MTAT.07.017
Applied Cryptography

Introduction, Randomness, PRNG, One-Time Pad, Stream Ciphers

University of Tartu

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Who am I?

Arnis Paršovs

MSc in Cyber Security
Tallinn University of Technology, 2012

Computer Science PhD student at UT
Who are you?

- MSc (Cyber Sec.) - 42
- MSc (Software Eng.) - 10
- MSc (Computer Sci.) - 8
- PhD (Computer Sci.) - 4
- BSc (Computer Sci.) - 3
- MSc Geography - 1
- MSc Physics - 1
- Open University - 1
- MSc (Software Eng.) - 10
- MSc (Cyber Sec.) - 42
Crypto courses in UT

- Cryptology I
- Cryptographic protocols
- Cryptology II
- Research seminar in cryptography
- Quantum cryptography
- Topics of mathematics in cryptology
- Applied cryptography
This course

- Practical course
- Learn by implementing
- No proofs – just intuition
Course timeline

16 weeks

- Lecture: Thu 10:15 – 12:00 (room 405)
- Practice: Thu 18:15 – 20:00 (room 206)

6 ECTS – 10 hours weekly

- 2 hours in class
- 8 hours on homework (may vary)
Grading

• Homework every week

• Homeworks give maximum 70% of final grade
  • Bonus points help to achieve the maximum

• Deadlines are strict!
  • Homework deadline – beginning of next lecture
  • May be extended if you have a good excuse
  • Late submission gets 50% of grade
  • Homeworks submitted later than 1 week after the deadline are not accepted

• Exam gives another 30% of final grade
  • Should be easy if you follow the lectures
Programming Environment

Course history:

- 2010: C, C++, Java
- 2011: Java
- 2012: Java
- 2013: Python
- ...
- 2018: Python

Test environment: Ubuntu 16.04.3, Python 2.7.x

Python packages from Ubuntu package repository (not pip)
Homework submission

- Create a private Bitbucket repository and grant me ‘read’ privileges:
  

- Homework templates will be published at course repository: https://bitbucket.org/appcrypto/2018/

- Feedback will be given using Bitbucket’s code comment feature

- Do not look on homework solutions of others!
  
  - Plagiarism cases will be handled in accordance with UT Plagiarism Policy
Academic Fraud

• It is academic fraud to collaborate with other people on work that is required to be completed and submitted individually.

• The homeworks in Applied Cryptography course are required to be completed and submitted individually!

• You can help your peers to learn by explaining concepts, but don’t provide them with answers or your own work!
  - If you don’t see the borders – work alone.

• Copying code samples from internet resources (e.g., stackoverflow.com) may be considered plagiarism:
  - the most basic building blocks may be OK
  - combination (composition) of building blocks is NOT OK
• If you don’t see the borders – limit yourself to Python API documentation.
Randomness

- Why do we need randomness in real life?
- Why do we need randomness in crypto?
  - For keys, nonces, etc.
- What is random sequence?
  - Sequence of numbers that does not follow any deterministic pattern
  - None of the numbers can be predicted based on previous numbers
  - Has no description shorter than itself
  - Sequence of bits that cannot be compressed
- Where we can get random numbers?
  - Can we flip a coin to get a random number?
  - Can a computer program generate random numbers?
  - Thermal noise, photoelectric effect, quantum phenomena
Pseudo-Random Number Generator (PRNG)
Deterministic algorithm that produces endless stream of numbers which are indistinguishable from truly random. PRNG is initialized using (hopefully) random 'seed' value.

Linux /dev/urandom implementation:

- Known part of the input does not allow to predict the output
- PRNG is used when true-RNG is not available
- Can be used to “extend” randomness
- Entropy of the output depends on the entropy of the input
Randomness

- Can we tell whether the sequence is random?
  
  \[ \ldots 41592653589 \ldots \]
  
  \[ 3.141592653589793 \ldots \]
  
  \[ \ldots 000000 \ldots \]

- Statistical randomness tests
Bits and Bytes

Bit string:
100010000011

\[2^{11} + 2^7 + 2^1 + 2^0\]

Most significant bit (msb) – left-most bit

Bytes - 8-bit collections (0-255)

Byte - basic addressable element
# ASCII Table

| Decimal | Character | ASCII Code | Character | ASCII Code | Character | ASCII Code | Character | ASCII Code | Character | ASCII Code | Character |
|---------|-----------|------------|-----------|------------|-----------|------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0       | <NULL>    | 32         | @         | 64         | "          | 96         | `          | 128       | Å          | 160       | †         | 192       | ć         | 224       | ±         |
| 1       | <SOH>     | 33         | !         | 65         | A          | 97         | a          | 129       | Å          | 161       | °          | 193       | i          | 225       | .         |
| 2       | <STX>     | 34         | "         | 66         | B          | 98         | b          | 130       | Ç          | 162       | ç          | 194       | n          | 226       | ,         |
| 3       | <ETX>     | 35         | #         | 67         | C          | 99         | c          | 131       | É          | 163       | £          | 195       | √         | 227       | "         |
| 4       | <EOT>     | 36         | $         | 68         | D          | 100        | d          | 132       | Ñ          | 164       | §          | 196       | f          | 228       | %         |
| 5       | <ENQ>     | 37         | %         | 69         | E          | 101        | e          | 133       | Ö          | 165       | •          | 197       | ≈          | 229       | Å         |
| 6       | <ACK>     | 38         | &         | 70         | F          | 102        | f          | 134       | Ü          | 166       | ¶          | 198       | Δ          | 230       | È         |
| 7       | <BEL>     | 39         | '         | 71         | G          | 103        | g          | 135       | á          | 167       | ß          | 199       | «          | 231       | Á         |
| 8       | <BS>      | 40         | (         | 72         | H          | 104        | h          | 136       | Å          | 168       | ®          | 200       | »          | 232       | Ë         |
| 9       | <TAB>     | 41         | )         | 73         | I          | 105        | i          | 137       | å          | 169       | ©          | 201       | ...        | 233       | È         |
| 10      | <LF>      | 42         | *         | 74         | J          | 106        | j          | 138       | à          | 170       | ™          | 202       | 234       | Í         |
| 11      | <VT>      | 43         | +         | 75         | K          | 107        | k          | 139       | á          | 171       | '          | 203       | À          | 235       | Í         |
| 12      | <FF>      | 44         | ,         | 76         | L          | 108        | l          | 140       | Å          | 172       | "          | 204       | À          | 236       | Í         |
| 13      | <CR>      | 45         | -         | 77         | M          | 109        | m          | 141       | ç          | 173       | ±          | 205       | Ō          | 237       | Ì         |
| 14      | <SO>      | 46         | .         | 78         | N          | 110        | n          | 142       | é          | 174       | Æ          | 206       | Ë          | 238       | Ô         |
| 15      | <SI>      | 47         | /         | 79         | O          | 111        | o          | 143       | े          | 175       | Ø          | 207       | Ò          | 239       | Õ         |
| 16      | <DLE>     | 48         | 0         | 80         | P          | 112        | p          | 144       | े          | 176       | ∞          | 208       | –          | 240       | •         |
| 17      | <DC1>     | 49         | 1         | 81         | Q          | 113        | q          | 145       | े          | 177       | ±          | 209       | –          | 241       | Ô         |
| 18      | <DC2>     | 50         | 2         | 82         | R          | 114        | r          | 146       | i          | 178       | ≤          | 210       | “          | 242       | Ú         |
| 19      | <DC3>     | 51         | 3         | 83         | S          | 115        | s          | 147       | i          | 179       | ≥          | 211       | ”          | 243       | Ù         |
| 20      | <DC4>     | 52         | 4         | 84         | T          | 116        | t          | 148       | i          | 180       | ¥          | 212       | ‘          | 244       | Ù         |
| 21      | <NAK>     | 53         | 5         | 85         | U          | 117        | u          | 149       | i          | 181       | μ          | 213       | ’          | 245       | î         |
| 22      | <SYN>     | 54         | 6         | 86         | V          | 118        | v          | 150       | ŋ          | 182       | ð          | 214       | ÷          | 246       | °         |
| 23      | <ETB>     | 55         | 7         | 87         | W          | 119        | w          | 151       | õ          | 183       | Σ          | 215       | ◦          | 247       | —         |
| 24      | <CAN>     | 56         | 8         | 88         | X          | 120        | x          | 152       | ò          | 184       | Π          | 216       | ý          | 248       | —         |
| 25      | <EM>      | 57         | 9         | 89         | Y          | 121        | y          | 153       | ð          | 185       | ÷          | 217       | Ý          | 249       | —         |
| 26      | <SUB>     | 58         | ;         | 90         | Z          | 122        | z          | 154       | ó          | 186       | j          | 218       | ।          | 250       | °         |
| 27      | <ESC>     | 59         | <         | 91         | [          | 123        | {          | 155       | ô          | 187       | a          | 219       | €          | 251       | °         |
| 28      | <FS>      | 60         | >         | 92         | \          | 124        | |          | 156       | ú          | 188       | ø          | 220       | <          | 252       | °         |
| 29      | <GS>      | 61         | =         | 93         | ]          | 125        | }          | 157       | ŭ          | 189       | Ω          | 221       | >          | 253       | °         |
| 30      | <RS>      | 62         | >         | 94         | ^          | 126        | ~          | 158       | ŭ          | 190       | æ          | 222       | fi         | 254       | °         |
| 31      | <US>      | 63         | ?         | 95         | _          | 127        | <DEL>     | 159       | ŭ          | 191       | ø          | 223       | fl         | 255       | °         |

http://www.asciitable.com/
Hexadecimal (Base16) Encoding

<table>
<thead>
<tr>
<th>Hex</th>
<th>Value</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>'0'</td>
<td>0</td>
<td>0000</td>
</tr>
<tr>
<td>'1'</td>
<td>1</td>
<td>0001</td>
</tr>
<tr>
<td>'2'</td>
<td>2</td>
<td>0010</td>
</tr>
<tr>
<td>'3'</td>
<td>3</td>
<td>0011</td>
</tr>
<tr>
<td>'4'</td>
<td>4</td>
<td>0100</td>
</tr>
<tr>
<td>'5'</td>
<td>5</td>
<td>0101</td>
</tr>
<tr>
<td>'6'</td>
<td>6</td>
<td>0110</td>
</tr>
<tr>
<td>'7'</td>
<td>7</td>
<td>0111</td>
</tr>
<tr>
<td>'8'</td>
<td>8</td>
<td>1000</td>
</tr>
<tr>
<td>'9'</td>
<td>9</td>
<td>1001</td>
</tr>
<tr>
<td>'A'</td>
<td>10</td>
<td>1010</td>
</tr>
<tr>
<td>'B'</td>
<td>11</td>
<td>1011</td>
</tr>
<tr>
<td>'C'</td>
<td>12</td>
<td>1100</td>
</tr>
<tr>
<td>'D'</td>
<td>13</td>
<td>1101</td>
</tr>
<tr>
<td>'E'</td>
<td>14</td>
<td>1110</td>
</tr>
<tr>
<td>'F'</td>
<td>15</td>
<td>1111</td>
</tr>
</tbody>
</table>

- One hex symbol represents 4 bits
- Two hex symbols needed to represent a byte

2E = 0010 1110
Base64 encoding

bn+ITbj/TRwcSAwT8CZnFZN0me5/AGdFIGNLBPPo7Nc07T6XTpsTw0QxnM++9xJXKkEEcaEn2Vo9MiAVPVUR5PsFGKZbL7coPRdHD058RokCF4aizWv6+Dqg0lsXsmXliWusnOQ==

- Can represent binary data using printable characters
- Base64 encoded data approximately 33% larger
Bitwise operations

AND:
• extract partition of bit string
  \[ \begin{array}{cccccccc}
  0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
  \hline
  0 & 0 & 0 & 0 & 0 & 1 & 0 & 0
  \end{array} \]
  >>> 60 & 6
  \[ \begin{array}{cccccccc}
  0 & 0 & 0 & 0 & 0 & 1 & 0 & 0
  \end{array} \] (AND)

OR:
• set specific bits
  \[ \begin{array}{cccccccc}
  0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
  \hline
  0 & 0 & 1 & 1 & 1 & 1 & 1 & 0
  \end{array} \]
  >>> 60 | 6
  \[ \begin{array}{cccccccc}
  0 & 0 & 1 & 1 & 1 & 1 & 1 & 0
  \end{array} \] (OR)

XOR:
• flip specific bits
  \[ \begin{array}{cccccccc}
  0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
  \hline
  0 & 0 & 1 & 1 & 1 & 0 & 1 & 0
  \end{array} \]
  >>> 60 ^ 6
  \[ \begin{array}{cccccccc}
  0 & 0 & 1 & 1 & 1 & 0 & 1 & 0
  \end{array} \] (XOR)

Shift:
• shift and pad with 0
  \[ \begin{array}{cccccccc}
  0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\
  \hline
  0 & 0 & 0 & 0 & 1 & 1 & 1 & 1
  \end{array} \] (right shift by two)
Bitwise operations: AND

- Extract bits we are interested in

Example:

\[0 0 1 1 1 1 0 0\]
\[0 0 0 0 0 0 1 1 0 0\] (bit mask)

\[\begin{array}{c}
0 0 0 0 0 0 1 0 0
\end{array}\]

Python:

```python
>>> 60 & 6
4
```
Bitwise operations: OR

- Set specific bits

Example:

<table>
<thead>
<tr>
<th>0 0 1 1 1 1 0 0</th>
<th>0 0 0 0 0 1 1 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>0 0 1 1 1 1 1 0</td>
<td></td>
</tr>
</tbody>
</table>

Python:

```python
>>> 60 | 6
62
```
Bitwise operations: XOR

- Flip specific bits

Example:

0 0 1 1 1 1 0 0
0 0 0 0 0 1 1 0
---------------
0 0 1 1 1 0 1 0 (XOR)

Python:

```python
>>> 60 ^ 6
58
```
Bitwise operations: Shift

- Shift (right or left) and pad with zeros

Example:

```
0 0 1 1 1 1 0 0
---------------
0 0 0 0 1 1 1 1 (right shift by two)
```

Python:

```
>>> 60 >> 2
15
>>> 15 << 1
30
```

- Fast multiplication and division by 2
One-Time Pad (OTP)

- Key generation: key (one-time pad) is random sequence the same length as plaintext
- Encryption operation: XOR ($\oplus$) the key with plaintext
- Decryption operation: XOR ($\oplus$) the key with ciphertext
One-Time Pad (OTP)

Information-theoretically secure (unbreakable), if:

- Key (one-time pad) is truly random
- Key is never reused

\[
\text{plaintext}_1 \oplus \text{key} = \text{ciphertext}_1 \\
\text{plaintext}_2 \oplus \text{key} = \text{ciphertext}_2 \oplus \text{plaintext}_2 = \text{key} \\
\text{key} \oplus \text{ciphertext}_1 = \text{plaintext}_1
\]

- Not used in practice
Stream Cipher

- Key generation: a small key “seeds” the PRNG
- Encryption operation: XOR (⊕) the key with plaintext
- Decryption operation: XOR (⊕) the key with ciphertext

Stream ciphers differ by the PRNG used
- Why is it less secure than one-time pad?
- Encryption on its own does not provide integrity!
- The same keystream must never be reused!
Stream Cipher
Solution – on every encryption add unique nonce to the key:

- The same nonce must never be reused!
- How to generate nonce?
  - Counter value
  - Random value
  - Current time
Questions

• Where we can get (true) random numbers?
• Why pseudo-random number is not as good as random number?
• What are the properties of random sequence?
• Can we tell whether the provided sequence is random?
• What happens to data if we XOR it with random data?
• Why brute-force attacks are ineffective in breaking one-time pad?
• Why unbreakable one-time pad is not used in enterprise products?
• How is stream cipher different from one-time pad?
Task: One-Time Pad (OTP)

Implement One-Time Pad cryptosystem.

Encryption should produce a random key file and encrypted output file:

```bash
$ chmod +x otp.py
$ ./otp.py encrypt datafile datafile.key datafile.encrypted
```

Decryption should use the key file and produce decrypted original plaintext file:

```bash
$ ./otp.py decrypt datafile.encrypted datafile.key datafile.plain
```

- Commit “01/otp.py” to your repository

  ```bash
  $ git add 01/otp.py
  $ git commit -m "01 homework solution" 01/otp.py
  $ git push
  ```
Task: Template

#!/usr/bin/env python
import os, sys  # do not use any other imports/libraries
# took x.y hours (please specify here how much time your solution required)

def encrypt(pfile, kfile, cfile):
    # your implementation here
    pass

def decrypt(cfile, kfile, pfile):
    # your implementation here
    pass

def usage():
    print "Usage:"
    print "encrypt <plaintext file> <output key file> <ciphertext output file>"
    print "decrypt <ciphertext file> <key file> <plaintext output file>"
    sys.exit(1)

if len(sys.argv) != 5:
    usage()
elif sys.argv[1] == 'encrypt':
    encrypt(sys.argv[2], sys.argv[3], sys.argv[4])
elif sys.argv[1] == 'decrypt':
    decrypt(sys.argv[2], sys.argv[3], sys.argv[4])
else:
    usage()
>>> "abraca" + 'dabra'
'abracadabra'

>>> for character in "foo":
...     print "char=%s" % (character)
char=f
char=o
char=o

>>> "abraca"[2:5]
'rac'

>>> "abracadabra".encode('hex')
'6162726163616461627261'

>>> "abracadabra".encode('base64')
'YWJyYWNhZGFicmE=

>>> "abracadabra".encode('base64').decode('base64')
'abracadabra'
Python

Python’s `str` data type can store any byte:

```python
>>> s = 'Abc\x00\x61'
>>> len(s)
5
>>> s[0], s[1], s[2], s[3], s[4]
('A', 'b', 'c', '\00', 'a')
>>> ord(s[0])
65
>>> chr(65)
'A'
```

- `ord()` can be used to convert byte to integer
- `chr()` can be used to convert integer to byte
Python: Bytes to Integer

```python
>>> s = 'abC'
>>> i = ord(s[0])
>>> i
97
>>> bin(i)
'0b1100001'
>>> i = i << 8
>>> bin(i)
'0b1100001000000000'
>>> i = i | ord(s[1])
>>> bin(i)
'0b110000101100010'
>>> i = i << 8
>>> bin(i)
'0b110000101100010000000000'
>>> i = i | ord(s[2])
>>> bin(i)
'0b11000010110001001000011'
>>> i
6382147
```

- Convert first byte to integer
- Left-shift integer 8 times
- Convert second byte to integer
- Load second integer in first 8 bits
- ...

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Task: One-Time Pad (OTP)

- **Encrypter:**
  - Read the file contents into byte string (e.g., `s = open('file.txt').read()`)
  - Convert plaintext byte string to one big integer
  - Obtain random byte string the same length as plaintext (use `os.urandom()`)
  - Convert random byte string to one big integer
  - XOR plaintext integer and key integer (**please, use this approach**)
  - Save the key (one-time pad) and XOR’ed result (ciphertext) to file:
    - Convert key integer to byte string:
      - Use bit masking and left shift
    - Once more: use bitwise operations!
      - Banned: functions `bin()`, `str()`, `int()`, `bytearray()` and operator `**`

- **Decrypter:**
  - Perform the operations in reverse order
Task: Test Case

$ echo -n -e "\x85\xce\xa2\xa2\x25" > file.enc
$ hexdump -C file.enc
00000000  85 ce a2 25                   |...%|
$ echo -n -e "\xe4\xac\xe1\x2f" > file.key
$ hexdump -C file.key
00000000  e4 ac e1 2f                   |.../|
$ ./otp.py decrypt file.enc file.key file.plain
$ hexdump -C file.plain
00000000  61 62 43 0a                   |abC.|

$ echo -n -e "\x00\x00\x61\x62\x43\x00" > file.plain
$ hexdump -C file.plain
00000000  00 00 61 62 43 00             |..abC.|
$ ./otp.py encrypt file.plain file.key file.enc
$ ./otp.py decrypt file.enc file.key fileorig.plain
$ hexdump -C fileorig.plain
00000000  00 00 61 62 43 00             |..abC.|

Value 0 can be encoded as empty file or file full of zero bytes.
Please!

- Do not waste your time on input validation
- Do not use imports/libraries that are not explicitly allowed
- Include information of how much time the tasks took (as a comment at the top of your source code)
- Give a feedback about parts that were hard to grasp or implement
- Make a note if something was wrong on slides or you have an idea for improvement
- Do not leave any unrequired debugging output in your solution
- Commit the solution to the main branch of your repository with the filename required

Thank you!