# INFS 766/INFT 865
## Internet Security Protocols

## Lectures 5 and 6
## 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]


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# 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

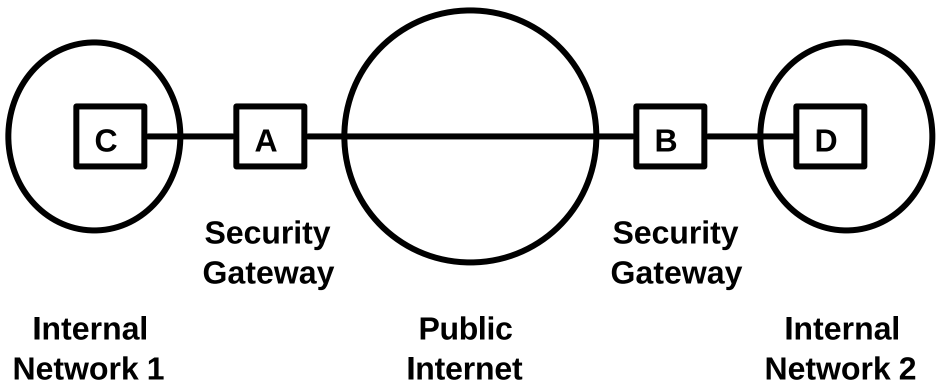




## IPSEC TRAFFIC PROTOCOLS

- 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



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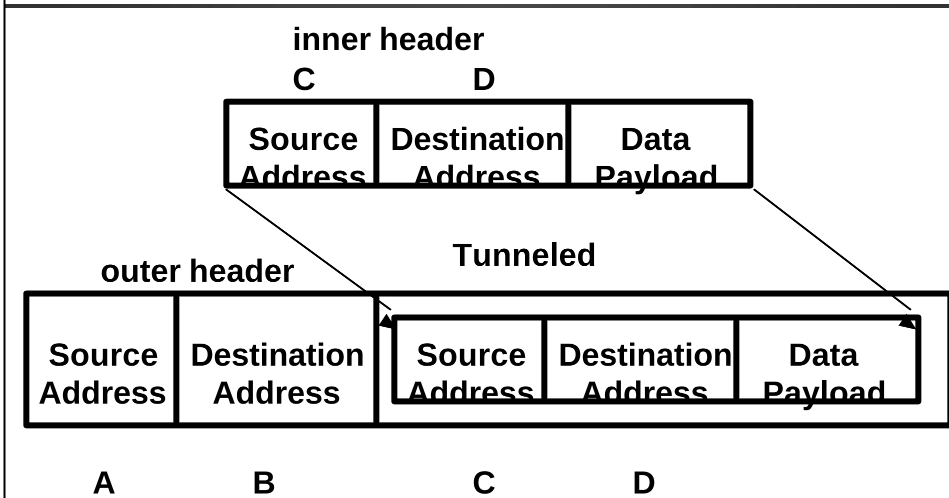
# IP TUNNELING



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## 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


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## 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)


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# 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, IV, key lifetime
  - authentication: algorithm, key, key lifetime
- lifetime of SA
- IPSEC protocol mode: transport, tunnel, wildcard
- path MTU (maximum transmission unit)


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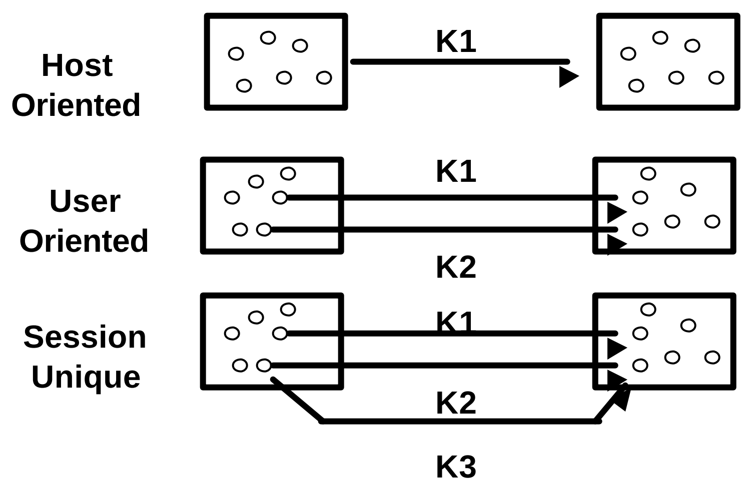
# IPSEC
# KEYING (SA) GRANULARITY





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# 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


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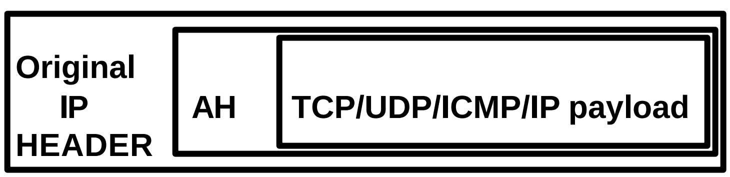
# IP AH TRANSPORT MODE




- 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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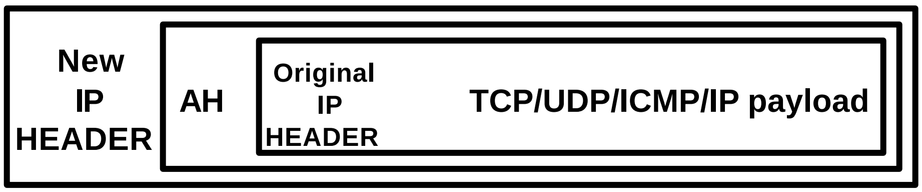
# IP AH TUNNEL MODE




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


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# 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



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# 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



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# 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



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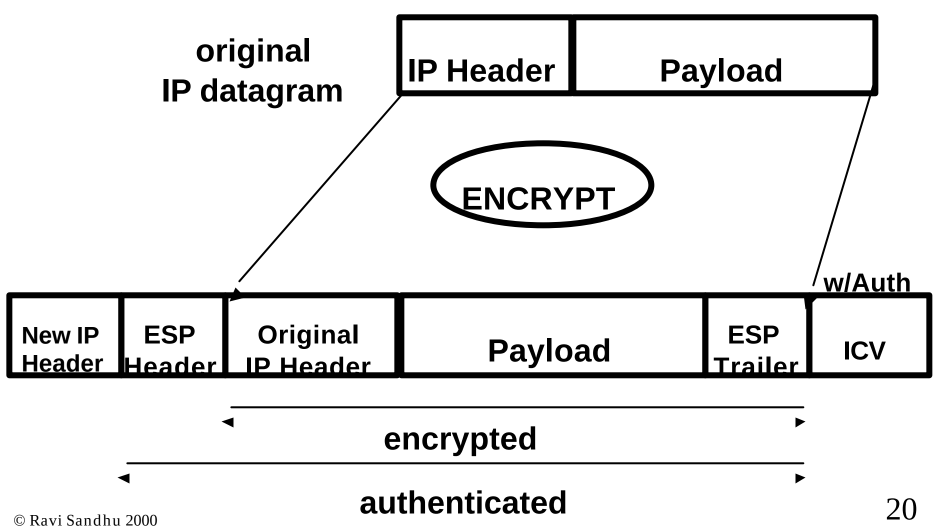
# ESP TUNNELING MODE



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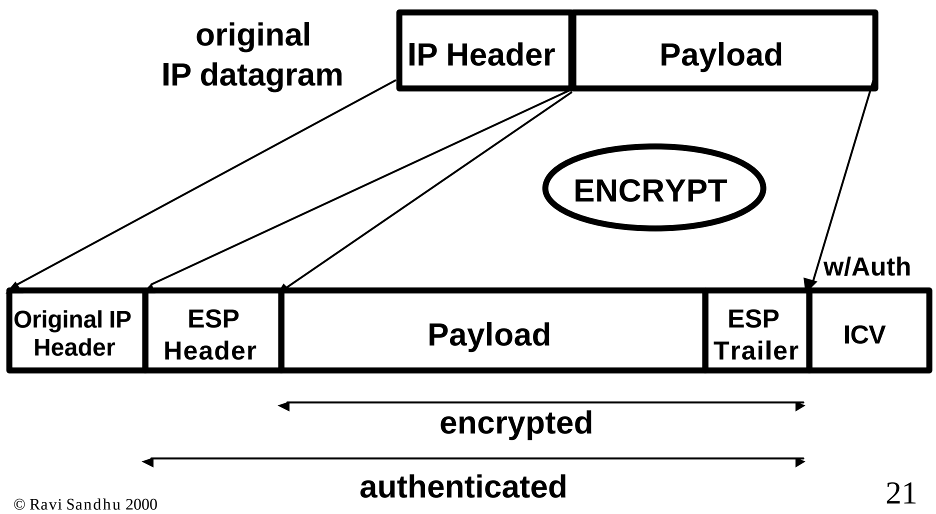
# ESP TRANSPORT MODE



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# 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



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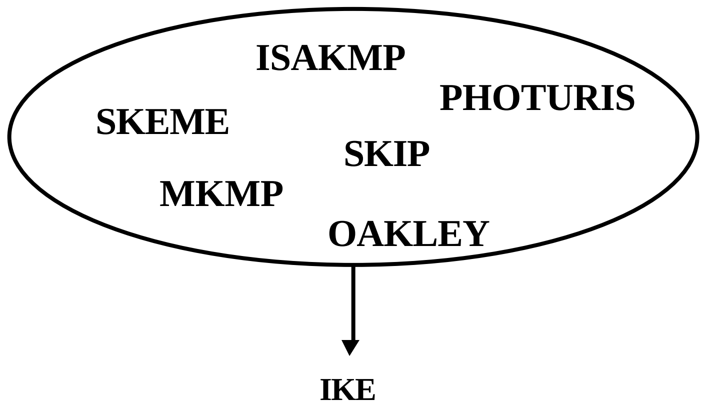
# INTERNET KEY EXCHANGE (IKE)

- Hybrid protocol



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# 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



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# 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**



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# 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**



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# 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



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# PHASE 1 AUTHENTICATION ALTERNATIVES

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



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# 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


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# COOKIE GENERATION

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


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# 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
```

# IPSEC IDs

| ID Type | Value |
|---|---|
| ------- | ----- |
| RESERVED | 0 |
| ID_IPV4_ADDR | 1 |
| ID_FQDN | 2 |
| ID_USER_FQDN | 3 |
| ID_IPV4_ADDR_SUBNET | 4 |
| ID_IPV6_ADDR | 5 |
| ID_IPV6_ADDR_SUBNET | 6 |
| ID_IPV4_ADDR_RANGE | 7 |
| ID_IPV6_ADDR_RANGE | 8 |
| ID_DER_ASN1_DN | 9 |
| ID_DER_ASN1_GN | 10 |
| ID_KEY_ID | 11 |



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# 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
```



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# 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



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# 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)
```



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## 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)**



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# 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)**



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# 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**



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# 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
```



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# 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
```



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# 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               -->
```



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# 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)
```



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# 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



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# 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.
```



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# 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



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# 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



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# 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)
```



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# 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



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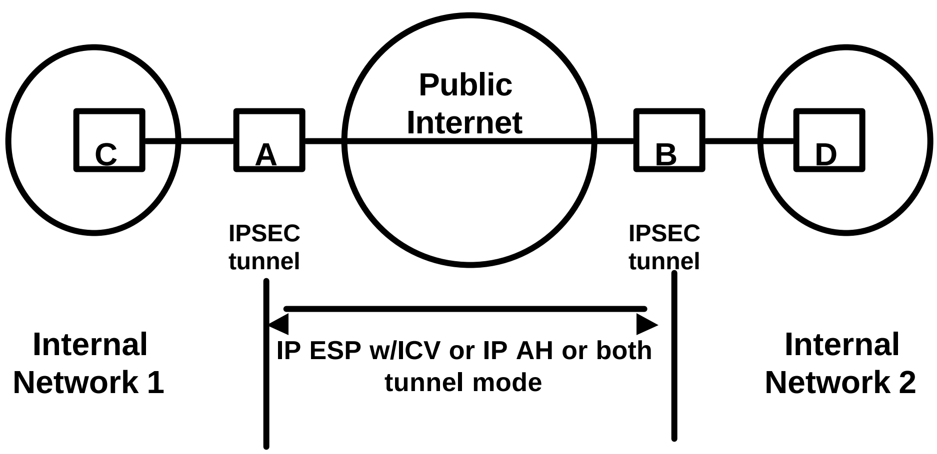
# VIRTUAL PRIVATE NETWORKS



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# WHAT IS TUNNELED

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



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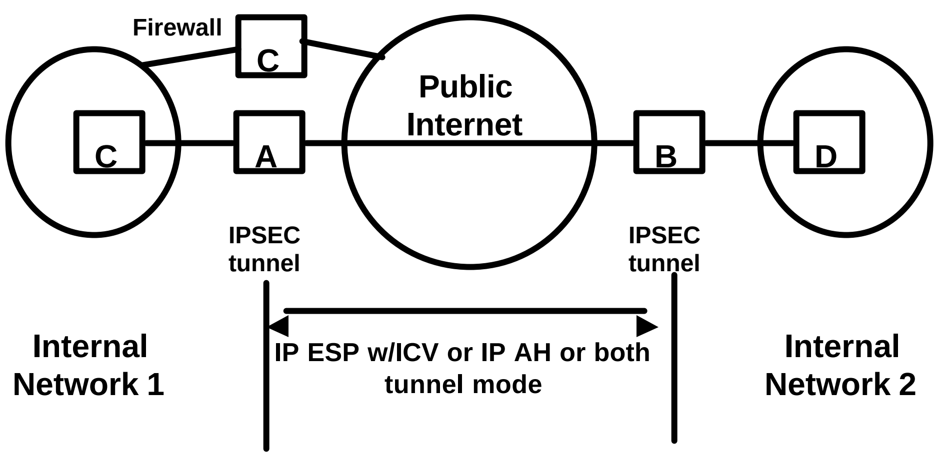
# VIRTUAL PRIVATE NETWORKS



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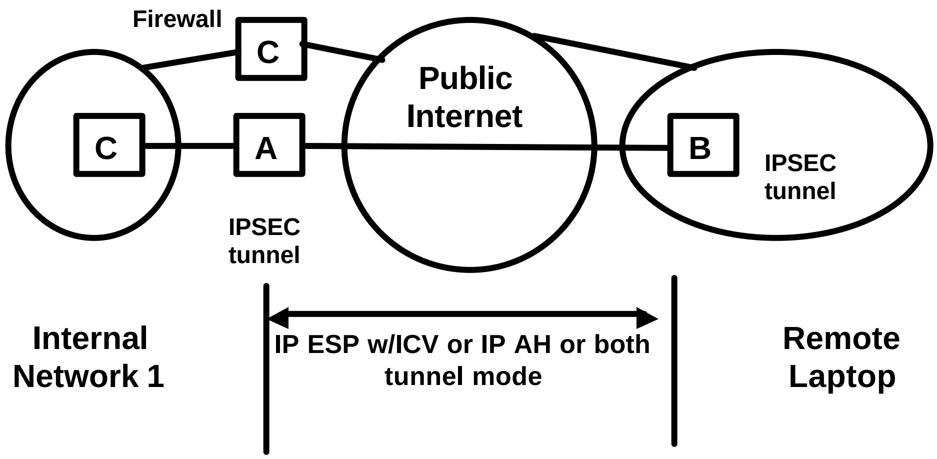
# SECURE REMOTE ACCESS








# 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