MTAT.07.017
Applied Cryptography

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

University of Tartu

Spring 2019
Who am I?

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MSc in Cyber Security
Tallinn University of Technology, 2012

Computer Science PhD student at UT
Who are you?

- MSc (Cyber Sec.) - 19
- MSc (Computer Sci.) - 8
- PhD (Computer Sci.) - 3
- Open University - 2
- BSc (Computer Sci.) - 1
- PhD (Materials Sci.) - 1
- MSc (Cyber Sec.) - 19
- MSc (Computer Sci.) - 8
Crypto courses in UT

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

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

16 weeks

- Lecture: Thu 10:15 – 12:00 (room 122)
- Practice: Thu 18:15 – 20:00 (room 405)

6 ECTS – 10 hours weekly

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

- Homework every week
- Homeworks give maximum 70% of the final grade
- Deadlines are strict!
  - Homework deadline – beginning of the next lecture
  - Late submission gets 50% of the grade
  - Homeworks submitted later than 1 week after the deadline are not accepted!
- Exam gives another 30% of the final grade
  - Should be easy if you follow the lectures
Homework submission

- Homeworks must be implemented in Python version 2.7
  - Test environment: Ubuntu 18.04, Python 2.7.x
  - Python packages from Ubuntu package repository (not pip)

- Create a private Bitbucket repository and grant me ‘read’ privileges:
  https://bitbucket.org/appcrypto/2019/src/master/setup/

- Add your repository to the course grading page at
  https://cybersec.ee/appcrypto2019/

- Homework templates will be published at course repository:
  https://bitbucket.org/appcrypto/2019/

- Feedback will be given using code comment feature

- Teaching assistance over e-mail not available

- 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

- Where do we need randomness in real life?
- Why do we need randomness in crypto?
  - For keys, passwords, 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?
  ...41592653589...
  3.141592653589793...
  ...
  ...000000.....

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

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

```
bn+ITbj/TRwcSAwT8CZnFZN0me5/AGdFIGNLBPo
7Nc07T6XTpsTw0QxnM++9xJXKkEEcaEn2Vo9MiAV
PVUR5PsFGKZbL7coPRdHD058RokCF4aizWv6+Dqg
0lsXsmXliWusn0Q==
```
Bitwise operations

AND:
- extract partition of bit string
  0 0 1 1 1 1 0 0
  0 0 0 0 0 1 1 0 (bit mask) >>> 60 & 6
  0 0 0 0 0 1 0 0 (AND)

OR:
- set specific bits
  0 0 1 1 1 1 0 0
  0 0 0 0 0 1 1 0 >>> 60 | 6
  0 0 1 1 1 1 1 0 (OR)

XOR:
- flip specific bits
  0 0 1 1 1 1 0 0
  0 0 0 0 0 1 1 0 >>> 60 ^ 6
  0 0 1 1 1 0 1 0 (XOR)

Shift:
- shift and pad with 0
  0 0 1 1 1 1 0 0 >>> 60 >> 2
  0 0 0 0 1 1 1 1 (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 1 1 0 (bit mask)
---------------
0 0 0 0 0 1 0 0 (AND)
```

Python:

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

- Set specific bits

Example:

```
0 0 1 1 1 1 0 0
0 0 0 0 0 1 1 0
---------------
0 0 1 1 1 1 1 0 (OR)
```

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 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 plaintext with key
• Decryption operation: XOR ($\oplus$) the ciphertext with key
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 plaintext with key
- Decryption operation: XOR (⊕) the ciphertext with key

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) – 3p

Implement One-Time Pad cryptosystem.

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

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

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

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

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

```
$ 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’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', '\x00', '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
>>> 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
  - ...
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\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.|

Note: When you are converting bytestring to integer, you are loosing the most significant zero bits.
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 feedback about the parts that were hard to grasp or you have an idea for improvement
- The output of your solution must byte-by-byte match the format of example output shown on slides
  - Remove any nonrequired debugging output before committing
  - Unless required, the solution must not create/delete any files
- Commit the (finished) solution to the main branch of your repository with the filename required

Thank you!