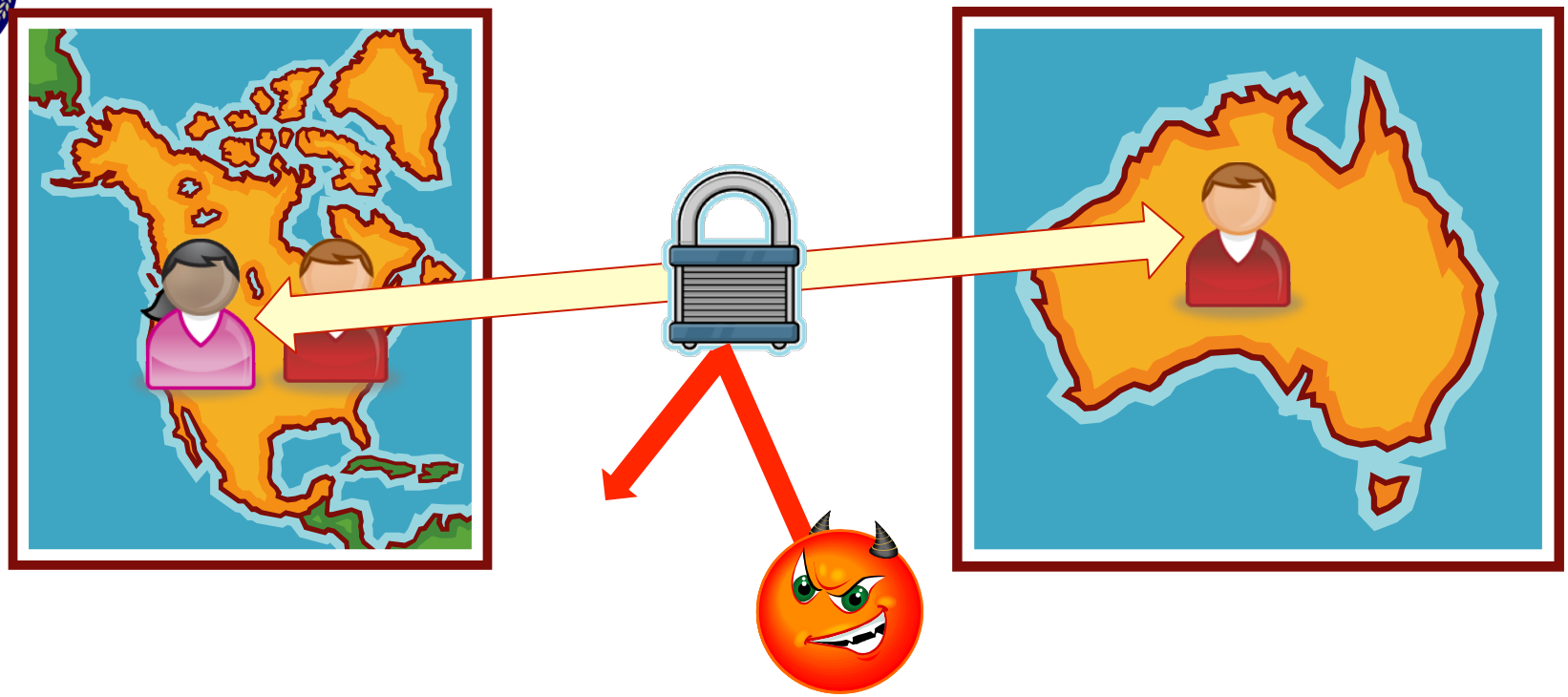
Applied Cryptography and Network Security

Adam J. Lee
adamlee@cs.pitt.edu
6111 Sennott Square

Lecture #3
January 14, 2014

University of Pittsburgh

A Motivating Scenario



How can Alice and Bob communicate over an untrustworthy channel?

Need to ensure that:

1. Their conversations remain secret (confidentiality)
2. Modifications to any data sent can be detected (integrity)

What is cryptography?

Cryptography

kryptos: hidden, secret

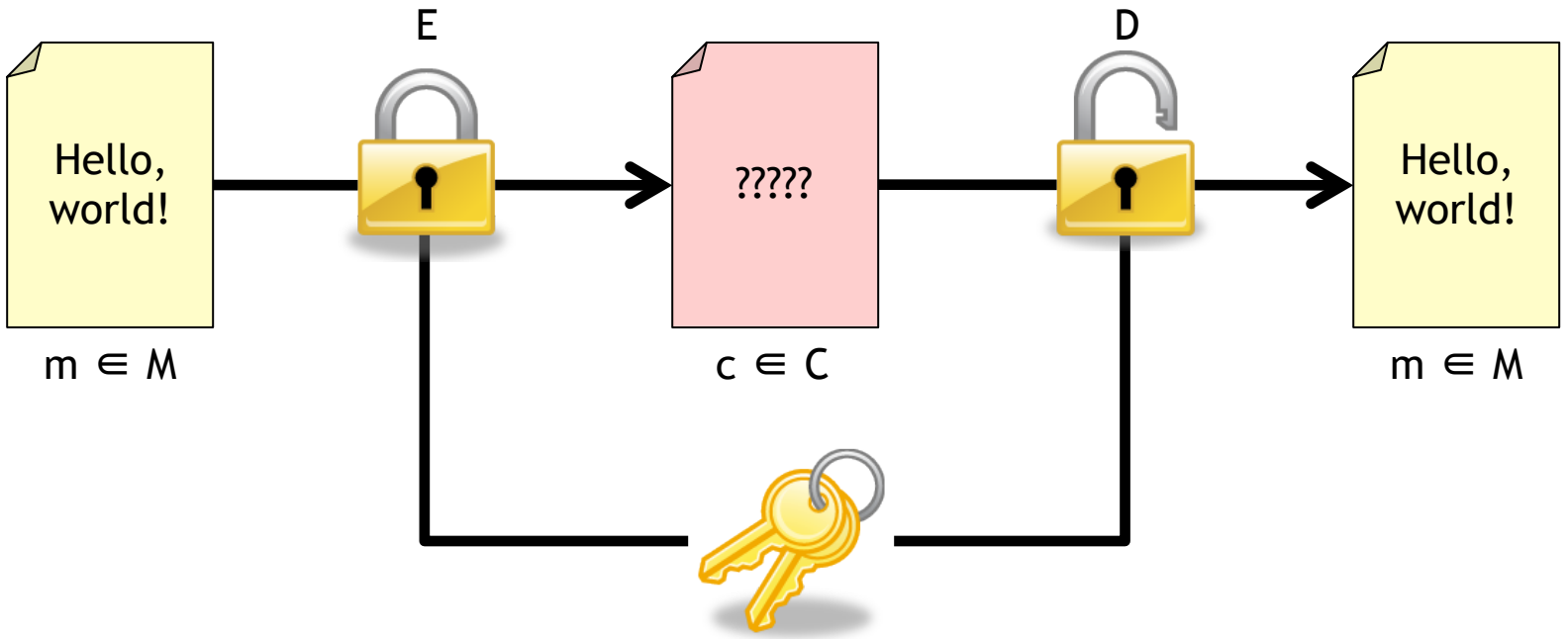
grafís: writing

Informally, cryptography is the study of methods for encoding and decoding secret messages

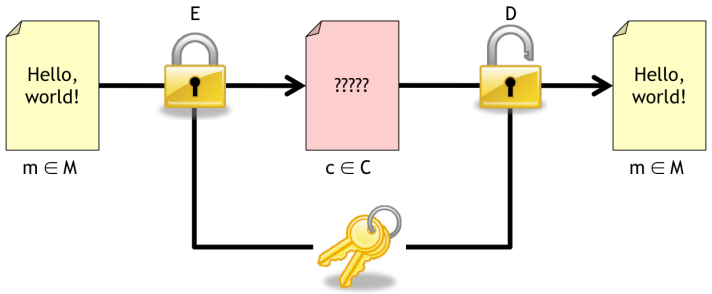
More formally…

A cryptosystem can be represented as the 5-tuple (E, D, M, C, K)

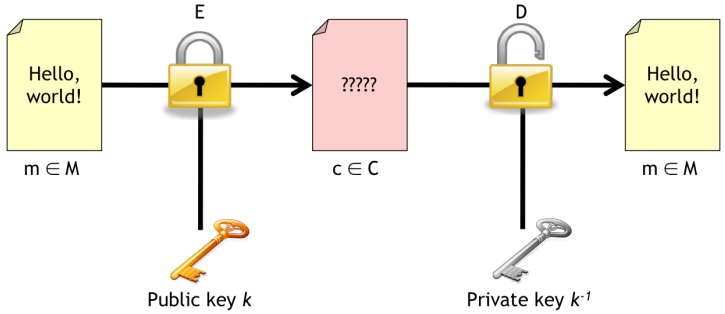
- M is a message space
- K is a key space
- $E : M \times K \rightarrow C$ is an encryption function
- C is a ciphertext space
- $D : C \times K \rightarrow M$ is a decryption function



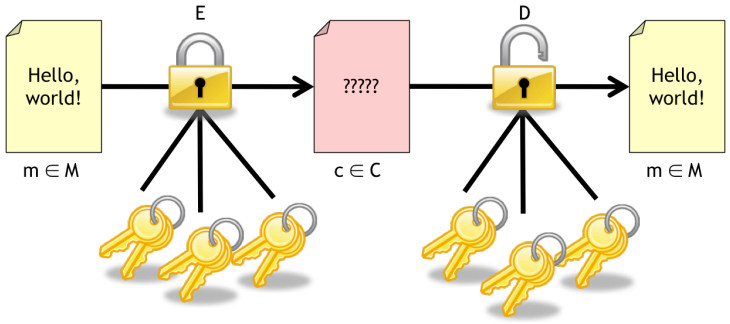
This semester, we will learn about several classes of cryptosystems



Symmetric/secret key cryptography



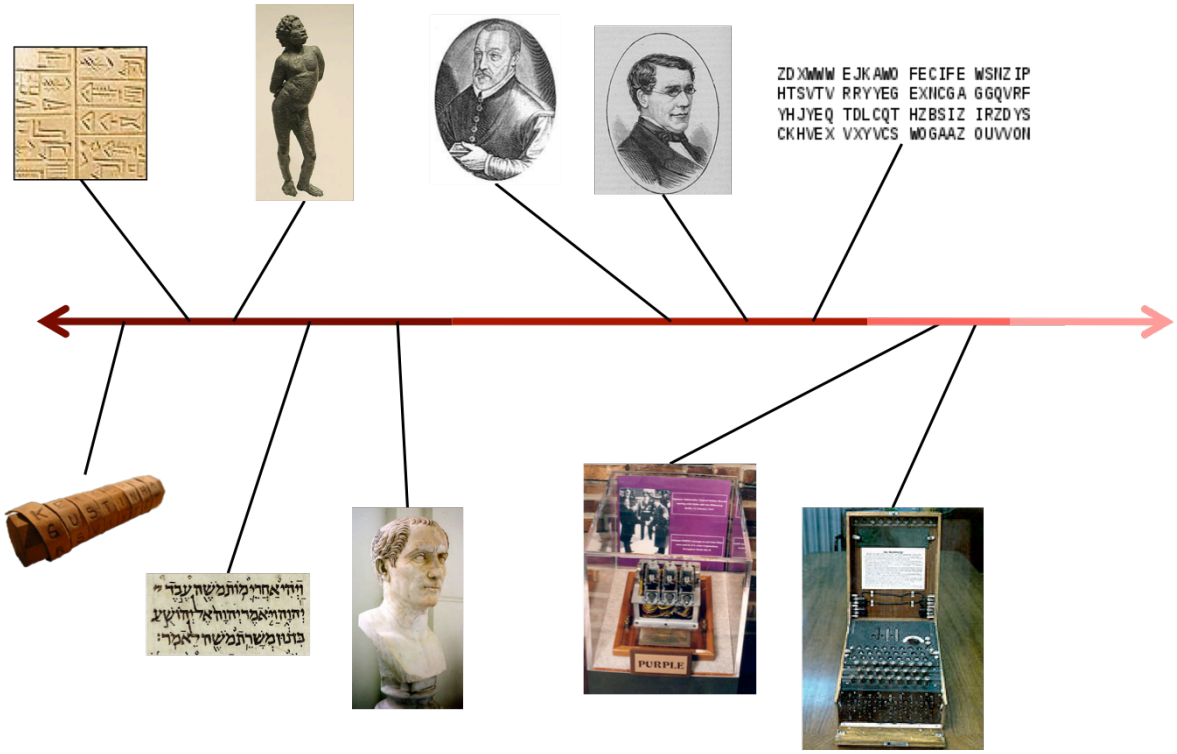
Asymmetric/public key cryptography



Threshold cryptography

Cryptography is simply a tool. Different jobs require different tools.

Roadmap



Cryptography is far from being a new field

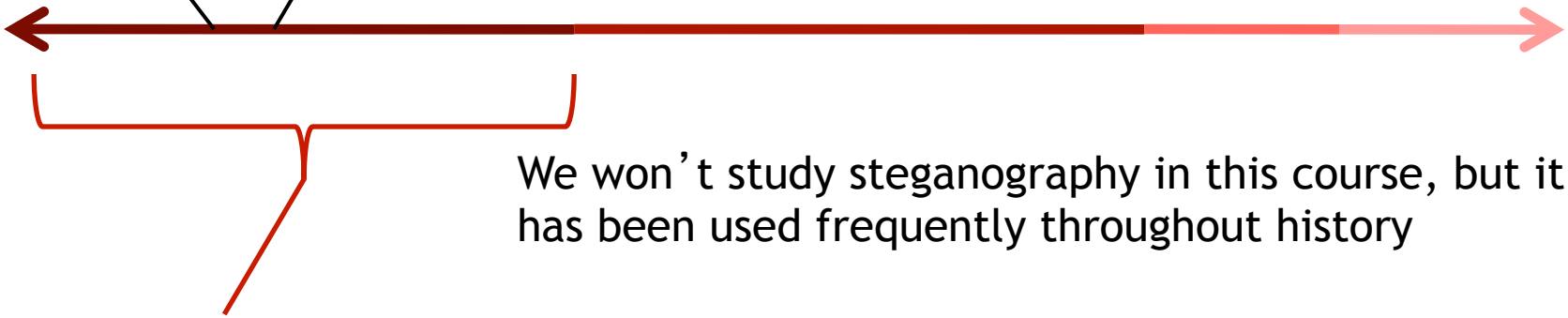
- Today, will be a history lesson of sorts
- Future lectures will focus on more recent developments

Cryptography Timeline I

Steganography deals with more literally hiding secrets

Examples from antiquity include:

- Hidden writing underneath wax tablets
- Tattoos on the heads of slaves



Ancient times (BCE)

We won't study steganography in this course, but it has been used frequently throughout history

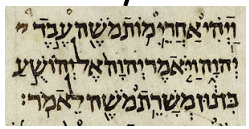
For example:

- Knots in knitting yarn, or patterns in clothes of couriers
- Invisible inks and other means of hiding text embedded in innocuous messages
- Messages embedded in JPEGs or packet delays
- …

Cryptography Timeline II

In addition to exploring steganography, ancient civilizations also developed a good number of cryptographic ciphers

While simple to break by today's standards, these ciphers nicely illustrate the basics of many modern cryptosystems



Examples include:

- Transposition ciphers
  - Scytale and rail-fence ciphers (7th century BCE)
- Substitution ciphers
  - Atbash cipher (500-600 BCE)
  - Caesar cipher (~100 BCE?)

A scytale is an ancient cryptographic tool

A transposition cipher reorders (i.e., transposes) the characters in the plaintext message that is to be encrypted

A scytale is a tool that was used in antiquity to create a primitive transposition cipher

To encrypt:

- Wrap a strip of leather or paper around the scytale
- Write the message across the strip lengthwise
- Unwrap strip and write down the characters on a sheet of paper (Why?)

To decrypt:

- Write the characters onto a strip of leather or paper
- Wrap the message strip around an identical scytale
- Read across the length of the scytale

Question: What is the key for this cipher?

The rail fence cipher is essentially a generalization of the cipher generated by using a scytale

To encrypt:

- Choose a number of "fence posts" (*f*)
- Write the message across the fence posts
- Transcribe the message by reading down each post

To decrypt:

- Set up *f* columns
- Write the first ⌈<message length> / *f*⌉ down post 1
- …
- Write last block of characters down post *f*
- Read across posts

Example: *f* = 3

ATTACK → ATT / ACK → AATCTK → ATT / ACK → ATTACK

The Atbash cipher is an early substitution cipher

Substitution ciphers substitute one or more characters in the ciphertext alphabet for one or more characters in the plaintext alphabet

The Atbash cipher is an extremely simple substitution cipher that was used by ancient Hebrew scholars

Table:

A	B	C	D	E	F	G	H	I	J	K	L	M
Z	Y	X	W	V	U	T	S	R	Q	P	O	N

Example: ATTACK → ZGGZXP

Question: What is the key for this cipher?

The Caesar cipher is another classical substitution cipher

The Caesar cipher is named after Julius Caesar, who used it to communicate with his generals

To encrypt:

- Choose a shift index *s*
- Apply the function $e(x) = x + s \bmod 26$

To decrypt:

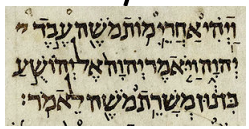
- Apply the function $d(x) = x - s \bmod 26$

Example: $s = 3$

- Encryption: ATTACK → 0 19 19 0 2 10 → 3 22 22 3 5 13 → DWWDFN
- Decryption: DWWDFN→ 3 22 22 3 5 13 → 0 19 19 0 2 10 → ATTACK

Cryptography Timeline III

ZDXWWW EJKAWO FECIFE WSNZIP
HTSVTV RRYYEG EXNCGA GGQVRF
YHJYEQ TDLCQT HZBSIZ IRZDYS
CKHVEX VXYVCS WOGAAZ OUVVON



"Medieval" cryptography further extended and improved upon the ideas developed in ancient times

Examples include:

- Vigenere cipher (1500s)
- Playfair cipher (1854)
- One-time pad (1917)

The Vigenere cipher is an improved version of the Caesar cipher

The Vigenere cipher was invented in 1553 by Giovan Battista Bellaso. It is misattributed to Blaise de Vigenere, who invented a stronger version of this cipher in the 19th century.

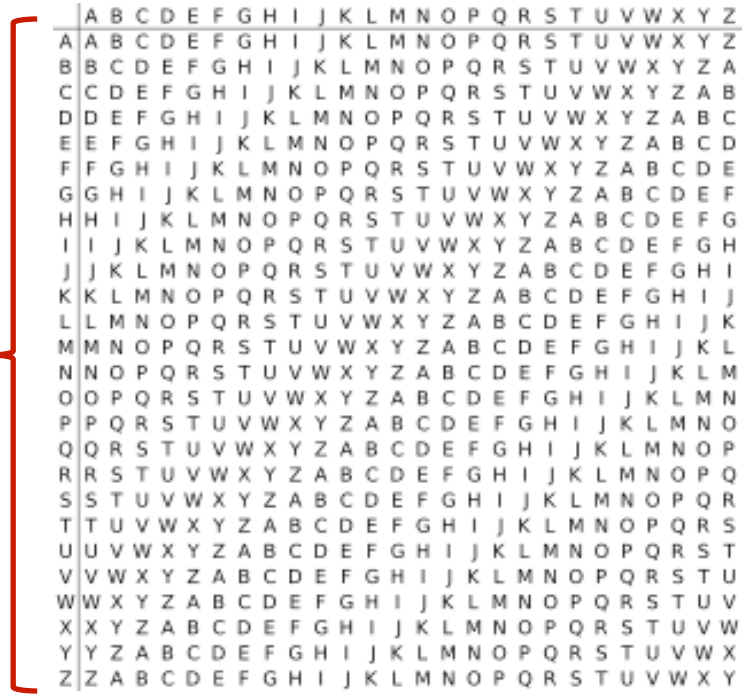
The Vigenere cipher basically uses a repeated key phrase to apply a different variant of the Caesar cipher to each plaintext letter.

Encryption and decryption can be aided by using a *tabula recta*

Example:

- Plaintext: ATTACKATDAWN
- Key: LEMONLEMONLE
- Ciphertext: LXFOPVEFRNHR

All possible Caesar ciphers



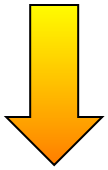
The similarity to the Caesar cipher is more readily apparent when viewed mathematically

Encryption: $e(p_i, k_i) = p_i + k_i \bmod 26$

Decryption: $d(c_i, k_i) = c_i - k_i \bmod 26$

Example:

- Plaintext: `ATTACKATDAWN` → `00 19 19 00 02 10 …`
- Key string: `LEMONLEMONLE` → `11 04 12 14 13 11 …`
- Ciphertext: `11 23 05 14 15 21 …`



`LXFOPW…`

The one-time pad is a further generalization of the Vigenere cipher

The one time pad was invented in the early 20th century as a telegraph cipher at AT&T, and saw a large number of military and diplomatic uses

How does it work?

- Choose a key that is as long as the plaintext that you wish to encrypt
- $E(p) = p \oplus k$
- $D(c) = c \oplus k$

Example: Using modular addition/subtraction instead of XOR

- Plaintext: `BUYTENSHARES`
- Key: `HIENVWKNUQCF`
- Ciphertext: `ICCGZJCUUHGX`

Note: A single ciphertext can recover any plaintext string!

- With key `LGAEMVEKRKAH`, the text `TICKLEGEORGE` can be recovered from the above ciphertext!

The Playfair cipher is a digraph substitution cipher

Digraph ciphers substitute pairs of letters—rather than single letters—for one another

The Playfair cipher was invented by Charles Wheatstone in 1854, but is named after Lord Lyon Playfair, who strongly promoted its use

Wheatstone

Playfair

To use this cipher, first build a 5x5 table using a secret keyphrase

- Write keyphrase left to right, top to bottom
- Skip any repeated letters
- Fill in any remaining letters (usually combining I/J, or skipping Q)

Example:

IHAVEADREAM →

I/J	H	A	V	E
D	R	M	B	C
F	G	K	L	N
O	P	Q	S	T
U	W	X	Y	Z

Encryption is carried out by following a few simple rules

1. Insert an X between any pair of repeated letters
   - `CLIMB A TREE → CLIMB A TREXE`
2. Break string to encrypt into pairs of letters
   - `CLIMB A TREXE → CL IM BA TR EX EX`
3. Encrypt digraphs using the table
   - If letters are on the same row, use letters to the right
   - If letters are in the same column, use letters below them
   - If letters are the corners of a box, use the other corners

This is perhaps best illustrated with an example…

Encrypting "CLIMB A TREE"

First apply rules 1 and 2: `CLIMB A TREE → CL IM BA TR EX EX`

```
I/J H A V E
 D  R M B C
 F  G K L N
 O  P Q S T
 U  W X Y Z
```

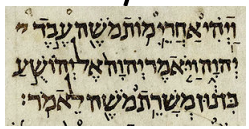
Now, we can use the 5x5 code box to encrypt each digraph:

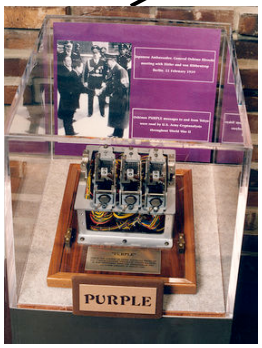
`CL IM BA RE EX EX →`

To decrypt, simply apply the rules in reverse

Cryptography Timeline IV

ZDXWWW EJKAWO FECIFE WSNZIP
HTSVTV RRYYEG EXNCGA GGQVRF
YHJYEQ TDLCQT HZBSIZ IRZDYS
CKHVEX VXYVCS WOGAAZ OUVVON





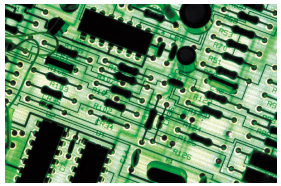
Unfortunately, classical cryptosystems are easy to break

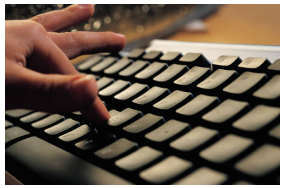
These (and other) algorithms were designed in a time when people were computers trying to break ciphers, and few people used cryptography

What does this mean?

- Relatively small keyspaces were OK
- Relying on an algorithm remaining secret was a less dubious assumption

Fast forward: 20th century





Widespread mechanical and digital computing device and pervasive communication invalidate the above assumptions

- Machines can systematically try all possible keys
- Security by obscurity breaks down

How can we define and measure the security of a cryptosystem?

When studying cryptosystems, we are generally concerned with three primary classes of attack

Hardest for the attacker

In a ciphertext only attack, the adversary is assumed to have stored some amount of ciphertext that can be analyzed offline to attempt to break the cipher.

In a known plaintext attack, the adversary is assumed to have collected some number of (plaintext, ciphertext) pairs that can be used to guide his attempt at breaking the cipher.

In a chosen plaintext attack, the adversary has access to the cryptographic algorithm and may encrypt anything that he chooses. The resulting (plaintext, ciphertext) pairs are then used to guide attempts at breaking the cipher.

Hardest to defend against

Despite the fact that ciphertext-only attacks are the hardest to carry out, most classical cryptosystems can be broken this way

Breaking the Caesar cipher is trivial

- Only 26 possible keys to try
- Alternately, frequency analysis can be used

The rail fence cipher is also easy to break

- We know that there are most likely less than <message length>/2 rails. For most messages, a computer can break this very quickly.
- *n*-gram frequency analysis can also be used

The Vigenere cipher also falls to this type of attack

Observation: The Vigenere cipher is really just *k* different Caesar ciphers, where *k* is the length of the key used

Therefore, breaking the Vigenere cipher is a two-step process:

1. Figure out *k*
2. Break each of the cipher's *k* Caesar ciphers

Breaking a Caesar cipher is easy, so the "hard" part is figuring out the key length, k… How do we do this?

Kasiski examination is one method of finding the key length of a Vigenere cipher

Intuition: Given enough ciphertext, short words like "the" will appear encrypted the same way multiple times.

The distance between these repeated blocks of ciphertext is typically a multiple of the keyword length!

Example:

- Plaintext: CRYPTO IS SHORT FOR CRYPTOGRAPHY
- Key: ABCDAB CD ABCDA BCD ABCDABCDABCD
- Ciphertext: CSASTP KV SIQUT GQU CSASTPIUAQJB

Note that finding multiple repeated blocks of ciphertext will make this attack even easier (Why?)

Known plaintext and chosen plaintext attacks simplify things even further…

Think about it:

- **Caesar cipher:** A match between a single pair of plaintext and ciphertext characters reveals the shift index *s*
- **Rail fence cipher:** Given a long enough string of ciphertext corresponding to a known piece of plaintext, *f* can be learned
- **Vigenere cipher:** If the length of the matching plaintext and ciphertext strings exceeds the key length *k*, the key can be easily recovered

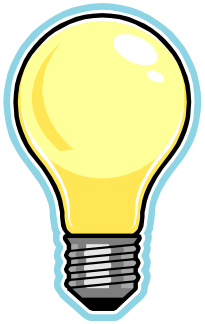
---

As a result, evaluating a cryptosystem typically involves making sure that it resists chosen plaintext attacks. As we will see later, even stronger attacker models are often assumed.

In short: Assume that your attacker knows as much as possible!

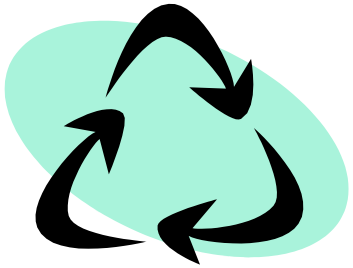
Although the one-time pad offers protection against these attacks, it is not a panacea

Potential Pitfalls:



Predictable Key Pads

- If the key can be guessed with high probability, it is no good!
- Note: The Allies broke a German version of the OTP this way during WWII
- Can break implementation even if the algorithm has perfect security!



Key Reuse

- Given $p_1 \oplus k$ and $p_2 \oplus k$, we can recover $p_1 \oplus p_2$
- If p_1 and p_2 have some predicable structure, this can leak information
- If we can choose one of the p_is, we can recover k!

Key Distribution

- We need as much key material as we have material to transmit!
- Inefficient if much communication is to occur...

Moving Forward…

In the short term:

- How do we build secure cryptosystems with short, manageable keys?
- How can we develop an assurance that these cryptosystems are reasonably strong?

In the medium term:

- Different tools for different jobs
- Choosing the right tool

In the long term:

- Applications of cryptography

Next lecture: The basics of modern symmetric key cryptography

Groups!

Threat Models?

Example: Intra-office Protected Subnet

The system will be deployed within a small organization to facilitate file sharing between members of the technical staff. All servers will be operated on a subnet that can only be accessed from a wired connection inside of the office building, and only machines whose MAC addresses have been explicitly authorized can connect to these wired ports. As such, it is assumed that only members of the technical staff can listen to communications on this subnet, and that servers on this subnet cannot communicate with the broader Internet.