CSE 127 Computer Security
Stefan Savage, Spring 2019, Lecture 7

Cryptography I: Primitives
based on slides by Kirill Levchenko
Cryptography: A Simple Example

- Alice, Bob, Eve in a classroom like this one
- Alice and Bob can pass notes ... via Eve
A Simple Example

- Alice wants to communicate to Bob whether or not she will work with him on CSE 127 Assignment 3
  - Think of this as one bit of information: “yes” or “no”

- Alice does not want Eve to know this
  ... but Eve can observe every message between them
A Simple Example

- How can Alice communicate with Bob without Eve knowing her answer?
- How can Bob know that the message is really from Alice without Eve being able to modify or spoof it?
Cryptography

- Cryptography provides mechanisms for enforcing confidentiality and integrity across time and space controlled by an adversary.

- Very broad subject.

- We focus primarily on using it as a tool in designing secure systems.
  - CSE107/207 goes deeper into design of compound primitives and security protocols
Motivation

- Two parties want to communicate securely
  - Secrecy: no one else can read messages
  - Integrity: messages cannot be modified
  - Authenticity: parties cannot be impersonated

- Example: Military orders
  - Enemy can’t know what the orders say
  - Enemy can’t modify the orders
  - Enemy can’t send fake orders
Setting

- Alice and Bob communicate by sending messages
Setting

- Alice and Bob communicate by sending messages
- Eve can read, create, modify, or block messages
- Attacker model determines Eve’s control of the channel between Alice and Bob
  - **Passive** attacker: can read only
  - **Active** attacker: can read, create, and possibly modify, block
  - **Man-in-the-middle (MitM)** attacker: can read, create, modify, block
A Simple Example

- Let’s say Alice and Bob pre-agree on a secret code:
  - “eagle”: “yes”
  - “snake”: “no”

- Alice sends message “eagle”
  - Bob knows this means yes
  - Eve learns nothing because she doesn’t know the code
A Simple Example

▪ What if Eve knows Alice and Bob have a secret code?
  – ... that the secret code is a pair of code words?
  – ... that the two code words are “eagle” and “snake”?

▪ Eve learns nothing even if she knows everything except which code word means “yes” and which means “no”

▪ Does this scheme provide confidentiality?
  – Only for a single message!

▪ Integrity? Authenticity?
The Basics

- Know your threat model!
- Know whether you need to protect *confidentiality*, *integrity*, or both.

*Confidentiality and integrity are protected by different cryptographic mechanisms!*

*Having one does not imply the other!!!*
The Basics

- Know your threat model!
- Know whether you need protection against a passive or active/MitM adversary.

*Systems that are secure against the former may not be secure against the latter.*
Encryption

- We usually want to encrypt more than one bit of information
  - In general — binary string of arbitrary length
  - Cipher: mechanical algorithm for transforming plaintext to/from ciphertext

- Plaintext \((m)\): unencrypted message to be communicated
  - From now on, assume this is a binary string

- Ciphertext \((c)\): encrypted version of message
  - Also a binary string (may not be same length as plaintext)

\[
c = E(m)
\]
\[
m = D(c)
\]
One-Time Pad

- We can achieve perfect secrecy if we XOR plaintext with a random stream of bits known only to Alice and Bob
- Why?

\[ c = m \oplus r \]

Plaintext (a binary string)

Random binary string of the same length as plaintext
One-Time Pad

- For a given ciphertext, every plaintext is equally probable
  - Probability taken over random choice of pad $r$

- Eagle-Snake protocol as a one-time pad:
  - Plaintext: yes $\to 1$, no $\to 0$
  - Ciphertext: “eagle” $\to 1$, “snake” $\to 0$
  - If $r = 0$: “eagle” = yes, “snake” = no
  - If $r = 1$: “eagle” = no, “snake” = yes

$$c = m \oplus r$$
One-Time Pads

- Perfect secrecy.
  - Used when perfect secrecy is necessary.
  - Requires a lot of pre-arranged secrets.
  - Each pad can only be used once.
    - Why?

- No integrity or authenticity.

Computational Cryptography

- Sharing large secrets is impractical.

- Modern cryptographic systems depend on small(-er) secrets.

- But, if the pre-arranged secret is smaller than the message, then not all plaintexts are equally probable.
  - Ciphertext reveals some information about plaintext.

- Practical cryptography has to sacrifice perfect secrecy.
  - It’s no longer impossible to learn anything about the plaintext from the ciphertext
    ... just computationally impractical for the adversary without the secret
    ... we hope
Computational Cryptography

- **Kerckhoffs’s Principle**: A cryptosystem should be secure even if everything about the system, except the [secret] key, is public knowledge.

- (related) Shannon’s Maxim: “the enemy knows the system”,
  - i.e., “one ought to design systems under the assumption that the enemy will immediately gain full familiarity with them”

- Assume all details of the algorithm are public.
  - **Only the key is secret**.
  - No reliance on “security through obscurity”.

Cryptographic Primitives

- **Symmetric** Cryptography
  - Alice and Bob share a *secret key* that they use to secure their communications.
  - Secret keys are random bit-strings.
  - aka Secret-Key or Shared-Key Cryptography.
Cryptographic Primitives

- **Asymmetric** Cryptography
  - Each subject has two keys: Private and Public
  - *Public keys* can be used by anyone for “unprivileged” operations
    - Encrypt message for intended receiver. Verify signature.
  - *Private keys* are secret and used for “privileged” operations
    - Decrypt message. Sign message.
  - Public and private key parts are related in algorithm-dependent way.
    - Can't just pick a random bit-string as your key as with symmetric keys.
    - Need a key-generation function.
  - aka Public-Key Cryptography
How Does It Work?

- Goal: learn how to use cryptographic primitives correctly
  - We will treat them as a black box that mostly does what it says

- To learn what’s inside black box take CSE 107/207, Number Theory, etc.

- Avoid making your own crypto at all costs!
  - This often fails, even when very smart people do it
How Does It Work?

- Symmetric cryptographic primitives [atomic]:
  1 part arcane magic and folk superstition +
  2 parts bitter experience of past failures
  - When a primitive gets broken — move on to another one
  - NIST developing SHA-3 for when SHA-2 is broken

- Asymmetric cryptographic primitives [atomic]:
  based on computational complexity of certain problems
  - Breaking one means breakthrough in solving hard problem
  - Have weathered the test of time better
Cryptographic Primitives

- **Encryption**: provides confidentiality, without integrity protection.
  - Formally: adversary can’t* distinguish which of the two plaintexts were encrypted without knowing the [secret] key.
    - * within practical computational bounds.
  - Does not provide integrity protection!
    - Changes to ciphertext may lead to predictable changes in decrypted plaintext.
    - Need separate message authentication.
Cryptographic Primitives

- **Message Authentication Code** (symmetric) and **Digital Signature** (asymmetric): provides integrity, without confidentiality.
  - Formally: adversary can’t* generate a valid MAC or signature for a new message without knowing the [secret] key.
    - * within practical computational bounds.
  - Does not provide confidentiality!
    - Need separate message encryption.
Brute Force

▪ All modern cryptography is breakable by brute force given enough knowledge about plaintext

▪ Try to decrypt ciphertext with every possible key until expected plaintext is found

▪ Attack complexity proportional to size of key space
  – Keys are just binary strings, size of key space expressed in bits
  – 64-bit key requires $2^{64}$ decryption attempts
Good News and Bad News

▪ “Encryption works. Properly implemented strong crypto systems are one of the few things that you can rely on.”
  – Edward Snowden

▪ “Crypto will not be broken. It will be bypassed.”
  – Adi Shamir
Hash Functions

- A cryptographic hash function maps arbitrary length input into a fixed-size string and has the following properties:

  - **Pre-image Resistance**
    - Given a specific hash function output, it is impractical to find an input (pre-image) that generates the given output.

  - **Collision Resistance**
    - It is impractical to find two inputs that hash to the same output.

\[ h = H(m) \]
Hash Functions

- SHA-2: Secure Hash Algorithm 2
  - Designed by NSA
  - Output: 224, 256, 384, or 512 bits
  - Recommended for use today
    - Do not use older, obsolete SHA-1 or MD5!!!
Hash Functions

- SHA-3: Secure Hash Algorithm 3
  - Result of NIST SHA-3 contest (original candidate name: Keccak)
  - Output: arbitrary size
  - Replacement if SHA-2 broken
Message Authentication Codes (MACs)

- Goal: Validate message integrity based on a shared secret.
  - How can Bob know that the message is really from Alice and has not been modified or spoofed by Eve?

- MAC: Message Authentication Code
  - Function of message and secret key.
  - Impractical to forge without knowing the key.
    - i.e. to come up with a valid MAC for a new message.

\[ a = MAC_k(m) \]
Message Authentication Codes (MACs)

- Alice sends $m||a$.
- Bob uses his copy of the secret key $k$ to independently compute $a'$ on $m$ and compare to the one received.
- Note, no confidentiality guarantees.

$$a = MAC_k(m)$$
Message Authentication Codes (MACs)

- MACs can be constructed out of hash functions or ciphers.
- HMAC: MAC based on hash function
  - HMAC-SHA2: HMAC construction using SHA-2
  - What’s wrong with just using a hash of the message $H(m)$ as a MAC?
  - What about $H(k||m)$?
  - Don’t make up your own MAC constructions!!!
- Cipher-based MACs covered later.

$$HMAC(k, m) = H((k'\oplus \text{opad}) || H((k'\oplus \text{ipad}) || m))$$
Symmetric Encryption

\[ c = E_k(m) \]

\[ m = D_k(c) \]
Symmetric Ciphers

- **Stream cipher**: generate a pseudorandom string of bits as long as the plaintext and XOR with plaintext
  - Pseudorandom: hard to tell apart from random
    - Hard: computationally hard to distinguish from random
  - Can’t reuse pad (remember one-time pad!)

- **Block cipher**: Encrypt/decrypt fixed-size blocks of bits
  - Need a way to encrypt longer or shorter messages
Cryptographic Randomness

- Cryptography relies on good random numbers.
- What is random?
  - Uniformly distributed?
  - Unpredictable?

- **Cryptographically Secure Pseudo-Random Number Generator (CSPRNG)** requirements:
  - Given the first $n$ bits of a random sequence, can’t* predict $(n+1)^{th}$ bit with probability better than $\frac{1}{2}$.
  - If internal state has been revealed (or guessed correctly), can’t* reconstruct the stream of random numbers prior to the revelation.
  - * within practical computational bounds.

```c
int getRandomNumber()
{
    return 4; // chosen by fair dice roll.
    // guaranteed to be random.
}
```
Cryptographic Randomness

- Cryptography relies on good random numbers.
  - Very common
  - Pay attention to randomness requirements when using cryptographic APIs.

- Need to know which library/system APIs return random numbers suitable for cryptographic use.
  - Do not seed PRNGs (exclusively) with low-entropy inputs, like date/time or process id.
Stream Ciphers

- Produces a pseudorandom **keystream**
  - Each key results in a unique, pseudorandom keystream
- To encrypt, keystream is XORed with plaintext
- To decrypt, keystream is XORed with ciphertext
- Example: ChaCha20
  - 256-bit keys
  - 96-bit *nonce (also called Initialization Vector)*
Stream Ciphers

- Insecure if key used more than once
  - Need mechanism to generate one-time keys from master
  - Or a random initialization value on each use

\[
\begin{array}{c}
\text{Key (} k \text{)} \\
\text{Stream Cipher} \\
\text{Initialization Vector (} IV \text{)} \\
\text{keystream} \quad 1011100100001010 \ldots \\
\oplus \\
\text{plaintext} \quad 0110110000101011 \ldots \\
\text{ciphertext} \quad 1101010100100001 \ldots
\end{array}
\]
Block Ciphers

- Block ciphers operate on fixed-size blocks
  - Common sizes: 64 and 128 bits
- A block cipher is typically a combination of permutation
  - Each input mapped to exactly one output
- ... and substitution
  - Some codewords mapped to other codewords
- Typically in multiple rounds
- Example: AES: Advanced Encryption Standard
  - Replacement for DES based on Rijndael cipher
  - Key size: 128, 192, 256 bits
  - Block size: 128 bits

[Diagram of block cipher encryption]

https://en.wikipedia.org/wiki/Block_cipher_mode_of_operation
Block Ciphers

- Block ciphers encrypt/decrypt fixed-size blocks.

- How to encrypt a message shorter than a block?
  - Pad plaintext to full block size
  - Must be able to unambiguously distinguish padding from plaintext
  - Don’t make up your own padding scheme!

- How to encrypt a message longer than a block?
  - “Chain” individual blocks
  - Methods of chaining are known as *modes of operation*. 
Electronic Code Book (ECB) Mode

- Naïve mode of operation: encrypt each block separately
  - As if looking it up in a code book. Known as Electronic Code Book (ECB) mode.

- **DO NOT USE!!!**
  - why?

[Diagram of ECB mode encryption]

https://en.wikipedia.org/wiki/Block_cipher_mode_of_operation
Electronic Code Book (ECB) Mode

- What if we encrypt this bitmap picture in ECB mode?
Electronic Code Book (ECB) Mode

- What if we encrypt this bitmap picture in ECB mode?
Cipher Properties

- Encryption and decryption are inverse operations:
  \[ m = D_k(E_k(m)) \]

- Informally: ciphertext reveals nothing about plaintext
  - More formally: can’t distinguish which of two plaintexts were encrypted without key
  - Is ECB secure under this definition?
    - \( E_k(m_o || m_o) \) is trivially distinguishable from \( E_k(m_o || m_t) \)

- Non-property: integrity
  - May be possible to change decrypted plaintext in known way
  - Need separate message authentication
Block Cipher Modes of Operation

- How else can we “chain” multiple blocks together?
- Padding
- Initialization Vector (iv)
- Tradeoffs
  - Parallelizable
  - Random access
  - Need decryption function?
Cipher Block Chaining (CBC) Mode

- XOR ciphertext block into next plaintext
- Use random IV
  - Subtle attack possible if attacker knows IV, controls plaintext

https://en.wikipedia.org/wiki/Block_cipher_mode_of_operation
Counter (CTR) Mode

- Encrypt successive counter values and XOR result with plaintext
- Block cipher becomes stream cipher

https://en.wikipedia.org/wiki/Block_cipher_mode_of_operation
Key Hygiene

- Do not use same key with different modes
  - (or for separate encryption and authentication operations)
Authenticated Encryption

- Many real-world systems were broken because encryption and authentication were combined in insecure ways.

- **Authenticated encryption** simultaneously provides confidentiality, integrity, and authenticity.
  - Designed to work with single key.

- Rule of thumb: If you have to select a symmetric-key cipher suite (in the next year), use one of the following:
  - **AES-GCM** (Galois/Counter Mode)
  - **ChaCha20+Poly1305AES**
Limitations of Symmetric Cryptography

- We can now protect confidentiality and integrity of messages without sharing very large secrets.
- But...
- We still need to establish pairwise keys
Asymmetric Cryptography

- aka *Public Key Cryptography*
- Two separate keys: *public key* and *private key* (secret)
- Public key known to everyone.
  - Given Alice’s public key
    - Anyone can send an encrypted message to Alice.
    - Anyone can verify that a message was signed by Alice.
- Private key is kept secret.
  - Only Alice can decrypt messages encrypted with her public key.
  - Only Alice can sign messages so that they can be verified with her public key.
Asymmetric Primitives

- Confidentiality: encryption and decryption.
- Integrity and Authenticity: signing and verification.
Asymmetric Cryptography

- Each subject has a public and private key.
- Keys related to each other in algorithm-dependent way.
  - Can’t just pick a random string as your key as with symmetric
  - Need a key-generation function
- Notation:
  - $K$: public key
  - $k$: private key
  - $r$: random bits.

$$(K, k) \leftarrow \text{Keygen}(r)$$
Asymmetric Encryption and Decryption

- Encryption uses public key
  \[ c = E_K(m) \]
- Decryption uses private key
  \[ m = D_k(c) \]
- Computationally hard to decrypt without private key.
- Messages are fixed size.
Asymmetric Usage

- Public directory contains everyone’s public key
- To encrypt to a person, get their public key from directory
- No need for shared secrets!
Signing and Verification

- Signing uses private key
  \[ s = S_k(m) \]
- Verification uses public key
  \[ V_K(m,s) \]
- Computationally hard to sign without private key.
- Messages are fixed size.
Asymmetric Encryption

- ElGamal encryption (1985)
  - Based on Diffie-Helman key exchange (1976)
  - Computational basis: hardness of discrete logarithms

- RSA encryption (1978)
  - Invented by Rivest, Shamir, and Adleman
  - Computational basis: hardness of factoring
Asymmetric Signatures

- **DSA: Digital Signature Algorithm (1991)**
  - Closely related to ElGamal signature scheme (1984)
  - Computational basis: hardness of discrete logarithms

- **RSA signatures**
  - Invented by Rivest, Shamir, and Adleman
  - Computational basis: hardness of factoring
### Key Sizes

#### Table 2: Comparable strengths

<table>
<thead>
<tr>
<th>Security Strength</th>
<th>Symmetric key algorithms</th>
<th>FFC (e.g., DSA, D-H)</th>
<th>IFC (e.g., RSA)</th>
<th>ECC (e.g., ECDSA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 80</td>
<td>2TDEA&lt;sup&gt;21&lt;/sup&gt;</td>
<td>( L = 1024 ) ( N = 160 )</td>
<td>( k = 1024 )</td>
<td>( f = 160-223 )</td>
</tr>
<tr>
<td>112</td>
<td>3TDEA</td>
<td>( L = 2048 ) ( N = 224 )</td>
<td>( k = 2048 )</td>
<td>( f = 224-255 )</td>
</tr>
<tr>
<td>128</td>
<td>AES-128</td>
<td>( L = 3072 ) ( N = 256 )</td>
<td>( k = 3072 )</td>
<td>( f = 256-383 )</td>
</tr>
<tr>
<td>192</td>
<td>AES-192</td>
<td>( L = 7680 ) ( N = 384 )</td>
<td>( k = 7680 )</td>
<td>( f = 384-511 )</td>
</tr>
<tr>
<td>256</td>
<td>AES-256</td>
<td>( L = 15360 ) ( N = 512 )</td>
<td>( k = 15360 )</td>
<td>( f = 512+ )</td>
</tr>
</tbody>
</table>

https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.800-57pt1r4.pdf
Practical Considerations

- Asymmetric cryptography operations generally much more expensive than symmetric operations
- Asymmetric primitives operate on fixed-size messages
- Usually combined with symmetric for performance
  - Use asymmetric to bootstrap ephemeral secret
Typical Encryption Usage

- Generate a ephemeral (one time) symmetric secret key
- Encrypt message using this ephemeral secret key
- Encrypt ephemeral key using asymmetric encryption
- Send encrypted message and encrypted ephemeral key

- Decryption: decrypt ephemeral key, use it to decrypt message

\[(E_K(k'), E_{k'}(M))\]
Typical Signature Usage

- **Signing:** Compute cryptographic hash of message and sign it using asymmetric signature scheme
- **Verification:** Compute cryptographic hash of message and verify it using asymmetric signature scheme
Summary: Symmetric Primitives

\[ A = \text{MAC}_k(M) \]
\[ C = \text{Enc}_k(M) \]
\[ M = \text{Dec}_k(C) \]
Summary: Asymmetric Primitives

\[(K, k) \leftarrow \text{Keygen}(r)\quad (K, k) \leftarrow \text{Keygen}(r)\]

\[C = E_K(M)\quad S = S_k(M)\]

\[M = D_k(C)\quad V_K(M, S)\]
Review

- Confidentiality and integrity are protected by different cryptographic mechanisms!
  - Having one does not imply the other!!!

- Kerckhoffs’s Principle: A cryptosystem should be secure even if everything about the system, except the [secret] key, is public knowledge.

- Use existing methods and tools. If possible, use existing applications...
  - Do not descend into lower layers unless you are an expert and brought back up.
  - Same goes for implementation. Do not modify or re-implement cryptographic libraries. Minor changes can lead to catastrophic failure.
    - Even if functionality is not affected (i.e. produces “correct” results)
Additional Resources

- *Cryptography Engineering* by Niels Ferguson, Bruce Schneier, and Tadayoshi Kohno

- NIST Cryptographic Standards and Guidelines

- Cryptographic Right Answers
  - [http://latacora.singles/2018/04/03/cryptographic-right-answers.html](http://latacora.singles/2018/04/03/cryptographic-right-answers.html)

- *A Few Thoughts on Cryptographic Engineering* by Matthew Green
  - [https://blog.cryptographyengineering.com/](https://blog.cryptographyengineering.com/)
Additional Resources

- *Introduction to Modern Cryptography* by Mihir Bellare
  - AKA CSE 107/207
  - [https://cseweb.ucsd.edu/~mihir/cse107/classnotes.html](https://cseweb.ucsd.edu/~mihir/cse107/classnotes.html)
  - [https://cseweb.ucsd.edu/~mihir/cse207/classnotes.html](https://cseweb.ucsd.edu/~mihir/cse207/classnotes.html)
  - [https://cseweb.ucsd.edu/~mihir/papers/gb.html](https://cseweb.ucsd.edu/~mihir/papers/gb.html)
Next time

- Key distribution and side channels