Good for Secure VPNs, Gateway to Gateway security or Host-to-Relay Security

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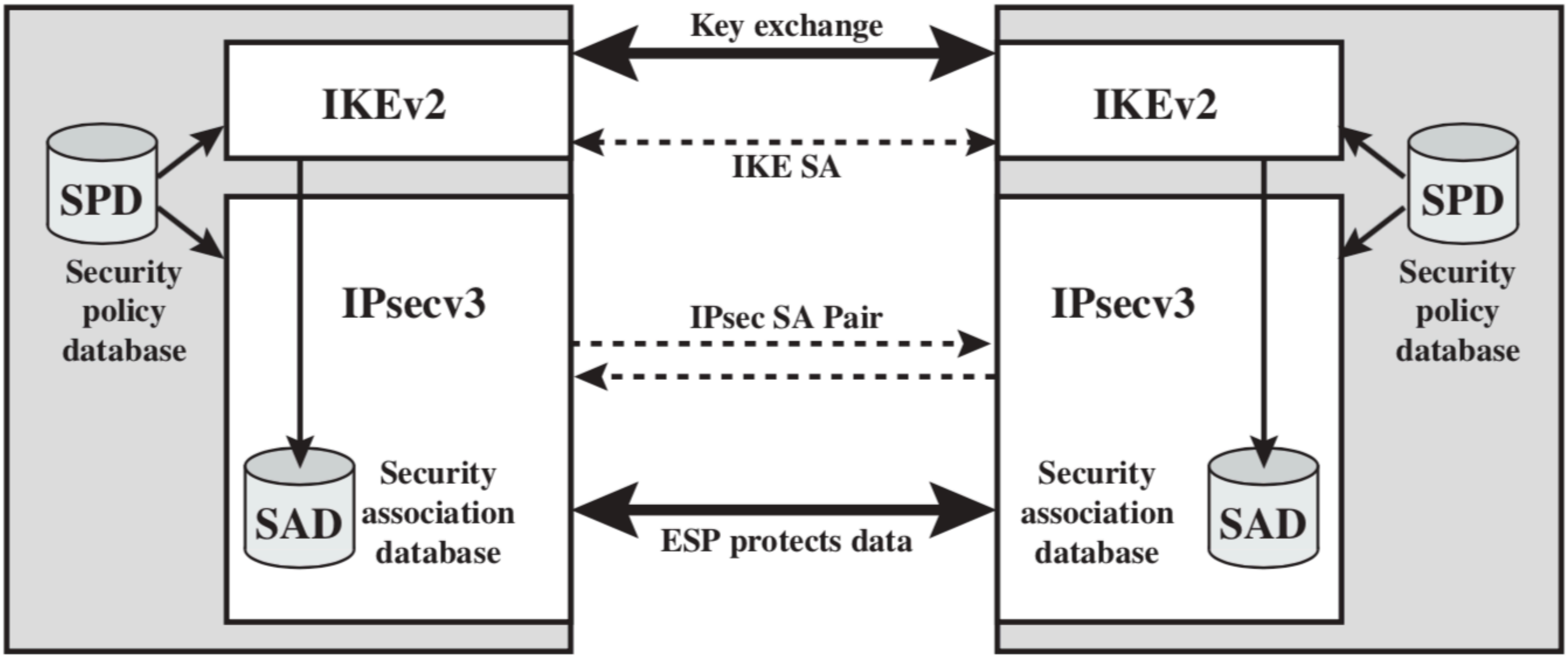
IPSec operation review



SADs, SPDs, and SAs

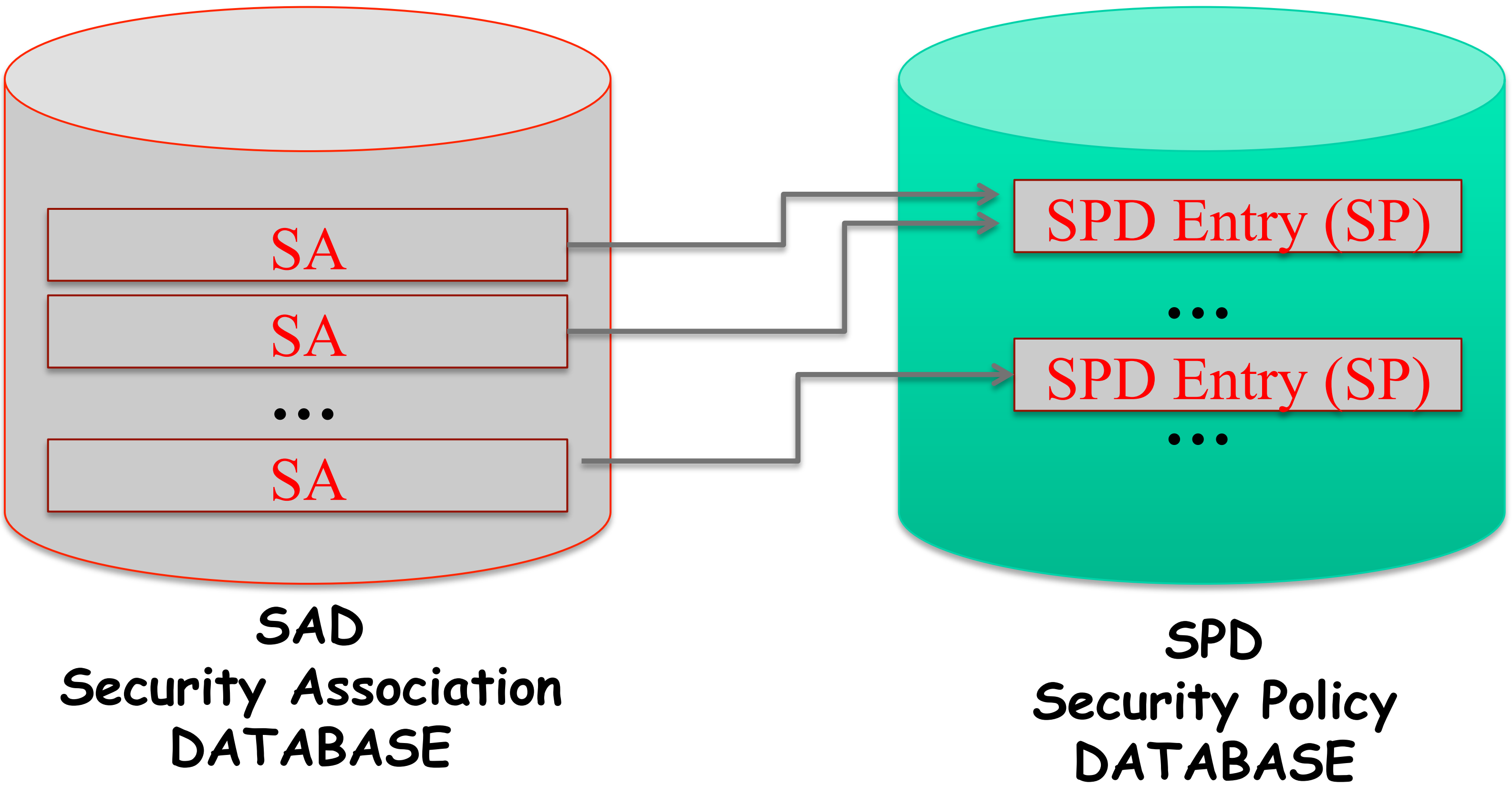
- **Management of Security Associations and Security Policies established and managed in IPSec endpoints**
- Determined by the information managed in two persistent "Databases":

  - **SAD (Security Association Database)**
    - Contains SAs (Security Associations) as entries
    - SA entries correspond to entries in the SPD

  - **SPD (Security Policy Database)**
    - In the SPD, the IPSec policies for each Security Association are established and maneged
    - Different SAs may share the same policy

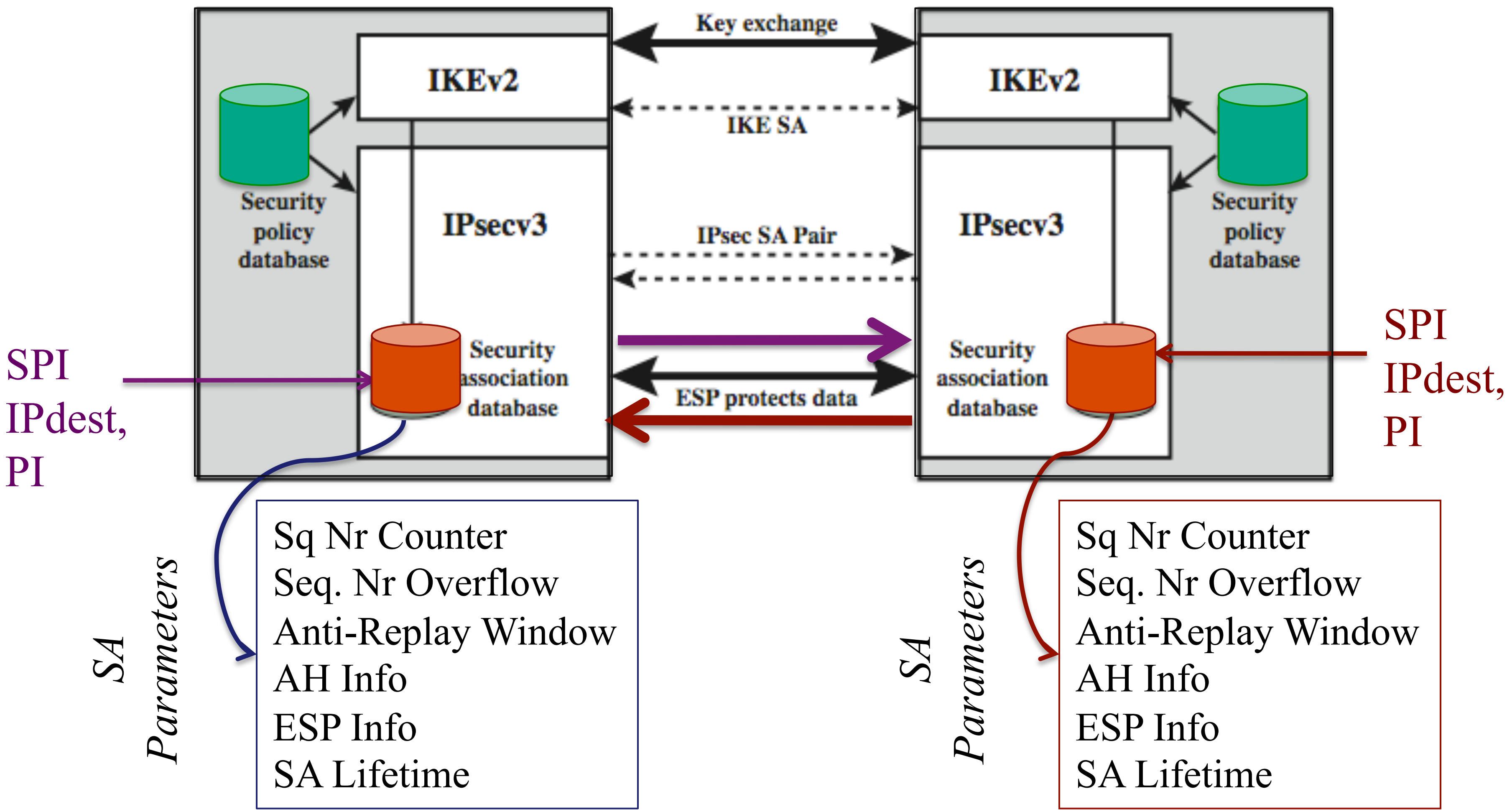
SADs, SPDs, and SAs

Each SA: defines a "One-Way" Relationship related to One-Way" IP FLOW between an IPSender sender & IPSec receiver that affords security policies for traffic flow in the right sense

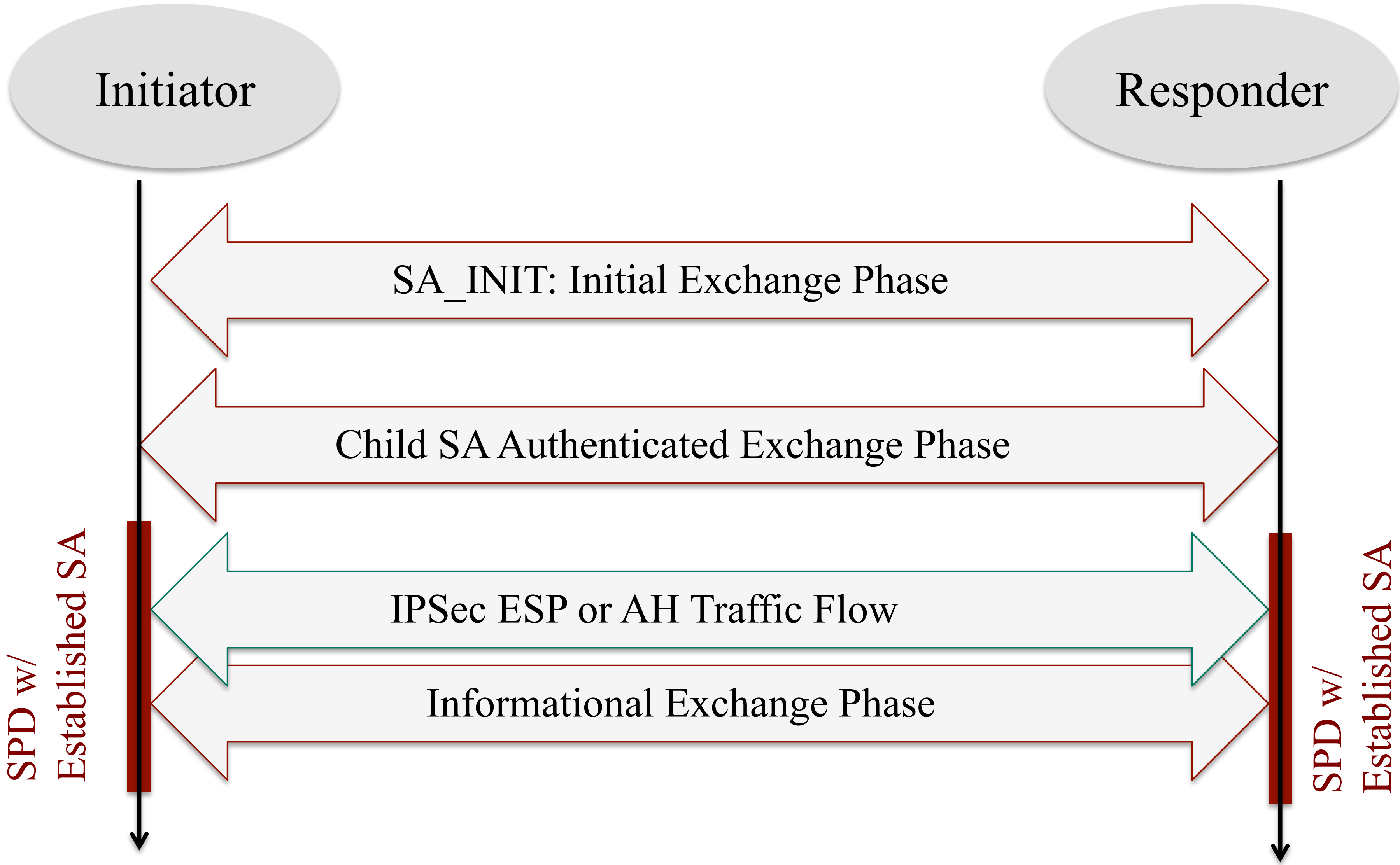


IPSec security policy management

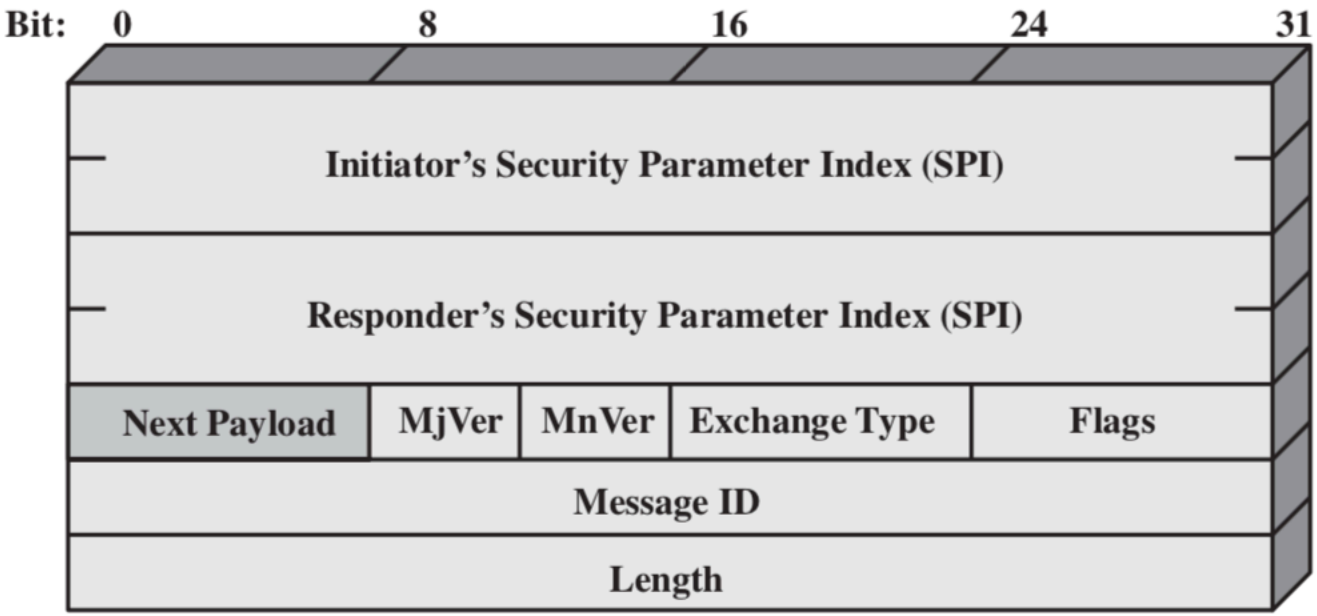
- IPSec architecture: IKEv2 + SPD and SAD
- Unidirectional Security Associations



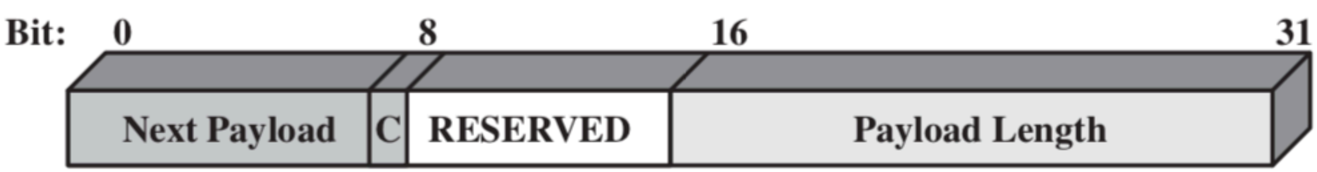
IKEv2 Exchanges



IKEv2 and ISAKMP

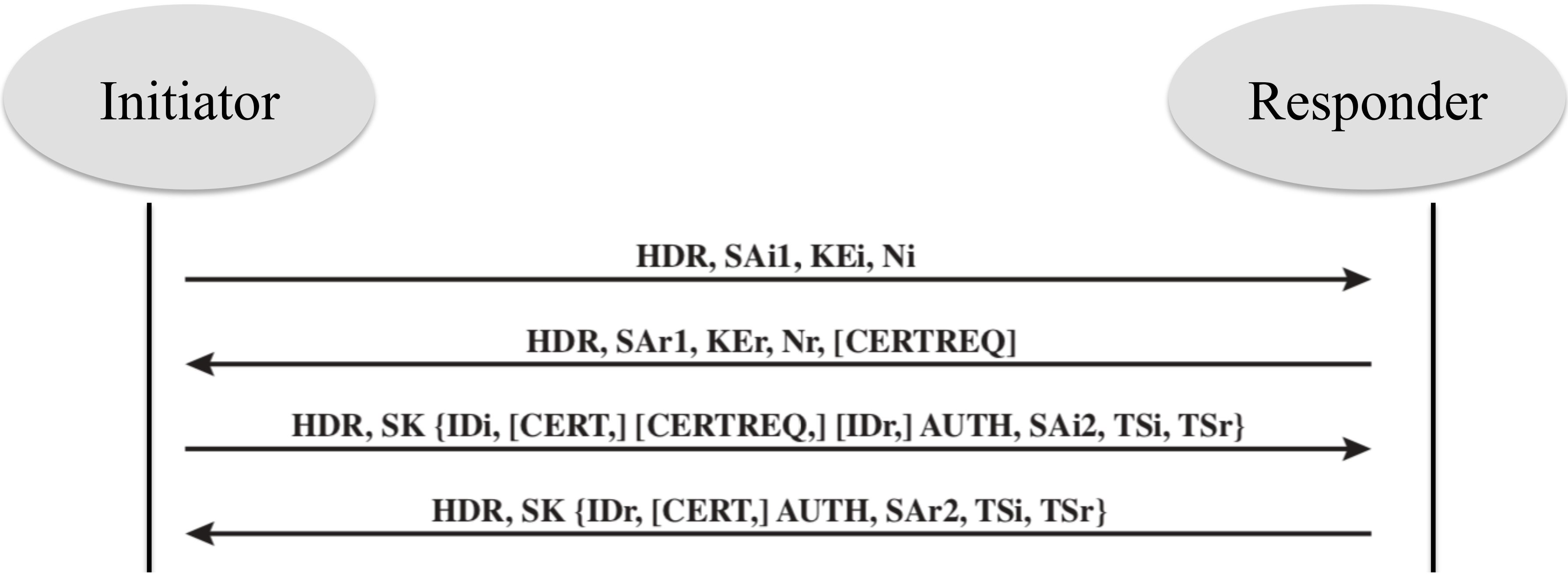


(a) IKE header



(b) Generic Payload header

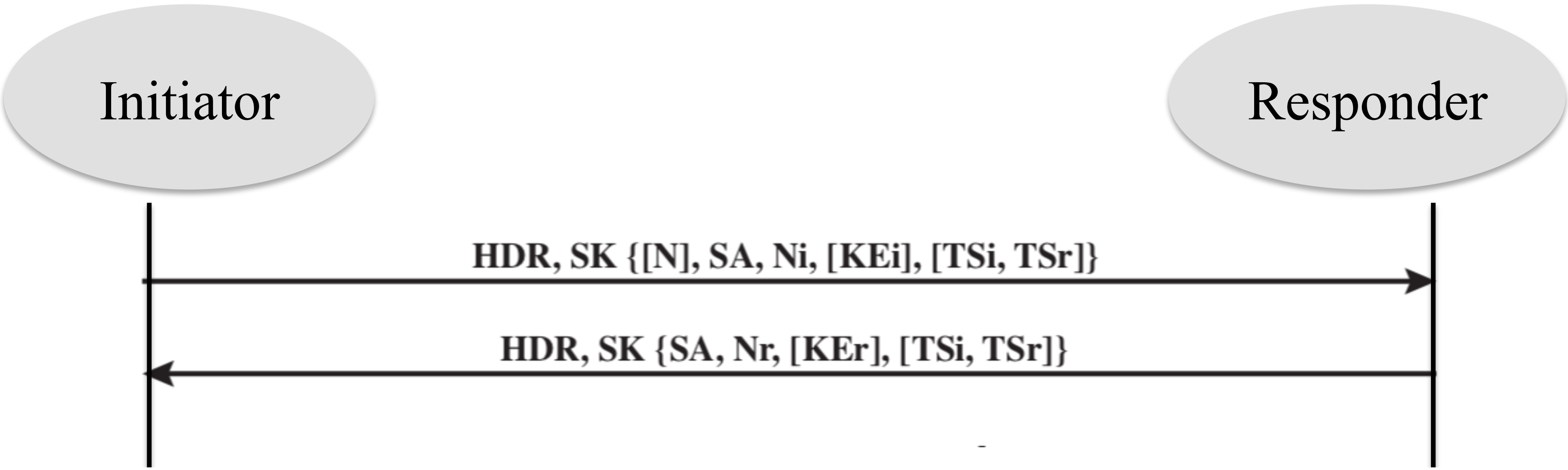
IKEv2 Exchanges: SA_INIT Phase



HDR = IKE header
SAx1 = offered and chosen algorithms, DH group
KEx = Diffie-Hellman public key
Nx= nonces
CERTREQ = Certificate request
IDx = identity
CERT = certificate

SK {...} = MAC and encrypt
AUTH = Authentication
SAx2 = algorithms, parameters for IPsec SA
TSx = traffic selectors for IPsec SA
N = Notify
D = Delete
CP = Configuration

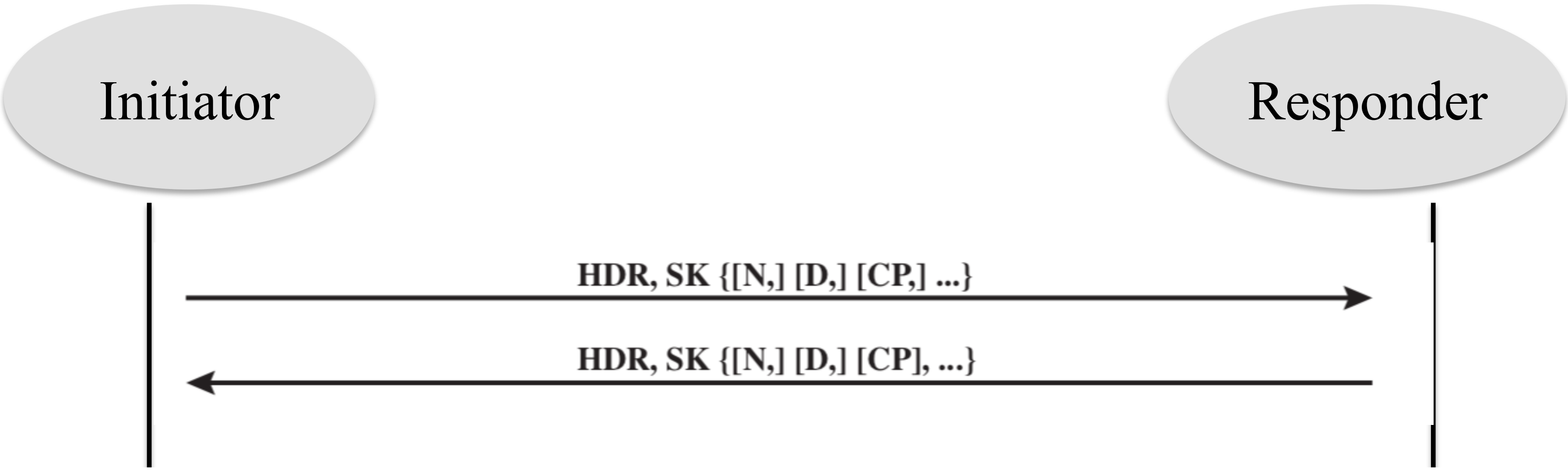
IKEv2 Exchanges: Child SA Phase



HDR = IKE header
SAx1 = offered and chosen algorithms, DH group
KEx = Diffie-Hellman public key
Nx= nonces
CERTREQ = Certificate request
IDx = identity
CERT = certificate

SK {...} = MAC and encrypt
AUTH = Authentication
SAx2 = algorithms, parameters for IPsec SA
TSx = traffic selectors for IPsec SA
N = Notify
D = Delete
CP = Configuration

IKEv2 Exchanges: Informational Phase

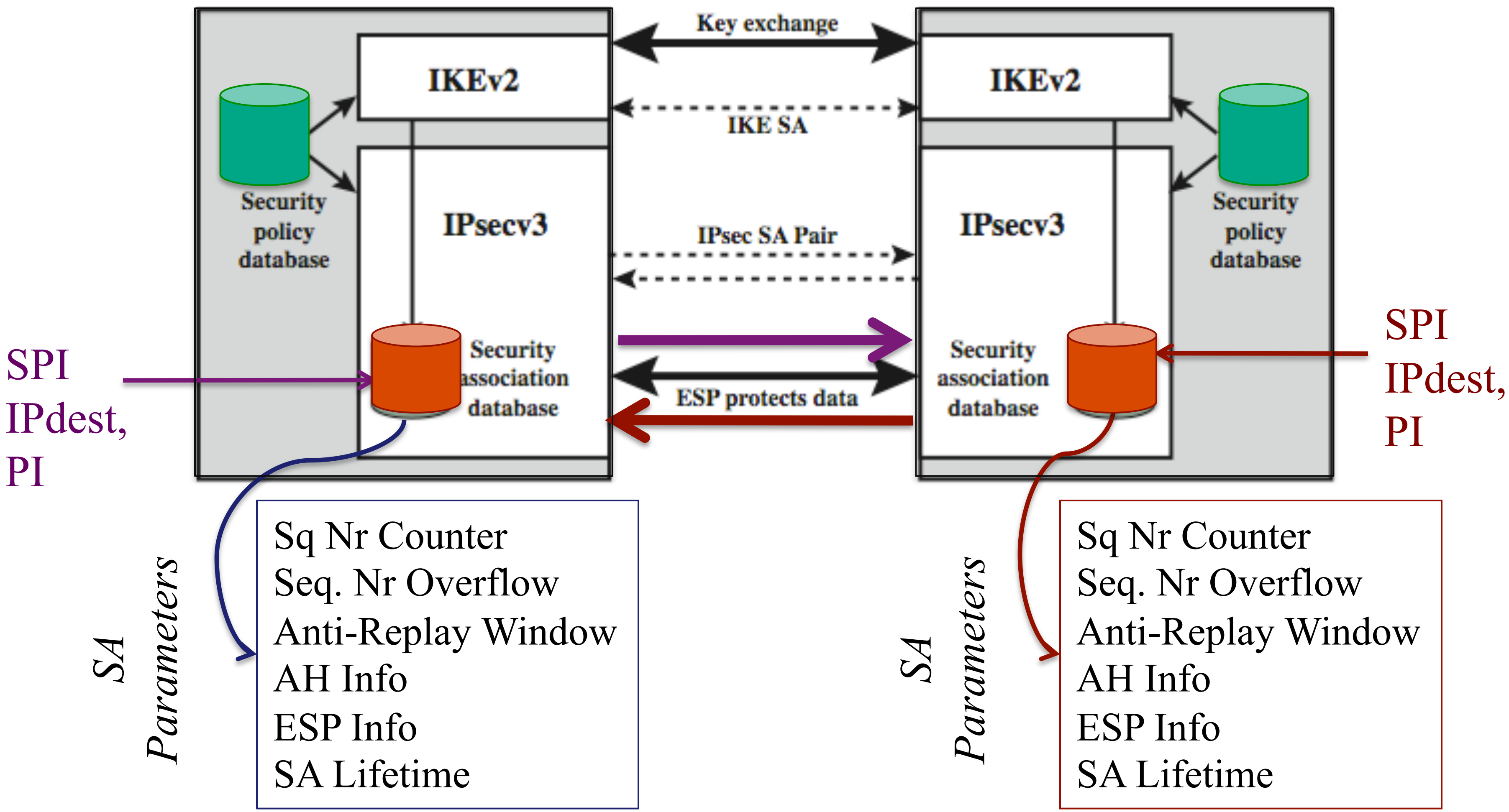


HDR = IKE header
SAx1 = offered and chosen algorithms, DH group
KEx = Diffie-Hellman public key
Nx= nonces
CERTREQ = Certificate request
IDx = identity
CERT = certificate

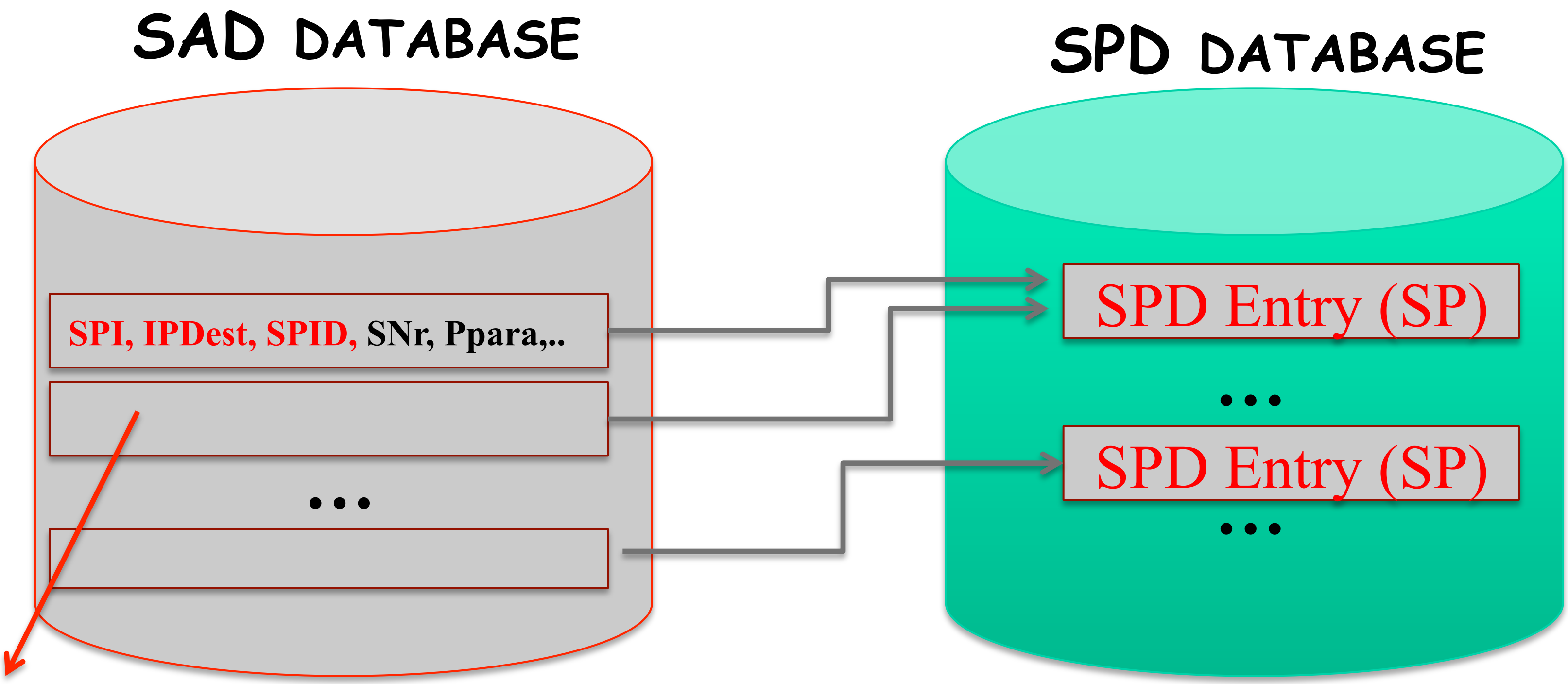
SK {...} = MAC and encrypt
AUTH = Authentication
SAx2 = algorithms, parameters for IPsec SA
TSx = traffic selectors for IPsec SA
N = Notify
D = Delete
CP = Configuration

IPSec security policy management

- IPSec architecture: IKEv2 + SPD and SAD
- Unidirectional Security Associations



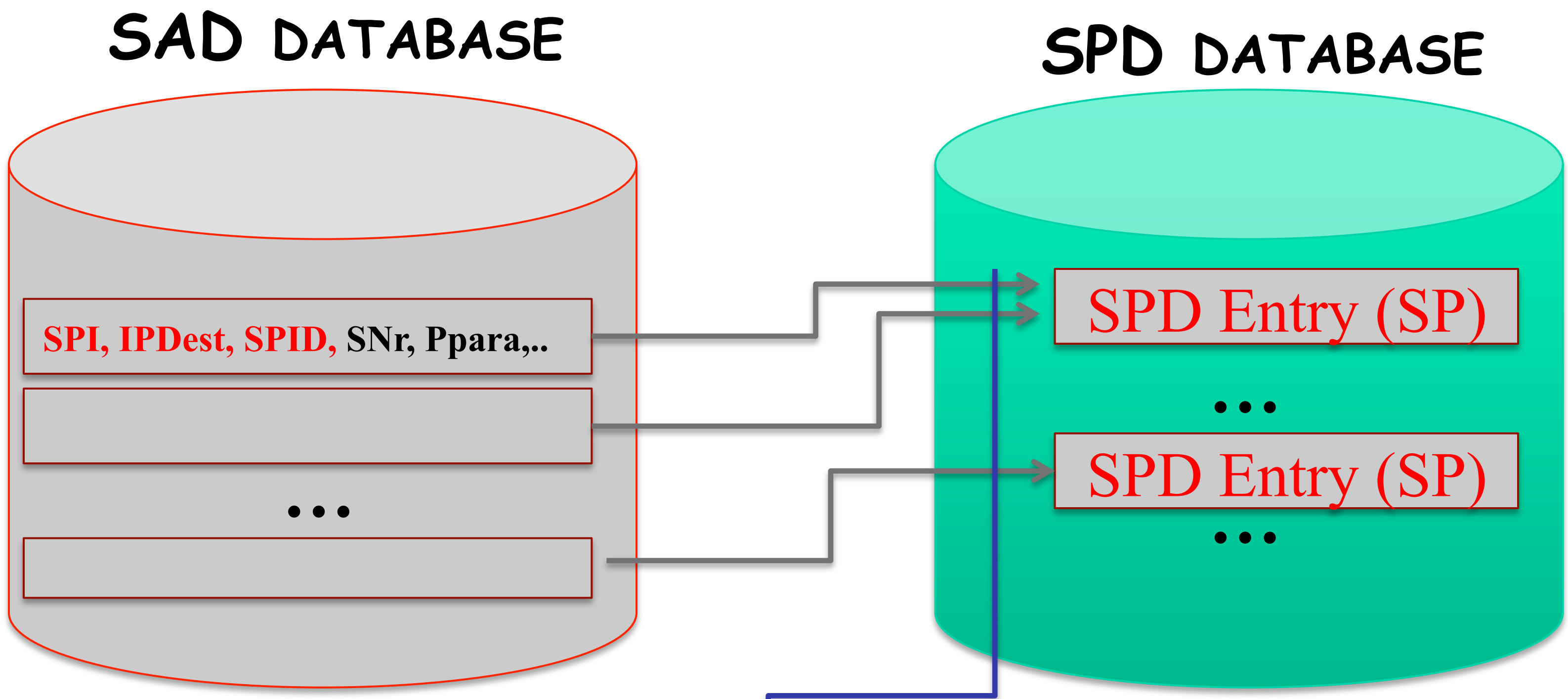
SADs, SPDs, SAs (and info in SAs)



- **An SA is defined by 3 parameters:**
  - **SPI: Security Parameters Index (SPI)**
    - Identifier travelling in the IPSec packet headers
  - **IP Destination Address**
  - **Security Protocol Identifier (SPID)**
- ... and additionally some other parameters
  - **Seq nr., AH & ESP info, SA lifetime, etc**

Sq Nr Counter
Seq. Nr Overflow
Anti-Replay Window
AH Info
ESP Info
SA Lifetime

SADs, SPDs, SAs (and info in SAs)



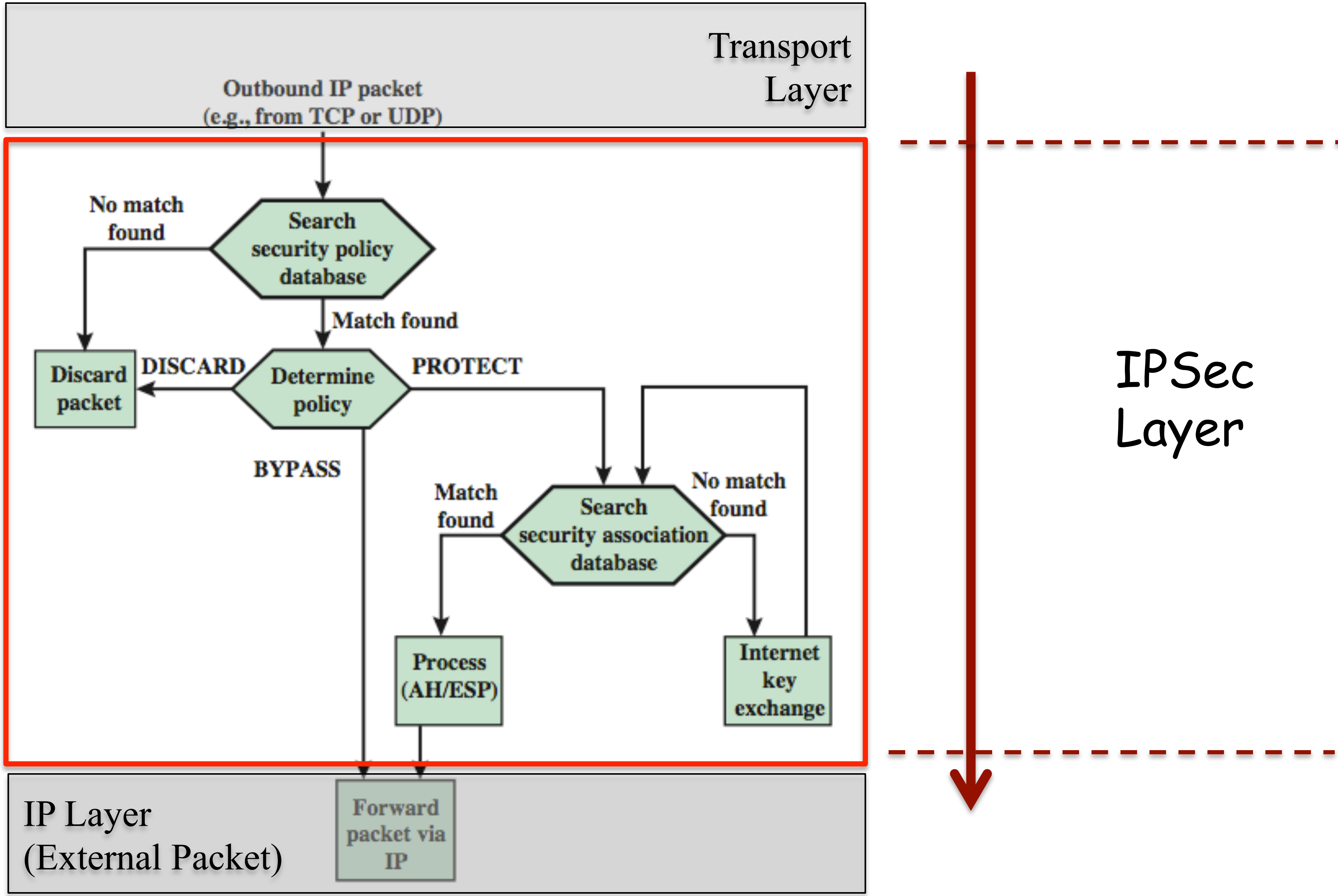
Protocol	Local IP	Port	Remote IP	Port	Action	Comment
UDP	1.2.3.101	500	*	500	BYPASS	IKE
ICMP	1.2.3.101	*	*	*	BYPASS	Error messages
*	1.2.3.101	*	1.2.3.0/24	*	PROTECT: ESP intransport-mode	Encrypt intranet traffic
TCP	1.2.3.101	*	1.2.4.10	80	PROTECT: ESP intransport-mode	Encrypt to server
TCP	1.2.3.101	*	1.2.4.10	443	BYPASS	TLS: avoid double encryption
*	1.2.3.101	*	1.2.4.0/24	*	DISCARD	Others in DMZ
*	1.2.3.101	*	*	*	BYPASS	Internet

Security Policy Database Implementation

- Relates IP traffic to specific SAs
  - Match subset of IP traffic to the relevant SA
  - Use Selectors to filter outgoing traffic to map
    - Different selectors can be used (see bibliography)
  - Based on: Local & Remote IP addresses, Next layer Protocol, Name, Local & Remote Ports

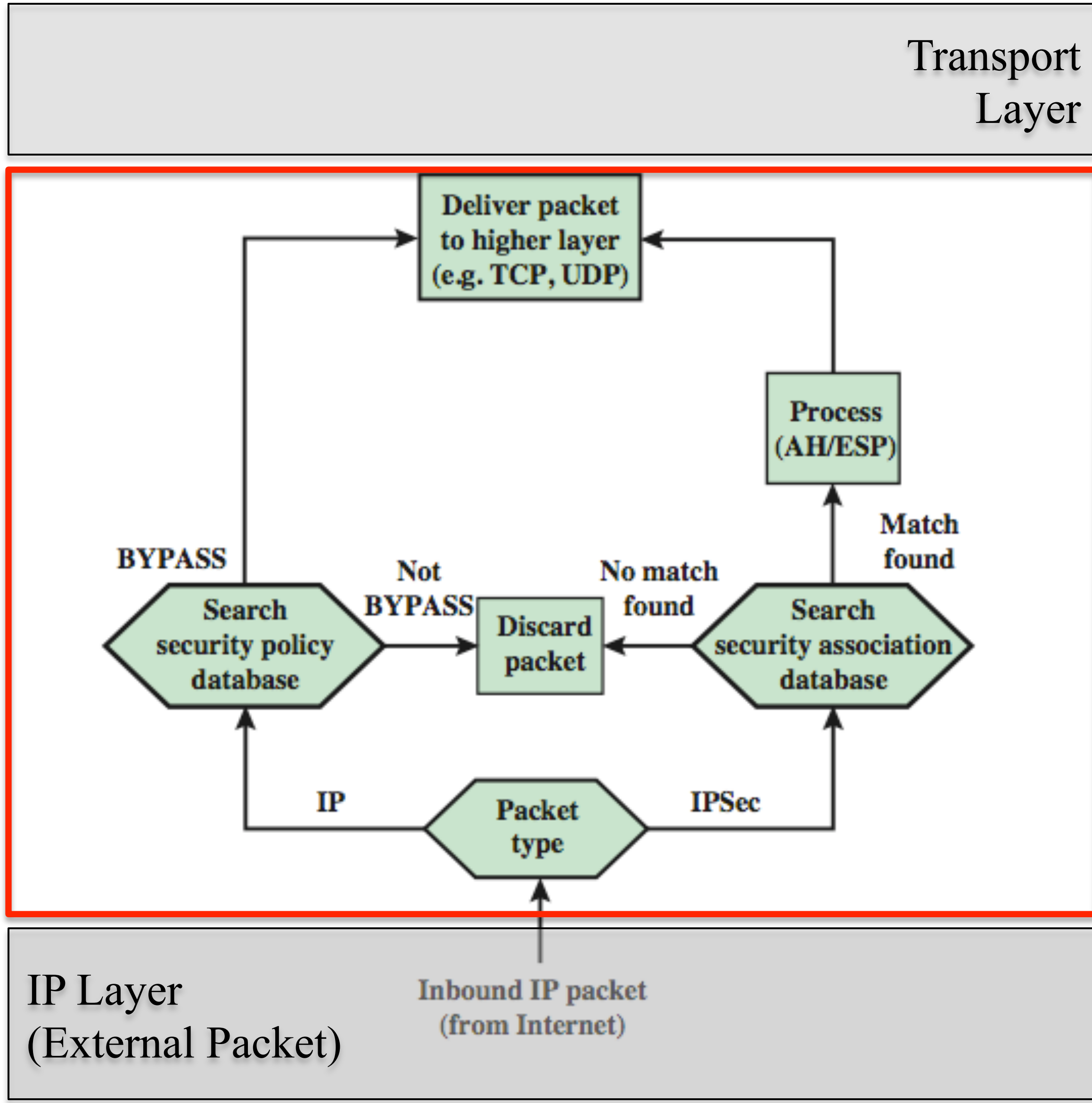
Protocol	Local IP	Port	Remote IP	Port	Action	Comment
UDP	1.2.3.101	500	*	500	BYPASS	IKE
ICMP	1.2.3.101	*	*	*	BYPASS	Error messages
*	1.2.3.101	*	1.2.3.0/24	*	PROTECT: ESP intransport-mode	Encrypt intranet traffic
TCP	1.2.3.101	*	1.2.4.10	80	PROTECT: ESP intransport-mode	Encrypt to server
TCP	1.2.3.101	*	1.2.4.10	443	BYPASS	TLS: avoid double encryption
*	1.2.3.101	*	1.2.4.0/24	*	DISCARD	Others in DMZ
*	1.2.3.101	*	*	*	BYPASS	Internet

IPSec: Processing of Outbound Packets



IPSec: Processing of Inbound Packets

IPSec
Layer



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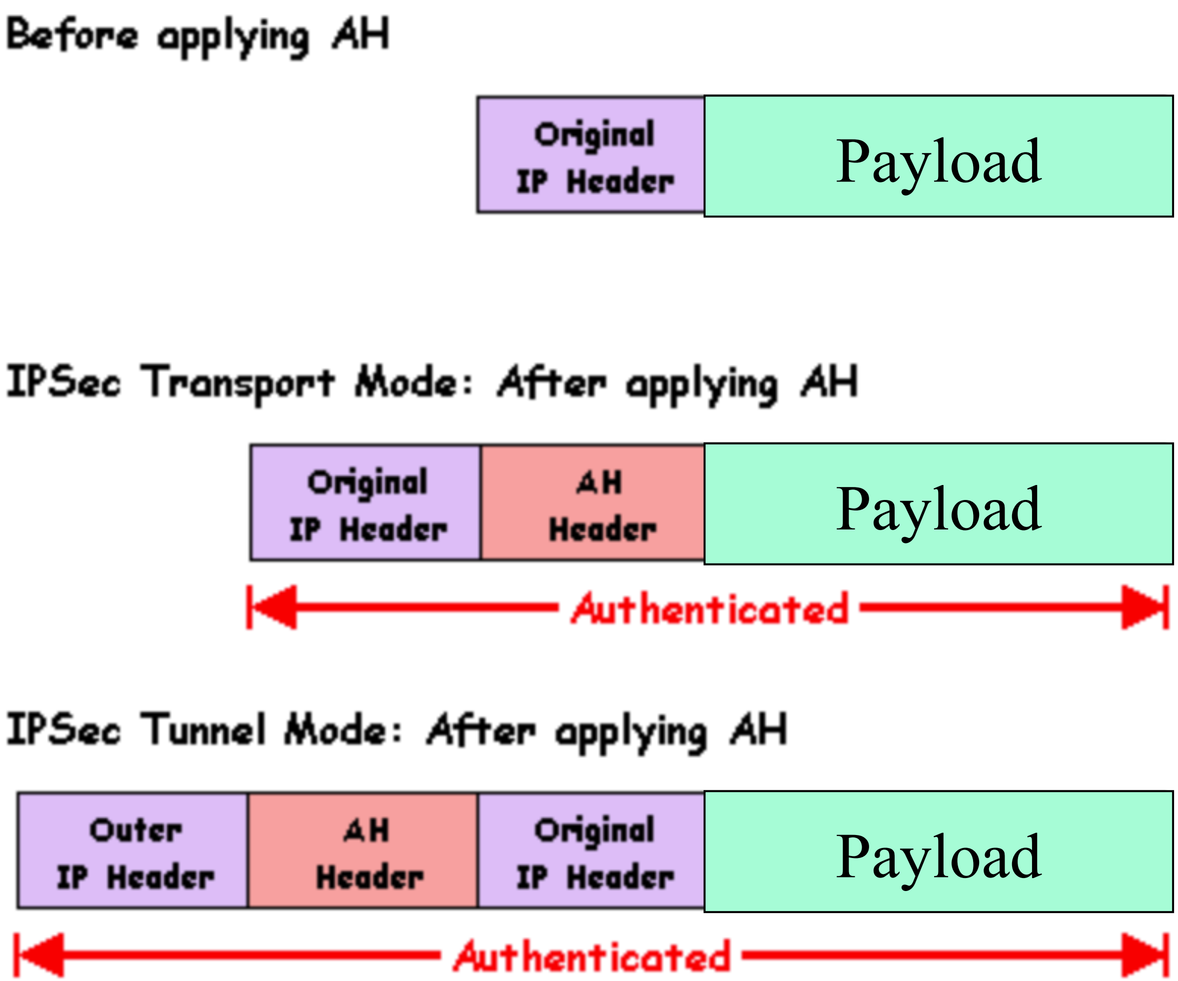
  - IPSec crypto-suite
  - Key Management Schemes

AH/IP in Transport and Tunnel modes

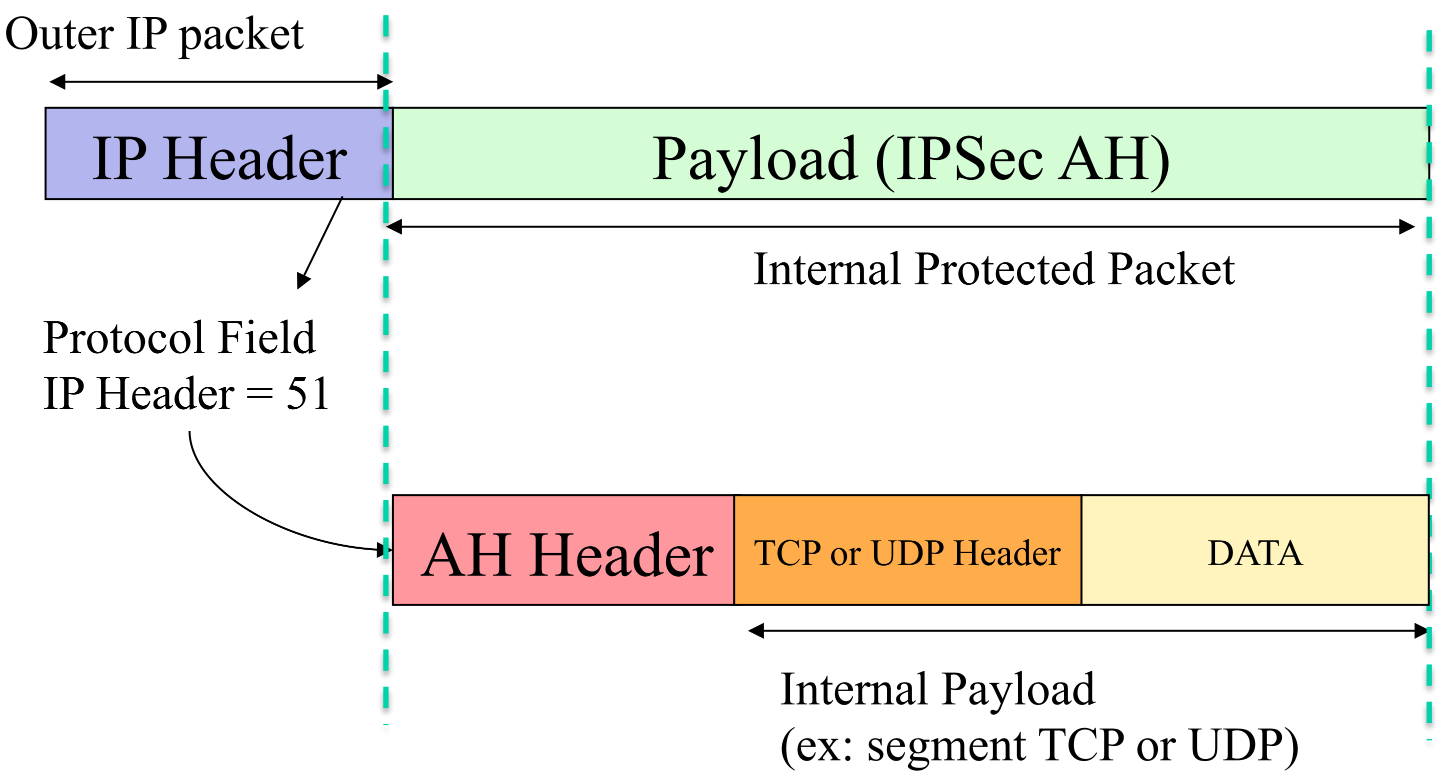


Transport Mode

Tunnel Mode

AH (Authentication Header Protocol)

Encapsulation:



AH Protocol

AH Header

0	8	16	31
Next Header	Payload Length	RES (NU)	RES (NU)
SPI			
Seq. number			
Auth Data (variable size Depending on the Message Authentication Method in the SA setup) (Default values in current implementations: HMAC => 96 bits)			

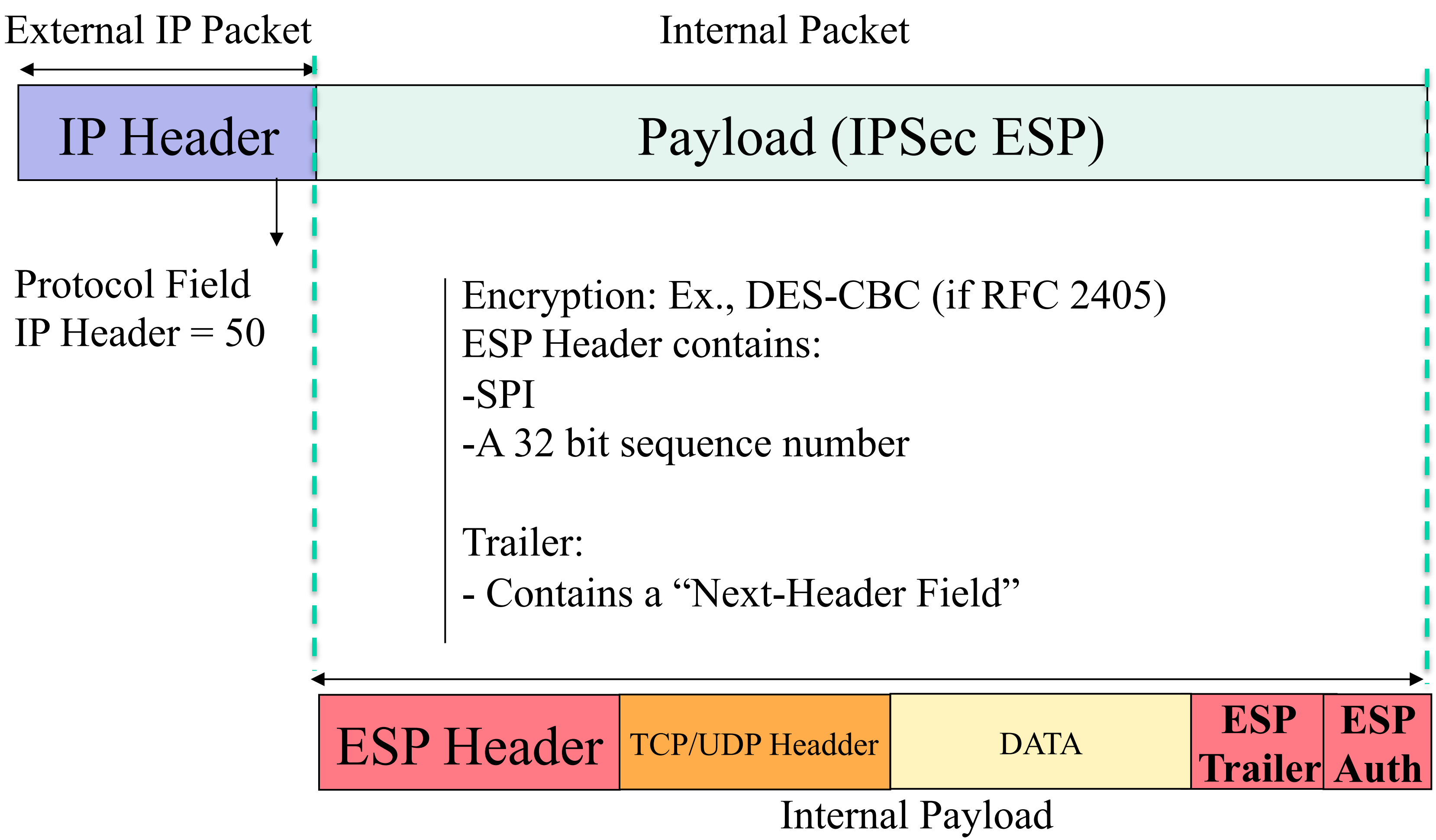
Auth Data (described in RFC 2402 ... => RFC 4302)
Contains an ICV (Integrity Check Value) computed as a 96 bit MAC (HMAC-MD5-96, ou HMAC-SHA-1.96)

Example of AH encapsulation (Wireshark)

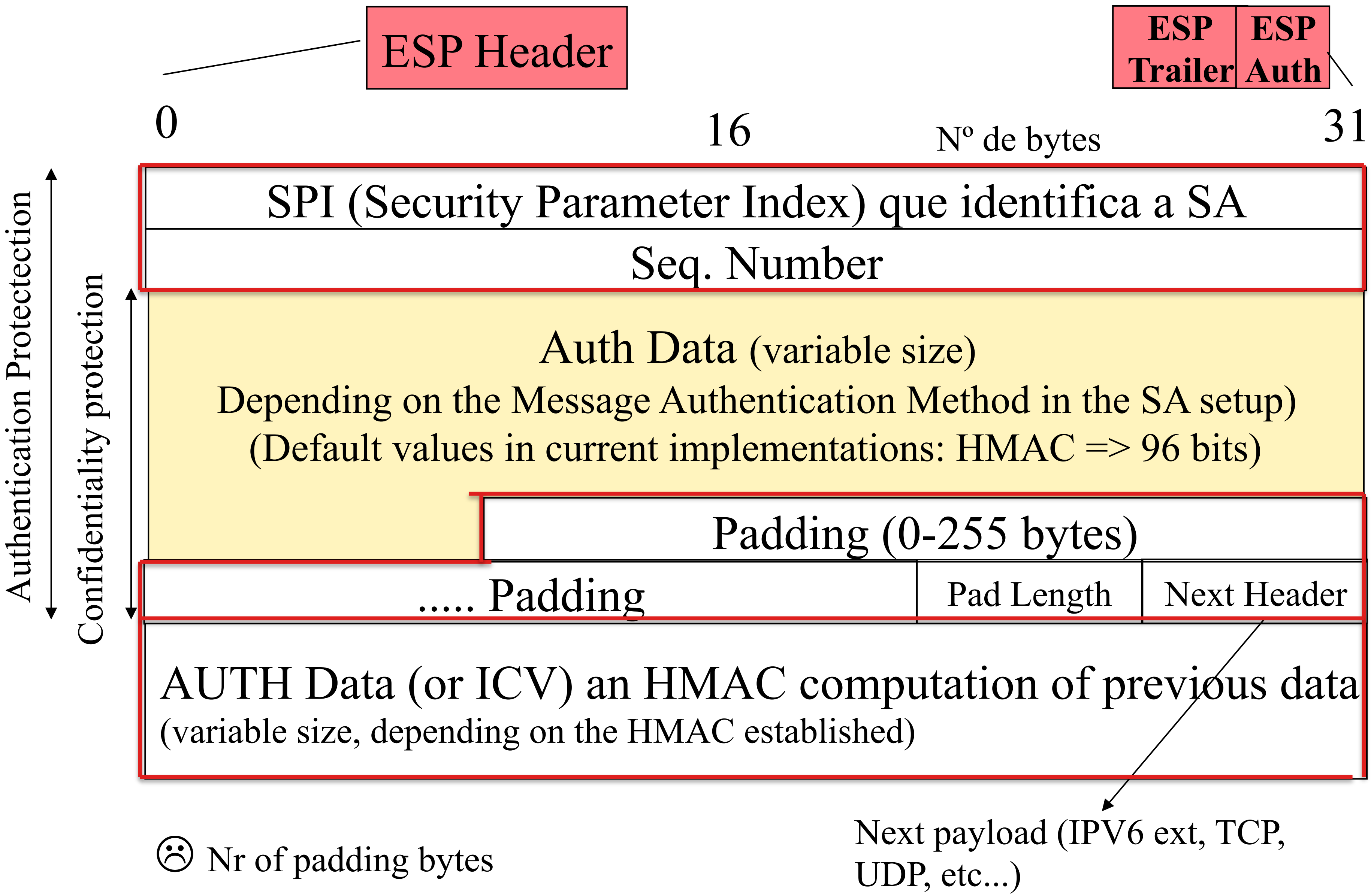
```
⊞ Frame 1: 158 bytes on wire (1264 bits), 158 bytes captured (1264 bits) on interface 0
⊞ Ethernet II, Src: Cisco_8b:36:d0 (00:1d:a1:8b:36:d0), Dst: Cisco_ed:7a:f0 (00:17:5a:ed:7a:f0)
⊟ Internet Protocol Version 4, Src: 192.168.12.1 (192.168.12.1), Dst: 192.168.12.2 (192.168.12.2)
    Version: 4
    Header Length: 20 bytes
  ⊞ Differentiated Services Field: 0x00 (DSCP 0x00: Default; ECN: 0x00: Not-ECT (Not ECN-Capable Transport))
    Total Length: 144
    Identification: 0x0215 (533)
  ⊞ Flags: 0x00
    Fragment offset: 0
    Time to live: 255
    Protocol: Authentication Header (51)
  ⊞ Header checksum: 0x1fd2 [validation disabled]
    Source: 192.168.12.1 (192.168.12.1)
    Destination: 192.168.12.2 (192.168.12.2)
    [Source GeoIP: Unknown]
    [Destination GeoIP: Unknown]
⊟ Authentication Header
    Next Header: IPIP (0x04)
    Length: 24
    AH SPI: 0x646adc80
    AH Sequence: 5
    AH ICV: 606d214066853c0390cfe577
⊟ Internet Protocol Version 4, Src: 192.168.12.1 (192.168.12.1), Dst: 192.168.12.2 (192.168.12.2)
    Version: 4
    Header Length: 20 bytes
  ⊞ Differentiated Services Field: 0x00 (DSCP 0x00: Default; ECN: 0x00: Not-ECT (Not ECN-Capable Transport))
    Total Length: 100
    Identification: 0x003c (60)
  ⊟ Flags: 0x00
      0... .... = Reserved bit: Not set
      .0.. .... = Don't fragment: Not set
      ..0. .... = More fragments: Not set
    Fragment offset: 0
    Time to live: 255
    Protocol: ICMP (1)
  ⊞ Header checksum: 0x2209 [validation disabled]
    Source: 192.168.12.1 (192.168.12.1)
    Destination: 192.168.12.2 (192.168.12.2)
    [Source GeoIP: Unknown]
    [Destination GeoIP: Unknown]
⊞ Internet Control Message Protocol
```

ESP - Encapsulation Security Payload

- More complex than AH (more overhead but more security concerns)



ESP


ESP Header
ESP Trailer
ESP Auth
0
16
Nº de bytes
31
SPI (Security Parameter Index) que identifica a SA
Seq. Number
Auth Data (variable size)
Depending on the Message Authentication Method in the SA setup)
(Default values in current implementations: HMAC => 96 bits)
Padding (0-255 bytes)
..... Padding
Pad Length
Next Header
AUTH Data (or ICV) an HMAC computation of previous data
(variable size, depending on the HMAC established)
Authentication Protectection
Confidentiality protection
☹ Nr of padding bytes
Next payload (IPV6 ext, TCP, UDP, etc...)

ESP (wireshark trace example)

```
⊞ Frame 2: 182 bytes on wire (1456 bits), 182 bytes captured (1456 bits) on interface 0
⊞ Ethernet II, Src: Cisco_8b:36:d0 (00:1d:a1:8b:36:d0), Dst: Cisco_ed:7a:f0 (00:17:5a:ed:7a:f0)
⊟ Internet Protocol Version 4, Src: 192.168.12.1 (192.168.12.1), Dst: 192.168.12.2 (192.168.12.2)
    Version: 4
    Header Length: 20 bytes
  ⊞ Differentiated Services Field: 0x00 (DSCP 0x00: Default; ECN: 0x00: Not-ECT (Not ECN-Capable Transport))
    Total Length: 168
    Identification: 0x023e (574)
  ⊞ Flags: 0x00
    Fragment offset: 0
    Time to live: 255
    Protocol: Encap Security Payload (50)
  ⊞ Header checksum: 0x1f92 [validation disabled]
    Source: 192.168.12.1 (192.168.12.1)
    Destination: 192.168.12.2 (192.168.12.2)
    [Source GeoIP: Unknown]
    [Destination GeoIP: Unknown]
⊟ Encapsulating Security Payload
    ESP SPI: 0x8bb181a7 (2343666087)
    ESP Sequence: 5
```

Encryption & Authentication Algorithms & Padding Processing

- ESP can encrypt payload data, padding, pad length, and next header fields
  - If needed have IV at start of payload data
  - Provides message content confidentiality, data origin authentication, connectionless integrity, an anti-replay service, limited traffic flow confidentiality
- ESP can have optional ICV for integrity
  - Is computed after encryption is performed
- ESP uses padding
  - To expand plaintext to required length
  - To align pad length and next header fields
  - To provide partial traffic flow confidentiality

Ex: Secure VPN access (fct.unl.pt)

- VPN Service https://www.div-i.fct.unl.pt/servicos/vpn
- Available by using VPN Server: vpn.fct.unl.pt
- Can use VPN Clients
  - Checkpoint Endpoint Security SW (MacOS, Windows)

- UDP-enabled ISAKMP and ESP Encapsulation
  - Can use for example Wireshark for Traffic Inspection and Analysis

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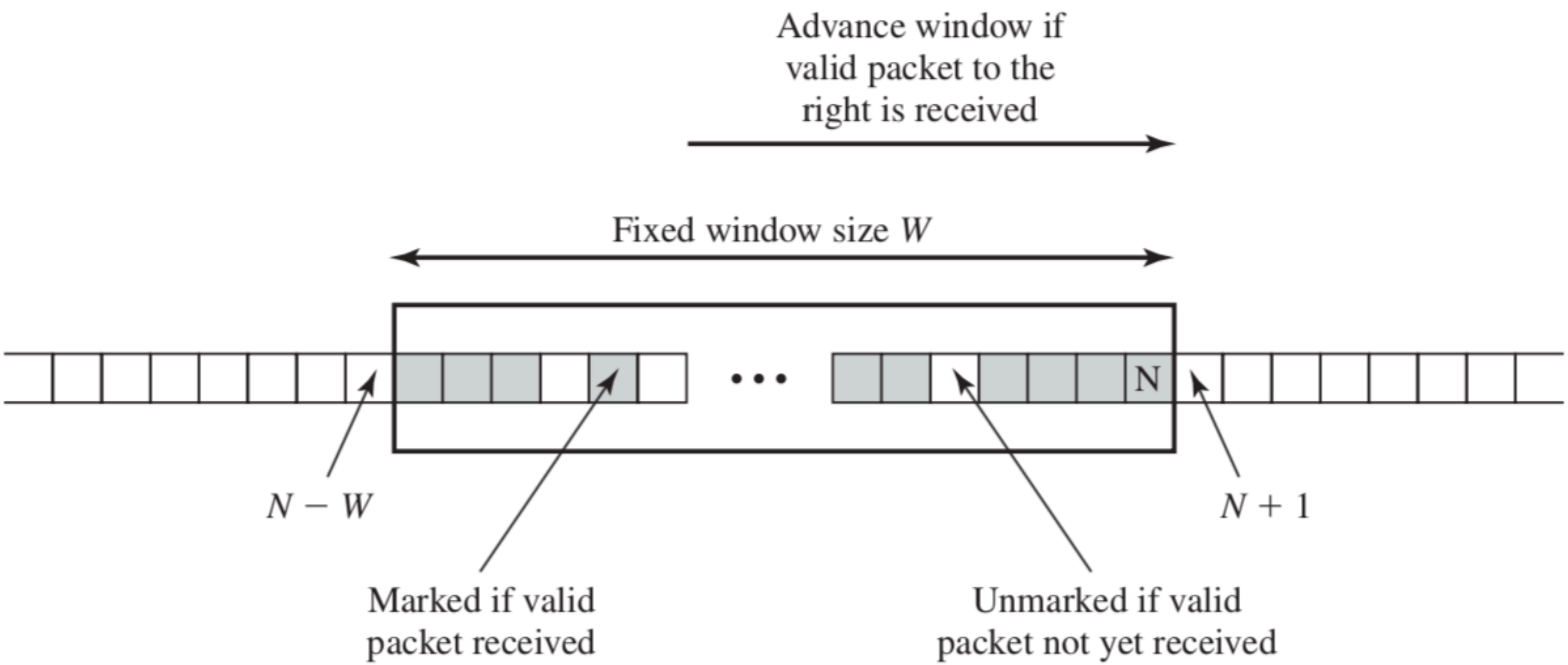
Anti-Replay Service

- Replay: what if attacker resends a copy of an authenticated packet
- IPSec Countermeasure: Use of a sequence number (SN) to thwart the attack
  - Sender initializes sequence number to 0 when a new SA is established
    - Increment SN for each packet
    - Must not exceed limit of $2^{32} - 1$
  - Receiver then accepts packets with seq numbers within a window of ($N - W+1$)
- But … What what if packets arrive out of order ?

Out-of-Order packets and control

- IPSec solution: Sliding window control



Processing of anti-replay windows

- If received packet falls with in the window and is new
  - Check MAC.
  - If the packet is authenticated, the corresponding slot in the window is marked (valid packet)
- If received packet is to the right of the window and is new
  - Check MAC.
  - If the packet is authenticated, the window is advanced
  - so that this sequence number is the right edge of the window, and the corresponding slot in the window is marked (valid packet).
- If received packet is to the left of the window or if authentication fails
  - the packet is discarded; generates a auditable event (logging).

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Combining Security Associations

- SA's can implement either AH or ESP (not both)
- But we can implement both
- Can combine SA's for flexibility vs. security tradeoffs: enforcement of **Security Association Bundles (SABs)**

- A SAB may terminate at different or same endpoints
  - Combination in different ways, by
    - **Transport adjacency**
    - **Iterated tunneling**

- Combining authentication & encryption w/ different IPSec sub-protocols
  - ESP with authentication
  - Bundled inner ESP & outer AH
  - Bundled inner transport & outer ESP

Example (wireshark traffic: ESP/AH/IP)

```
⊞ Frame 5: 178 bytes on wire (1424 bits), 178 bytes captured (1424 bits) on interface 0
⊞ Ethernet II, Src: Cisco_8b:36:d0 (00:1d:a1:8b:36:d0), Dst: Cisco_ed:7a:f0 (00:17:5a:ed:7a:f0)
⊟ Internet Protocol Version 4, Src: 192.168.12.1 (192.168.12.1), Dst: 192.168.12.2 (192.168.12.2)
    Version: 4
    Header Length: 20 bytes
  ⊞ Differentiated Services Field: 0x00 (DSCP 0x00: Default; ECN: 0x00: Not-ECT (Not ECN-Capable Transport))
    Total Length: 164
    Identification: 0x0056 (86)
  ⊞ Flags: 0x00
    Fragment offset: 0
    Time to live: 255
    Protocol: Authentication Header (51)
  ⊞ Header checksum: 0x217d [validation disabled]
    Source: 192.168.12.1 (192.168.12.1)
    Destination: 192.168.12.2 (192.168.12.2)
    [Source GeoIP: Unknown]
    [Destination GeoIP: Unknown]
⊟ Authentication Header
    Next Header: Encap Security Payload (0x32)
    Length: 24
    AH SPI: 0xa90dc9aa
    AH Sequence: 1
    AH ICV: 157ba6cc340b1a30049ea551
⊟ Encapsulating Security Payload
    ESP SPI: 0xd2264f7a (3525726074)
    ESP Sequence: 1
```

More on flexibility: SABs vs. Modes

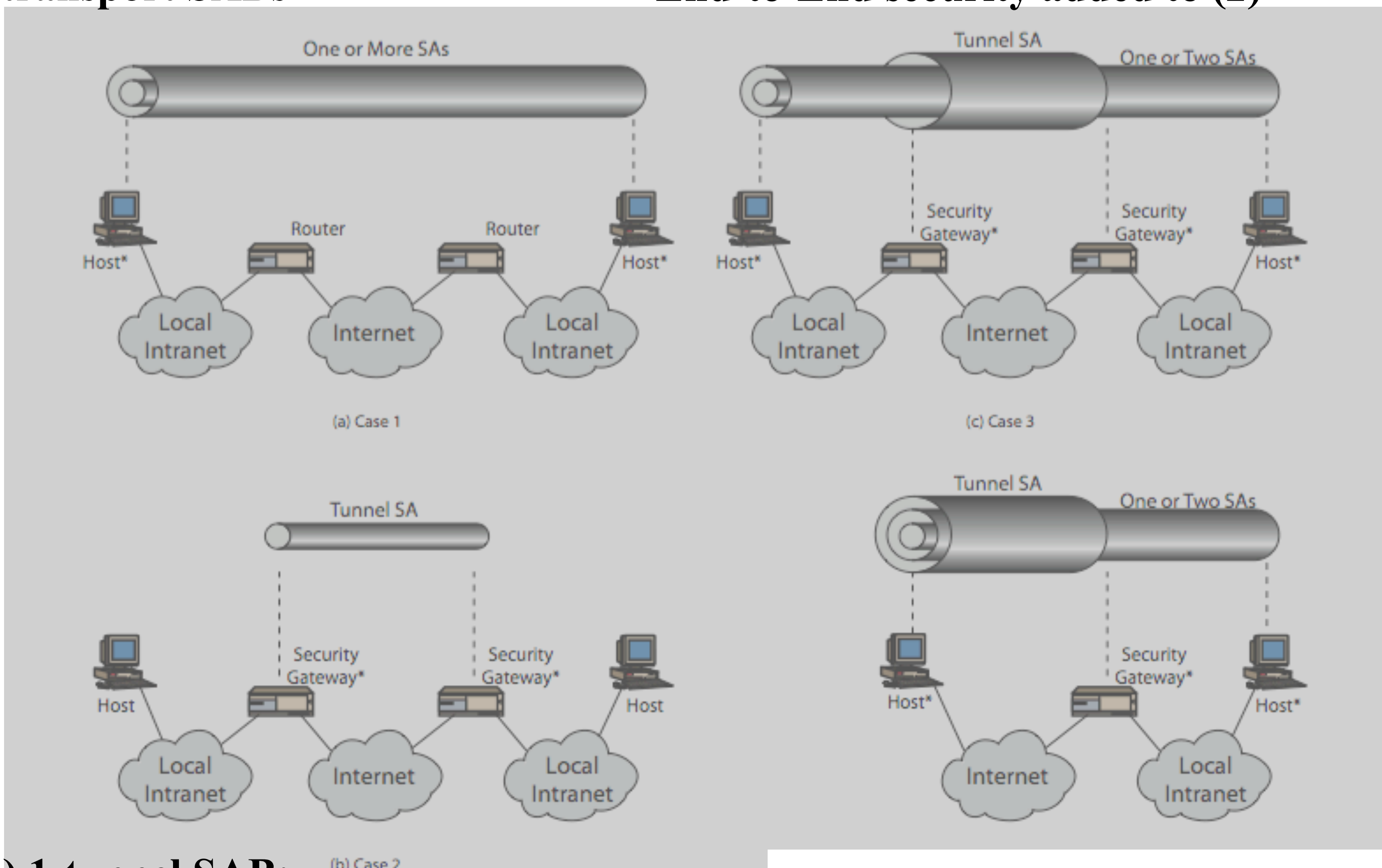
- To maximize tradeoffs, the combination can be done involving:
  - SA bundles with different policies
  - And different IPSec modes
  - Exploring adjacency or iteration

  - Many possible combinations according to the security and flexibility requirements

SA combinations and Bundles

(1)
2-transport SABs

(3) 2-transport SABs and 1-tunnel SAB
End-to-End security added to (2)



(2) 1-tunnel SAB:
ex of single tunneled VPN solution

(4) 1-2 Transport SABs and
1 Tunnel SA: A secure Remote Access

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IPSec Cryptographic Suites

- IPSec uses a variety of cryptographic algorithm types
  - RFC4308 defines VPN cryptographic suites
    - VPN-A matches common corporate VPN security using 3DES & HMAC
    - **VPN-B has stronger security for new VPNs implementing IPsecv3 and IKEv2 using AES**
  - RFC4869 updated to RFC 6379 defines four cryptographic suites compatible with US NSA specs
    - Provide choices for ESP & IKE
    - AES-GCM, AES-CBC, HMAC-SHA, ECP, ECDSA
- … Ongoing / Evolving standardization (IETF): IPSec WG

IPSec cryptosuite (summary)

As defined for VPNs (RFC 4308)

IPSec w/ IKE v1 **IPSec w/ IKE v2,v3**

	VPN-A	VPN-B
ESP encryption	3DES-CBC	AES-CBC (128-bit key)
ESP integrity	HMAC-SHA1-96	AES-XCBC-MAC-96
IKE encryption	3DES-CBC	AES-CBC (128-bit key)
IKE PRF	HMAC-SHA1	AES-XCBC-PRF-128
IKE Integrity	HMAC-SHA1-96	AES-XCBC-MAC-96
IKE DH group	1024-bit MODP	2048-bit MODP

As defined for VPNs NSA suite (RFC 6379)

IPSec w/ NSA Security Level Suite B

	GCM-128	GCM-256	GMAC-128	GMAC-256
ESP encryption/ Integrity	AES-GCM (128-bit key)	AES-GCM (256-bit key)	Null	Null
ESP integrity	Null	Null	AES-GMAC (128-bit key)	AES-GMAC (256-bit key)
IKE encryption	AES-CBC (128-bit key)	AES-CBC (256-bit key)	AES-CBC (128-bit key)	AES-CBC (256-bit key)
IKE PRF	HMAC-SHA-256	HMAC-SHA-384	HMAC-SHA-256	HMAC-SHA-384
IKE Integrity	HMAC-SHA-256-128	HMAC-SHA-384-192	HMAC-SHA-256-128	HMAC-SHA-384-192
IKE DH group	256-bit random ECP	384-bit random ECP	256-bit random ECP	384-bit random ECP
IKE authentication	ECDSA-256	ECDSA-384	ECDSA-256	ECDSA-384

IPSec, ECC and more recent developments

- RFC 8031 *(was draft-ietf-ipsecme-safecurves)*
  - **Curve25519 and Curve448** for the Internet Key Exchange Protocol Version 2 (IKEv2) Key Agreement

- **Curve25519: public Keys w/ 256 bits**
  - Curve25519 is intended for the ~128-bit security level, comparable to the 256-bit random ECP Groups (group 19) defined in RFC 5903, also known as NIST P-256 or secp256r1. Curve448 is intended for the ~224-bit security level.
- **Curve448: public keys w/ 448 bits**

Curve25519 and Curve448 are designed to facilitate the production of high-performance constant-time implementations. Implementers are encouraged to use a constant-time implementation of the functions. This point is of crucial importance, especially if the implementation chooses to reuse its ephemeral key pair in many key exchanges for performance reasons.

IPSec Cryptosuites (Some Improvements)

RFC 8031 *(was draft-ietf-ipsecme-safecurves)*

- **Curve25519 and Curve448 for the Internet Key Exchange Protocol Version 2 (IKEv2) Key Agreement**

RFC 8019 *(was draft-ietf-ipsecme-ddos-protection)*

- **Protecting Internet Key Exchange Protocol Version 2 (IKEv2) Implementations from Distributed Denial-of-Service Attacks**

RFC 7619 *(was draft-ietf-ipsecme-ikev2-null-auth)*

- **The NULL Authentication Method in the Internet Key Exchange Protocol Version 2 (IKEv2)**

RFC 7427 *(was draft-kivinen-ipsecme-signature-auth)*

- **Signature Authentication in the Internet Key Exchange Version 2 (IKEv2)**

RFC 7321 *(was draft-ietf-ipsecme-esp-ah-reqts)*

- **Cryptographic Algorithm Implementation Requirements and Usage Guidance for Encapsulating Security Payload (ESP) and Authentication Header (AH)**

RFC 6989 *(was draft-ietf-ipsecme-dh-checks)*

- **Additional Diffie-Hellman Tests for the Internet Key Exchange Protocol Version 2 (IKEv2)**

Cryptosuite updates: RFCs 4308 to 7321

- ESP Authenticated Encryption (Combined Mode Algorithms)
  - **SHOULD+** AES-GCM with a 16 octet ICV [RFC4106]
  - MAY AES-CCM [RFC4309]

- ESP Encryption Algorithms
  - **MUST** NULL [RFC2410]
  - **MUST** AES-CBC [RFC3602]
  - MAY AES-CTR [RFC3686]
  - MAY TripleDES-CBC [RFC2451]
  - **MUST NOT** DES-CBC [RFC2405]

Cryptosuite updates: RFCs 4308 to 7321

- ESP Authentication
  - **MUST** HMAC-SHA1-96 [RFC2404]
  - **SHOULD+** AES-GMAC with AES-128 [RFC4543]
  - **SHOULD** AES-XCBC-MAC-96 [RFC3566]
  - MAY NULL [RFC4303]

Authentication for IKE v2 (RFC 7427)

- Hash Algorithm
  - SHA1
  - SHA2-256
  - SHA2-384
  - SHA2-512
- Digital Signatures:
  - PKCS#1 1.5 RSA
  - SHA1, SHA2-256, SHA2-384, SHA2-512 WithRSAEncryption
  - DSA with SHA1 and SHA2-256
  - ECDSA with SHA1, SHA2-256, SHA2-384, SHA2-512
  - RSASSA-PSS
  - RSASSA-PSS and SHA-256
- Keysizes: Standardization conservative: in general the statement is the recommendation to be aware of "transitions" in keysizes, according to PKI management recommendations (currently transition > 2048 bits)

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IPSec Key Management

- Handles key generation & distribution
  - SA establishment process
- Typically need 2 pairs of keys
  - 2 per direction for AH (1 key) and ESP (1 key)

- **Manual key management**
  - Sysadmin manually configures every system
    - Setup (different admin facilities in different systems) for SAs establishment and SP Enforcements

- Automated key management
  - Dynamic (on-demand) establishment of SAs and SPs

History of IKE

- Early contenders (in the IKE standardization origin):
  - Photuris: Authenticated DH with cookies & Identity Hiding
  - SKIP: Auth. DH with long-term exponents
- **ISAKMP**:
  - A protocol specifying only payload formats & exchanges (i.e., an empty protocol)
  - Adopted by the IPsec working group

Photuris and Oakley: a Modified Photuris;
  - Designed to work on ISAKMP
- **IKE: A particular (evolved) Oakley/ISAKMP combination**
- **Evolution: from IKE v.1 to IKE v2.0**

Supplementary Materials

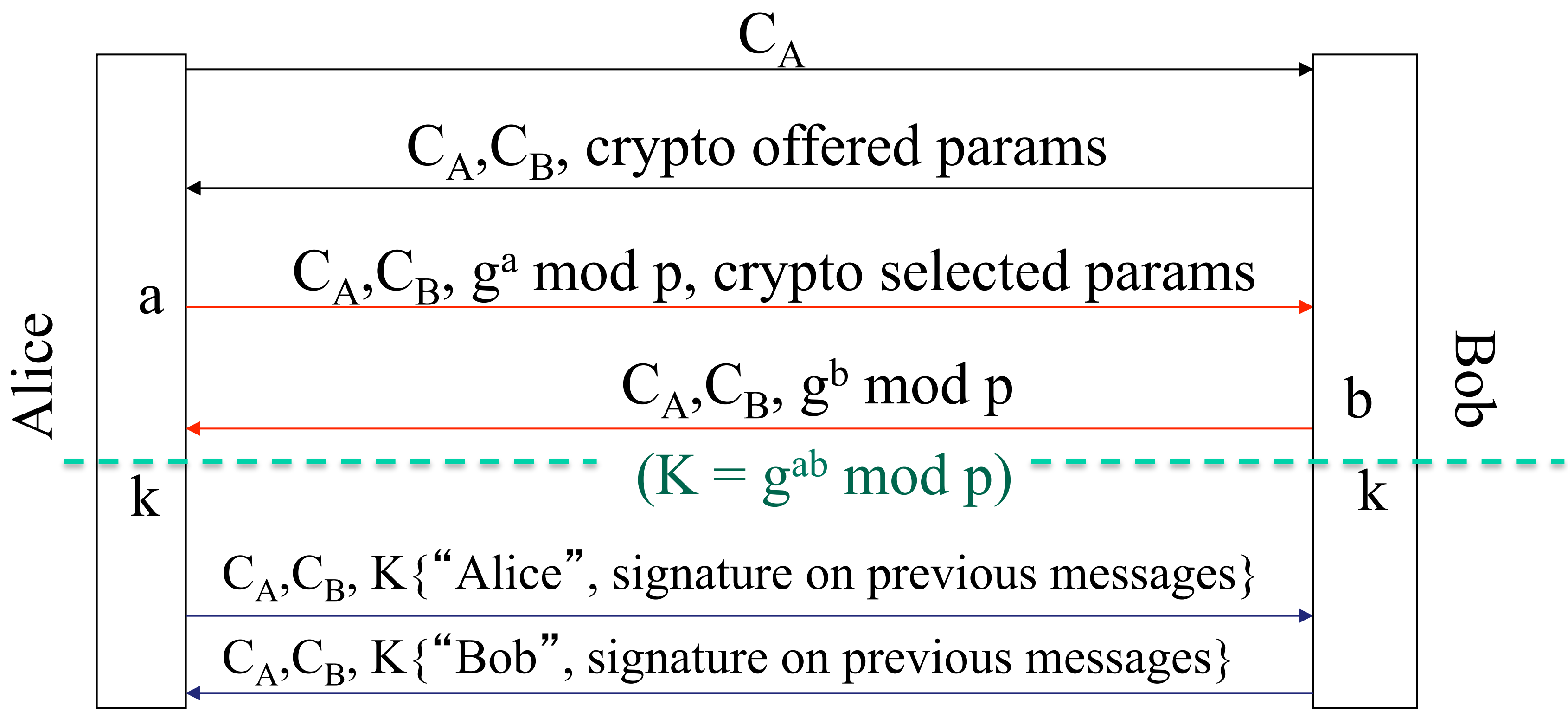
- IKEv1 and IKEv1/ISAMP
- Phitouris and Oakley Schemes

Oakley Key Exchange Protocol

- Based on Diffie-Hellman key exchange
- Adds features to address weaknesses
  - No info on parties, man-in-middle attack, cost
  - Adds cookies, groups (global params), nonces, and DH key exchange with authentication

- Can use ECC (defined curves) for ECDSA agreements

Photuris Model based on DH Key establishment



C_A: Alice's cookie; for connection ID

C_B: Bob's cookie; against DoS

Signed Agreement: ex., ECCDSA

Fast Authentication w/ HMACs

Photuris - Features

- DoS protection by cookies
  (note: C_B can be stateless)
- Authentication & integrity protection of the messages by a combined signature at the last rounds
- Identity hiding from passive attackers (How?)

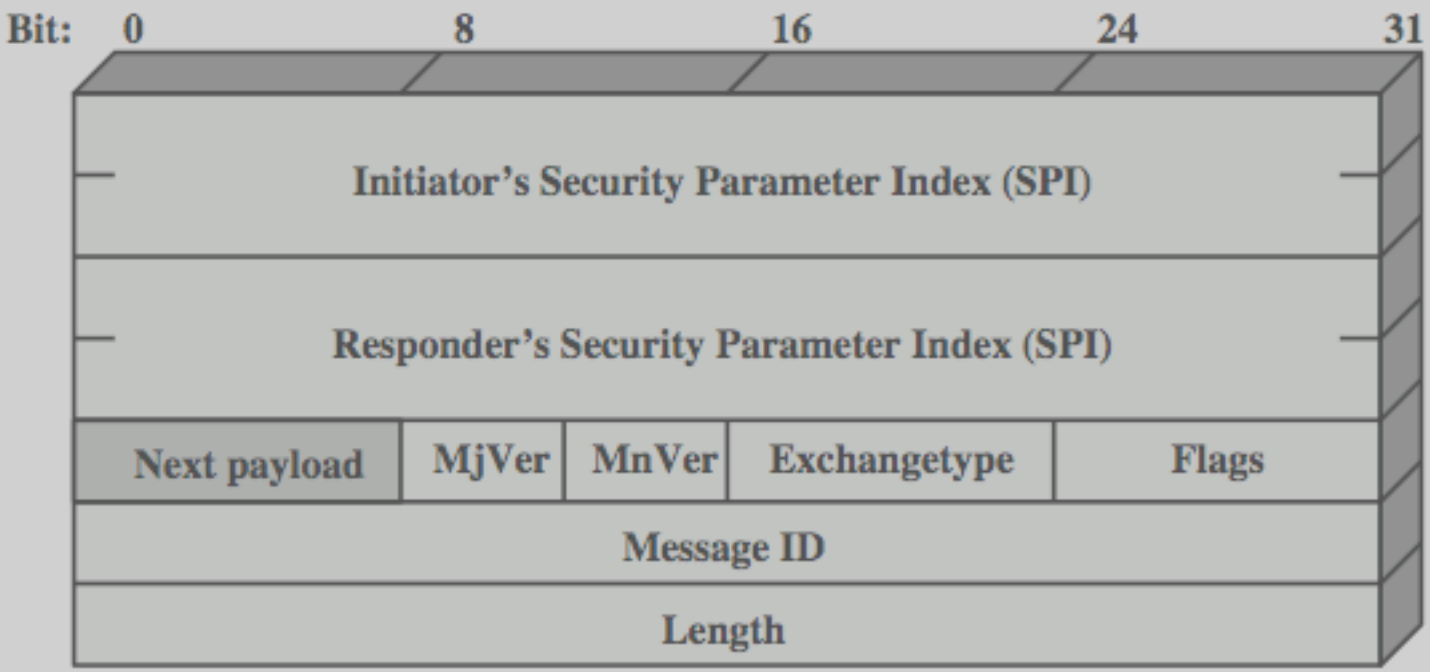
ISAKMP

Internet Security Association and Key Management Protocol

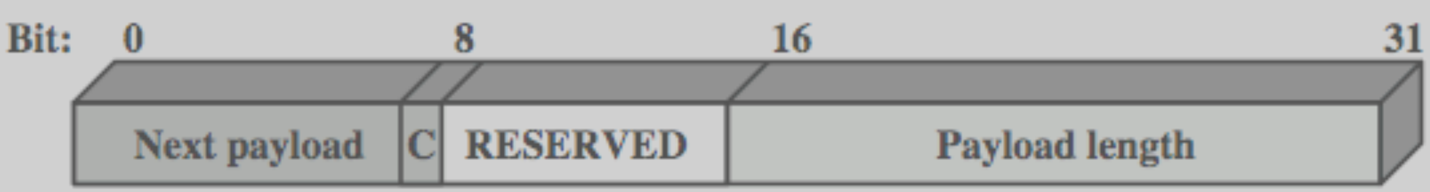
- Provides framework for key management
- Defines procedures and packet formats to establish, negotiate, modify, & delete Sas
- Independent of key exchange protocol, encryption alg, & authentication method

- **Used by IKEv1 (IKE v1/ISAKMP)**
- **IKEv2 no longer uses Oakley & ISAKMP terms … introduced simplifications and improvements ... but basic functionality is same**

ISAKMP message formats



(a) IKE Header



(b) Generic Payload Header

IKE(v1) /ISAKMP

- IKE v1 is now under a smooth deprecation process…

IKE(v1) /ISAKMP : Two Phases

Phase 1:

- does authenticated DH, establishes session key & "ISAKMP SA"
- two possible modes: Main & Aggressive
- two keys are derived from the session key:
  SKEYID_e: to encrypt Phase 2 messages
  SKEYID_a: to authenticate Phase 2 messages

Phase 2:

- IPsec SA & session key established; messages encrypted & authenticated with Phase 1 keys
- Additional DH exchange is optional (for PFS)

IKE v.1: Phase 1 Exchange

Two possible modes:

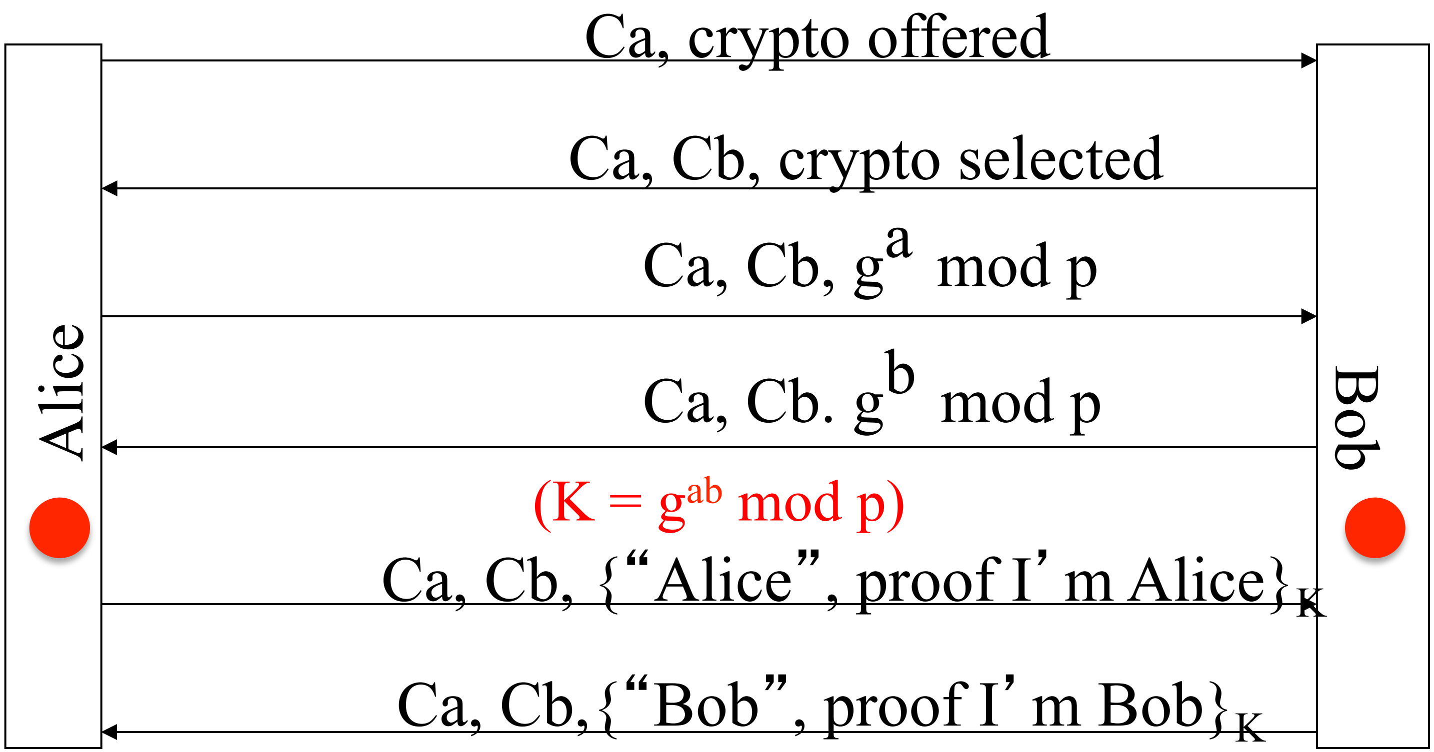
- **Main mode: 6 rounds; provides identity hiding**
- **Aggressive mode: 3 rounds**

Types of authentication:

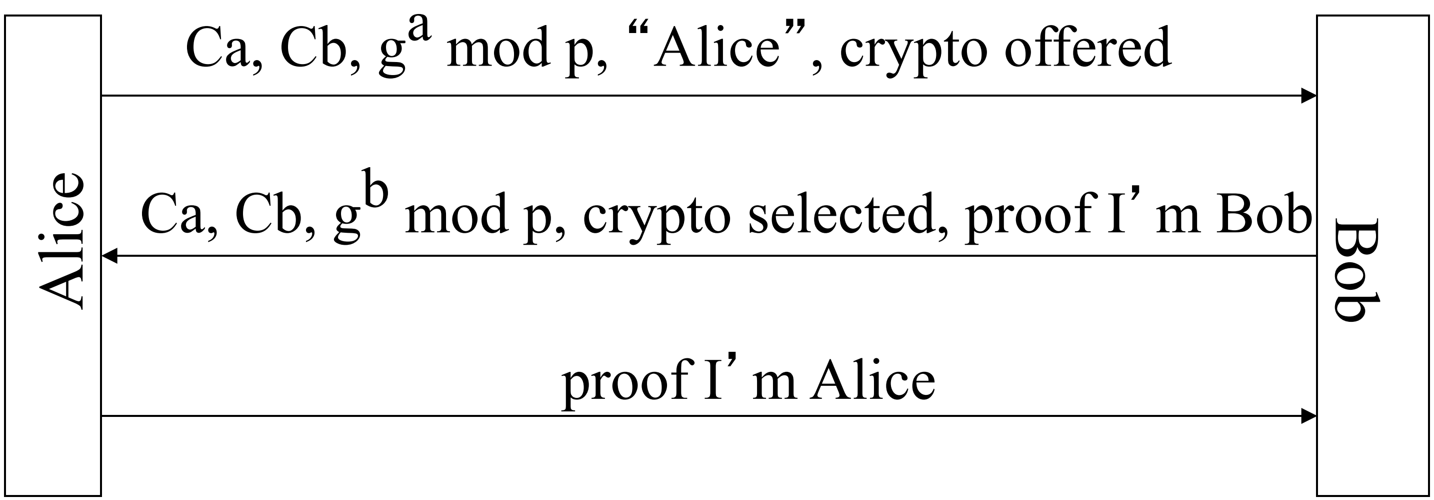
- MAC with pre-shared secret key
- digital signatures
- public key encryption
  - original: all public key encryption
  - revised: public + secret key encryption

(Each type has its benefits; but is it worth the complexity?)

IKE v.1: Phase 1 – Main Mode (generic)



IKE v.1 Phase 1 – Aggressive Mode (generic)



IKE v.1 : Phase 1 Issues & Problems

Crypto parameters:

Alice presents all algorithm combinations she can support (may be too many combinations)

Authentication:

- Certain fields (why not all?!) of the protocol messages are hashed & signed/encrypted in the final rounds
- Not included: Bob's accepted parameters (problematic)

Cookies & Statelessness:

- Cookie protection: similar to "Photuris cookies"
- Bob is no longer stateless (problematic) since "crypto offered" must be remembered from message 1.

IKE v.1: Phase 1 Issues (cont)

Session Keys:

- **2 session keys** (1 for enc. & 1 for auth.) are generated (from the initial established K).
- **So, there are 4 keys; 2 for each direction**

Complexity:

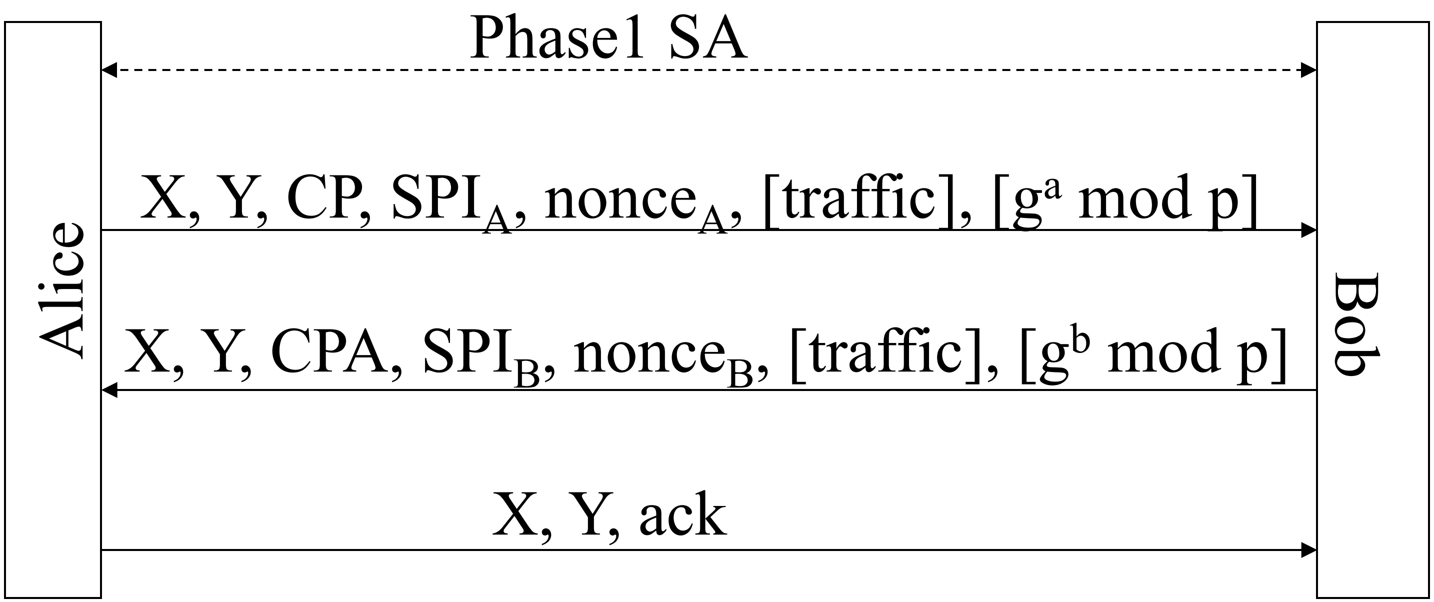
- 8 different protocols are defined
  - 2 modes
  - Each with 4 types of authentication methods

- **Regarded as unnecessarily flexible, lack of relevant issues and complex**

IKE v.1: Phase 2 Exchange

- Establishes IPsec SA & session key
- Runs over the IKE SA established in Phase 1. (message are encrypted/authenticated with Phase 1 keys)
- Key generation: based on Phase 1 key, SPI, nonces.
- DH exchange: Optional (for PFS).
- IPsec Traffic Selector: Established optionally. Specifies what traffic is acceptable. (e.g., What port numbers are allowed to use this SA.)

IKE v.1 : Phase 2



- X: pair of cookies generated in Phase 1
- Y: session identifier
- traffic: IPsec traffic selector (optional)

IKEv2 Protocol

Aims of

- Simplifying IKEv1
- Fixing some bugs (vulnerabilities)
- Fixing ambiguities
- While remaining as close to IKEv1 as possible. (… "no gratuitous changes")

IKEv2 History … (IETF standardization roadmap)

From 1998 (First IKE)
RFC 2409

5/2005	RFC 4109, IKE v1
12/2005	RFC 4306, IKE v2 (1st version)
08/2008	RFC 5282, IKE v2 : Auth. Enc. Algorithms w/ Encrypted Payload Basically: AES w/ GCM and AES w/CCM
09/2010	RFC 5996, IKE v2 (bis, revision of 1st version)
	RFC 5998, IKE v2 (bis): update for EAP-Only Authent. Flexibility/resuse of EAP Auth. Methods and configurable options
07/2013	RFC 6989, IKE v2 (bis) w/ Additional D-H Tests (DH Imp. Validations, ECCDSA Sign.)
10/2014	RFC 7296, IKE v2 (bis, obsolets 5996)

IKEv2 History ... (IETF standardization roadmap)

10/2014 RFC 7296, IKE v2 (bis, obsoletes 5996)

- ECCDSA – DH Param. Redifinitions, nd integration of EAP
- Update for ambiguity issues on verifications, error handling...
- Optimizing latency: 2 round trips (4 messages)
- Rekeying schemes w/ 1 round trips (2 messages)

→ HDR, SAi1, KEi, Ni

← HDR, SAr1, KEr, Nr, [CERTREQ]

→ HDR, SK {IDi, [CERT,] [CERTREQ,] [IDr,] AUTH, SAi2, TSi, TSr}

← HDR, SK {IDr, [CERT,] AUTH, SAr2, TSi, TSr}

IKEv2 History … (IETF standardization roadmap)

10/2014 RFC 7296, IKE v2 (bis, obsoletes 5996)
-)

01/2015 RFC 7427, IKE v2 (update of 7296)
Signature Authentication and clarifications
sha1 and sha2 (256,384,512) w/RSA and PKCS#1
DSA w/ sha1 and sha256
ECDSA w/ sha1, sha256, sha384 and sha512
RSASSA-PSS

01/2016 RFC 7670 (updates 7296)
Use of other RAW PK types
(not only DER encodings, as PKCS#1)
due to the need of interpretation of the
SubjectPublicKeyInfo in X509v3 (RFC 5280)
- New Cerificate encoding formats
- Ambiguity/Lack of suport: IDs vs. related Public keys

IKEV2 Exchanges

- Different exchanges are defined for flexibility
  - Addressing security and performance tradeoffs
  - Interesting to automatic setup in different SAs, different iterated or adjacent combinations and different modes for each specific purposes

IKEv2 - Main Features

- Only one mode of authentication: Public key signatures based on X509 Certificates

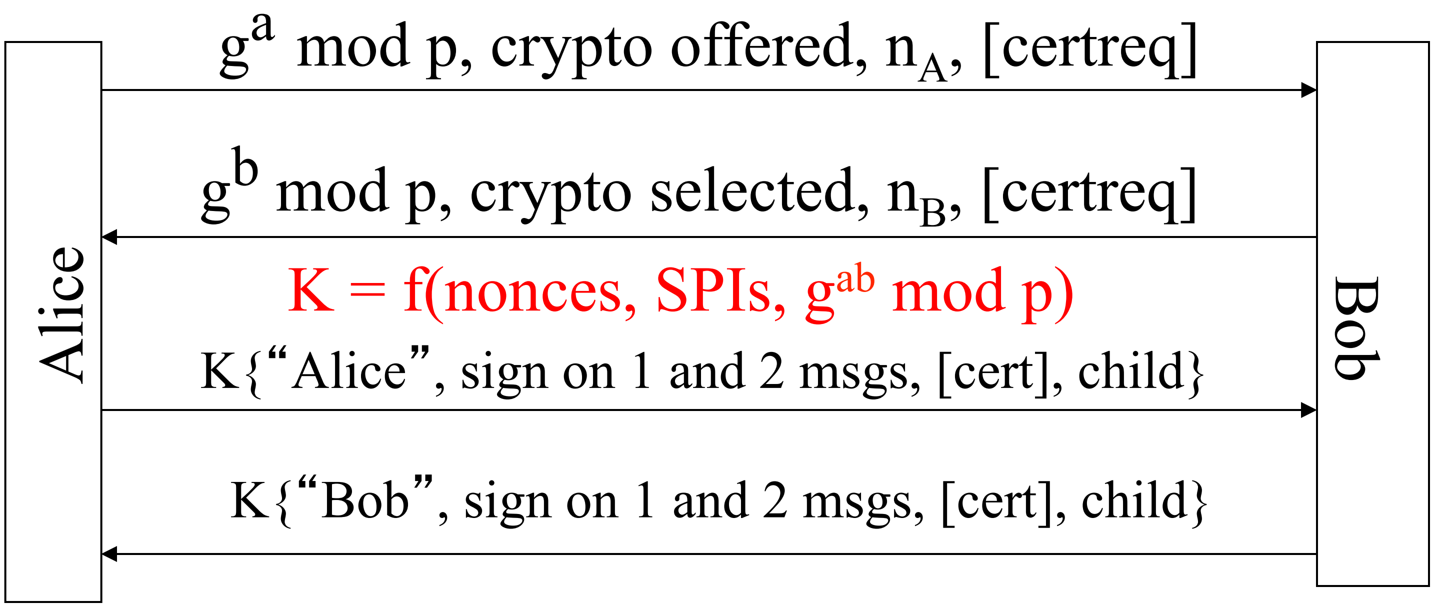
- Three possible runs
  - **Initial**: IKE SA + IPsec SA are established in the same protocol, in 4 messages. (~ Phase 1)
  - **Child-SA-Exchanges**: Additional child SAs, if needed, are established in 2 messages. (~ Phase 2)
  - **Informational Exchanges**

- DoS protection optional, via cookies (stateless).
- Crypto negotiation is simplified
  - Support for well defined / standardized "cryptosuites"
  - Ability to say "any of these enc., with any of these hash..."

IKEv2 - The Exchange Protocol (cont)

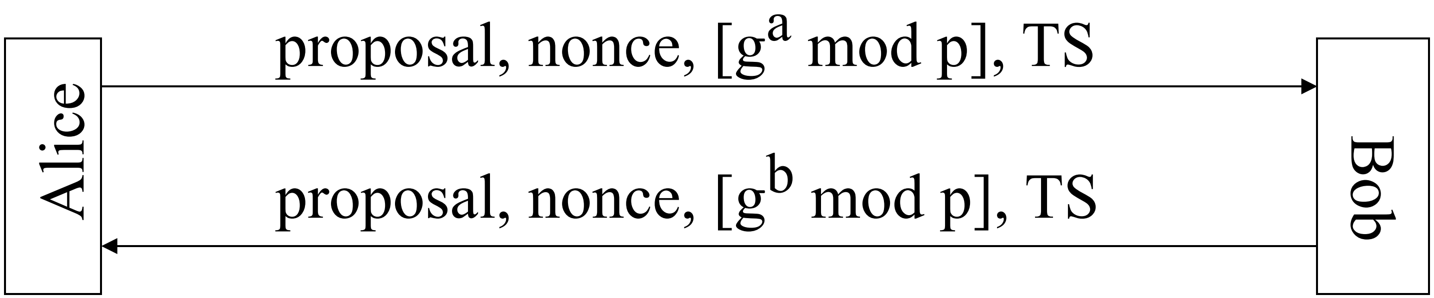
- DoS protection: Optional; by Bob responding the first message with a (stateless) cookie.
- Originally, designed with 3 rounds. Later 4 rounds is agreed on:
  - Initiator needs a 4th message anyway to know when to start the transmission.
  - Extra msgs for cookie exchange can be incorporated into 4 msgs, if Alice repeats msg.1 info in msg.3
- Preserves identity hiding from passive attackers.

IKEv2 - The base exchange protocol



- Bob can optionally refuse the first message and require return of a cookie.
- Adds extra 2 messages.

IKEv2 - Child SA Creation



- Proposal: crypto suites, SPI, protocol (ESP, AH, IP compression)
- TS: Traffic selector
- Derived keys: Function of IKE keying material, nonces of this exchange, plus optional DH output.

IKEv2 complete exhange

Initiator → Responder

HDR, SAi1, KEi, Ni →

← HDR, SAr1, KEr, Nr, [CERTREQ]

HDR, SK {IDi, [CERT,] [CERTREQ,] [IDr,] AUTH, SAi2, TSi, TSr} →

← HDR, SK {IDr, [CERT,] AUTH, SAr2, TSi, TSr}

(a) Initial exchanges

HDR, SK {[N], SA, Ni, [KEi], [TSi, TSr]} →

← HDR, SK {SA, Nr, [KEr], [TSi, TSr]}

(b) `CREATE_CHILD_SA` exchange

HDR, SK {[N,] [D,] [CP,] ...} →

← HDR, SK {[N,] [D,] [CP], ...}

(c) Informational exchange

HDR = IKE header
SAx1 = offered and chosen algorithms, DH group
KEx = Diffie-Hellman public key
Nx= nonces
CERTREQ = Certificate request
IDx = identity
CERT = certificate
SK {...} = MAC and encrypt
AUTH = Authentication
SAx2 = algorithms, parameters for IPsec SA
TSx = traffic selectors for IPsec SA
N = Notify
D = Delete
CP = Configuration

Other IKEv2 Features

Reliability:

- All messages are request/response.
- Initiator is responsible for retransmission if it doesn't receive a response.

Traffic selector negotiation:

- In IKEv1: Responder can just say yes/no.
- In IKEv2: Negotiation ability added.

Rekeying:

- Either side can rekey at any time.
- Rekeyed IKE-SA inherits all the child-SAs.

Revision: Suggested Readings and Study

Readings:

W. Stallings, Network Security Essentials – Applications and Standards

- Ed.. 2011 Chap 8 IP Security, 9.1 to 9.6, pp. 302 to 335
- Ed.. 2017 Chap 9 IP Security, 9.1 to 9.6, pp. 302 to 335