Secure Channel

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Review: Encryption, MACs

• We can protect confidentiality or integrity of a message against Dolev-Yao attacker

• Today:
  – What if we want to protect confidentiality and integrity?
  – What if we want to have a conversation not just a single message...?
CONFIDENTIALITY & INTEGRITY
Authenticated encryption

• Newer block cipher modes designed to provide confidentiality and integrity
  – **OCB**: Offset Codebook Mode
  – **CCM**: Counter with CBC-MAC Mode
  – **GCM**: Galois Counter Mode

• Or, you could combine encryption schemes with MAC schemes...
Encrypt and MAC

0. $k_E = \text{Gen}_E(len)$
   $k_M = \text{Gen}_M(len)$

1. A: $c = \text{Enc}(m; k_E)$
   $t = \text{MAC}(m; k_M)$

2. A -> B: c, t

3. B: $m' = \text{Dec}(c; k_E)$
   $t' = \text{MAC}(m'; k_M)$
   if $t = t'$
      then output $m'$
   else abort
Encrypt and MAC

• **Pro:** can compute Enc and MAC in parallel

• **Con:** MAC must protect confidentiality
  (not actually a requirement we ever stipulated)

• **Example:** `ssh` (Secure Shell) protocol
  – recommends AES-128-CBC for encryption
  – recommends HMAC with SHA-2 for MAC
Aside: Key reuse

- Never use same key for both encryption and MAC schemes
- **Principle:** every key in system should have unique purpose
Encrypt then MAC

1. A: \( c = \text{Enc}(m; k_E) \)
   \[ t = \text{MAC}(c; k_M) \]

2. A \rightarrow B: c, t

3. B: \( t' = \text{MAC}(c; k_M) \)
   \[ \text{if } t = t' \]
   then output \( \text{Dec}(c; k_E) \)
   else abort
Encrypt then MAC

- **Pro:** provably most secure of three options [Bellare & Nampreprepre 2001]
- **Pro:** don't have to decrypt if MAC fails
  - resist DoS

- Example: IPsec (Internet Protocol Security)
  - recommends AES-CBC for encryption and HMAC-SHA1 for MAC, among others
  - or AES-GCM
MAC then encrypt

1. A: \( t = \text{MAC}(m; k_M) \)
   \( c = \text{Enc}(m,t; k_E) \)
2. A \( \rightarrow \) B: c
3. B: \( m',t' = \text{Dec}(c; k_E) \)
   if \( t' = \text{MAC}(m'; k_M) \)
   then output \( m' \)
   else abort
MAC then encrypt

• **Pro:** provably next most secure
  – and just as secure as Encrypt-then-MAC for strong enough MAC schemes
  – HMAC and CBC-MAC are strong enough

• Example: SSL (Secure Sockets Layer)
  – Many options for encryption, e.g. AES-128-CBC
  – For MAC, standard is HMAC with many options for hash, e.g. SHA-256
Authenticated encryption

• Three combinations:
  – Enc and MAC
  – Enc then MAC
  – MAC then Enc

• Let’s unify all with a pair of algorithms:
  – AuthEnc(m; ke; km): produce an authenticated ciphertext x of message m under encryption key ke and MAC key km
  – AuthDec(x; ke; km): recover the plaintext message m from authenticated ciphertext x, and verify that the MAC is valid, using ke and km
    • Abort if MAC is invalid
CONVERSATIONS
Protection of conversation

• **Threat:** attacker who controls the network
  – Dolev-Yao model: attacker can read, modify, delete messages

• **Harm:** conversation can be learned (violating confidentiality) or changed (violating integrity) by attacker

• **Vulnerability:** communication channel between sender and receiver can be controlled by other principals

• **Countermeasure:** all the crypto we’ve seen so far...
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Channel:

• Bidirectional communication between two principals
• But their roles are not identical
  – Client and server, initiator and responder, etc.
  – We'll call them Alice and Bob
  – Same two principals might well have two parallel conversations in which they play different roles
• Communication might be...
  – spatial: over network
  – temporal: over storage
    • "Conversation with yourself"
Secure channel

Secure:

• The channel does not reveal anything about messages except for their timing and size (Confidentiality)

• If Alice sends a sequence of messages m1, m2, ... then Bob receives a subsequence of that, and furthermore Bob knows which subsequence (Integrity)
  – And the same for Bob sending to Alice
Secure channel

Implications of security goals...

• No guarantee that any messages are ever received (subsequence could be empty) (no Availability goal)
• No attempt at anonymity
• No attempt to defend against traffic analysis
• Received messages:
  – are in order (or at least orderable)
  – are not modified
  – are attributable to the other principal
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Pieces of the puzzle:

• Use authenticated encryption to protect confidentiality and integrity
  – Block cipher + mode
  – MAC

• Use message numbers to further protect integrity

• Use a key establishment protocol and key derivation function to create shared session keys
Secure channel

Pieces of the puzzle:

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**Message numbers**

- Aka *sequence numbers*
- Every message that Alice sends is numbered
  - 1, 2, 3, ...
  - numbers increase monotonically
  - never reuse a number
- Bob keeps state to remember last message number he received
- Bob accepts only increasing message numbers
- And ditto all the above, for Bob sending to Alice
  - so each principal keeps two independent counters: messages sent, messages received
Message numbers

What if Bob detects a gap? e.g. 1, 2, 5
• Maybe Mallory deleted messages 3 and 4 from network
• Maybe Mallory detectably changed 3 and 4, causing Bob to discard them
• In either case, channel is under active attack
  – Absent availability goals, time to PANIC: abort protocol, produce appropriate information for later auditing, shut down channel

What if network non-maliciously dropped messages or will deliver them later?
• Let's assume underlying transport protocol guarantees that won't happen (e.g. TCP)
Message numbers

• Message number usually implemented as a fixed-size unsigned integer, e.g., 32 or 48 or 64 bits

• What if that int overflows and wraps back around to 0?
  – Message number must be unique within conversation to prevent Mallory from replaying old conversation
  – So conversation must stop at that point
  – Can start a new conversation with a new session key
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Pieces of the puzzle:

• Use authenticated encryption to protect confidentiality and integrity
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• Use message numbers to further protect integrity

• Use a key establishment protocol and key derivation function to create shared session keys
Session keys

• For now, let's assume Alice and Bob already have a single shared session key $k$
  – Recall: session key is used for limited time then discarded
  – Here, the session duration is a single conversation
• But a single key isn't good enough...
  – Need a key for the block cipher
  – Need a key for the MAC
• And recall:
  – Principle: every key in system should have unique purpose
  – Implies: should not use same key for both Enc and MAC algorithms
  – Also implies: should not use same keys for
    • Alice $\rightarrow$ Bob, vs.
    • Bob $\rightarrow$ Alice
Key derivation

• Have one key: k
• Need four keys:
  1. kea: Encrypt Alice to Bob
  2. keb: Encrypt Bob to Alice
  3. kma: MAC Alice to Bob
  4. kmb: MAC Bob to Alice
• How to get four out of one: use a cryptographic hash function H to derive keys...
  1. kea = H(k, "Enc Alice to Bob")
  2. keb = H(k, "Enc Bob to Alice")
  3. kma = H(k, "MAC Alice to Bob")
  4. kmb = H(k, "MAC Bob to Alice")
Key derivation

• Why hash?
  – Destroys any structure in input
  – Produces a fixed-size output that can be truncated, as necessary, to produce key for underlying algorithm
  – Unlikely to ever cause any of four keys to collide
  – Even if one of four keys ever leaks, hard to invert hash to recover k and learn the other keys

• Small problem: maybe the output of H isn't compatible with the output of Gen
  – For most block ciphers and MACs, not a problem
    • they happily take any uniformly random sequence of bits of the right length as keys
  – For DES, it is a problem
    • has weak keys that Gen should reject
  – For many asymmetric algorithms, it would be a problem
    • keys have to satisfy certain algebraic properties
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Pieces of the puzzle:

• Use **authenticated encryption** to protect confidentiality and integrity
  – Block cipher + mode
  – MAC

• Use message numbers to further protect integrity

• Use a key establishment protocol and key derivation function to create shared session keys
To send a message from A to B

1. A:

   increment sent_ctr;
   if sent_ctr overflows then abort;
   \( x = \text{AuthEnc}(\text{sent}\_\text{ctr}, m; \text{kea}; \text{kma}) \)

2. A -> B: \( x \)

3. B:

   \( i,m = \text{AuthDec}(x; \text{kea}; \text{kma}) \);
   increment rcvd\_ctr;
   if \( i \) != rcvd\_ctr then abort;
   output m
To send a message from B to A

1. B:
   increment sent_ctr;
   if sent_ctr overflows then abort;
   \( x = \text{AuthEnc}(\text{sent}_\text{ctr}, m; \text{keb}; \text{kmb}) \)

2. B \( \rightarrow \) A: x

3. A:
   \( i,m = \text{AuthDec}(x; \text{keb}; \text{kmb}) \);
   increment rcvd_ctr;
   if \( i \neq \text{rcvd}_\text{ctr} \) then abort;
   output m
Secure channel

Pieces of the puzzle:

• Use authenticated encryption to protect confidentiality and integrity
  – Block cipher + mode
  – MAC

• Use message numbers to further protect integrity

• Use a **key establishment protocol** and key derivation function to create shared session keys
Session key generation

Back to this assumption:

*For now, let's assume Alice and Bob already have a single shared session key $k$*

We need a means for Alice and Bob to generate that key...

To be continued!
Upcoming events

• [today] A2 due, A3 out (Part I can be done now; Part II best tackled after Monday’s lecture)

Most conversations are simply monologues delivered in the presence of a witness. – Margaret Millar