BTI 4201: From Symmetric Encryption to Secure Channels

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20.5.2022

Learning Objectives

Example: Attack on CBC Stateful IV

Beyond IND-CPA

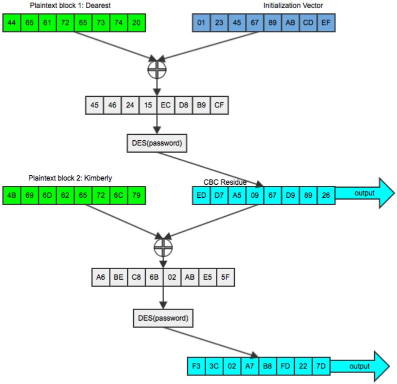
Real-world use of cryptographic primitives (exercise)

Symmetric key establishment protocols

Secure channels

Part I: Attack on CBC

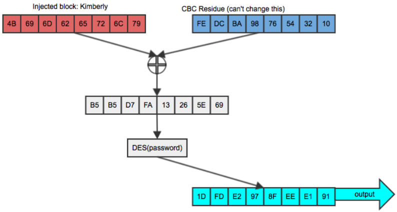
Attacking CBC stateful IV (1/5)[1]



Goal: confirm "Kimberly" was sent!

Attacking CBC stateful IV (2/5)

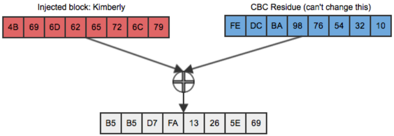
Setup: Get oracle to encrypt "Kimberly":



Given random CBC residue, this does not help.

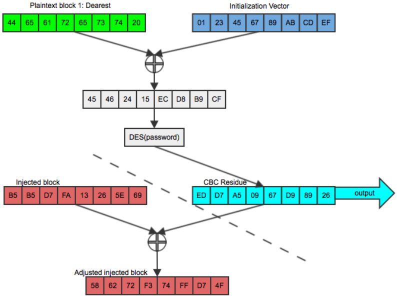
Attacking CBC stateful IV (3/5)

CBC residue is XORed with input, get rid of it first using *predicted* IV:



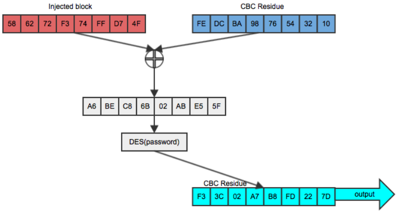
Attacking CBC stateful IV (4/5)

Then add the residue from the original encryption:



Attacking CBC stateful IV (5/5)

Now confirm the output matches:



If output matches, original text was “Kimberly”.

Summary

For CBC, if an attacker can:

- guess the plaintext corresponding to any ciphertext block they have seen before, and
- can predict a future IV, and
- can submit a suitable message to be encrypted with that IV,

then they can verify their guess.

Is this attack an issue?

- Requires guessing the entire block
- Requires access to encryption oracle
- Block size is say 8 bytes, so 2^{256} trials

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BEAST (2011) made this attack practical by shifting each unknown plaintext byte to a position in the block just after 7 bytes of known plaintext.

IND-CPA Secure Schemes

- The CTR random IV symmetric encryption scheme is IND-CPA secure.
- The CTR stateful IV encyption scheme (ensuring no IV re-use) is IND-CPA secure.
- The CBC *random* IV symmetric encryption scheme is IND-CPA secure.

Pseudo random functions (PRF)

- A *pseudo random function (PRF)* is a function that is (computationally) indistinguishable from a true random function
- The previous positive results are true under the *assumption* that the block cipher used (e.g. AES) is a PRF.
- Assumption really means that this is a commonly shared belief of the crypto community. No proof exists!
- Breaking any of these schemes thus means breaking the PRF property of the underlying block cipher.

The crucial security property of a secure block cipher is that it is a PRF!

Part II: Chosen Ciphertext Attacks

IND-CPA vs. Chosen Ciphertext

IND-CPA is **not** the strongest security model!

- The adversary does not have access to a *decryption* oracle
- With a decryption oracle, an adversary can be allowed to ask for *some* messages of its choice to be decrypted.
- Security is achieved only if *other* messages still remain indistinguishable.

Indistinguishability under Chosen Ciphertext Attacks (IND-CCA)

The adversary's goal is the same as in IND-CPA (determine b given $\mathtt{enc}(k, M_b^i)$) for sequences of messages $M_{0,1}^i$).

Setup Generate random key k, select $b \in \{0, 1\}$.

Oracle E Given M, return $C := \mathtt{enc}(k, M)$.

Oracle D Given C', return $M := \mathtt{dec}(k, C')$.

The additional restriction $C' \neq C$ must be imposed on the use of Oracle D: The adversary is not allowed to ask for decryption of a ciphertext C that was previously returned by the encryption oracle.

Examples for IND-CCA Insecure Schemes

CTR schemes are IND-CCA insecure:

"Say $\langle r, C \rangle$ is a ciphertext of some l-bit message M, and we flip bit i of C, resulting in a new ciphertext $\langle r, C' \rangle$. Let M' be the message obtained by decrypting the new ciphertext. Then M' equals M with the i-th bit flipped. Thus, by making a decryption oracle query of $\langle r, C' \rangle$ one can learn M' and thus M."

–Symmetric Encryption by Mihir Bellare and Phillip Rogaway

Problem

IND-CCA does not provide authenticity!

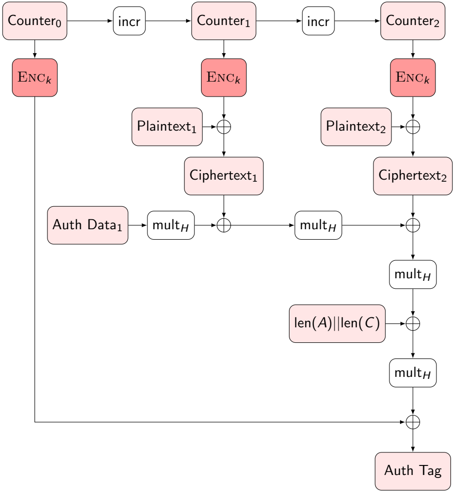
Real-world security

- Schemes providing authenticated encryption are IND-CCA secure.
- For details, see presentation linked from course Web site at
  `https://grothoff.org/christian/teaching/2022/4201/`

Break

Part III: Real-world symmetric encryption

GCM encryption



Using encryption APIs

GNU libgcrypt is a C library offering a wide range of cryptographic primitives.

1. `# apt install libgcrypt20-dev`
2. `# apt install gcc gdb valgrind emacs`
3. Download source templates (`exercise.txt`) from course Git

Example: AES256 GCM (encrypt.c)

```
char key[256/8], iv[96/8];
char plaintext[] = "Hello world";
char ciphertext[sizeof (plaintext)];
gcry_cipher_hd_t cipher;

gcry_cipher_open (&cipher, GCRY_CIPHER_AES256,
         GCRY_CIPHER_MODE_GCM, 0);
gcry_cipher_setkey (cipher, key, sizeof (key));
gcry_cipher_setiv  (cipher, iv,  sizeof (iv));
gcry_cipher_encrypt (cipher,
       ciphertext, sizeof (ciphertext),
       plaintext,  sizeof (plaintext));
gcry_cipher_close (cipher);
```

Example: AES256 GCM (decrypt.c)

```
char key[256/8], iv[96/8];
char plaintext[1024];
char ciphertext[sizeof (plaintext)];
gcry_cipher_hd_t cipher;

size_t plen = read (STDIN_FILENO,
                    ciphertext, sizeof (ciphertext));
gcry_cipher_open (&cipher, GCRY_CIPHER_AES256,
          GCRY_CIPHER_MODE_GCM, 0);
gcry_cipher_setkey (cipher, key, sizeof (key));
gcry_cipher_setiv  (cipher, iv,  sizeof (iv));
gcry_cipher_decrypt (cipher,
       plaintext,  plen,
       ciphertext, plen);
gcry_cipher_close (cipher);
```

Handling partial reads (decrypt.c)

```
char plaintext[1024];
size_t plen = 0;

while (1) {
  ssize_t inlen = read (STDIN_FILENO,
                        &ciphertext[plen],
                        sizeof (ciphertext) - plen);
  if (-1 == inlen) {
    fprintf (stderr,
             "Failed to read input\n");
    return 1;
  }
  if (0 == inlen)
    break;
  plen += inlen;
}
```

Tasks (1/3)

- Use the provided `encrypt` and `decrypt` programs to encrypt "Hello world" text using AES256+GCM and then decrypt it.
- Study the `libgcrypt` documentation. Use it to switch the program to use AES256+CBC instead.
- Switch back to AES256+GCM. Extend the program to obtain, transmit and verify the authentication tag.
- Extend the program to authenticate additional plaintext data that is not at all encrypted.

Tasks (2/3)

- Write a new program `hash.c` to compute the SHA-256 hash of the data read from `stdin`. Output the result in HEX and compare to `sha256sum`.
- Modify your program to use `SHA-512` instead.
- Write a new program `kdf.c` to compute the SCRYPT key derivation function. Output the result in HEX.

Tasks (3/3)

- Modify your programs to perform 10000 iterations each time before generating any output.
- Measure the time the various operations take.
- Modify your programs to process 1 MB of input instead of the 11 bytes of “Hello world”.
- Again, measure the time the various operations take.
- Change the IV length from 96 bits to 128 bits for AES256+GCM and measure again.

Break

Part IV: Symmetric key establishment protocols

Key Establishment Security goals

The basic security goals of key establishment are:

- *Key secrecy:* Session keys must not be known by anyone else than Alice, Bob (and maybe some trusted third party). Mallory must not learn anything about session keys.
- *Authenticity:* One party can be assured about the identity of the other party it shares the session key with. That is, Alice knows that she has session key with Bob.
- *Freshness of keys:* Mallory must not be able to replay old session keys.

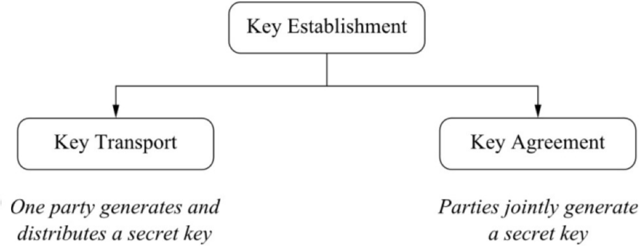
Protocols

- *Key establishment* is realized by using *protocols* whereby a shared secret becomes available to two or more parties, for subsequent cryptographic use.
- Until now, we have been discussing non-interactive crypto primitives, in the following we look at crypto protocols.
- It is *even harder* to design secure protocols, than designing non-interactive primitives. In fact, there is a long list of protocols designed by famous (and not so famous) cryptographers that were found to be flawed.

Session keys

- Key establishment protocols result *in shared secrets* which are typically called (or used to derive) session keys.
- Ideally, a session key is an ephemeral secret, i.e., one whose use is *restricted to a short time period such as a single telecommunications connection (or session)*, after which all trace of it is eliminated.
- Motivation for ephemeral keys includes the following:
  1. To limit available ciphertext (under a fixed key) for cryptanalytic attack;
  2. To limit exposure, with respect to both time period and quantity of data, in the event of (session) key compromise;
  3. To avoid long-term storage of a large number of distinct secret keys by creating keys only when actually required;
  4. To create independence across communications sessions or applications.

Classification of key establishment methods



Chapter 13 of Understanding Cryptography by Christof Paar and Jan Pelzl

Private channels

- Let us informally refer to a *private channel* as an authentic and confidential channel.
  - Exchange of secret keys on a USB stick
  - Pre-installation of keys on a company laptop
- Symmetric key distribution is impossible without private channels.
- Private channels are, loosely speaking, "complicated", "inefficient", "expensive".
- The goal in the following is to:
  - *Reduce the number* of private channels required to exchange keys.
  - Use an *initial private channel* today to exchange a secret key that they may use *tomorrow for establishing a secure channel over an insecure link*.

Storytime

Once upon a time...

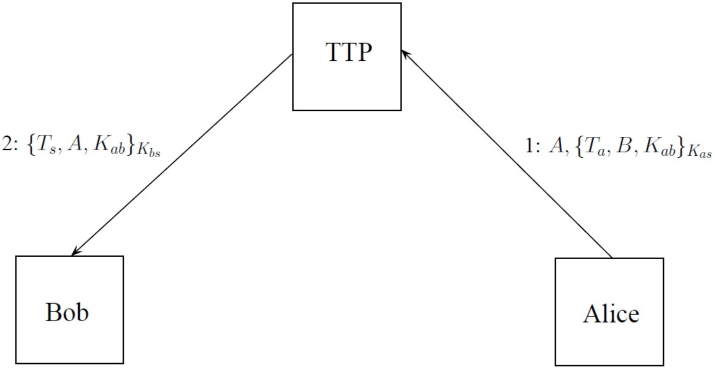
Neumann-Stubblebine

1. Alice sends A, R_A to Bob.
2. Bob sends $B, R_B, E_B(A, R_A, T_B)$ to Trent, where T_B is a timestamp and E_B uses a key Bob shares with Trent.
3. Trent generates random session key K and sends $E_A(B, R_A, K, T_B), E_B(A, K, T_B), R_B$ to Alice where E_A uses a key Alice shares with Trent.
4. Alice decrypts and confirms that R_A is her random value. She then sends to Bob $E_B(A, K, T_B), E_K(R_B)$.
5. Bob extracts K and confirms that T_B and R_B have the same value as in step 2.

Denning-Sacco

1. Alice sends A, B to Trent
2. Trent sends Alice $S_T(B, K_B), S_T(A, K_A)$
3. Alice sends Bob $E_B(S_A(K, T_A)), S_T(B, K_B), S_T(A, K_A)$
4. Bob decrypts, checks signatures and timestamps

Wide-Mouth Frog protocol

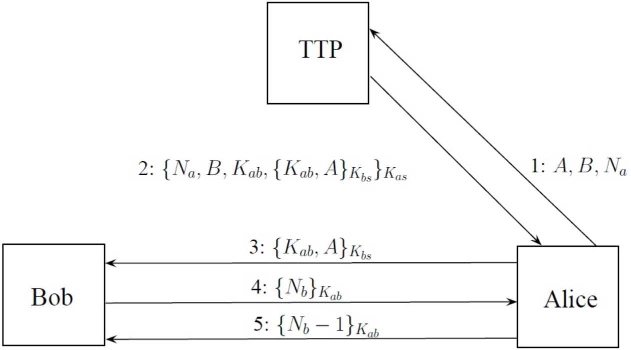


Wide-Mouth Frog protocol

The wide-mouth frog protocol has some conceptual shortcomings:

- Assumes synchronized clocks between the parties to achieve freshness.
- Although having synchronized clocks seems to be straight-forward, this is actually not the case.
  - Synchronized clocks under normal conditions is indeed easy (you have that in Windows, Linux...).
  - Synchronized clocks under attack is much harder: you need to have another protocol that securely synchronizes clocks.
  - But as soon as clock synchronization becomes security relevant, you can bet that it gets attacked.
- Bob must trust Alice that she correctly generates the session key.

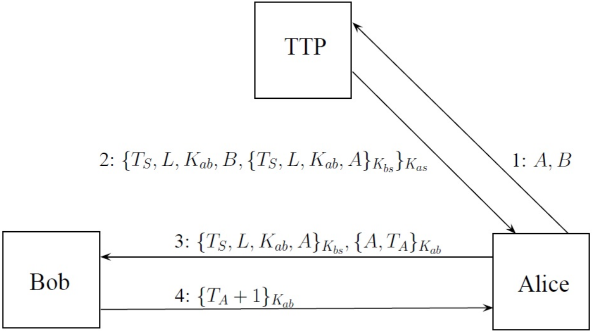
Needham-Schroeder protocol



Needham-Schroeder protocol

- Needham is one of the IT security pioneers. Protocol was conceived in 1978 and is one of the most widely studied security protocols ever.
- Removes timestamps and introduces nonces to achieve freshness.
- The session keys are generated by TTP in on the previous slide, thus removes problem of Wide-Mouth Frog protocol.
- Protocol is insecure against *known session key attacks*. Adversary who gets session key can replay the last three messages and impersonate A to B.
  - The reason for this problem is that B does not know whether the session key is fresh.
  - This vulnerability was discovered only some times after the protocol was published. Thus, even the smartest and most experienced people can fail to design secure crypto protocols.

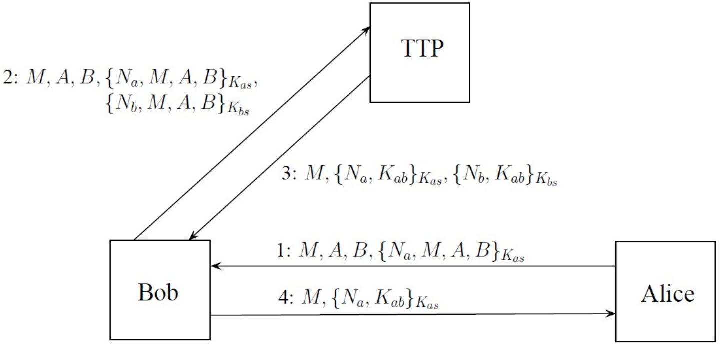
Kerberos


TTP
2: $\{T_S, L, K_{ab}, B, \{T_S, L, K_{ab}, A\}_{K_{bs}}\}_{K_{as}}$
1: A, B
3: $\{T_S, L, K_{ab}, A\}_{K_{bs}}, \{A, T_A\}_{K_{ab}}$
Bob
4: $\{T_A + 1\}_{K_{ab}}$
Alice

Kerberos

- Developed at MIT around 1987, made it into Windows 2000, and is still used as the authentication / key establishment / authorization mechanism within Windows.
- Quite similar to Needham-Schroeder, but removes weakness against known session key attacks using synchronized clocks.
- Shorter than Needham-Schroeder: only 4 messages instead of 5.

Otway-Rees protocol

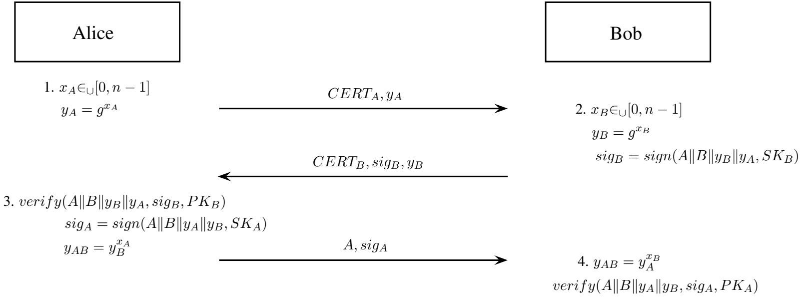


Otway-Rees protocol

- Only 4 messages as Kerberos, but completely different messages.
- Does not require clock synchronization.
- Has a number of problems $\Rightarrow$ Homework!

Station to station key agreement protocol

Common input: $\mathbb{Z}^*{}_p$ and $g \in \mathbb{Z}^*{}_p$, and n such that $g^n \equiv 1 \mod p$



- The protocol above is a simplified version of the STS protocol to illustrate the idea of authenticating messages with public keys.
- For a detailed spec refer to `http://en.wikipedia.org/wiki/Station-to-Station_protocol`

Station to station key agreement protocol

- The "station to station protocol" is the DH protocol made secure against MIM attacks:
  - The idea is simple: Alice and Bob basically sign all the messages they exchange in the Diffie - Hellman protocol.
  - The "exchange of authenticated signing keys" is done using certificates.
- Station to station protocol is the basis for the practically important *IKE* (Internet Key Exchange protocol).
- The bottom line is: one cannot establish authenticated keys without bootstrapping the system using an "exterior authentication mechanism" (e.g., without first establishing public key certificates for Alice and Bob).

RSA key transport

https://www.theinquirer.net/inquirer/news/2343117/ietf-drops-rsa-key-transport-from-ssl

Lessons Learned

- Do not try to be too clever, over-optimization is often the cause for vulnerabilities
- Which optimizations you can do (and which optimization actually matter) depends on your assumptions (adversary model, system capabilities)
- Which protocol to use depends on your performance goals and communications capabilities (all-to-all communication, trusted party, latency, bandwidth and computational constraints)

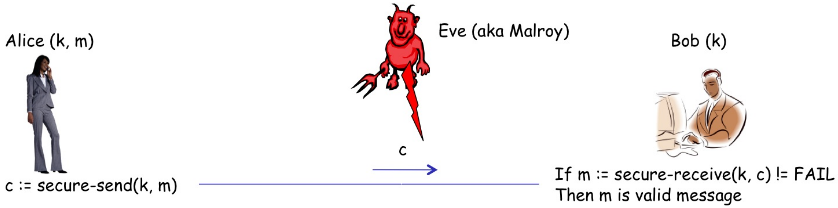
Break

Part V: Secure Channels

Overview

- By *secure channel* we refer to a logical channel running on top of some insecure link (typically the Internet) that provides
  - Confidentiality
  - Integrity and authenticity
  - Message freshness
- Secure channels are probably one of the most important applications of crypto in the real world.
- Many well known secure network protocols such as TLS/SSL, VPNs, IPSec, WPA etc but also application specific (e.g., secure VoIP), and proprietary protocols (maybe Skype?) make use of secure channels.
- Essentially all these protocols build upon the basic ideas we discuss in the following.
- It is also possible to get it wrong, e.g., the WEP protocol has a series of security flaws.

Secure channel



Secure channel - Secure send

```
secure-send(m, k_E, k_M) {
    STATIC msgsnt := 1
    IF (msgsnt ≥ MAX_MSGS) THEN RETURN ⊥
    c := ENC(k_E, m)
    m̃ := msgsnt||LENGTH(c)||c
    t := MAC(k_M, m̃)
    SEND(m̃||t)
    msgsnt := msgsnt + 1
}
```

Secure channel - Secure receive

```
secure-receive(C, k_E, k_M) {
    STATIC msgrcvd := 0
    (msgsnt, len, c, t) = PARSE(C)
    IF (t ≠ MAC(k_M, msgsnt||len||c)) THEN RETURN ⊥
    IF (msgsnt ⩽ msgrcvd) THEN RETURN ⊥
    m := DEC(k_E, c)
    msgrcvd := msgsnt
    RETURN m
}
```

Remarks

- The *freshness property* based on counters guarantees the following: If $m_1, m_2, \ldots, m_n$ denote the messages send using secure-send(), then secure-receive() can guarantee that the messages $m_1, m_2, \ldots, m_n$ being received are subsequence of the messages sent.
- Counters give no timing guarantees, i.e., the adversary Mallory can delay messages at will.
- Timing guarantees can be achieved using
  - Time-stamps
  - Challenges
- No security protocol can prevent Mallory from discarding messages.
- MACs provide not just integrity protection but also *authenticity*, as discussed earlier.
- Further reading material: Chapter 8 in Practical Cryptography by Schneier & Ferguson.

Remarks

- Typically, secure-send() and secure-receive() are run by both parties using a secure channel.
- Each party will have an independent key-pair (enc & MAC).
- In practice, one introduces the notion of a session (e.g., e-banking). Consists of a session ID in the header, which allows the receiver to look-up session state (keys, counters etc.) when receiving a message.
- Generally better is the use of authenticated encryption, where the block-cipher mode guarantees confidentiality **and** integrity.
- For more info see last week's slides on AES-GCM and `http://en.wikipedia.org/wiki/Authenticated_encryption`

Break

Part IV: Extended Security Objectives for Secure Channels

Repudiation vs. non-repudiation

- Digital signatures allow *proving* that someone said something
- Alice may be happy to authenticate to Bob, but not to Eve or Mallory!

Repudiation vs. non-repudiation

- Digital signatures allow *proving* that someone said something
- Alice may be happy to authenticate to Bob, but not to Eve or Mallory!
- Bob may turn "evil" and use Alice's statements against her later

⇒ Signatures may provide too much (authentication *and* non-repudiation)

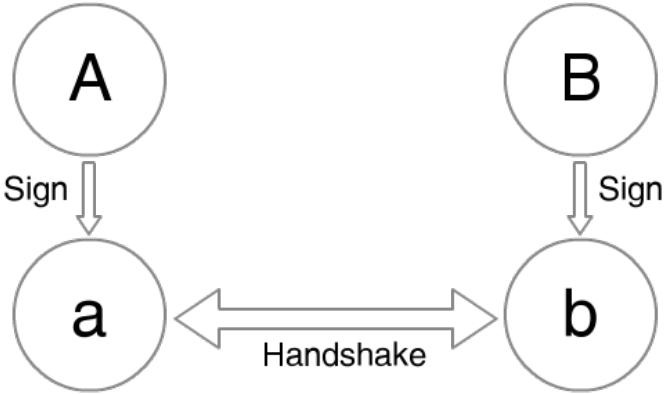
Off-the-record (OTR) protocols allow *repudiation*

OTR (Idea)

$$S_A(T_A) \tag{1}$$

$$S_B(T_B) \tag{2}$$

$$HKDF(DH(T_A, T_B)) \tag{3}$$



OTR (Real)

The OTR protocol protects the above KX by wrapping it inside another ephemeral key exchange:

$$K_1 := DH(T_A^1 || T_B^1) \quad (4)$$

$$E_{K_1}(S_A(T_A^2)) \quad (5)$$

$$E_{K_1}(S_B(T_B^2)) \quad (6)$$

$$K_2 := HKDF(DH(T_A^2, T_B^2)) \quad (7)$$

$$(8)$$

To achieve forward secrecy, OTR keeps rolling out new keys $T_{A,B}^i$. To improve deniability, OTR publishes the old MAC keys once the conversation progresses.

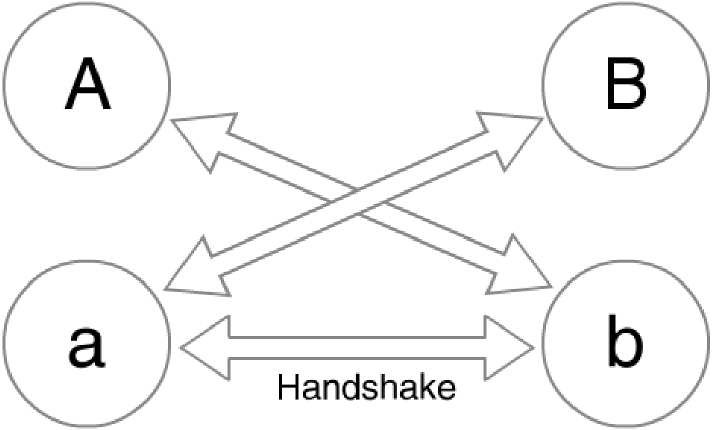
Is OTR deniable?

Is OTR deniable?

Both parties still have proof that they communicated: $S_X(T_X)$!

3DH (Trevor Perrin)

A: $K = HKDF(DH(T_a, T_B)||DH(T_a, B)||DH(a, T_B))$
B: $K = HKDF(DH(T_A, T_b)||DH(T_A, b)||DH(A, T_b))$



A Message from God (Dominic Tarr)

With 3DH, what happens if Alice's private key (a, T_a) is compromised?

A Message from God (Dominic Tarr)

With 3DH, what happens if Alice's private key (a, T_a) is compromised?

M: $K = HKDF(DH(T_a, T_G)||DH(T_a, G)||DH(a, T_G))$
A: $K = HKDF(DH(T_a, T_G)||DH(T_a, G)||DH(a, T_G))$

Forward secrecy

What happens if your private key is compromised
to your *past* communication data?

Static keys vs. ephemeral keys

Diffie-Hellman with:

- static keys allow authenticated encryption without signatures
- ephemeral keys protect against replay attacks and provide forward secrecy