Computer Security: Secret Key Crypto

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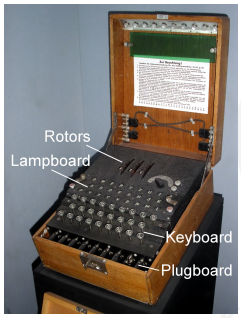
Version: fall 2011

Outline

Old cryptographic systems

Scytala from Sparta



German Enigma from WWII

Check out http://cryptomuseum.com/ for a large collection of (Dutch) devices

Situation & terminology

topic of *cryptography* — topic of *cryptanalysis*

Officially,

$$\textit{cryptology} \quad = \quad \text{cryptography} \; + \; \text{cryptanalysis}$$

This is the official, somewhat outdated terminology. But often "crypto" or "cryptography" is used for "cryptology".

Example encryption

Example

The message:

Dit wil ik versleutelen!

becomes (with PGP-encrypt, in hexadecimals):

30a4 efde f665 d409 4946 c8b0 d82b 7620
312c bf1b 7f3a 8781 086d 069b b6e0 60a2
94c2 9b27 440c affd 5343 ca47 d0b4 afce 5719

Modern, software-based crypto systems are virtually unbreakable, when:
- well-designed and openly evaluated
- properly used

Crypto system

The en/de-cryption is done with:

$$\begin{array}{c}\text{crypto system}\\ \text{(or secret code, or cipher)}\end{array} \quad = \quad \left\{ \begin{array}{l} \text{algorithm} \\ \quad + \\ \text{key (parameter of the algorithm)} \end{array} \right.$$

Kerckhoffs principle

The strength of the crypto system must rely solely on the strength of the key; the algorithm must be (assumed to be) public.

Modern interpretation of this principle:
- Algorithm must arise from public competition (organised by NIST for AES & next hash)
- Non-public algorithms must be distrusted (think of DVD-encryption, GSM, Mifare, ..., all broken)

Ordering crypto primitives via numbers of keys

number of keys	name	key names	notation
0	hash functions	—	$h(m)$
1	symmetric crypto	shared, secret	$K\{m\}$
2	asymmetric crypto (or public key crypto)	public & private keypair	$\{m\}_K$

We start with symmetric key crypto.

First a few words on . . . words

- Crypto systems transform plaintext to cipher text
- They transform words to words
- Words (aka. strings) are sequences of letters, taken from an alphabet.

Alphabets

In principle, an alphabet is an arbitrary set A. In this context, the elements $a \in A$ are called letters.

In practice, an alphabet is a finite set $A = \{a_1, \ldots, a_n\}$ of letters. Examples:

- $A = \{0, 1\}$, the alphabet of bits
- $A = \{a, b, c, \ldots, z\}$, the alphabet of lowercase Latin characters;
- $A = \{00, 01, \ldots, 7F\}$ the ASCII alphabet, as hexadecimals; (Recall: $7F = 127 = 2^7 - 1$.)
- The extended ASCII alphabet of 256 characters
- UTF alphabets involve even more characters (depending on version, like UTF-16, UTF-32)

Words

A word over an alphabet A is a finite sequence $w = a_1 a_2 \cdots a_n$ of letters $a_i \in A$. The length of this w is n, obviously.

One writes $A^\star$ for the set of words over A (aka. the Kleene star)

For instance, $\{0, 1\}^\star$ is the set of binary words.

We write $|$, or sometimes just a comma, for concatenation of words. Hence:

$$a_1 a_2 \cdots a_n \mid b_1 b_2 \cdots b_m \quad = \quad a_1 a_2 \cdots a_n b_1 b_2 \cdots b_m.$$

On binary words with the same length we write $\oplus$ for bitwise XOR:

$$\begin{array}{l}(a_1 a_2 \cdots a_n) \oplus (b_1 b_2 \cdots b_n) \\ \quad = \quad (a_1 \mathbf{XOR}\ b_1)(a_2 \mathbf{XOR}\ b_2) \cdots (a_n \mathbf{XOR}\ b_n).\end{array}$$

Encryption/decryption are functions from words to words (usually binary).

Symmetric crypto: three basic techniques

Suppose we have a message/word m and wish to (symmetrically) encrypt it to $K\{m\}$, using key K. There are three basic techniques:

1. Substitution: exchange characters from the alphabet, like in Caesar's cipher.
   The key K is: the character substitution/exchange function
2. Transposition: exchange positions of characters, block-by-block.
   The key K is: the position exchange function
3. One-time-pad: take bitwise XOR with keystream, for binary messages only.
   The key K is: the keystream, which must have at least the same length as the message

Ciphers like DES and AES involve repeated combinations of substitution and transposition, depending on a secret key

Substitution: exchange of characters

The key is a function $K \colon A \longrightarrow A$, which is bijective: it has an inverse $K^{-1} \colon A \longrightarrow A$, satisfying

$$K^{-1} \circ K = \text{identity} = K \circ K^{-1}.$$

This reversibility is needed for decryption.

This substition function K is extended to words via:

$$m = a_1 a_2 \cdots a_n \quad \text{becomes} \quad K\{m\} = K(a_1)K(a_2) \cdots K(a_n).$$

Substitution: Example

- Caesar's cipher is determined by the substitution function/key

$$C\colon \{a, b, \ldots, z\} \longrightarrow \{a, b, \ldots, z\},$$

given by:

$$C(a) = d, \quad C(b) = e, \quad \ldots \quad C(z) = c.$$

- **Example**:

$$\begin{aligned} C\{\text{ikbengek}\} &= C(\text{i})C(\text{k})C(\text{b})C(\text{e})C(\text{n})C(\text{g})C(\text{e})C(\text{k}) \\ &= \text{lnehqjhn}. \end{aligned}$$

- What is the inverse function $C^{-1}\colon \{a, \ldots, z\} \longrightarrow \{a, \ldots, z\}$? Use it to describe decryption!
- rot13 is a 13-step-shift, which is its own inverse.

Substitution: weakness

The main attack on substitution ciphers is frequency analysis.

- In English, e is the most common letter, followed by t, o, a, n, i, etc. There are frequency tables on the web.
- The most frequently occurring letter in a (substitution) ciphertext corresponds thus most probably to e. You will see this most clearly by doing an exercise.

Transposition: exchange of positions

Transposition via blocks and keys

- For a transposition cipher one first chooses a blocksize N, like $N = 64$, or $N = 128$, or $N = 256$.
- The key K is an exchange of positions within such a block, via a bijective function $K\colon \{1, 2, \ldots, N\} \longrightarrow \{1, 2, \ldots, N\}$.

Encryption of words/messages

- A word m is first chopped-up into blocks of length N, as in:

$$m = \underbrace{a_1 a_2 \cdots a_N}\ \underbrace{b_1 b_2 \cdots b_N}\ \cdots$$

- At the end arbitrary letters (like x) are added to fill the remaining block: this is called padding
- For encryption of m the transposition K is applied per block:

$$K\{m\} = \underbrace{a_{K(1)} a_{K(2)} \cdots a_{K(N)}}\ \underbrace{b_{K(1)} b_{K(2)} \cdots b_{K(N)}}\ \cdots$$

Transposition: Example

Transposition of *ikbengek*

- Choose blocksize, say $N = 3$
- Choose key $K\colon \{1, 2, 3\} \longrightarrow \{1, 2, 3\}$ by:

$$K(1) = 3, \quad K(2) = 1, \quad K(3) = 2.$$

- Now encrypt a message block-by-block:

$$\begin{aligned} K\{\text{ikbengek}\} &= K\{\underbrace{\text{ikb}}\ \underbrace{\text{eng}}\ \underbrace{\text{ekx}}\} \\ &= \underbrace{\text{bik}}\ \underbrace{\text{gen}}\ \underbrace{\text{xek}} \\ &= \text{bikgenxek}. \end{aligned}$$

The letter 'x' is add for padding: filling up empty spaces

Columnar transposition example

- The key is an ordinary word, say bart
- The plain text is written under the key, as in:

b	a	r	t
i	k	b	e
n	k	n	e
t	t	e	r
g	e	k	x

- Now read off the cipher text as columns, using the alphabetical order of the key:

kkteintgbnekeerx

- See e.g. http://practicalcryptography.com/ciphers/columnar-transposition-cipher/
- Or many software tools, like GCipher under linux

Transposition: weakness

- First, a transposition does not change the letter frequencies. This is often an indication of transposition
- Next, use a lot of fiddling, exploiting frequent 2-letter combinations.

Combining substitution and transposition

Example: Vigenère cipher

- It applies different (shift) substitution ciphers, depending on the letters of a keyword
- This is called a polyalphabetic cipher.

DES and AES

Combine substitution and transposition in several rounds

One-time pad (OTP)

- Assume a binary message $m = b_1 b_2 \cdots b_n \in \{0,1\}^\star$, so that $b_i \in \{0,1\}$.
- Assume a key of (at least) the same length $K = k_1 k_2 \cdots k_n \in \{0,1\}^\star$.
- For encryption, perform bitwise XOR, as in:

$$K\{m\} \quad = \quad (b_1 \mathbf{XOR} k_1)(b_2 \mathbf{XOR} k_2) \cdots (b_n \mathbf{XOR} k_n).$$

- Decryption is the same as encryption, using basic properties of XOR:

$$\begin{array}{rcl} (b \mathbf{XOR} k) \mathbf{XOR} k & = & b \mathbf{XOR} (k \mathbf{XOR} k) \\ & = & b \mathbf{XOR} 0 \\ & = & b. \end{array}$$

One-time pad in practice

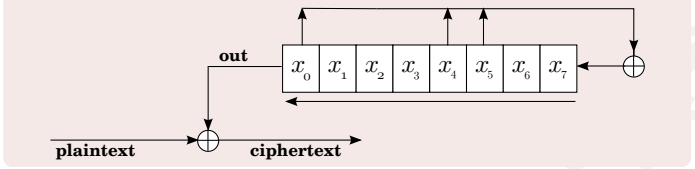
- OTPs are very secure, in principle, when the key material is truely random
- . . . but OTPs require a lot of key material (one can use, say a DVD as shared secret key)
- Running out of key material is a problem, because keys may never be re-used, XOR-ing ciphertexts reveals information:

$$(b \mathbf{XOR} k) \mathbf{XOR} (c \mathbf{XOR} k) \quad = \quad b \mathbf{XOR} c.$$

- Mistakes like this happen in practice!
  - In the Mifare CLASSIC cipher, part of the key stream is re-used (for parity bits), leaking some information. Also, the "abort" command is sent encrypted, leaking further keystream.
  - By Russian spies in the 1940s, who ran out of keys. The US-UK Venona project recoverd a lot of traffic, and revealed famous atom spies like Klaus Fuchs

One-time pad key stream generator via LFSR

Example LFSR = Linear Feedback Shift Register



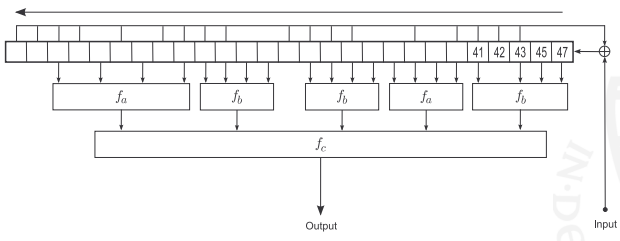
- With every clock cycle the register shifts to the left, and a new value $x_7 = x_0 \mathbf{XOR} x_4 \mathbf{XOR} x_5$ is shifted in on the right.
- Illustration: if the current state is 11001010, then the next state is: 10010100

LFSR usage

- LFSRs are frequently used, since they are
  - easy to implement in cheap hardware
  - fast
- They can be analysed using basic linear algebra (eg. are all possible states actually reached?)
- The Mifare CLASSIC chipcard (from early 1990s) has two LFSRs:
  - a 16-bit register for generating (very weak!) "randoms"
  - a 48-bit register (plus "filter" function) for its Crypto1 stream cipher

  This system is completely broken (too few bits, design errors)
- Also the A5/1 used in GSM works with three different LFSRs. It is also broken.

Mifare CLASSIC LFSR



- The Mifare producer (NXP) tried to prevent publication of this LFSR via a court case (*kort geding*) in July 2008.
- Probably all of you have this LFSR in your pocket!

Symmetric crypto, in practice I

Common implementations (see Wikipedia for details)

- DES from 1977, with 64 bit blocks and 56 bits keys.
  DES is now obsolete, only surviving as triple-DES, in:

$$3\mathrm{DES} = \left(\cdot \xrightarrow[\text{encrypt}]{K_1} \cdot \xrightarrow[\text{decrypt}]{K_2} \cdot \xrightarrow[\text{encrypt}]{K_1} \cdot \right)$$

  Keys are now $112 = 2 * 56$ bits long.
  Backwards compatibility is achieved via $K_1 = K_2$.
  DES is fast in hardware, slow in software.
- AES from 1997 (elected standard since 2001).
  Standard block length is 128 bit, key lengths are 128 and 256.
  AES is fast, both in hardware and software.

Different application modes will be discussed later.

Symmetric crypto, in practice II

In this course

We often use $K\{m\}$ as a *black box* for symmetric encryption, without being very specific about which kind of cipher is used; in practice we assume the cipher is unbreakable.

Main disadvantages of symmetric crypto

- Large number of keys: if N people wish to communicate pairwise securely, one needs: $\binom{N}{2} = \frac{N(N-1)}{2}$ different secret keys.
  - By using a Trusted Third Party (TTP) it can be reduced to N.
- If Alice and Bob share a key K, and Bob is sloppy and looses K, this affects Alice.

Security protocols are notoriously difficult

Roger Needham:

> *Security protocols are three-line programs that people still manage to get wrong*

Famous example: The Needham-Schroeder mutual authentication protocol (see later) which contained an error that remained undetected for some 20 years

- An attack was found in 1996 by Gavin Lowe, using a model checker
- The attack involved two different interleaved runs of the protocol

What is a security protocol, really?

- A security protocol is a list of communications of the form

$$A \longrightarrow B : m$$

  which is read as: Alices sends message m to Bob.
- The sequence of such messages is intended to achieve a security goal, like confidentiality, integrity, one-way/mutual authentication, non-repudiation, etc.
- At each step of the protocol the beliefs of the participants change: eg. after receiving such return message, Alice knows that Bob has seen ...
- if something goes wrong, the protocol is aborted.

Attacker model

- Implicitly there is an attacker ("Eve") who tries to undermine the goal of the protocol
  - "Dolev-Yao" attacker capabilities are assumed: the attacker can read, delete, copy, rebuild messages
  - but the attacker cannot break encryptions (with unknown keys) or hashes
- Security protocols are important part of the field (and of this course)
  - You must known basic protocol primitives by heart

Protocol basics for confidentiality

Assume Alice and Bob share a secret key K_{AB}, and can do symmetric encryption.

(The index 'AB' in K_{AB} has no mathemtical meaning; it suggests notationally that it it is a shared key between A and B.)

Confidential exchange of a message m proceeds via:

$$A \longrightarrow B : K_{AB}\{m\}$$

Is confidentiality achieved? Can Eve read the plaintext m? What are the assumptions involved?

Sequence numbers

- We study abstract security protocols — not actual implementations
- But in such implementations, all messages should be numbered. Hence we should really send:

$$A \longrightarrow B\colon K_{AB}\{i, m\}$$

where $i \in \mathbb{N}$ is a so-called sequence number. It should be incremented with every message (overflow must be handled)
- Sequence numbers are used primarily against loss and replay of messages
  - an additional advantage is that identical message yield different ciphertexts.
- We do not mention sequence numbers explicitly, and assume they are already included implicitly (when needed)

Also integrity?

Question: does $A \longrightarrow B\colon K\{m\}$ also guarantee integrity?

NO! For example,

- Assume the encryption is done via a one-time pad
- An attacker can easily change one bit in the ciphertext
- Possibly the result still makes sense — but has a different meaning

Hence: there is no automatic (cryptographic) test that B can perform in order to verify that the message he receives is the one that was sent by A.

Security in the future

- Recall that the attacker can read (and store) all messages; he can do this over a long time period.
- Hence the strength of the encryption (e.g. keylength) must be chosen appropriately.
  - Tables available online, e.g. `keylength.com`
- Remember *Venona*: if a key ever gets (partially) compromised, old messages may become readable.
  - Some protocols protect against such compromise, and are called forward secure

Protocol basics for integrity

Suppose Alice and Bob wish to be really sure that what Bob receives is what has been sent by Alice.

They use:

$$A \longrightarrow B\colon m, K_{AB}\{m\}$$

$$\text{(or, more efficiently} \quad A \longrightarrow B\colon m, K_{AB}\{h(m)\}\text{)}$$

where h is a hash function (see below).

- Is the integrity goal achieved? How? What will Bob detect when Eve replaces the plaintext m by m'?
- What are the assumptions?
- Is confidentiality also achieved?

Both confidentiality and integrity

Obvious combinations:

$$A \longrightarrow B\colon K\{m\}, K\{K\{m\}\} \qquad \text{or} \qquad A \longrightarrow B\colon K\{m, K\{m\}\}$$

- This is not wise for one-time pads, since the message is revealed by two successive encryptions.
- One should use two different keys, one for confidentiality, and one for integrity.
- One can then still argue where to put the emphasis of the protection
  - confidentiality first $K_1\{m\}, K_2\{K_1\{m\}\}$
  - integrity first $K_1\{m, K_2\{m\}\}$.

  In general integrity is more important than confidentiality, so it needs to be protected better, like in the second option.

Authentication via shared secret

It is quite common to use a shared secret for authentication

- if I first share a secret with you, then I will henceforth conclude that anyone who can produce this secret is you.
- Example of authentication by "something you know"
- Problem: in every authentication session, the secret is used in the clear.

Something you know examples

- Passwords used by (military) guards to allow access.

  (The use of the secret word *Scheveningen* for this purpose in May 1940 also involved authenticaton "by skill")

- PINs in ATM/payment transactions: one-way authentication between a customer (C) and the bank (B).

  $C \longrightarrow B$: number of card of C (e.g. via magnetic stripe)
  $B \longrightarrow C$: "prove that you are C"
  $C \longrightarrow B$: PIN of C

  This is very weak and has led to widespread skimming

Authentication by challenge-response

It is much better to achieve authentication without using the shared secret *in the clear*.

- **Idea:** send a riddle that can only be solved (efficiently) with the secret key
- It is important that the riddle is fresh upon every use.

  (Which attacker capabilities are used to exploit a non-fresh riddle?)
- Typically this freshness is achieved via a nonce: a number used once.
  - Range of numbers is relevant (say 2^{128})
  - Also randomness / unpredictability

Challenge-response authentication examples

$$A \longrightarrow B\colon A, N_A \qquad (N_A \text{ is a fresh nonce})$$
$$B \longrightarrow A\colon K_{AB}\{N_A\}$$

At this stage A knows she is talking to B, because only B, so she assumes, posseses the shared key K_{AB} and can compute $K_{AB}\{N_A\}$.

There are several inessential variations:

$$A \longrightarrow B\colon A, K_{AB}\{N_A\}$$
$$B \longrightarrow A\colon N_A$$

Or:

$$A \longrightarrow B\colon A, K_{AB}\{N_A\}$$
$$B \longrightarrow A\colon K_{AB}\{N_A + 1\}$$

NOTE: authentication key must be different from encryption key!

Two-way authentication options

Naive two-way, combined version:

$$A \longrightarrow B\colon A, N_A$$
$$B \longrightarrow A\colon K_{AB}\{N_A\}, N_B$$
$$A \longrightarrow B\colon K_{AB}\{N_B\}$$

Or:

$$A \longrightarrow B\colon K_{AB}\{N_A, \text{timestamp}\}$$
$$B \longrightarrow A\colon N_A$$

Nonces, timestamps, sequence numbers

All of these alternatives for freshness have pros and cons:

- Nonces require a secure random number generator
- Timestamps require reliable/secure/synchronised clocks
- sequence numbers are predictable (so should be used more carefully) and can wrap around.

Reflection attack (*Koekje van eigen deeg*)

A reflection attack is possible for the "naive" two-way protocol by mixing two sessions (written as 'a' and 'b'):

Protocol

$$A \longrightarrow B\colon A, N_A$$
$$B \longrightarrow A\colon K_{AB}\{N_A\}, N_B$$
$$A \longrightarrow B\colon K_{AB}\{N_B\}$$

Attack

$$(a) \quad E \longrightarrow B\colon A, N_A$$
$$(a) \quad B \longrightarrow E\colon K_{AB}\{N_A\}, N_B$$
$$(b) \quad E \longrightarrow B\colon A, N_B$$
$$(b) \quad B \longrightarrow E\colon K_{AB}\{N_B\}, N$$
$$(a) \quad E \longrightarrow B\colon K_{AB}\{N_B\}$$

In the end B thinks that he is talking to A, but in reality he is talking to the intruder Eve (E). Note that Eve can take the initiative for this attack.

Attack prevention

A solution is to this attack is to use different keys for the two challenges, as in:

$$A \longrightarrow B\colon A, N_A$$
$$B \longrightarrow A\colon K_{AB}\{N_A\}, N_B$$
$$A \longrightarrow B\colon (K_{AB}+1)\{N_B\}$$

Another solution is to let A use even nonces, and B odd ones.

Initiator must authenticate first

Yet another solution is to let the initiator authenticate itself first, as in:

$A \longrightarrow B$: "Hi, I'm A; let's talk"
$B \longrightarrow A$: "Sure, but first increment $K_{AB}\{N_B\}$"
$A \longrightarrow B\colon K_{AB}\{N_B+1\}, K_{AB}\{N_A\}$
$B \longrightarrow A$: "Wow, you're really A; this shows I'm B: $K_{AB}\{N_A-1\}$"
$A \longrightarrow B$: "Great; we now also have a session key" (namely $N_A \oplus N_B$)

- Letting the initiator start is a good idea in general
- Also, obtaining a session key from mutual authentication, with input from both sides.

Man-in-the-middle attack

Also there is a man in the middle attack to the naive two-way version:

Protocol

$$A \longrightarrow B\colon A, N_A$$
$$B \longrightarrow A\colon K_{AB}\{N_A\}, N_B$$
$$A \longrightarrow B\colon K_{AB}\{N_B\}$$

Attack

$$A \longrightarrow E\colon A, N_A$$
$$E \longrightarrow B\colon A, N_A$$
$$B \longrightarrow E\colon K_{AB}\{N_A\}, N_B$$
$$E \longrightarrow A\colon K_{AB}\{N_A\}, N_B$$
$$A \longrightarrow E\colon K_{AB}\{N_B\}$$
$$E \longrightarrow B\colon K_{AB}\{N_B\}$$

- As a result, A thinks that E is B, and B thinks that E is A.
- Note that Eve does not take the initiative, but waits until she can intercept an initiative of A.

More on man-in-the-middle attacks

- Possible for the car key example earlier on (option 4); reconstruct it yourself (techno drama!)
- Serious attack scenario in internet banking
  - Often occurring as "man-in-the-browser" attack
  - Attacker manipulates what is shown in the browser, and sends false date to the bank (via usual encrypted connection)
- Forged certificates obtained in DigiNotar attack were probably used by Iran to do a man-in-the-middle attack on Gmail users
  - by setting up a false intermediate Gmail site
- Nice story, but historically probably not correct: Ross Anderson's Mig-in-the-middle (look-up via Google)

Diversified keys

Recall the key management problem of secret key crypto:

- Each pair of users needs their own secret key: requires $\frac{n(n-1)}{2}$ keys for n users
- Problematic with smart cards, talking to many card terminals

Solution: Diversified keys: compute secret key of each card C from the identity of C, using some (super secret) masterkey K, say as $K_C = K\{\mathrm{Id}_C\}$.

The card can then authenticate itself to a terminal T via:

$C \longrightarrow T\colon \mathrm{Id}_C$ (T checks Id_C is in range, and computes K_C)
$T \longrightarrow C\colon N$
$C \longrightarrow T\colon K_C\{N\}$.

This is used in OV-chip, chipknip (but not in Luxembourg's eGo public transport card; all those cards have the same key!)

Active attack overview

- Replay attack
  - typically, eavesdropped message is sent again
  - for instance login name + password
  - countermeasure: freshness, via nonces or noncens
- Reflection attack
  - typical attack on challenge-response protocols
  - data from one session is re-used in another session
  - countermeasure: include sufficient identity information
- Man-in-the-middle (MITM) attack
  - *passive* MITM version, without modification: relay attack (any router performs a relay attack, in a strict sense)
  - *active* MITM version involves re-encryptions

Authentication for e-passports

- Since 2006 NL passport contain contactless chip with name, date-of-birth, BSN etc. plus a digital photograph
- Since 2009 also fingerprints
- Main aim: combat look-alike fraud, i.e. using someone else's passport
- Access to the chip is delicate matter:
  - should be impossible for "someone next to you in the bus"
  - should require consent of passport holder
  - sensitive data (finger prints) only for countries that are friends
- Chosen approach: accessibility of
  - picture, name etc. after user consent, via "BAC"
  - finger prints only after (two-way) terminal authentication

Authentication for e-passports: consent

- Passports contain a (thick) plastic page, with embedded:
  - photo of cardholder + authenticity marks
  - chip + antenna
  - at the bottom: 2-line Machine Readable Zone (MRZ) containing, date-of-issuance, BSN, document nr. etc.
- Essence of Basic Access Control (BAC):
  - cryptographic key for communicating with the chip can be derived from MRZ
  - how to do so is public (and can be automated, e.g. at border control)
- Idea of consent: when you hand over your e-passport, the receiver can read the MRZ and talk to the chip

BAC keys for e-passports

- Two 3DES keys are derived from MRZ:
  - K_{enc}, for confidentiality
  - K_{mac}, for integrity

  These keys are fixed, but are used to obtain session keys to protect the communication between card and reader
- Relevant MRZ-input for these 2 keys
  - passport nr.
  - birth date
  - expiry date
- In early approaches the MRZ had too little entropy, e.g. because documentnrs. were sequential

BAC protocol for e-passports

Assume a card reader Rdr has derived the keys K_{enc} and K_{mac} of a passport PsP

$$PsP \xrightarrow[(8 \text{ byte nonce})]{N_P} Rdr$$

$$PsP \xleftarrow[\text{where } m = (N_P, N_R, K_R)]{K_{\text{enc}}\{m\},\ K_{\text{mac}}\{h(m)\}} Rdr$$

$$PsP \xrightarrow[\text{where } n = (N_P, N_R, K_P)]{K_{\text{enc}}\{n\},\ K_{\text{mac}}\{h(n)\}} Rdr$$

K_P and K_R are contributions from both sides to a session key, like in: $K = K_P \oplus K_R$.
(h is a hash function that will be introduced later; ignore for now)

Two passport vulnerabilities

- These are "level below" attacks, using implementation details
- They exploit differences in how different smart cards react to different events—without knowing secret keys
  - Not all countries have the same card producers, so low level differences are likely
  - The international standards (from ICAO) do not precisely specify how to react to each possible failure
- Sources are recent research papers (on the web):
  1. [RMP'08] H. Richter, W. Mostowski, and E. Poll, *Fingerprinting Passports*, NLUUG, 2008.
  2. [CS'10] T. Chothia and V. Smirnov, *A Traceability Attack Against e-Passports*, Financial Crypto, 2010.

Fingerprinting e-passports [RMP'08]

Idea: send deliberately wrong (out-of-protocol) messages and inspect the resulting byte-sequences for different countries:

	Commands						
	44	82	84	88	A4	B0	B1
	Rehab. CHV	Ext. Auth.	Get Chall.	Int. Auth.	Select File	Read Binary	Read Binary
Australian	6982	6985	6700	6700	9000	6700	6700
Belgian	—	6E00	—	6700	6A86	6986	6700
Dutch	—	6700	6700	6982	6A86	6982	6982
French	6982	6F00	6F00	6F00	6F00	6F00	6F00
German	—	6700	6700	—	6700	6700	—
Greek	6982	63C0	6700	6982	9000	6986	6700
Italian	—	6700	—	—	—	—	—
Polish	6982	6700	6700	6700	9000	6700	—
Swedish	6982	6700	6700	—	9000	6700	—
Spanish	—	6700	6700	—	6700	6700	—

Hence, passports from different countries can be distinguished externally, via their reactions. Is this a problem?

Excursion on timing attacks

- Suppose you write a software module for checking a PIN
- A stupid way is to check the digits one-by-one, after the whole PIN has been entered, giving an error message as soon as a digit is wrong.
- This approach is vulnerable to a timing attack:
  - accurately measure the time that it takes to get an error message
  - you will see timing differences between an errors in the n-th digit and in the $n+1$-th digit.
  - hence you can try to find the PIN digit-by-digit.
- Such timing attacks occur in practice, and can be quite subtle
  - For e-passports they were found in [CS'10].
  - They exist(ed) in many implementations
  - Including the open source version (from Nijmegen), now fixed, see: http://jmrtd.org

Timing attack on the e-passport [CS'10]

- Recall the second message from the BAC protocol:

$$PsP \xleftarrow{K_{\mathsf{enc}}\{m\},\ K_{\mathsf{mac}}\{h(m)\}} Rdr \quad \text{where } m = (N_P, N_R, K_R)$$

- Many implementations do the following consecutively:
  1. check the MAC in the second part, for integrity
  2. decrypt the first part with K_{enc} and check the nonce N_R
- An error in the first MAC-check will thus appear sooner than an error in the second nonce-check
- (Some implementations, like the French one, even give different error messages)

How to exploit the e-passport timing attack

- Suppose I can eavesdrop an entire session for the e-passport of, say, Wilders
  - this means that I have a pair $K_{\mathsf{enc}}\{m\},\ K_{\mathsf{mac}}\{h(m)\}$
  - with secret keys K_{enc} and K_{mac} from his e-passport
- Now I can check for an arbitrary passport if it is the one from Wilders or not!
  - ask a passport for a nonce
  - replay the above message, and time the response
  - the nonce-check will always fail, but:
    - if the MAC-check succeeds, the passport is from Wilders!
    - if the MAC-check fails, it is not
- In order to exploit this in a physical attack, you need to get pretty close to Wilders
  - in that case you also have other attack options
  - but note: the timing attack can be fully automated

Intermediate conclusion

Security in practice is subtle and bloody difficult!

Encrypting large messages

- We have seen how to encrypt or decrypt (eg. with DES/3DES/AES) message blocks of fixed lengths, such as 64, 128 or 256 bits
- For larger or continuous messages (streams) there are several ways to apply such blockwise systems
- Especially streams require a special approach
  - you don't want wait until you have 8 keystrokes (256 bits) before you have enough to fill a block and start encrypting
  - similarly for real-time audio or video

Four modes of operation: overview

	En/de-crypt units separately	**En/de-crypt units dependently**
Block cipher (large message)	**ECB** (electr. code book)	**CBC** (cipher block chaining)
Stream cipher (continuous message, handled per 8 bits, say)	**OFB** (output feedback)	**CFB** (cipher feedback)

en.wikipedia.org/wiki/Block_cipher_modes_of_operation has good explanations & pictures

ECB: electronic code book

- ECB is the naive way to proceed: a larger message is first divided into an appropriate number of blocks, possibly using padding. Then these blocks are encrypted one-by-one.
- Explicitly, chop-up a large message m into blocks m_i

$$m = m_0\, m_1\, m_2\, \cdots\, m_N$$

and then encrypt these blocks one-by-one:

$$K\{m_0\}\, K\{m_1\}\, K\{m_2\}\, \cdots\, K\{m_N\}$$

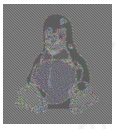
- Decryption is done in the same block-by-block style

ECB properties

ECB is rarely used because it has two big disadvantages:

1. repeated occurrence of the same block can be detected in the ciphertext. Wikipedia example:

under ECB gives



2. swapping of blocks of ciphertext may go unnoticed
   - certainly if things still make sense after decryption
   - Recall: confidentiality does not guarantee integrity

CBC: Cipher Block Chaining

- With CBC one XORs each block with the encrypted previous one before encryption, like in:

$$c_{n+1} \;=\; K\{m_{n+1} \oplus c_n\}$$

- The first block uses an initialisation vector (IV), as in:

$$c_0 \;=\; K\{m_0 \oplus IV\}$$

- This IV may either be:
  - sent openly
  - be always the same (but then changes in the first block of repeated transmissions are detectable)
- How to do decryption?

CBC properties

- If one block of ciphertext is garbled during transmission, two blocks are lost during decipherment.
  - with Propagating cipher-block chaining (PCBC) changes in the ciphertext propagate indefinitely
- The last result c_N may also be used as Message Authentication Code (CBC-MAC), to protect the integrity of the message.

OFB: Output Feedback mode

- One first generates a one-time pad (aka. keystream) in advance from an initialisation vector, namely as:

$$K\{IV\}, K\{K\{IV\}\}, K\{K\{K\{IV\}\}\}, \ldots$$

- Next, one XORs it with the incoming stream, typically in a byte-per-byte manner.
- If bits are garbled, the loss is limited to those bits. But if sender and receiver get out of sync, everything will be lost.
- A variation called Counter Mode (CTR) uses

$$c_n \;=\; m_n \oplus K\{IV + n\}.$$

This is convenient in file storage, since it allows direct access to arbitrary blocks.

CFB: Cipher feedback mode

Generate the one-time pad in a way that depends on the cleartext, as in: