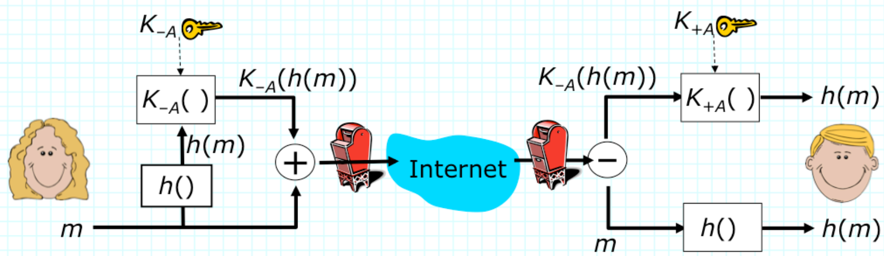
18. Application, Network and Link Layer Security

- Secure email
- Secure Socket Layer (SSL)
- Securing VPNs with IPSec
- Securing Wireless LANs

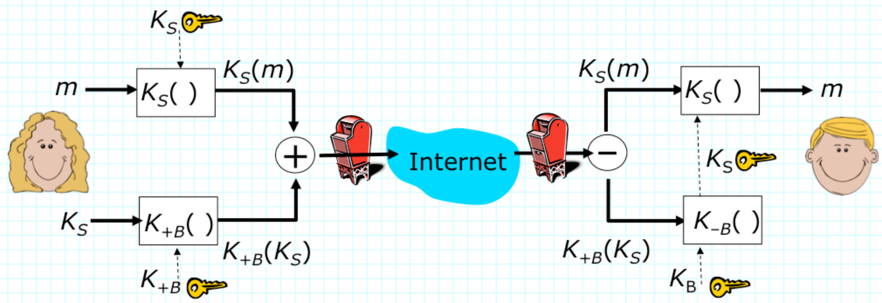
Jon Turner – based on slides from Kurose & Ross

Sending a Signed Email



- Alice wants to send signed e-mail m, to Bob
  - » computes message digest (hash of message) and encrypts it with private key
  - » sends both m and $K_{-A}(h(m))$ to Bob
- Bob checks message
  - » uses Alice's public key to obtain original message digest
  - » computes message digest directly and compares

Sending Confidential Email



- Alice wants to send confidential e-mail, *m*, to Bob
  - » generates random symmetric private key, K_S
  - » encrypts message with K_S (for efficiency)
  - » also encrypts K_S with Bob's public key
  - » sends both $K_S(m)$ and $K_B(K_S)$ to Bob
- Bob uses private key to recover symmetric key created by Alice, then decrypts message

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Issues with Secure Email

- Many mail clients support encrypted email (Outlook, Thunderbird, Apple)
  - » straightforward to use, in principle
- Key distribution problem inhibits widespread use
  - » need correspondent's public key in order to encrypt messages
  - » but how do you get their key in reliable way
- Original PGP system used so-called "web-of-trust"
  - » individuals to certify keys of other individuals they know
  - » appealing idea, but has not been broadly successful
- Alternate approach uses certificates obtained from certificate authority
  - » less effective than for web-site authentication
  - » certificate cost barrier to users, little benefit until universal

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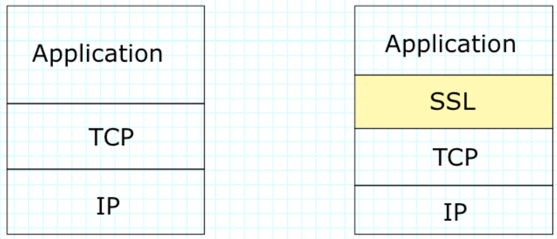
Secure Sockets Layer



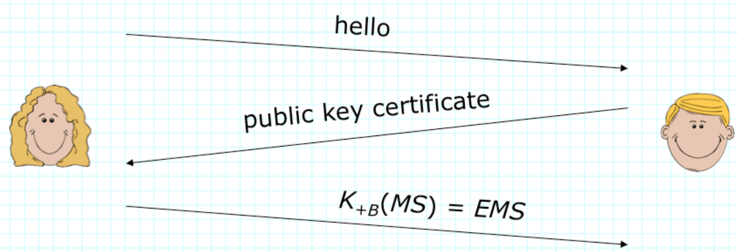
normal application *application with SSL*

- Supports secure TCP connections
  - » provides privacy, authentication, data integrity
  - » used by almost all web browsers (https) for e-commerce
  - » application libraries available for C/C++, python, Java,...
- Note: TCP header is *not* protected
- TLS (RFC 2246) is IETF standard version

Main Phases in SSL

- *Handshake:* Alice and Bob exchange and verify certificates, agree on shared secret
  - » usually, only server provides certificate
  - » most data sent in clear at this point
- *Key derivation:* Alice and Bob use shared secret to derive set of keys
  - » different keys for different purposes
- *Data transfer:* data to be transferred is broken up into series of records
  - » data integrity checked for each record
- *Connection closure:* special messages to securely close connection
  - » prevents premature termination by an attacker

Basic Handshake (simplified)



MS: master secret

EMS: encrypted master secret

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Key Derivation

- Considered bad to use same key for more than one cryptographic operation
  - » use different keys for message authentication code (MAC) and encryption
- Four keys:
  - » K_c = encryption key for data sent from client to server
  - » M_c = MAC key for data sent from client to server
  - » K_s = encryption key for data sent from server to client
  - » M_s = MAC key for data sent from server to client
- Keys derived from key derivation function (*KDF*)
  - » takes master secret and (possibly) some additional random data and creates the keys

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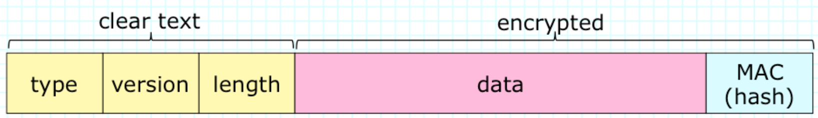
Data Records

- Why not encrypt data in constant stream?
  - » so we can check data integrity as we process stream
    - e.g., with instant messaging, we want to check integrity of each line, not just the whole session
  - » but if stream is encrypted, why do we need to check integrity?
    - attacker can still corrupt data in way that might disrupt application
- So, break stream in series of records
  - » to support variable length records, add length field
  - » each record carries a hash based on secret MAC key, *M*
    - hash computed over entire record
  - » receiver can check and act on each record as it arrives



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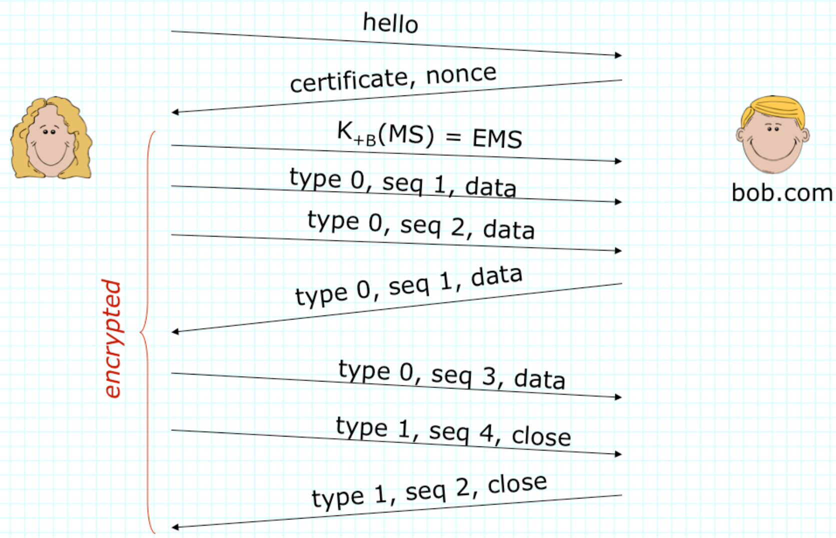
Replay Attacks, Premature Closure

- Problem: attacker can capture and replay records or re-order records
  - » solution: include sequence number when performing MAC hash
    - h_M(seq#+record)
  - » note: no explicit sequence number field
    - sender/receiver simply count records and use appropriate seq#
- Problem: attacker could replay entire session
  - » solution: define random nonce at start of session and use it to generate keys
- Problem: attacker could close connection early using FIN
  - » solution: type field has special value for last record of session

Basic SSL: Summary



More Details

- SSL supports several cipher suites
  - » symmetric encryption algorithm
    - options include DES, 3DES, AES, RC2, RC4
  - » public-key algorithm - RSA
  - » MAC algorithm - MD5, SHA
- Cipher suite negotiated during handshake
  - » client offers choice
  - » server picks one

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SSL Handshake Details

1. Client sends list of algorithms it supports, along with client nonce
2. Server chooses algorithms from list; sends back: choice + certificate + server nonce
3. Client verifies certificate, extracts server's public key, generates *pre-master secret*, encrypts with server's public key, sends to server
4. Client and server independently compute encryption and MAC keys from pre-master secret and nonces
5. Client/Server exchange hash of all the handshake messages (these are encrypted)
   » to detect tampering of handshakes (such as removing stronger encryption methods from list of options)

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Implementing SSL/TLS Apps in Java

- To implement SSL/TLS apps, need key pair
- Java apps obtain keys and certificates from a *keystore*
  - » a keystore is a password-protected binary file containing multiple entries
    - *key entry* holds private key and certificate containing public key
    - *certificate entry* contains a certificate with public key of some "trusted peer"
    - a *truststore* is a keystore with only certificate entries
    - each entry is identified by a string called an "alias"
- *Keytool* is a utility for creating/managing keystores
  - » keytool -genkey -alias mykey -keystore kstore
  - » keytool –list –keystore kstore
  - » keytool -export -keystore kstore -alias myKey -file certs.cer
  - » keytool -import -keystore tstore -alias myCert -file certs.cer

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Engineering

Secure Echo Server

```
import javax.net.ssl.SSLServerSocket;
import javax.net.ssl.SSLServerSocketFactory;
import javax.net.ssl.SSLSocket;
import java.io.*;
public class EchoServer {
  public static void main(String[] args) throws Exception
    System.console().writer().print("password:");
    System.console().writer().flush();
    char[] password = System.console().readPassword();

    System.setProperty("javax.net.ssl.keyStore",args[0]);
    System.setProperty("javax.net.ssl.keyStorePassword",
          new String(password));

    SSLServerSocket listenSock = (SSLServerSocket)
       SSLServerSocketFactory.getDefault().createServerSocket(30123);
    SSLSocket connSock = (SSLSocket) listenSock.accept();

    BufferedReader fromClient = ...;
    BufferedWriter toClient = ...;
    String string = null;
    while ((string = fromCllient.readLine()) != null) {
      toClient.write(string); toClient.newLine(); toClient.flush();
} } }
```

Get password for keystore

Set system properties identifying keystore file and its password

from connSock

Create secure listening socket, then accept incoming

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Secure Echo Client

Set system properties identifying truststore file and its password

```
import javax.net.ssl.SSLSocket;
import javax.net.ssl.SSLSocketFactory;
import java.io.*;
public class EchoClient {
  public static void main(String[] args) throws Exception {
    System.setProperty("javax.net.ssl.trustStore",args[1]);
    System.setProperty("javax.net.ssl.trustStorePassword",
            "echoECHO");

    SSLSocket sock = (SSLSocket)
      SSLSocketFactory.getDefault().createSocket(args[0], 30123);

    BufferedReader sysin = ...;
    BufferedReader fromServer ...;
    BufferedWriter toServer ...;

    String string = null;
    while ((string = sysin.readLine()) != null) {
      toServer.write(string); toServer.newLine();
      toServer.flush();
      System.out.println(fromServer.readLine());
} } }
```

Create secure socket to remote server

Network Layer Security – IPsec

- Protects *all* data sent between two network layer components
  - » sending component encrypts datagram payload
    - could be TCP or UDP segment, ICMP message, OSPF message
- Used mainly for *Virtual Private Networks* (VPN)
  - » allows remote host to communicate securely with corporate network across public internet using encrypted tunnel
  - » two main protocols
    - *Authentication Protocol* (AP) – authentication, message integrity
    - *Encapsulation Security Protocol* (ESP) – also, confidentiality
- IPsec operates between pairs of endpoints
  - » requires some shared state, which is called a *Security Association* (SA)
    - an SA supports one-way communication, so typically used in pairs

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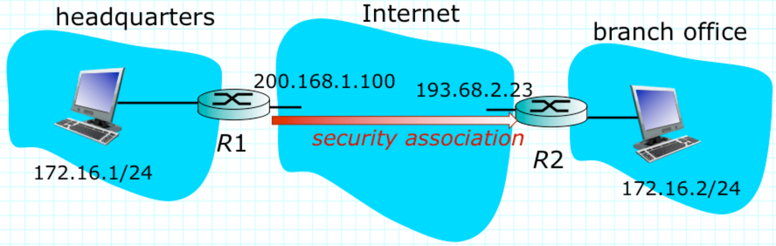
Example SA from R1 to R2



R1 stores for SA:

- 32-bit SA identifier: *Security Parameter Index (SPI)*
- origin SA interface (200.168.1.100)
- destination SA interface (193.68.2.23)
- type of encryption used (e.g., 3DES with CBC)
  - » and encryption key
- type of integrity check used (e.g., HMAC with MD5)
  - » and authentication key

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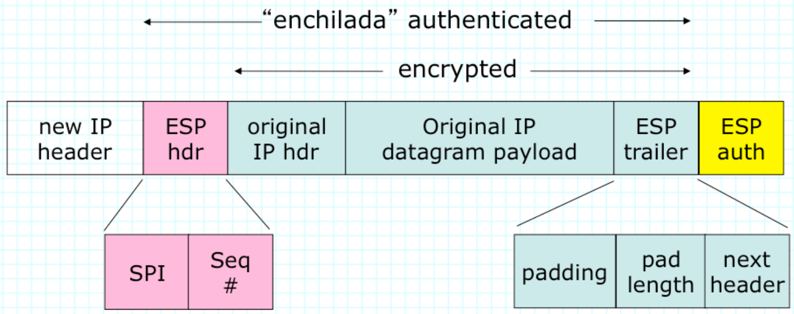
SAD and SPD

- SA Database
  - holds state information for all SAs
  - when sending IPsec datagram,sender accesses SAD to determine how to process datagram
  - when IPsec datagram is received, SPI in IPsec header used to select entry from receiver's SAD
- Security Policy Database
  - used by gateway router to decide if IPsec should be used when forwarding an outgoing packet
    - not all packets require IPsec
  - looks for entry in Security Policy Database, based on protocol and source and destination IP addresses
  - entry specifies which SA to use

IPsec Datagram – tunnel mode



- ESP trailer: padding for block ciphers
- ESP header:
  - » SPI, so receiving entity knows what to do
  - » sequence number, to thwart replay attacks (no wrap-around)
- MAC in ESP authentication field is created with shared secret key

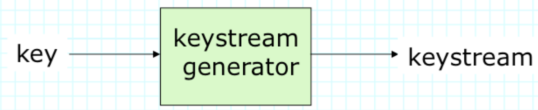
Creating Security Associations

- Can be done manually, but that's usually not practical
  - » SAs can be created automatically using Internet Key Exchange protocol (IKE)
- IKE operates in two phases
  - » first phase creates a secure channel used in second phase
    - includes authentication to verify identities of endpoints
  - » second phase used to create one or more SAs for use between the two entities

Securing Wireless LANs

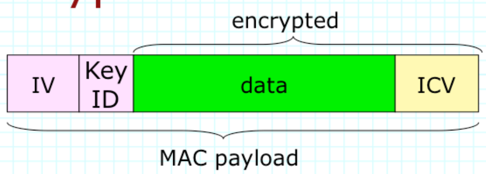
- Wired Equivalent Privacy (WEP) was original security protocol for 802.11
  - » not very secure, but still makes useful case study
  - » uses symmetric key cryptography to provide confidentiality, end-host authorization and data integrity
    - keys are exchanged "out-of-band"
  - » self-synchronizing: each packet separately encrypted
  - » designed for efficiency – implementable in hardware or software
- 802.11i standard includes much stronger security mechanisms
  - » choice of encryption methods
  - » separate authentication server
    - typically uses public key encryption for authentication and key distribution

Symmetric Stream Ciphers



- Combine each byte of keystream with byte of plaintext to get ciphertext:
  - » $m(i)$ = i-th unit of message
  - » $ks(i)$ = i-th unit of keystream
  - » $c(i)$ = i-th unit of ciphertext
  - » $c(i) = ks(i) \oplus m(i)$ ($\oplus$ = exclusive or)
  - » $m(i) = ks(i) \oplus c(i)$
- WEP uses RC4
  - » key combines a shared secret (40 or 104 bits) with a 24 bit *Initialization Vector* (IV) to generate key stream
    - separate IV per frame, sent as clear text

WEP Encryption



- Integrity Check Value computed over data
  - » four-byte hash/CRC for data integrity
- Initialization Vector (IV) created for each packet
  - » sent with packet
  - » sender and receiver combine IV with shared key to initialize keystream generator
- Key ID is an 8-bit identifier
- Data in frame + ICV are encrypted with RC4
  - » bytes of keystream are XORed with bytes of data & ICV
  - » IV & keyID are appended to encrypted data to create payload
  - » payload inserted into 802.11 frame

Breaking 802.11 WEP encryption

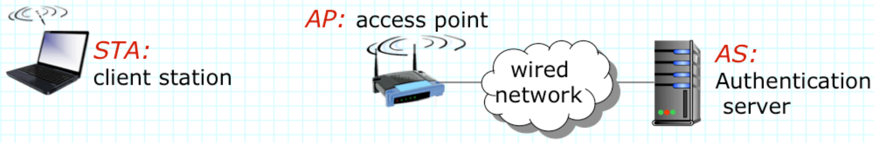
Security hole:

- 24-bit IV, one IV per frame, -> IV's eventually reused
- IV transmitted in plaintext, so IV reuse easily detected

Attack:

- » Trudy induces Alice to encrypt known plaintext $d_1\ d_2\ d_3\ d_4$ …
- » Trudy sees: $c_i = d_i$ XOR k_i^{IV}
- » Trudy knows $c_i\ d_i$, so can compute k_i^{IV}
- » Trudy knows encrypting key sequence $k_1^{IV}\ k_2^{IV}\ k_3^{IV}$ …
- » next time IV is used, Trudy can decrypt!

802.11i: four phases of operation



1. Discovery of security capabilities

2. STA and AS mutually authenticate, together generate Master Key (MK). *AP serves as "pass through"*

3. STA derives Pairwise Master Key (PMK)

3. AS derives same PMK, sends to AP

4. STA, AP use PMK to derive Temporal Key (TK) used for message encryption, integrity

EAP: Extensible Authentication Protocol

- EAP: end-end client (mobile) to authentication server protocol
- EAP sent over separate “links”
  - » mobile-to-AP (EAP over LAN)
  - » AP to authentication server (RADIUS over UDP)