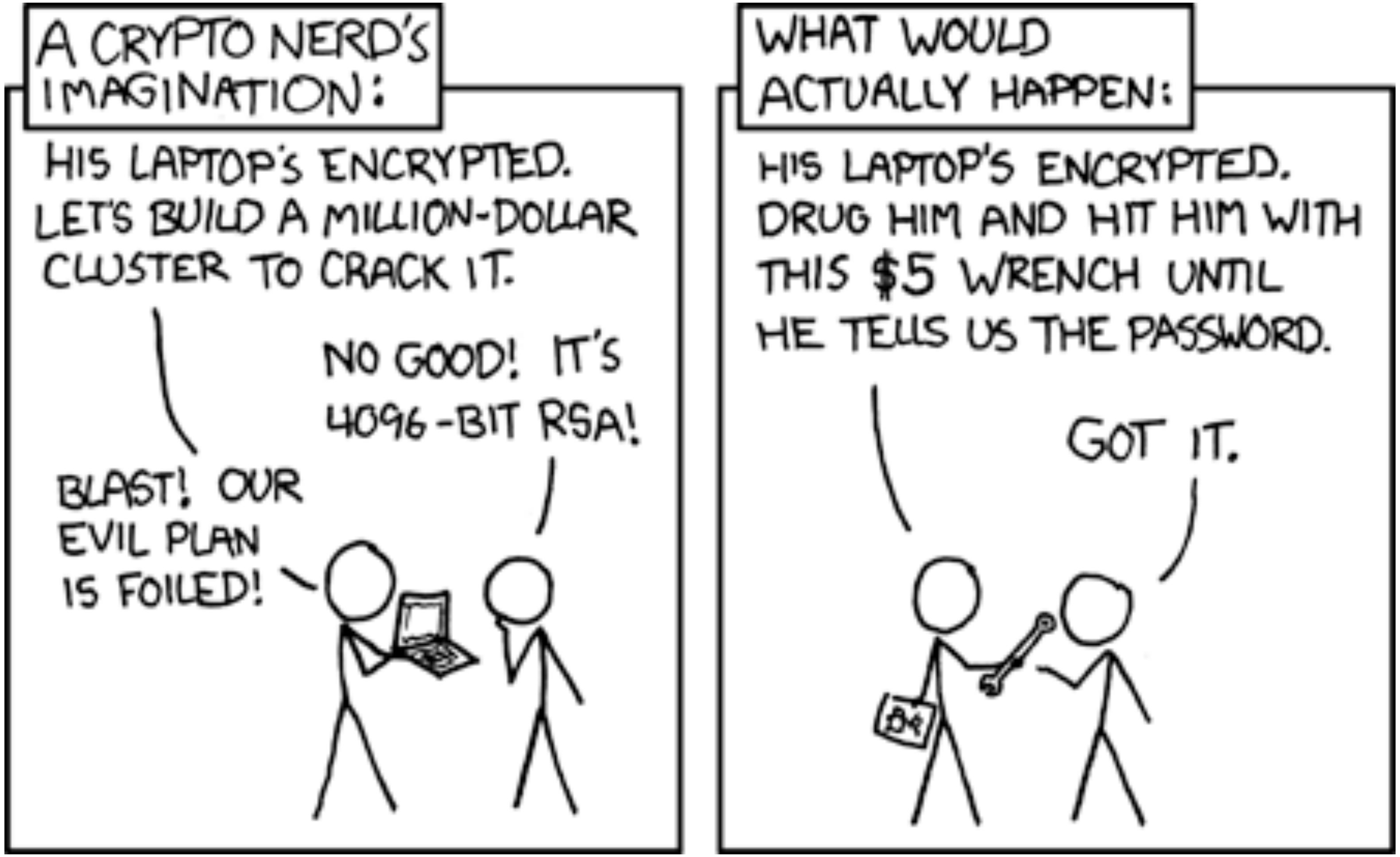
CS 88: Security and Privacy

10: Introduction to Cryptography

02-27-2024

slides adapted from Dave Levine, Vitaly Shmatikov, Christo Wilson, and Franzi Roesner

SWARTHMORE COLLEGE



XKCD: http://xkcd.com/538/

Cryptography

- Cryptography: An ancient art
  - 500BC – 20^{th} century: Design -> break -> repair -> break -> repair ->.....
- Modern Cryptography: Cryptography as a ***science***
  - relies on rigorous threat models
  - firm theoretical foundations and proofs!

Modern Cryptography

Design, analysis and implementation of mathematical techniques for securing information, systems and computation against adversarial attacks.

Modern Cryptography: How many of the following actions involve cryptography ?

1. Git cloning your lab repo
2. Connecting to Swarthmore's WiFi
3. Updating software on your device
4. Making online purchases

A. One of these
B. Two of these
C. Three of these
D. Four of these

Modern Cryptography

If you don't understand what you want to achieve, how can you possibly know when (or if) you have achieved it?

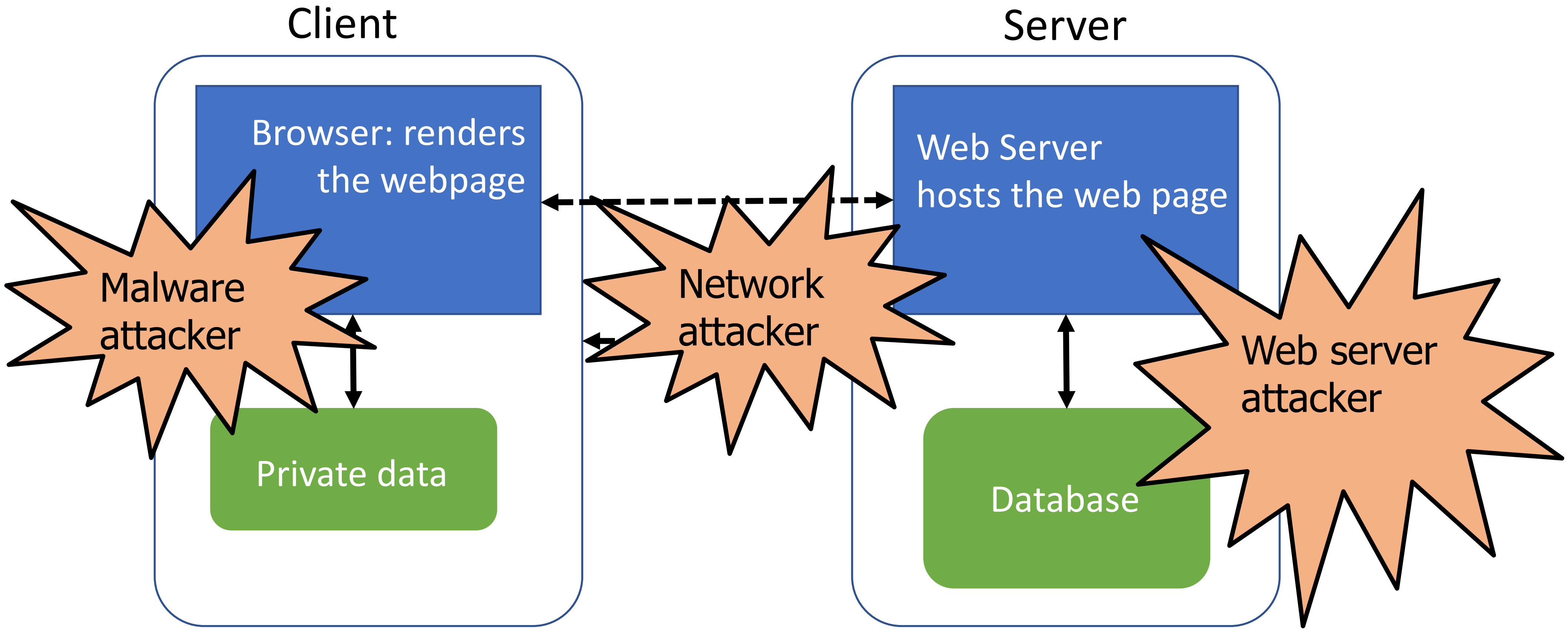
Modern Cryptography

Importance of clear assumptions:

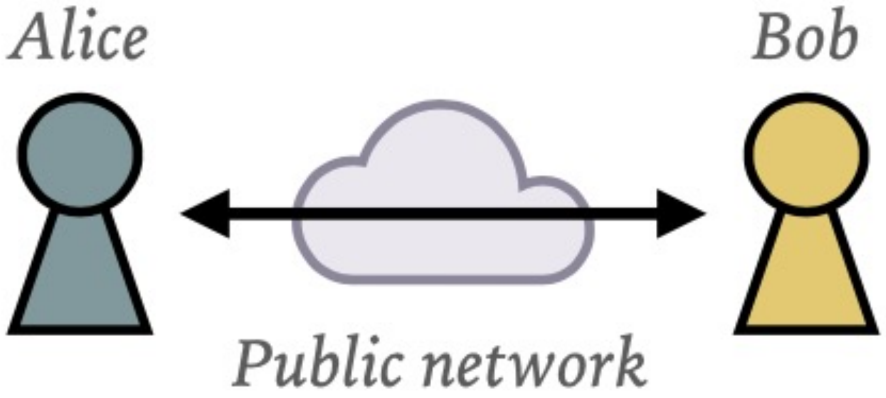
- allows researchers to validate assumptions
- comparison between schemes based on different assumptions
- re-adjust for weaknesses in assumptions

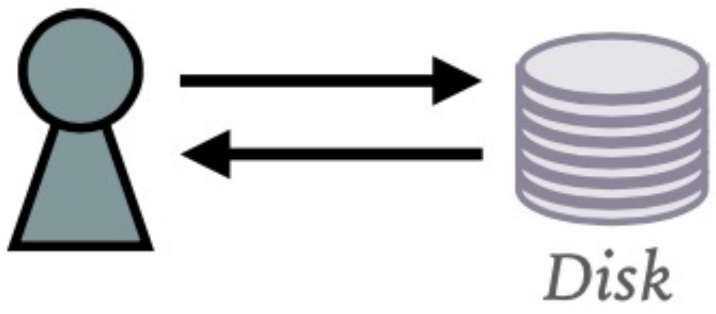
any new cryptographic construction should be proven secure with respect to a specific definition, and a set of clearly stated assumptions

Where Does the Attacker Live?



Scenarios and Goals





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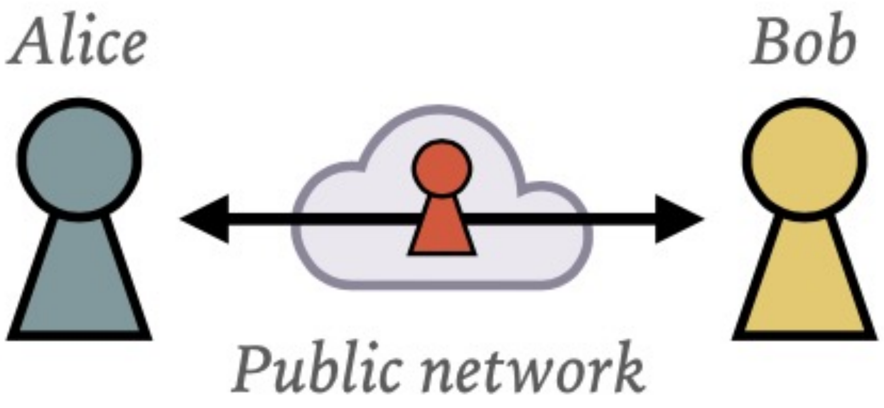
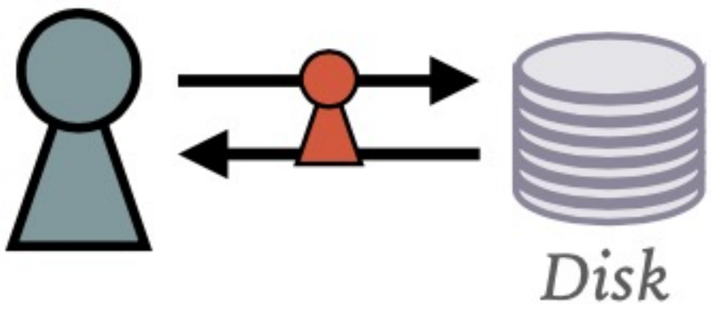
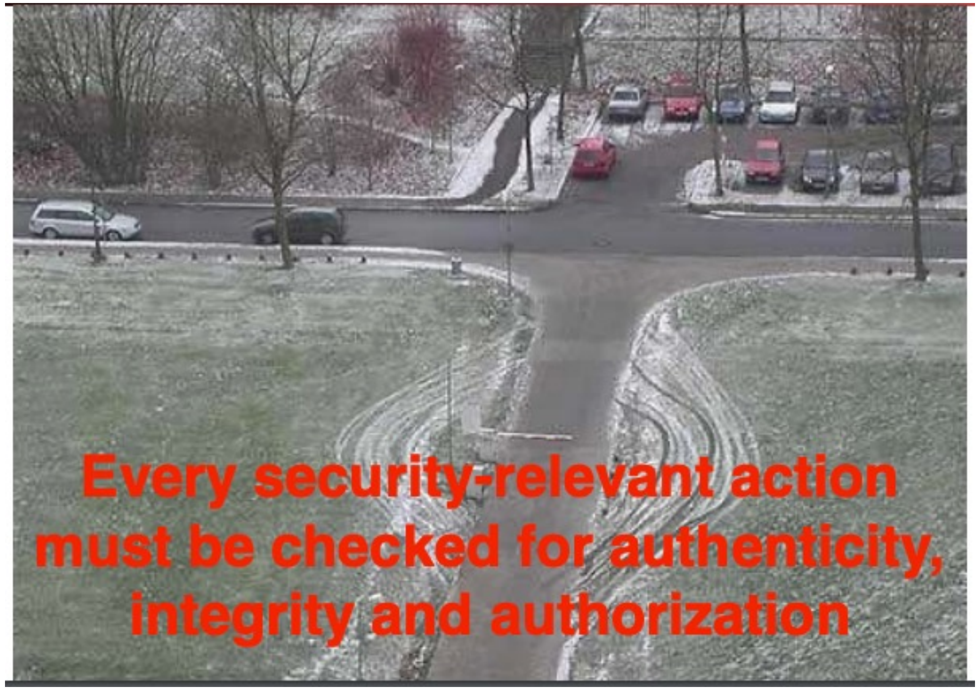




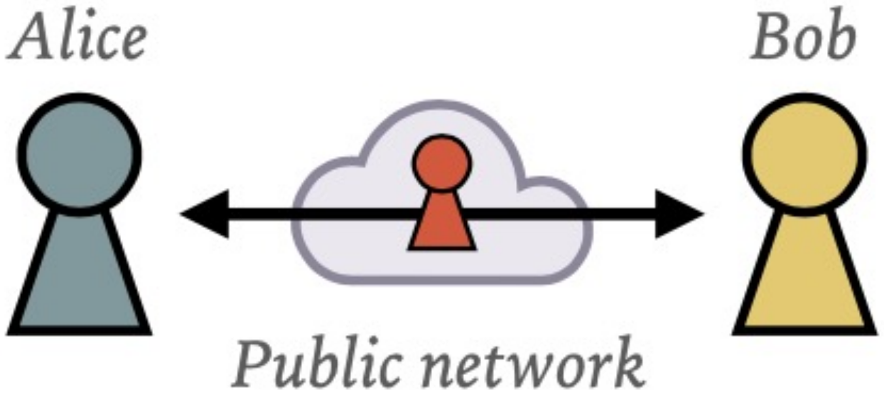
Confidentiality	Keep others from reading Alice's messages/data
Integrity	Keep others from undetectably tampering with Alice's messages/data
Authenticity	Keep others from undetectably impersonating Alice (keep her to her word too!)

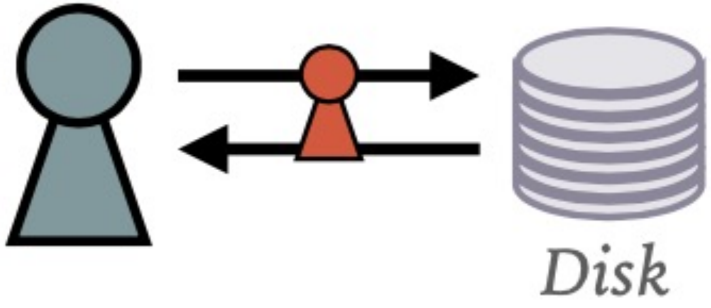
Recall the Bigger Picture

- Cryptography: small piece of a larger system
- Protect the entire system (recall: the weakest link)
  - physical security
  - OS security
  - Network security
  - Users
  - Cryptography
- Cryptography is a crucial part of this toolbox



Cryptography: Terms





Encryption (E): The process of transforming a message so that its meaning is not obvious
Decryption (D): The process of transforming an encrypted message back into its original form.
Plaintext (P): Original, unencrypted form of a message
Ciphertext (C): The encrypted form of a message

Formal Notation: We seek a cryptosystem for which P = D (E (P))

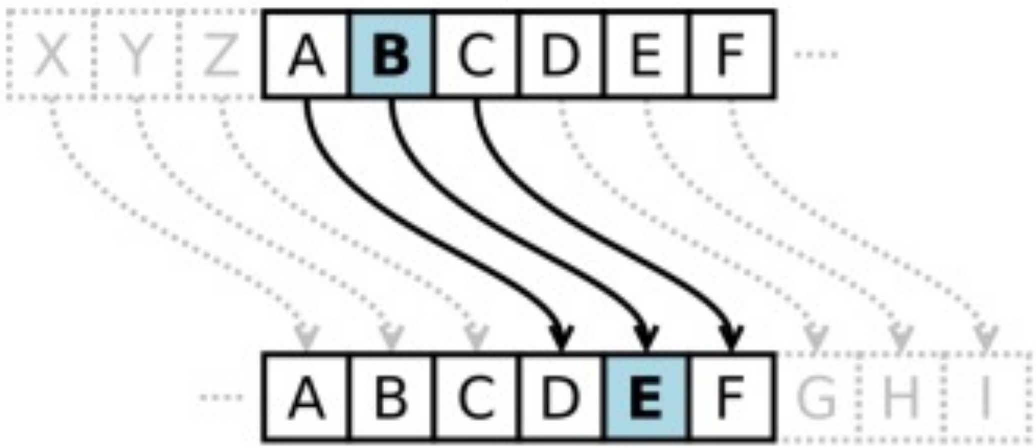
Historical Ciphers

- Substitution Cipher
  - Monoalphabetic - Ceasar’s Cipher – fixed subst. over the entire message
  - Polyalphabetic – a number of substitutions at different positions in the message
- Transposition Ciphers
- Codebooks
- Machines

Recommended Reading: The Codebreakers by David Kahn, The Code Book by Simon Singh

Ceasar Cipher: Substitution Cipher

Plaintext letters replaced with letters fixed shift way in the alphabet.



Example:

- Plaintext: HEY BRUTUS BRING A KNIFE TO THE PARTY.
- Ciphertext: KHB EUXWXV EULQJ D NQLIH WR WKH SDUWB
- Key Shift 3:
  - ABCDEFGHIJKLMNOPQRSTUVWXYZ
  - DEFGHIJKLMNOPQRSTUVWXYZABC

Ceasar Cipher: Substitution Cipher

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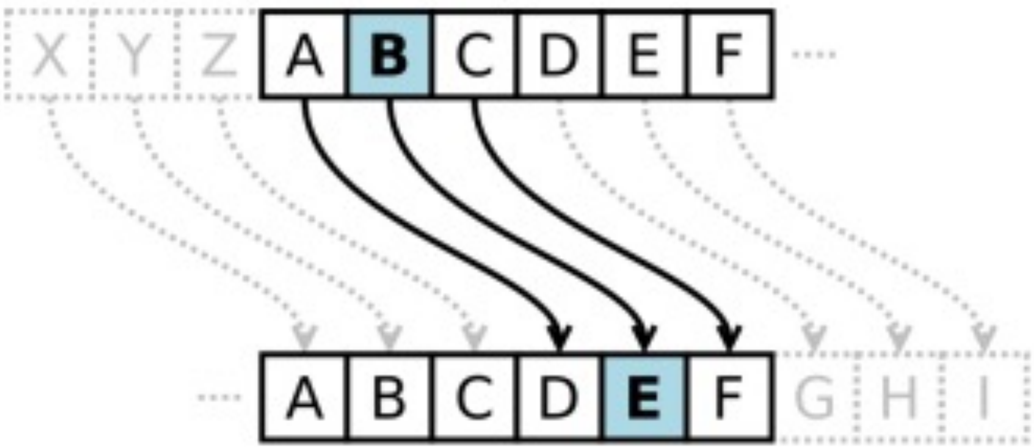

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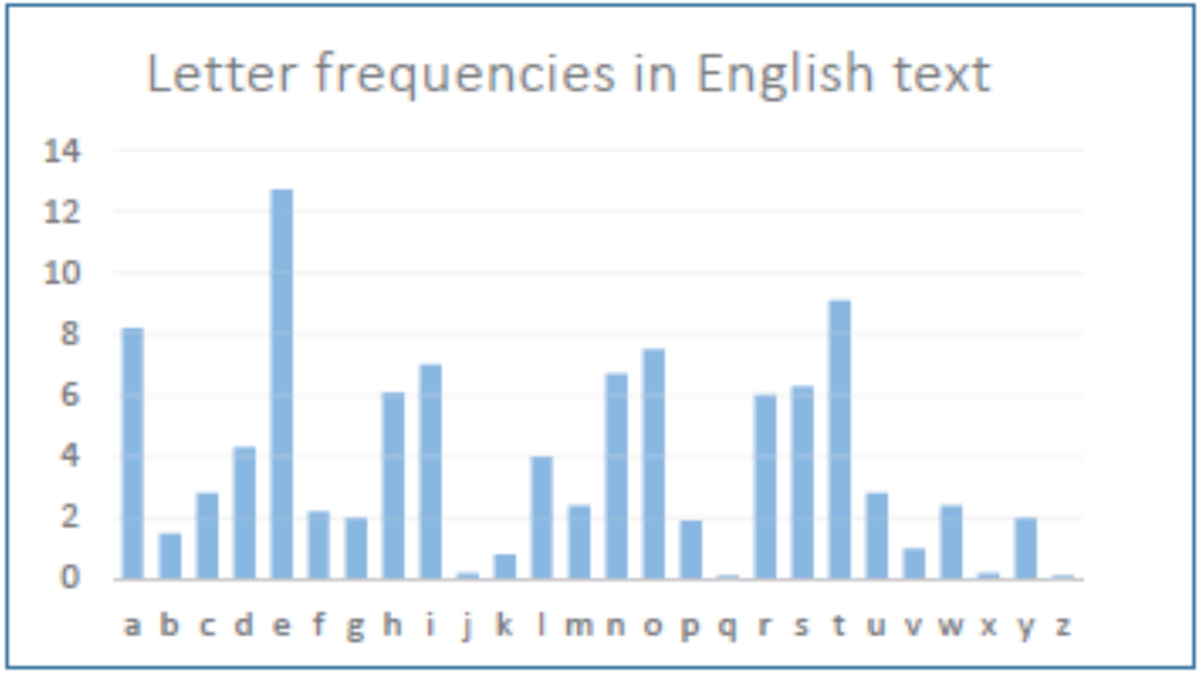
- Encryption and Decryption are symmetric.
- Key space?
  - 26
- Attack shift ciphers?
  - brute force

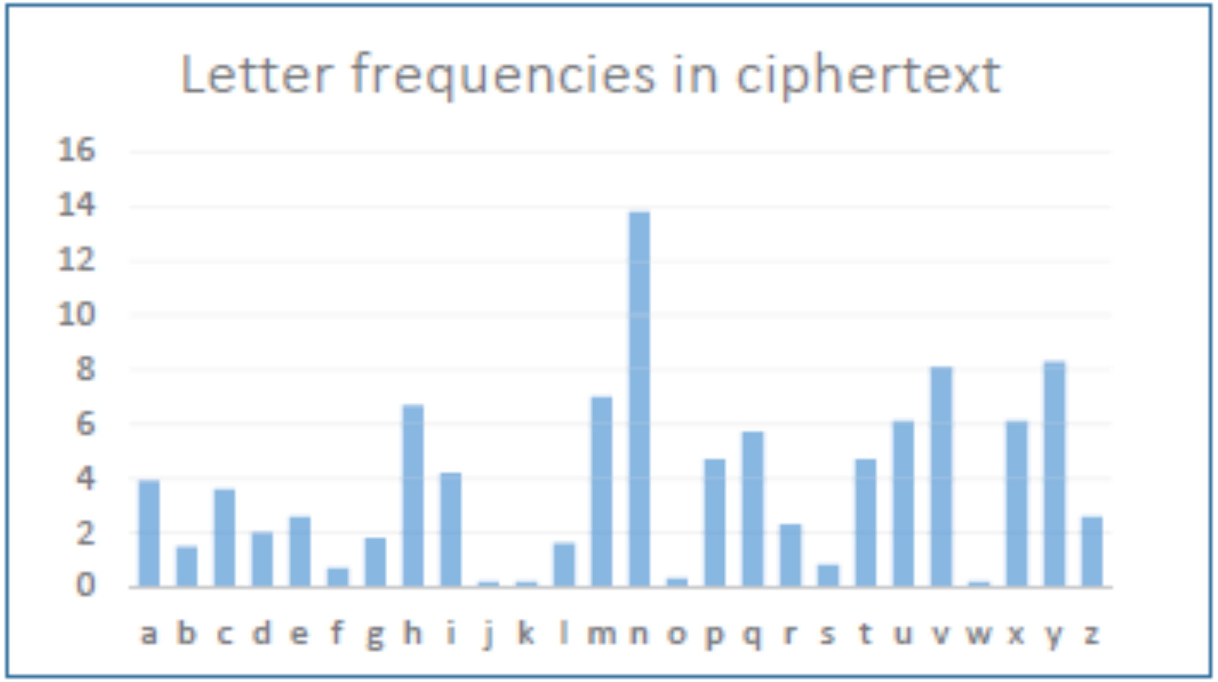
Substitution Cipher

- Superset of shift ciphers: each letter is substituted for another one.
- One implementation: Add a secret key
- Example
  - Plaintext: ABCDEFGHIJKLMNOPQRSTUVWXYZ
  - Cipher: ZEBRASCDFGHIJKLMNOPQTUVWXY
- “state-of-the-art” for thousands of years

Monoalphabetic Substitution Cipher

- What is the key space?
  - 26! approx. = 2^88
- Launching an attack?
  - frequency analysis: the study of frequency of letters or groups of letters (grams).
  - Common letters: T, A, E, I, O
  - Common 2-letter combinations (bi-grams): TH, HE, IN, ER
  - Common 3-letter combinations (tri-grams): THE, AND, ING.





Cryptanalysis of Monoalphabetic Substitution

- Dominates cryptography through the first millennium
- Frequency analysis (Al-Kindi from 800 AD)
- Lessons?
    - Use large blocks: instead of replacing ~6 bits at a time, replace 64 or 128 bits
        - Leads to block ciphers like DES and AES
    - Use different substitutions to prevent frequency analysis
        - Leads to polyalphabetic substitution ciphers and stream ciphers

Vigenère Cipher (1596)

- Main weakness of monoalphabetic substitution ciphers:
  - Each letter in the ciphertext corresponds to only one letter in the plaintext
- Polyalphabetic substitution cipher
  - Given a key $K = (k_1, k_2, \ldots, k_m)$
  - Shift each letter p in the plaintext by k_i, where i is modulo m

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Plaintext	CRYPTOGRAPHY	
Key	LUCKLUCKLUCK	(Shift 11 20 2 10 11 20 2 11 …)
Ciphertext	NLAZEIIBLJJI	

Kasisky Test

Plaintext	T	H	E	S	U	N	A	N	D	T	H	E	M	A	N	I	N	T	H	E	M	O	O	N
Key	K	I	N	G	K	I	N	G	K	I	N	G	K	I	N	G	K	I	N	G	K	I	N	G
Ciphertext	D	P	R	Y	E	V	N	T	N	B	U	K	W	I	A	O	X	B	U	K	W	W	B	T

Distance = 8

- Repeating patterns (of length >2) in ciphertext are a tell
  - Likely due to repeated plaintext encrypted under repeated key characters
  - The distance is likely to be a multiple of the key length

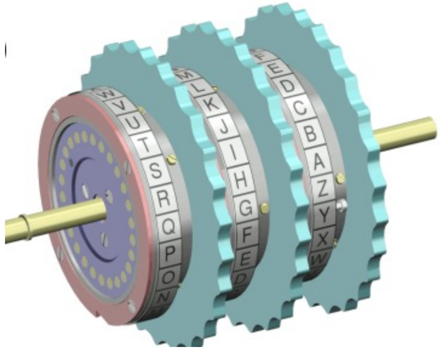
Cryptanalysis of Vigenère Cipher

- Cracking Vigenère (1854 or 1863)
  1. Guess the key length *x* using Kasisky test of index of coincidence
  2. Divide the ciphertext into *x* shift cipher encryptions
  3. Use frequency analysis on each shift cipher

- Lessons?
  - As key length increases, letter frequency becomes more random
  - If key never repeated, Vigenère wouldn't be breakable!

- WW2 German Enigma machine
  - Polyalphabetic substitution cipher
    - Substitution table changes from character to character
    - Rotors control substitutions
- Allies broke Enigma (even before the war), significant intelligence impact
- Computers were built to break WW2 ciphers, by Alan Turing and others

Enigma Machine



- Use rotors that change position after each key
- Key: initial setting of the rotors
- Key space?
  - 26^n for n rotors
- KeyGen:
  - Choose rotors, rotor orders, rotor positions, and plugboard settings
  - 158,962,555,217,826,360,000 possible keys!

Cryptanalysis: Enigma

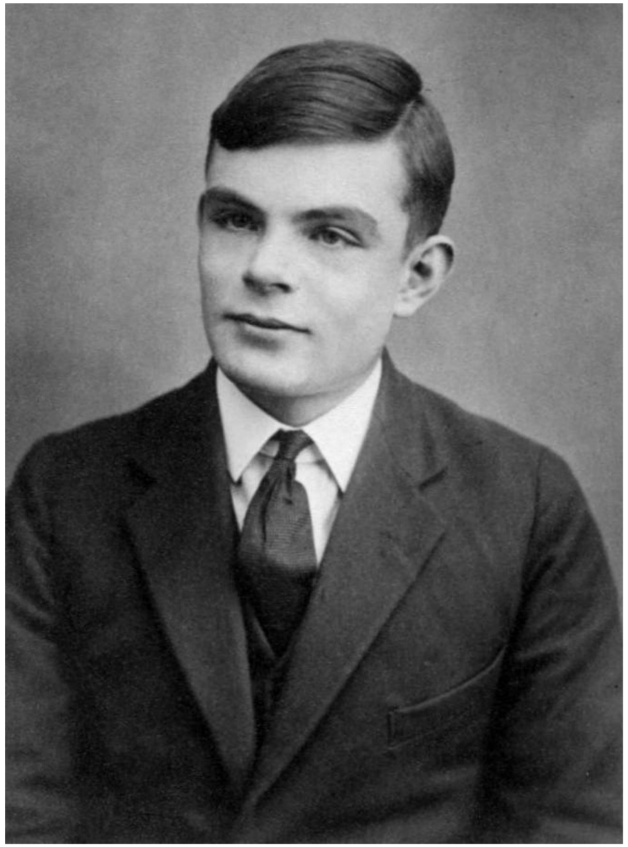
- Polish and British cryptographers built BOMBE, a machine to brute-force Enigma keys
- Why was Enigma breakable?
  - Kerckhoff's principle: The Allies stole Enigma machines, so they knew the algorithm
  - Known plaintext attacks: the Germans often sent predictable messages (e.g. the weather report every morning)
  - Chosen plaintext attacks: the Allies could trick the Germans into sending a message (e.g. "soldiers at Normandy")
  - Brute-force: BOMBE would try many keys until the correct one was found

BOMBE machine

Legacy of Enigma

- Alan Turing, one of the cryptographers who broke Enigma, would go on to become one of the founding fathers of computer science

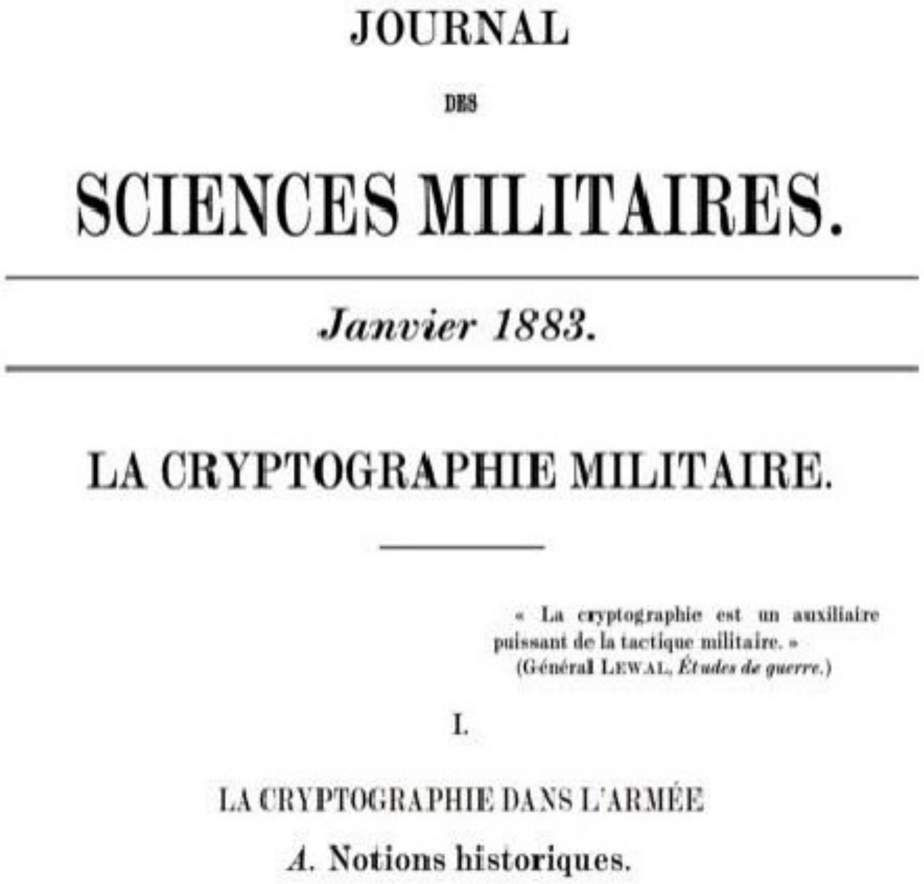
- Most experts agree that the Allies breaking Enigma shortened the war in Europe by about a year



Alan Turing

Kerckhoffs' principle

Encryption and Decryption and Key Generation Algorithm are publicly known. *The only unknown is the shared secret key*



JOURNAL

DES

SCIENCES MILITAIRES.

Janvier 1883.

LA CRYPTOGRAPHIE MILITAIRE.

« La cryptographie est un auxiliaire puissant de la tactique militaire. »
(Général LEWAL, *Études de guerre.*)

I.

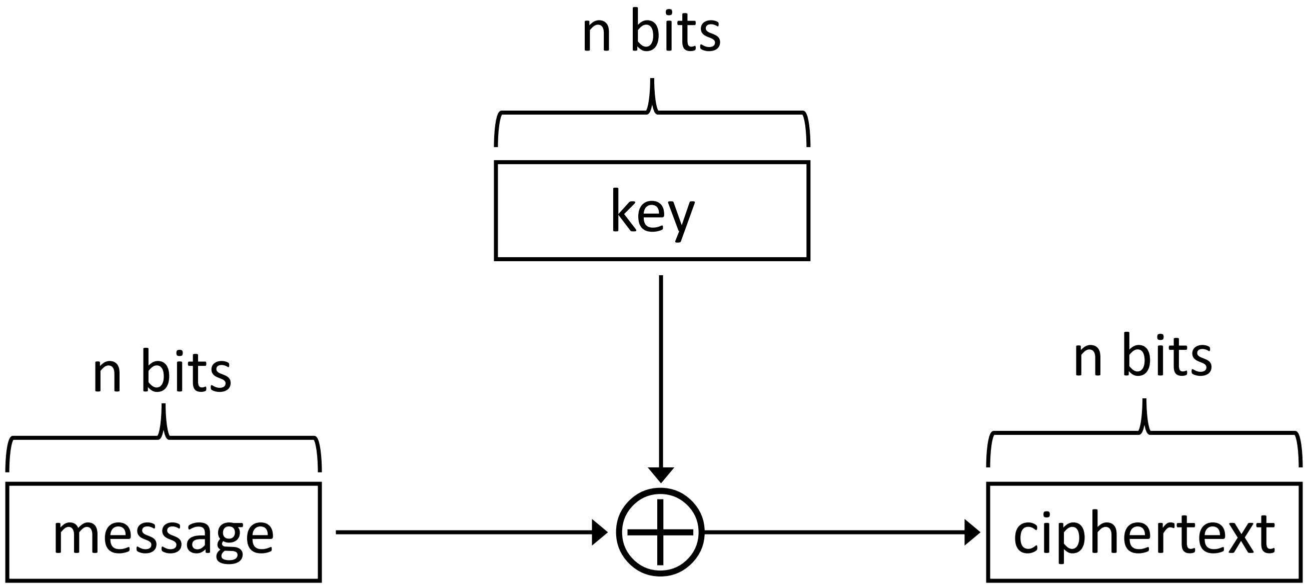
LA CRYPTOGRAPHIE DANS L'ARMÉE

A. Notions historiques.

Wikipedia

One Time Pad (1920s)

- Fix vulnerability in Vigenère cipher: use very long keys
- Key is a random string: at least as long as the plaintext
- Plaintext: Message that is n bits long
- Key: $\{0, 1\}^n$ sequence of n bits chosen uniformly at random.



Review: XOR

The XOR operator takes two bits and outputs one bit

$0 \oplus 0 = 0$
$0 \oplus 1 = 1$
$1 \oplus 0 = 1$
$1 \oplus 1 = 0$

Useful properties of XOR

$x \oplus 0 = x$
$x \oplus x = 0$
$x \oplus y = y \oplus x$
$(x \oplus y) \oplus z = x \oplus (y \oplus z)$
$(x \oplus y) \oplus x = y$

Review: XOR Algebra

Algebra works on XOR too

$y \oplus 1 = 0$	Goal: Solve for y
$y \oplus 1 \oplus 1 = 0 \oplus 1$	XOR both sides by 1
$y = 1$	Simplify with identities

One-Time Pads: Key Generation

Alice

K	0	1	1	0	0	1	0	1	0	1	1	1

The key K is a randomly-chosen bitstring.

Recall: We are in the symmetric-key setting, so we'll assume Alice and Bob both know this key.

One-Time Pads: Encryption

Alice

K	0	1	1	0	0	1	0	1	0	1	1	1
M	1	0	0	1	1	0	0	1	0	1	0	0

The plaintext M is the bitstring that Alice wants to encrypt.

Idea: Use XOR to scramble up M with the bits of K.

One-Time Pads: Encryption

Alice

K	0	1	1	0	0	1	0	1	0	1	1	1
	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$
M	1	0	0	1	1	0	0	1	0	1	0	0
	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
C	1	1	1	1	1	1	0	0	0	0	1	1

Encryption algorithm: XOR each bit of K with the matching bit in M.

The ciphertext C is the encrypted bitstring that Alice sends to Bob over the insecure channel.

One-Time Pads: Decryption

Bob

K	0	1	1	0	0	1	0	1	0	1	1	1

C	1	1	1	1	1	1	0	0	0	0	1	1

Bob receives the ciphertext C. Bob knows the key K. How does Bob recover M?

One-Time Pads: Decryption

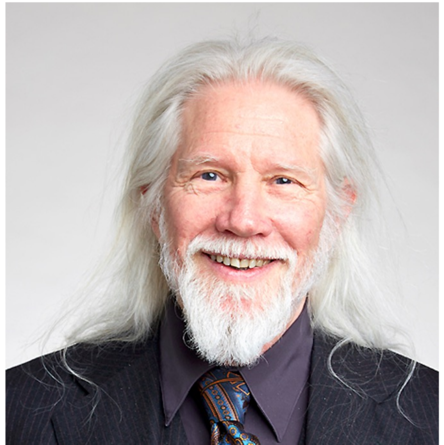
Bob

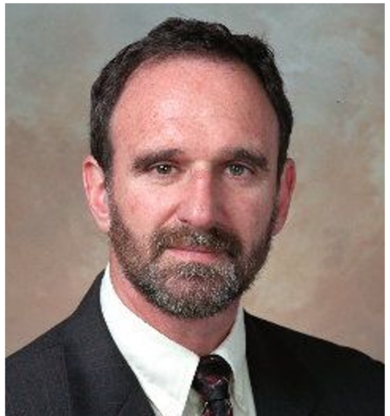
K	0	1	1	0	0	1	0	1	0	1	1	1
	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$
C	1	1	1	1	1	1	0	0	0	0	1	1
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
M	1	0	0	1	1	0	0	1	0	1	0	0

Decryption algorithm: XOR each bit of *K* with the matching bit in *C*.

Cryptography by Computers

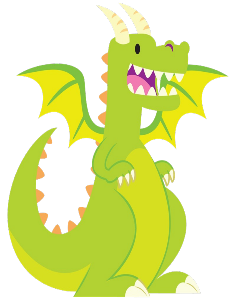
- The modern era of cryptography started after WWII, with the work of Claude Shannon
- "New Directions in Cryptography" (1976) showed how number theory can be used in cryptography
  - Its authors, Whitfield Diffie and Martin Hellman, won the Turing Award in 2015 for this paper
- *This is the era of cryptography we'll be focusing on.*





How Cryptosystems work today

- Layered approach:
  - Cryptographic protocols (e.g., CBC mode encryption)
  - Built on: Cryptographic primitives (block ciphers)
- Flavors of cryptography:
  - Symmetric: private key
  - Asymmetric: public key
- Public algorithms: Kerckhoff's principle
- *Security proofs based on assumptions (not this course)*
- Warning! Here be dragons!
  - careful about inventing your own
  - Use vetted libraries to apply crypto algorithms



Cryptosystem Stack

- Primitives:
  - AES/DES
  - ESA / ElGamal / Elliptic Curve
- Modes
  - Block mode (CBC, ECV, CTR, GCM..)
  - Padding structures
- Protocols:
  - TLS, SSL, SSH
- Usage of protocols:
  - Browser security
  - Secure remote logins

Flavors of Cryptography

- Symmetric cryptography
  - Both communicating parties have access to a shared random string K, called the key.
- Asymmetric cryptography
  - Each party creates a public key p_k and a secret key s_k
  - Inventors won Turing Award!

Kerckhoff’s Principle

- Security of a cryptographic object should depend only on the secrecy of the secret (private) key.
- Security should not depend on the secrecy of the algorithm itself.
- Foreshadow: Need for randomness – the key to keep private