INFS 766
Internet Security Protocols

Lectures 7 and 8
IPSEC

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IPSEC ROADMAP

- **Security Association**
- **IP AH (Authentication Header) Protocol**
- **IP ESP (Encapsulating Security Protocol)**
- **Authentication Algorithm**
- **Encryption Algorithm**
- **IKE (Key Exchange)**
- **[IP Compression Protocol and Algorithms]**

SECURITY DEPENDS UPON

- **secure protocols but also much more**
  - **cryptographic strength**
  - **implementation quality**
  - **good random number sources**
  - **end system security**
  - **system management**
  - **……………..**

IPSEC TRAFFIC PROTOCOLS

- **security extensions for IPv4 and IPv6**
- **IP Authentication Header (AH)**
  - **authentication and integrity of payload and header**
- **IP Encapsulating Security Protocol (ESP)**
  - **confidentiality of payload**
- **ESP with optional ICV (integrity check value)**
  - **confidentiality, authentication and integrity of payload**

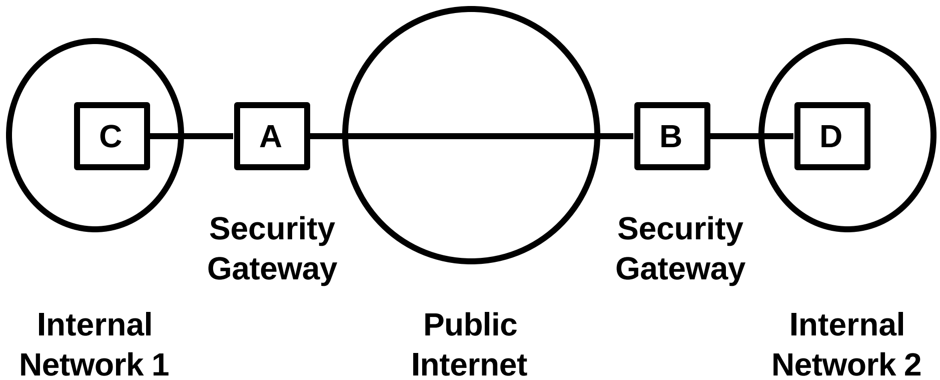
IPSEC TRAFFIC PROTOCOLS

- **security services**
  - **authentication and integrity**
  - **confidentiality**
  - **replay prevention**
  - **partial traffic flow confidentiality**
  - **compression**
- **algorithm-independent with standard defaults**
- **secret-key technology**

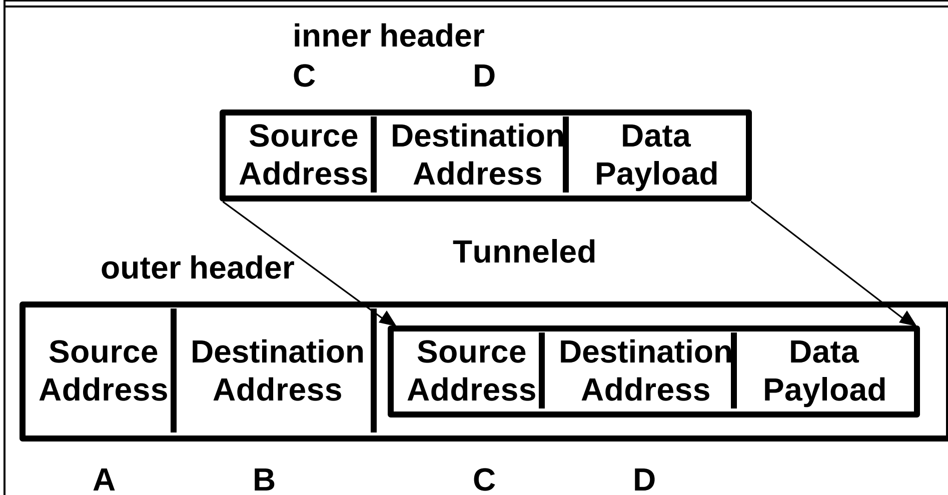
IPSEC TRAFFIC PROTOCOLS

- **both IP AH and IP ESP can operate in**
  - **transport mode**
    - **end-to-end**
  - **tunnel mode**
    - **security-gateway to security-gateway**
- **transport mode and tunnel model can coexist**

IP TUNNELING



IP TUNNELING



IPSEC
SECURITY ASSOCIATION (SA)

- SA is a one-directional relationship between sender and receiver
- SA applies to AH or ESP but not both
- two-way secure exchange of IP packets requires two (or more) SAs
- unicast (multicast will come later)
- SAs are established by
  - management protocols (IKE)
  - manually

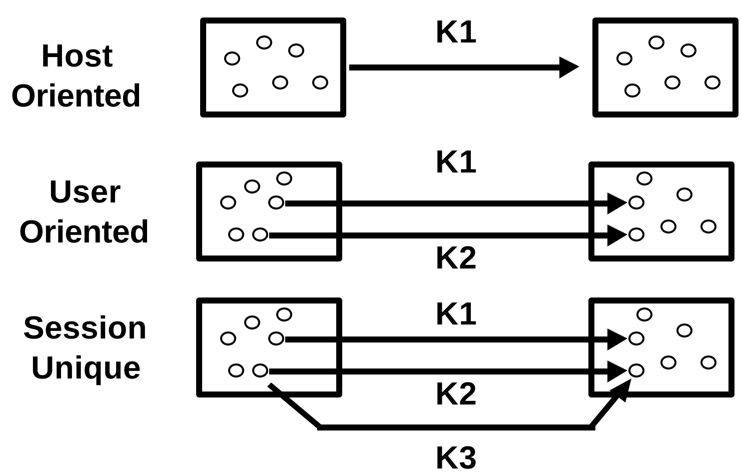
IPSEC
SECURITY ASSOCIATION (SA)

- referenced by a 32 bit security parameter index (SPI) carried in each IPSEC packet
- SA for an IP packet is uniquely identified by
  - SPI
  - destination address
  - security protocol (AH or ESP)

IPSEC
SECURITY ASSOCIATION (SA)

- **sequence number counter: 32 bit**
- **overflow flag: indicating abort or not on overflow**
- **anti-replay window**
- **AH information: algorithm, key, key lifetime**
- **ESP information:**
  - **encryption: algorithm, key, key lifetime**
  - **authentication: algorithm, key, key lifetime**
- **lifetime of SA**
- **IPSEC protocol mode: transport, tunnel, wildcard**
- **path MTU (maximum transmission unit)**

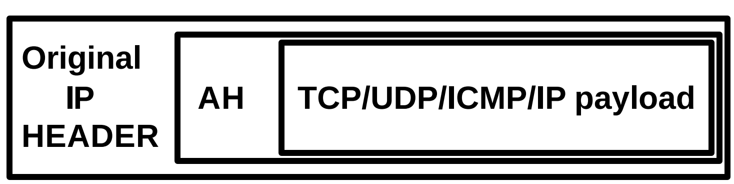
IPSEC
KEYING (SA) GRANULARITY



IP AUTHENTICATION HEADER

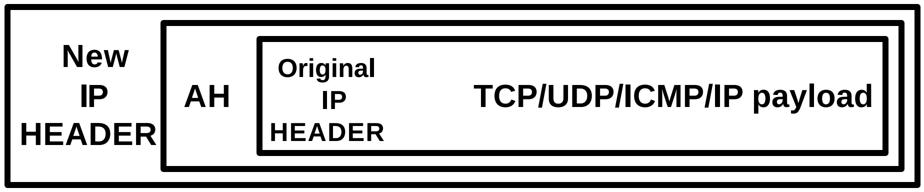
- IPv4 and IPv6 packets
  - data origin authentication
  - data integrity
  - replay prevention (optional as per SA)
- MAC on IP packet header and data payload
- IP header fields that change hop-by-hop set to 0 for MAC computation

IP AH TRANSPORT MODE



- protocol field of IP header is 51 (for AH payload)
- AH in turn contains protocol field specifying protocol of actual payload, e.g., TCP or UDP or ICMP or IP

IP AH TUNNEL MODE



- IP AH is a single protocol
- transport or tunnel mode is determined by SA
  - actually SA can allow both

IP AUTHENTICATION HEADER FIELDS

- next header: 8 bit protocol field
- length: 8 bit field specifying length of authentication data in 32 bit words
- unused: 16 bit set to 0
- SPI: 32 bit
- sequence number: 32 bit
- integrity check value (ICV): some multiple of 32 bits, e.g., 96, 128, 160
  - must support HMAC-MD5-96, HMAC-SHA-1-96

IP AUTHENTICATION HEADER

- **prevents IP spoofing attacks**
  - **at performance cost**
- **prevents replay attacks**
  - **sequence number added in revision**
- **can be widely and strongly deployed without concern of crypto-politics**

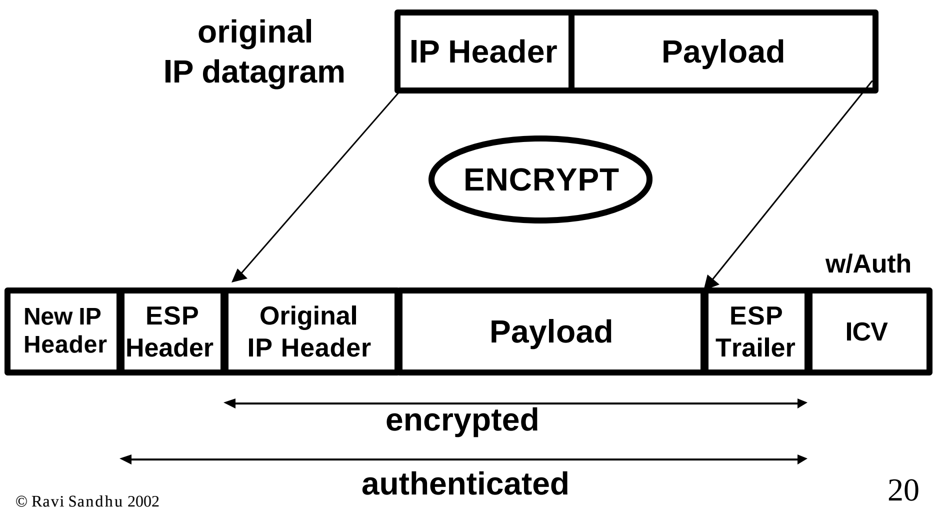
ANTI-REPLAY MECHANISM

- **Sequence number starts at 1 and cannot go past 2^{32}-1**
- **receiver keeps a window of min size 32 (64 preferred, larger is ok)**
  - **packets to left of window are discarded**
  - **repeated packets within window are discarded**
  - **authentic packets to right of window cause window to move right**

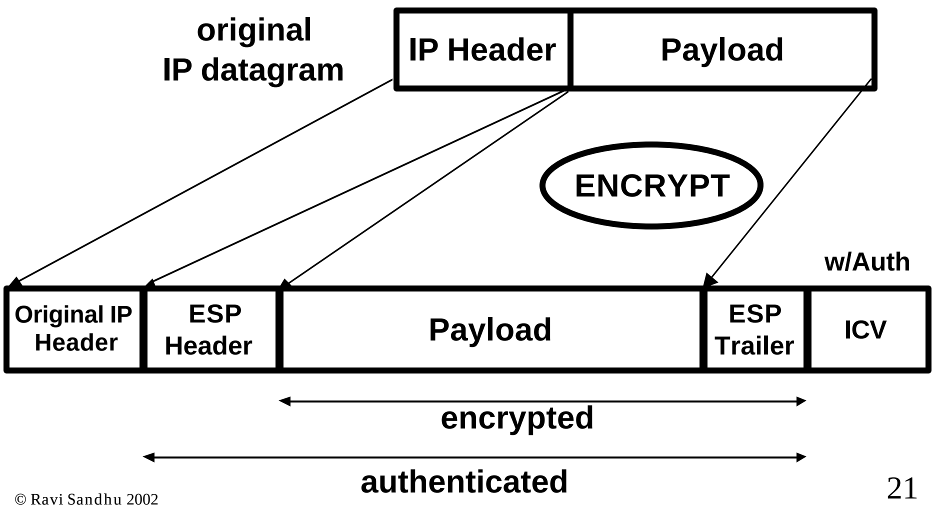
IP ENCAPSULATING SECURITY PAYLOAD (ESP)

- IPv4 and IPv6
  - ESP: data confidentiality
  - ESP w/Auth: data confidentiality, authentication, integrity
  - ESP w/Auth is an option within ESP
- ESP header (cleartext)
  - security parameter index (SPI)
  - sequence number: 32 bit
  - Initial Value for CBC
- ESP trailer (encrypted)
  - padding
  - next header (identifies payload protocol)
- ESP w/Auth authentication
  - ICV: for authentication option
  - applies only to encrypted payload and not to header

ESP TUNNELING MODE



ESP TRANSPORT MODE

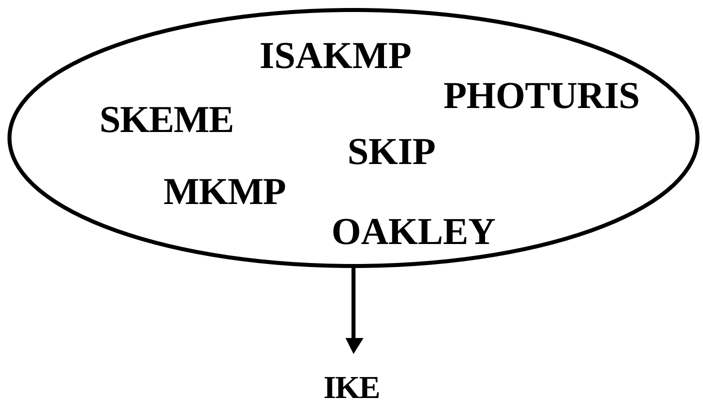


ESP

- **protocol 50**
  - **ESP w/Auth determined by SA**
- **ESP header**
  - **SPI, IV in cleartext**
- **ESP trailer**
  - **padding info, payload protocol is encrypted**
- **tunnel mode provides partial traffic flow confidentiality**

INTERNET KEY EXCHANGE (IKE)

- Hybrid protocol



ISAKMP

- Internet security association and key management protocol
- separates key management from key exchanges
- complex general protocol used in a specific way in IKE
  - can apply to protocols other than IPSEC
- for IPSEC uses UDP over IP

IKE

- ISAKMP phase 1: establishes ISAKMP SA
  - Main mode (DH with identity protection)
  - Aggressive mode (DH without identity protection)
- Between phases
  - New group mode
- ISAKMP phase 2: establishes SA for target protocol
  - Quick mode

DIFFIE-HELLMAN KEY ESTABLISHMENT

A $y_A=a^{x_A} \bmod p$ public key

$y_B=a^{x_B} \bmod p$ public key **B**

private key x_A

private key x_B

$$k = y_B^{x_A} \bmod p = y_A^{x_B} \bmod p = a^{x_A * x_B} \bmod p$$

system constants: p: prime number, a: integer

PERFECT FORWARD SECRECY

- **Use a different DH key-pair on each exchange**
- **DH public keys need to be authenticated**
  - **authentication can be done by many techniques**
- **Loss of long-term (authentication) keys does not disclose session keys**

PHASE 1 AUTHENTICATION ALTERNATIVES

- **public-key signature**
- **preshared-key**
- **public-key encryption**
- **revised public-key encryption**

COOKIE EXCHANGE

- **Phase 1 employs cookie exchange to thwart (not prevent) denial of service attacks**
- **A -> B: Cookie_Request**
  - **A's cookie, 64 bit random number**
- **B -> A: Cookie_Response**
  - **includes A and B's cookies**
- **all further Phase 1 and Phase 2 messages include both cookies**
  - **ISAKMP SA is identified by both cookies**
  - **IPSEC protocol SA is identified by SPI**

COOKIE GENERATION

- **hash over**
  - **IP Source and Destination Address**
  - **UDP Source and Destination Ports**
  - **a locally generated random secret**
  - **timestamp**

IKE DEFAULT OAKLEY DH GROUPS

- Group 1
  - MODP, 768 bit prime p, g=2
- Group 2
  - MODP, 1024 bit prime p, g=2
- Group 3
  - EC2N, 155 bit field size
- Group 4
  - EC2N, 185 bit field size
- private groups can be used

IKE NOTATION

HDR	ISAKMP header whose exchange type is the mode
HDR*	indicates payload encryption
SA	SA negotiation payload, initiator MAY provide multiple proposals, responder replies with one
<P>_b	body of payload <P>
SAi_b	body of the SA payload (minus generic headers)
CKY-I	Initiator's cookie
CKY-R	Responder's cookie
g^xi	initiator’s DH public value
g^xr	responder’s DH public value
g^xy	Diffie-Hellman shared secret
KE	key exchange containing DH public values
Ni	initiator nonce
Nr	responder nonce
Idii	identification payload for ISAKMP initiator
Idir	identification payload for ISAKMP responder
SIG	signature payload, data signed varies
CERT	certificate payload
HASH	hash payload

IKE NOTATION

```
prf(key, msg) keyed pseudo-random function (often MAC)

SKEYID    string derived from secret material known only to the active
          players in the exchange
SKEYID_e  keying material used by the ISAKMP SA to protect confidentiality
          of its messages.
SKEYID_a  keying material used by the ISAKMP SA to protect authentication
          of its messages.
SKEYID_d  keying material used to derive keys for non-ISAKMP SAs


<x>y      "x" is encrypted with the key "y"

-->       initiator to responder
<--       responder to initiator

|         concatenation of information
[x]       indicates that x is optional
```


SKEYS, HASH AND SIG

```
SKEYID_d = prf(SKEYID, g^xy | CKY-I | CKY-R | 0)
SKEYID_a = prf(SKEYID, SKEYID_d | g^xy | CKY-I | CKY-R | 1)
SKEYID_e = prf(SKEYID, SKEYID_a | g^xy | CKY-I | CKY-R | 2)
```

```
HASH_I = prf(SKEYID, g^xi | g^xr | CKY-I | CKY-R | SAi_b | IDii_b )
HASH_R = prf(SKEYID, g^xr | g^xi | CKY-R | CKY-I | SAi_b | IDir_b )
```

HASH_I and HASH_R used directly for MAC authentication OR
digitally signed by SIG_I and SIG_R

MAIN MODE WITH DIGITAL SIGNATURES

```
 Initiator                             Responder
-----------                           -----------
 HDR, SA                      -->
                              <--      HDR, SA
 HDR, KE, Ni                  -->
                              <--      HDR, KE, Nr
 HDR*, IDii, [ CERT, ] SIG_I -->
                              <--      HDR*, IDir, [ CERT, ] SIG_R
```

```
SKEYID   = prf(Ni_b | Nr_b, g^xy)
```


AGGRESSIVE MODE WITH DIGITAL SIGNATURES

```
 Initiator                             Responder
-----------                           -----------
 HDR, SA, KE, Ni, IDii        -->
                              <--      HDR, SA, KE, Nr, IDir,
                                            [ CERT, ] SIG_R
 HDR, [ CERT, ] SIG_I         -->
```

```
SKEYID   = prf(Ni_b | Nr_b, g^xy)
```

MAIN AND AGGRESSIVE MODE WITH PRE-SHARED KEY

```
MAIN MODE
Initiator                              Responder
----------                            -----------
HDR, SA                 -->
                        <--     HDR, SA
HDR, KE, Ni             -->
                        <--     HDR, KE, Nr
HDR*, IDii, HASH_I      -->
                        <--     HDR*, IDir, HASH_R

AGGRESSIVE MODE
Initiator                              Responder
-----------                           -----------
HDR, SA, KE, Ni, IDii -->
                      <--     HDR, SA, KE, Nr, IDir, HASH_R
HDR, HASH_I           -->
```

SKEYID = prf(pre-shared-key, Ni_b | Nr_b)

MAIN MODE WITH PUBLIC KEY ENCRYPTION

```
Initiator                               Responder
-----------                             -----------
HDR, SA                      -->
                             <--     HDR, SA
HDR, KE, [ HASH(1), ]
  <IDii_b>PubKey_r,
    <Ni_b>PubKey_r           -->
                                     HDR, KE, <IDir_b>PubKey_i,
                             <--             <Nr_b>PubKey_i
HDR*, HASH_I                 -->
                             <--     HDR*, HASH_R
```

HASH(1) is hash of responder’s certificate

SKEYID = prf(hash(Ni_b | Nr_b), CKY-I | CKY-R)

AGGRESSIVE MODE WITH PUBLIC KEY ENCRYPTION

```
Initiator                                Responder
-----------                              -----------
HDR, SA, [ HASH(1),] KE,
  <IDii_b>Pubkey_r,
   <Ni_b>Pubkey_r          -->
                                         HDR, SA, KE, <IDir_b>PubKey_i,
                           <--                <Nr_b>PubKey_i, HASH_R
HDR, HASH_I                -->
```

Provides identity protection

HASH(1) is hash of responder’s certificate

SKEYID = prf(hash(Ni_b | Nr_b), CKY-I | CKY-R)

AUTHENTICATION WITH PUBLIC-KEY ENCRYPTION

- **does not provide non-repudiation**
- **provides additional security since attacked must break both**
  - **DH key exchange**
  - **public-key encryption**
- **provides identity protection in aggressive mode**
- **revised protocol reduces public-key operations**

MAIN MODE WITH REVISED PUBLIC KEY ENCRYPTION

```
 Initiator                              Responder
-----------                            -----------
 HDR, SA                        -->
                                <--     HDR, SA
 HDR, [ HASH(1), ]
   <Ni_b>Pubkey_r,
   <KE_b>Ke_i,
   <IDii_b>Ke_i,
   [<Cert-I_b>Ke_i]           -->
                                        HDR, <Nr_b>PubKey_i,
                                             <KE_b>Ke_r,
                                <--          <IDir_b>Ke_r,
 HDR*, HASH_I                   -->
                                <--     HDR*, HASH_R
```


MAIN MODE WITH REVISED PUBLIC KEY ENCRYPTION

```
Ne_i = prf(Ni_b, CKY-I)
Ne_r = prf(Nr_b, CKY-R)
```

```
Ke_i is leftomost 320 bits of K1 | K2 | K3 where
K1 = prf(Ne_i, 0)
K2 = prf(Ne_i, K1)
K3 = prf(Ne_i, K2)

Similarly for Ke_r
```

AGGRESSIVE MODE WITH REVISED PUBLIC KEY ENCRYPTION

```
 Initiator                          Responder
-----------                        -----------
 HDR, SA, [ HASH(1),]
   <Ni_b>Pubkey_r,
   <KE_b>Ke_i, <IDii_b>Ke_i
   [, <Cert-I_b>Ke_i ]     -->
                                    HDR, SA, <Nr_b>PubKey_i,
                                         <KE_b>Ke_r, <IDir_b>Ke_r,
                           <--           HASH_R
 HDR, HASH_I               -->
```


PHASE 2 QUICK MODE

```
 Initiator                          Responder
-----------                        -----------
 HDR*, HASH(1), SA, Ni
   [, KE ] [, IDci, IDcr ] -->
                           <--     HDR*, HASH(2), SA, Nr
                                         [, KE ] [, IDci, IDcr ]
 HDR*, HASH(3)             -->
```

```
HASH(1) = prf(SKEYID_a, M-ID | SA | Ni [ | KE ] [ | IDci | IDcr ])
HASH(2) = prf(SKEYID_a, M-ID | Ni_b | SA | Nr [ | KE ] [ | IDci | Idcr ] )
HASH(3) = prf(SKEYID_a, 0 | M-ID | Ni_b | Nr_b)
```

PHASE 2 QUICK MODE

```
If no PFS there is no KE payload and new keying material is

    KEYMAT = prf(SKEYID_d, protocol | SPI | Ni_b | Nr_b).

If PFS there is KE payload and new keying material is

    KEYMAT = prf(SKEYID_d, g(qm)^xy | protocol | SPI | Ni_b | Nr_b)

where g(qm)^xy is the shared secret from the ephemeral DH
exchange of this Quick Mode (which must then be deleted)

In either case, "protocol" and "SPI" are from the ISAKMP Proposal
Payload that contained the negotiated Transform.
```

Two SAs are established
- One in each direction
- Keys are different because of different SPIs

PHASE 2 QUICK MODE

```
Additional key material can be generated if needed as follows

    KEYMAT = K1 | K2 | K3 | ...
     where
       K1 = prf(SKEYID_d, [ g(qm)^xy | ] protocol | SPI | Ni_b | Nr_b)
       K2 = prf(SKEYID_d, K1 | [ g(qm)^xy | ] protocol | SPI | Ni_b | Nr_b)
       K3 = prf(SKEYID_d, K2 | [ g(qm)^xy | ] protocol | SPI | Ni_b | Nr_b)
       etc.
```

PHASE 2 QUICK MODE

```
Multiple SA's and keys can be negotiated with one exchange as follows:

     Initiator                        Responder
    -----------                      -----------
     HDR*, HASH(1), SA0, SA1, Ni,
       [, KE ] [, IDci, IDcr ] -->
                              <--    HDR*, HASH(2), SA0, SA1, Nr,
                                        [, KE ] [, IDci, IDcr ]
     HDR*, HASH(3)             -->

Results in 4 security associations-- 2 each way for both SA0 and SA1
```


NEW GROUP MODE

- sandwiched between phase 1 and 2
- group can be negotiated in phase 1
- new group mode allows nature of group to be hidden
  - in phase 1 only group id is communicated in clear

NEW GROUP MODE

```
 Initiator                           Responder
-----------                         -----------
 HDR*, HASH(1), SA         -->
                           <--       HDR*, HASH(2), SA
```

```
HASH(1) = prf(SKEYID_a, M-ID | SA)
HASH(2) = prf(SKEYID_a, M-ID | SA)
```


VIRTUAL PRIVATE NETWORKS

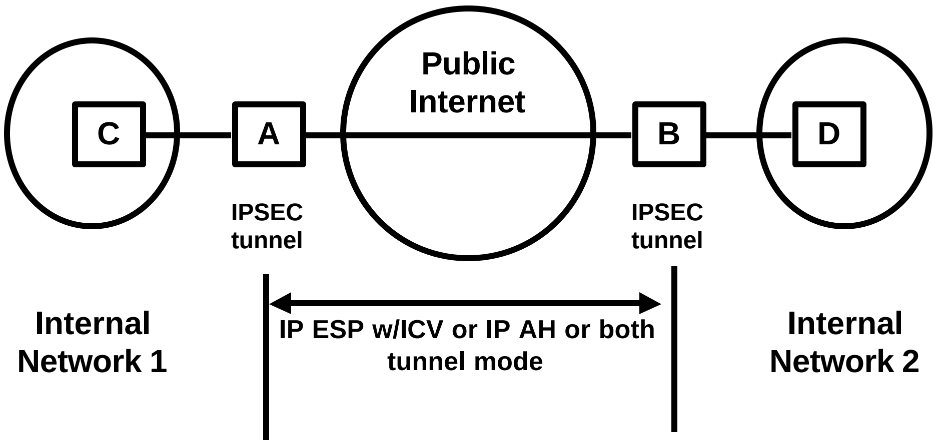
VPNs

- VPNs are used to securely connect networks using tunnels (virtual circuits) over the Internet
- Secure remote access is used to securely connect a single computer using tunnels (virtual circuits) over the Internet

VPN TECHNOLOGIES

- IPSEC
  - layer 3 VPN (standards based), layer 2 VPN (proprietary)
- PPTP (Point-to-point tunneling protocol)
  - Microsoft layer 2 VPN, built in security with known flaws
- L2F (layer 2 forwarding)
  - Cisco layer 2 VPN, no security, phasing out
- L2TP (layer 2 tunneling protocol)
  - emerging IETF standard, needs IPSEC security
- SSL (layer 4 tunnel)
  - proprietary approaches, tunnel IP over SSL-protected TCP

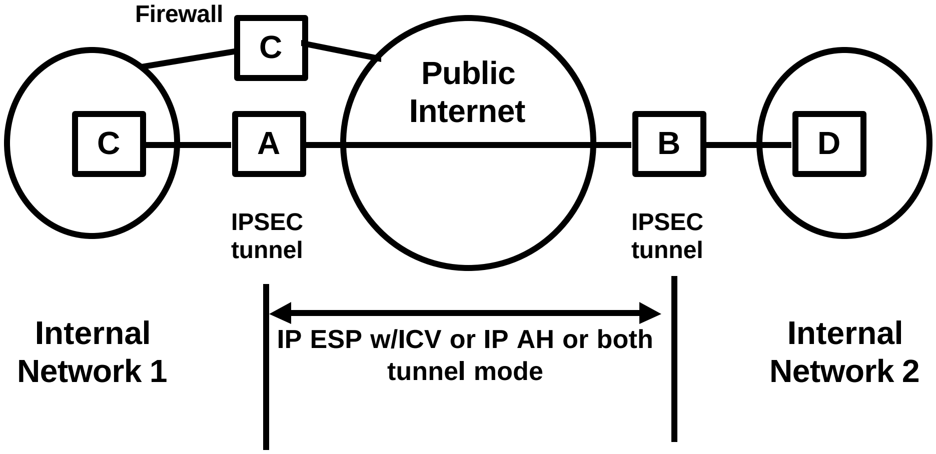
VIRTUAL PRIVATE NETWORKS



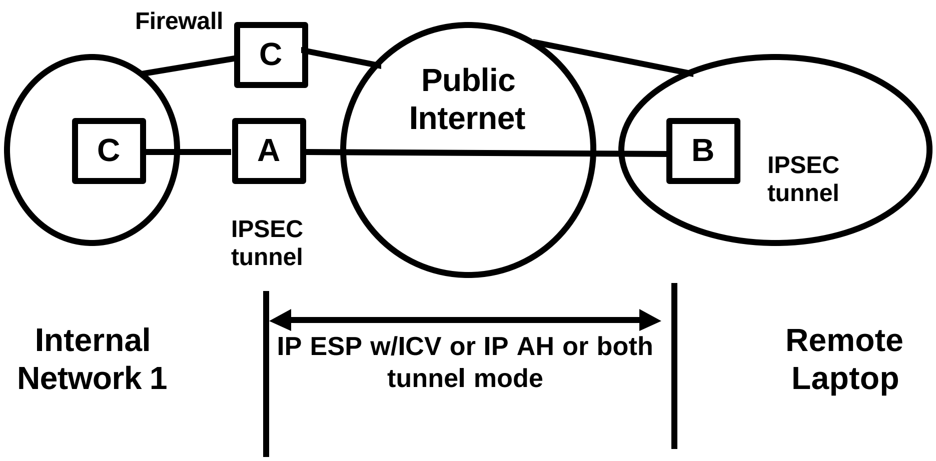
WHAT IS TUNNELED

- IPSEC tunnel can be used to tunnel
  - IP packets
    - IPSEC standard approach
  - layer 2 packets
    - virtual switched LAN (VSLAN)
    - proprietary approaches

VIRTUAL PRIVATE NETWORKS



SECURE REMOTE ACCESS



PPTP VPNs

- Originally intended for secure remote access
- enhancements for network to network VPNs
- known security flaws
  - remedied in version 2

PPTP VPNs

- Voluntary tunneling
  - PPTP tunnel from client to network
- Compulsory tunneling
  - PPTP tunnel from ISP to network
  - client to ISP dial-in via PPP is unprotected