

# BTI 4201: From Symmetric Encryption to Secure Channels

Christian Grothoff

Berner Fachhochschule

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# Learning Objectives

Example: Attack on CBC Stateful IV

Beyond IND-CPA

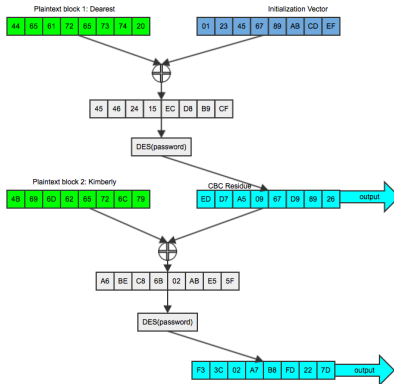
Real-world use of cryptographic primitives (exercise)

Symmetric key establishment protocols

Secure channels

## Part I: Attack on CBC

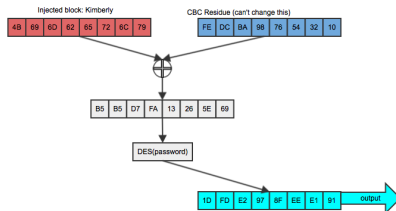
# Attacking CBC stateful IV (1/5)<sup>1</sup>



Goal: confirm "Kimberly" was sent!

## Attacking CBC stateful IV (2/5)

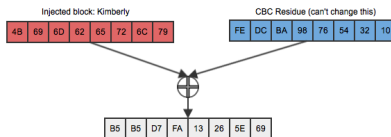
Setup: Get oracle to encrypt “Kimberly”:



Given random CBC residue, this does not help.

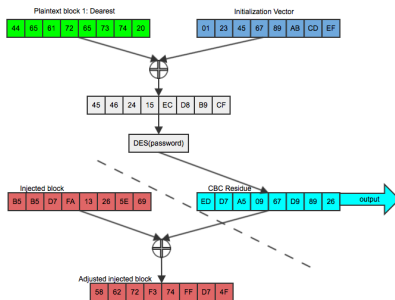
# Attacking CBC stateful IV (3/5)

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



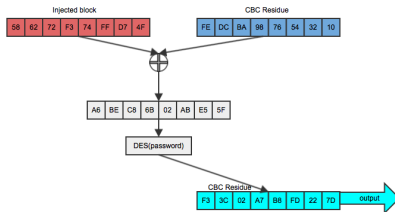
# Attacking CBC stateful IV (4/5)

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 encryption 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  $\text{enc}(k, M_b^i)$ ) for sequences of messages  $M_{0,1}^i$ ).

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

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

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

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!**

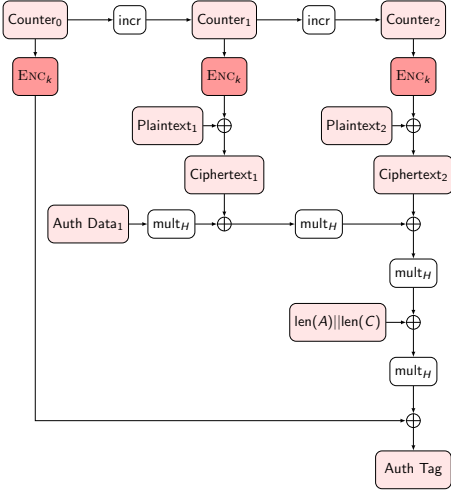
## Real-world security

- ▶ Schemes providing authenticated encryption are IND-CCA secure.
- ▶ For details, see presentation linked from course Web site at

<https://grothoff.org/christian/teaching/2023/4201/>

## 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.tgz`) 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

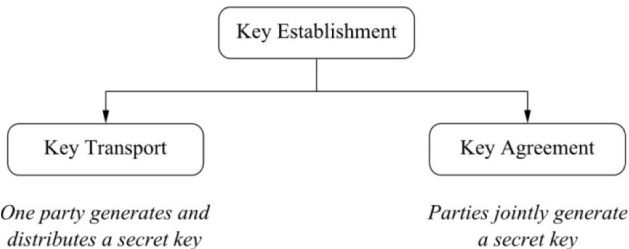
- ▶ *Key establishment* is realized by using *protocols* whereby a shared secret becomes available to two or more parties, for subsequent cryptographic use.
- ▶ Until now, we have been discussing non-interactive crypto primitives, in the following we look at crypto protocols.
- ▶ It is *even harder* 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



## 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...**

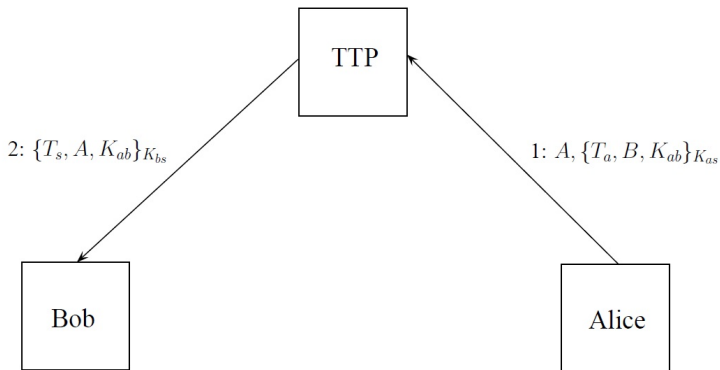
## Neumann-Stubblebine

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



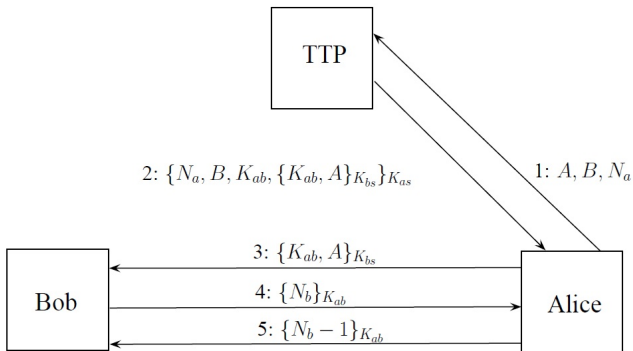
## Wide-Mouth Frog protocol

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.



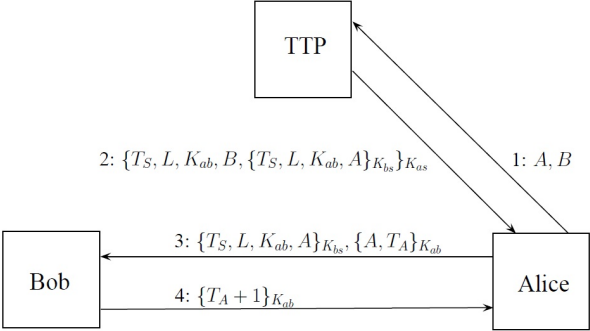
# Needham-Schroeder protocol



## 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.

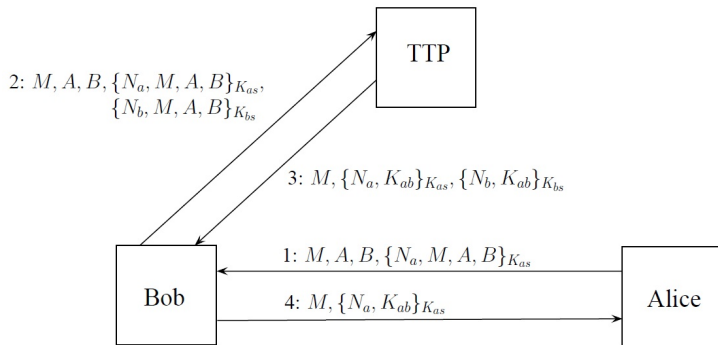
# Kerberos



# 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

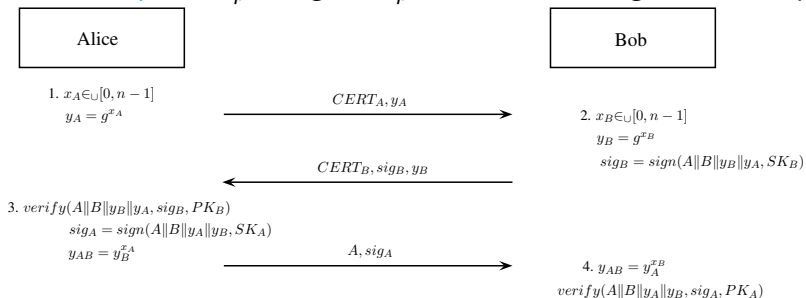


## Otway-Rees protocol

- ▶ 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  $g^n \equiv 1 \pmod p$



- ▶ 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](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](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)

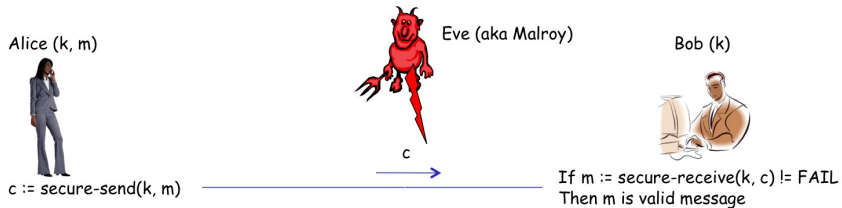
**Break**

## 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 ( $msgsnt \geq MAX_{MSGs}$ ) THEN RETURN  $\perp$   
   $c := ENC(k_E, m)$   
   $\tilde{m} := msgsnt || LENGTH(c) || c$   
   $t := MAC(k_M, \tilde{m})$   
  SEND( $\tilde{m} || t$ )  
   $msgsnt := msgsnt + 1$   
}
```

## Secure channel - Secure receive

```
secure-receive( $C, k_E, k_M$ ) {  
  STATIC  $msgrcvd := 0$   
  ( $msgsent, len, c, t$ ) =  $PARSE(C)$   
  IF ( $t \neq MAC(k_M, msgsent || len || c)$ ) THEN RETURN  $\perp$   
  IF ( $msgsent \leq msgrcvd$ ) THEN RETURN  $\perp$   
   $m := DEC(k_E, c)$   
   $msgrcvd := msgsent$   
  RETURN  $m$   
}
```



## Remarks

- ▶ The *freshness property* based on counters guarantees the following: If  $m_1, m_2, \dots, m_n$  denote the messages sent using `secure-send()`, then `secure-receive()` can guarantee that the messages  $m_1, m_2, \dots, m_n$  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-recv()` 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](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)

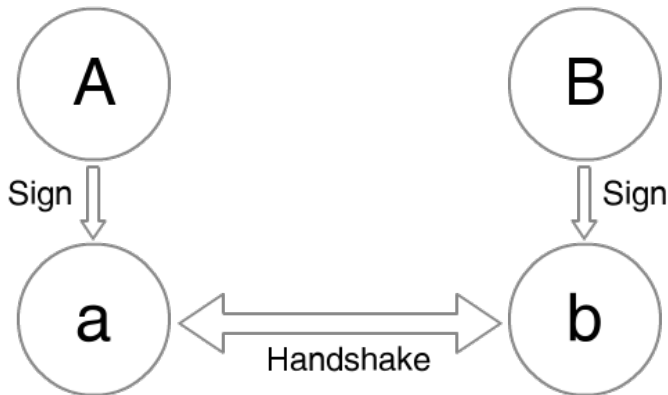
Off-the-record (OTR) protocols allow *repudiation*

# OTR (Idea)

$$S_A(T_A) \quad (1)$$

$$S_B(T_B) \quad (2)$$

$$HKDF(DH(T_A, T_B)) \quad (3)$$



## 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?

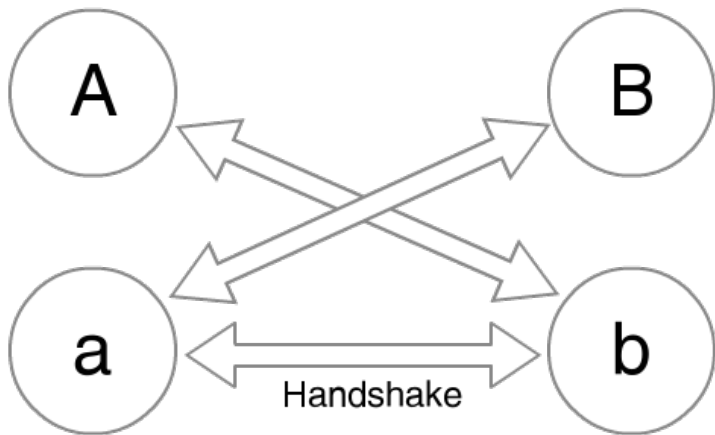
Is OTR deniable?

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

## 3DH (Trevor Perrin)

A:  $K = \text{HKDF}(\text{DH}(T_a, T_B) \parallel \text{DH}(T_a, B) \parallel \text{DH}(a, T_B))$

B:  $K = \text{HKDF}(\text{DH}(T_A, T_b) \parallel \text{DH}(T_A, b) \parallel \text{DH}(A, T_b))$



## 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?

$$M: K = \text{HKDF}(\text{DH}(T_a, T_G) \parallel \text{DH}(T_a, G) \parallel \text{DH}(a, T_G))$$

$$A: K = \text{HKDF}(\text{DH}(T_a, T_G) \parallel \text{DH}(T_a, G) \parallel \text{DH}(a, T_G))$$

## 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