Cryptology for IoT

Modules M4, M6, M8
Session of 24th May, 2022.

M6.1 Briefing of the session
M6.2 Friedman Test
M6.3 Hill Climbing
M6.4 Final Exercise using Hill Climbing

Prof.: Guillermo Botella

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Prof.: Guillermo Botella

M6.1 Briefing of today

- Keeping going with Cryptography and Cryptoanalysis (Crypto lab v1 and v2)
  - Slides and supplementary videos
  - Deal with Unknown cipher
  - Friedman Test
  - Hill Climbing
- Create and break our own Homophonic Substitution code
- I warn you for tomorrow 25^{th} May. We will go to the Socrative. Second quiz (continuation of First quiz)
  - Please study the slides!

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Friedman Test for classical and modern crypto

Cryptanalysis

Cost / Fitness Function

Where Do We Need and Use Them?

. Entropy

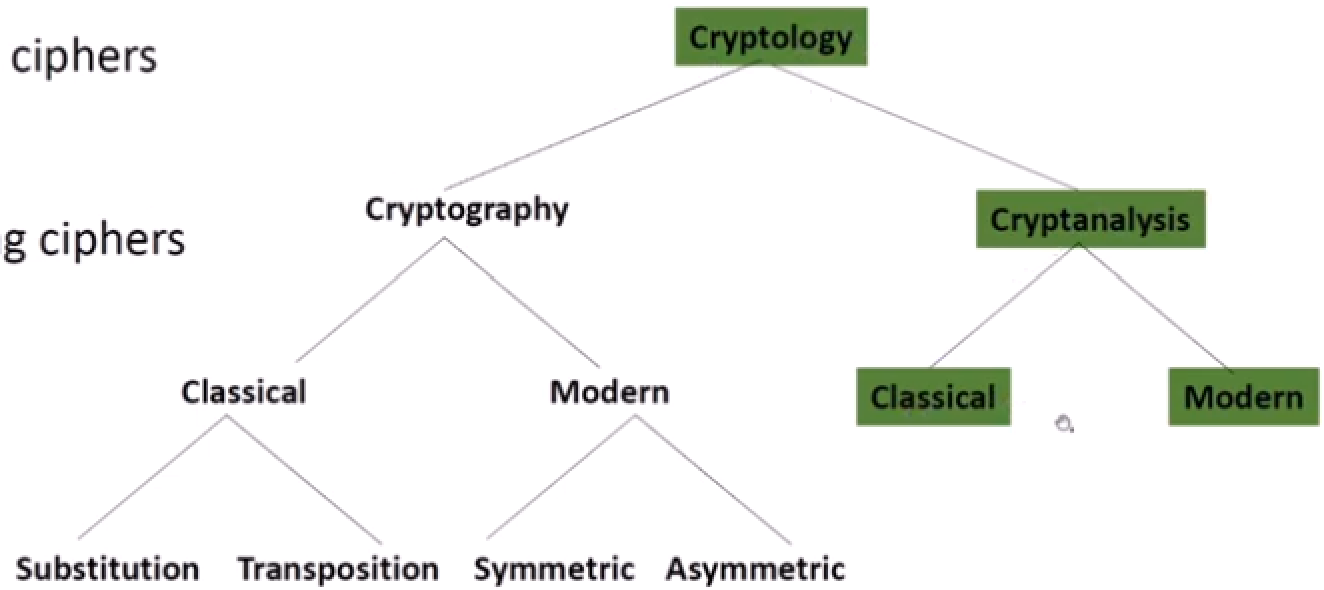
. Language Models

. Index of Coincidence

Friedman Test for classical and modern crypto

Cryptography
Art of making ciphers

Cryptanalysis
Art of breaking ciphers



Friedman Test for classical and modern crypto

- The Index of Coincidence (IoC) is a **statistical value**. It is the **probability** that **two letters randomly drawn** (from **different positions** of a given text) **are the same**
- The inventor of the Index of Coincidence was **William Friedman**
- It is defined as

$$IoC = \sum_{i=A}^{Z} \frac{n_i \cdot (n_i - 1)}{N \cdot (N-1)}$$

- The sum of the number of each letter n_i multiplied with the sum of each letter minus one $(n_i - 1)$ divided by the sum of all letters N multiplied by the sum of all letters minus one $(N-1)$
- English texts have an IoC of about 0.066 and German texts have an IoC of about 0.078
- Random texts have an IoC of about $\frac{1}{\#(letters\ in\ alphabet)} \rightarrow \frac{1}{26} = 0.038$

Friedman Test for classical and modern crypto

- The IoC was used by Friedman in the **Friedman Test** to determine the keylength of a polyalphabetic substitution cipher, e.g. the Vigenère cipher (not part of this video)
- We use the IoC as **cost or fitness function** in **modern heuristics** to **improve our (putative) key** during e.g. hill climbing
- The **closer the IoC** of the current decrypted plaintext is to the **IoC of the assumed language**, the **"better" is our key**
- The IoC can be used when other statistical values can't be used (e.g. ADFGVX, Enigma rotors)

Friedman Test for classical and modern crypto

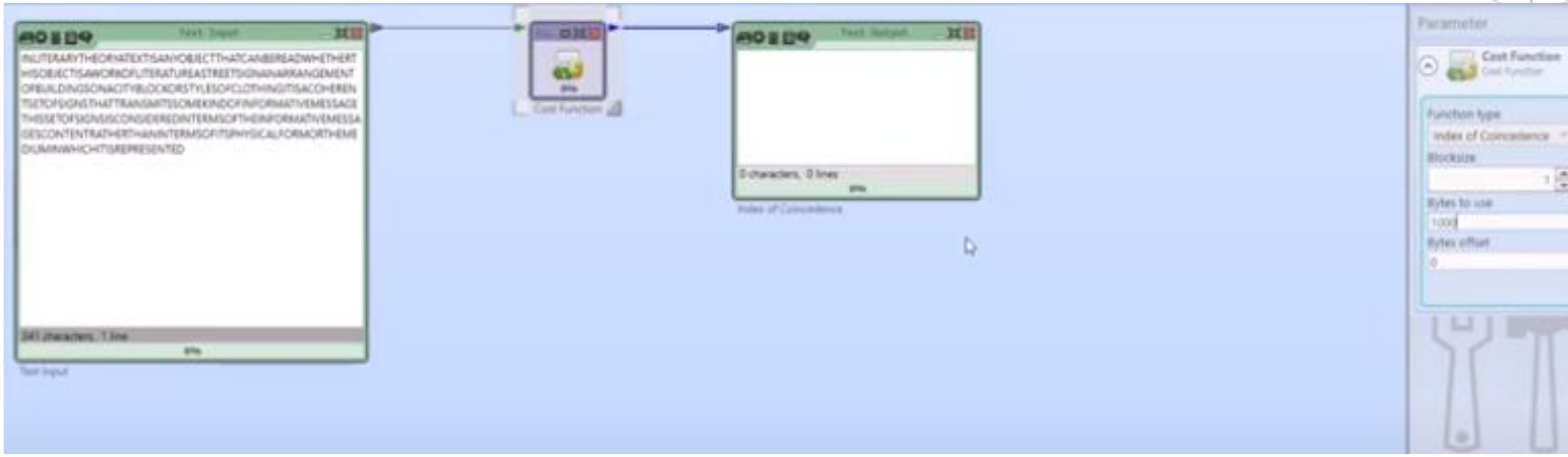
- Example Calculation:
  INLITERARYTHEORYATEXTISANYOBJECTTHATCANBEREADWHETHERTHISOBJECTISAWORKOFLITERATUREA
  STREETSIGNANARRANGEMENTOFBUILDINGSONACITYBLOCKORSTYLESOFCLOTHINGITISACOHERENTSETOF
  SIGNSTHATTRANSMITSSOMEKINDOFINFORMATIVEMESSAGETHISSETOFSIGNSISCONSIDEREDINTERMSOFT
  HEINFORMATIVEMESSAGESCONTENTRATHERTHANINTERMSOFITSPHYSICALFORMORTHEMEDIUMINWHICHIT
  ISREPRESENTED

$N = 341$

$n_A = 23, n_B = 5, n_C = 11, n_D = 7, n_E = 40, n_F = 11, n_G = 8, n_H = 16, n_I = 33,$
$n_J = 2, n_K = 3, n_L = 7, n_M = 12, n_N = 25, n_O = 24, n_P = 2, n_R = 25, n_S = 32,$
$n_T = 40, n_U = 3, n_V = 2, n_W = 3, n_X = 1, n_Y = 6$

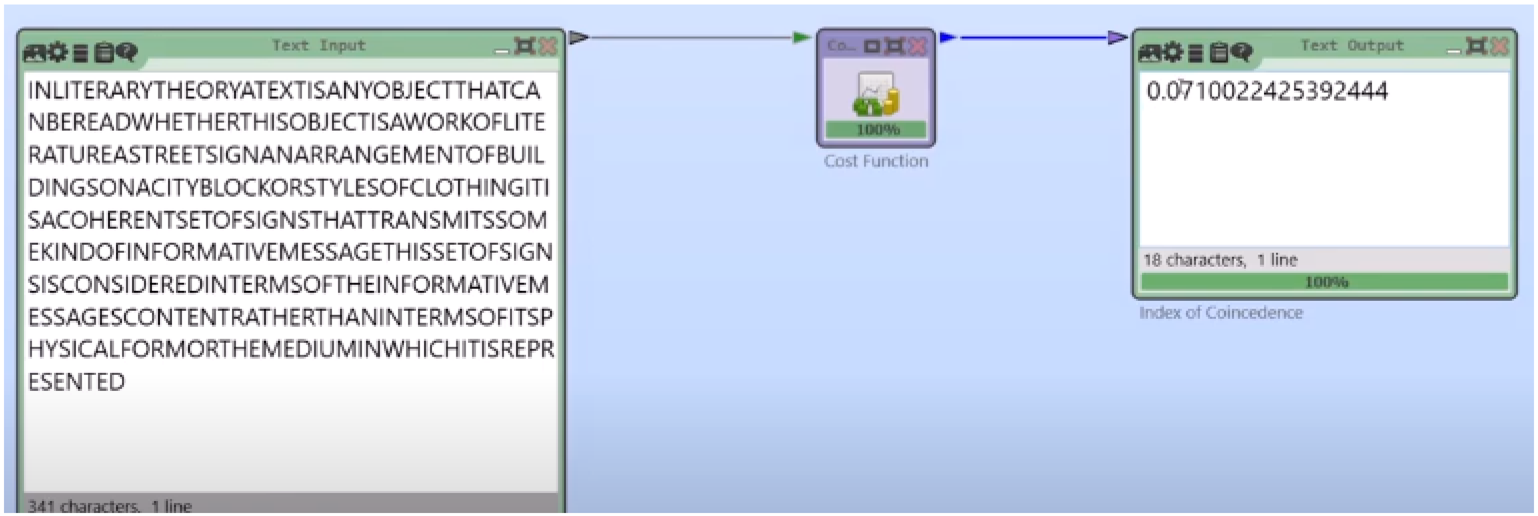
$$IoC = \frac{23 \cdot 22}{341 \cdot 340} + \frac{5 \cdot 4}{341 \cdot 340} + \frac{11 \cdot 10}{341 \cdot 340} + \dots + \frac{6 \cdot 5}{341 \cdot 340} = 0.071002243$$

Friedman Test for classical and modern crypto



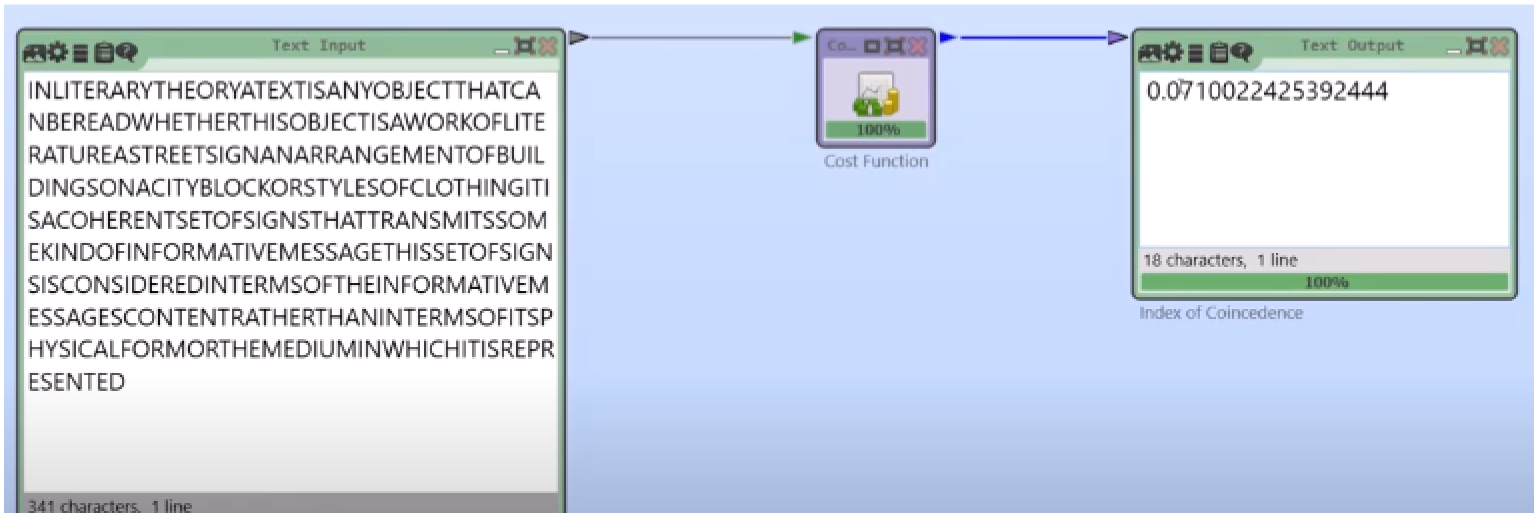
- Blocksize = 1
- 1000 bytes to use!

Friedman Test for classical and modern crypto



- Blocksize = 1
- 1000 bytes to use!

Friedman Test for classical and modern crypto



- Blocksize = 1
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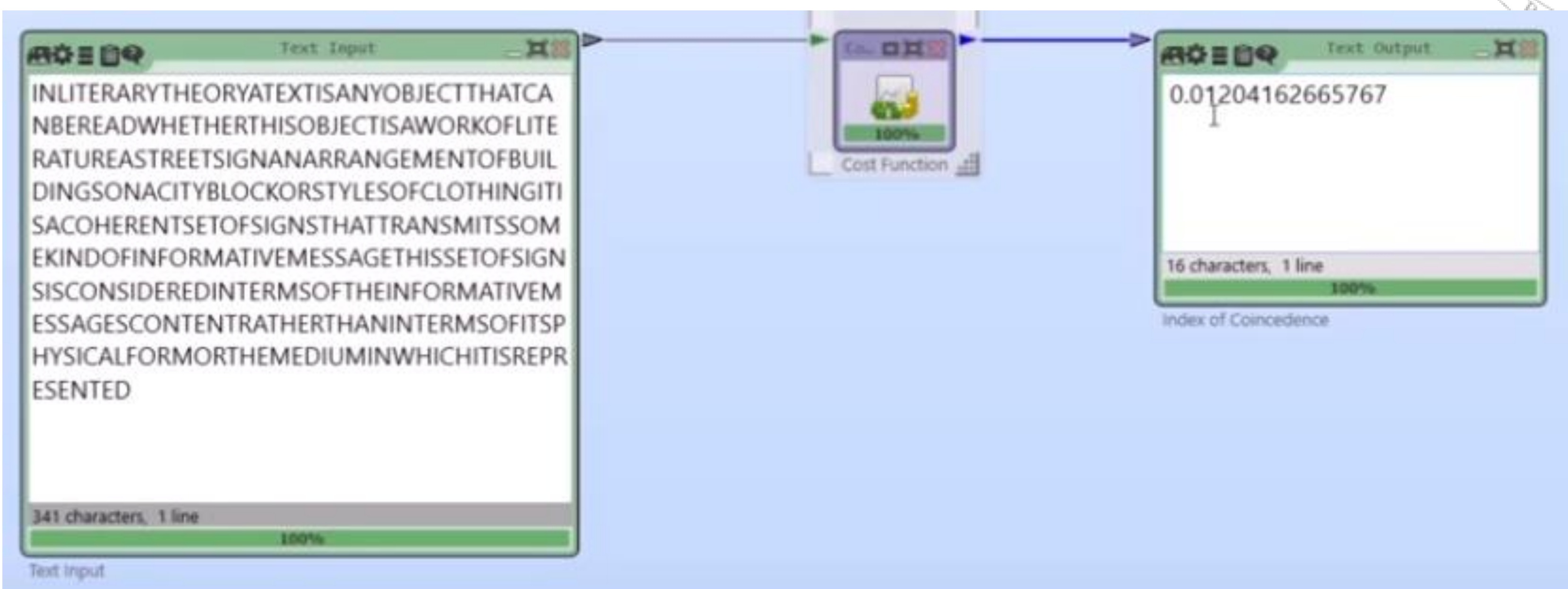
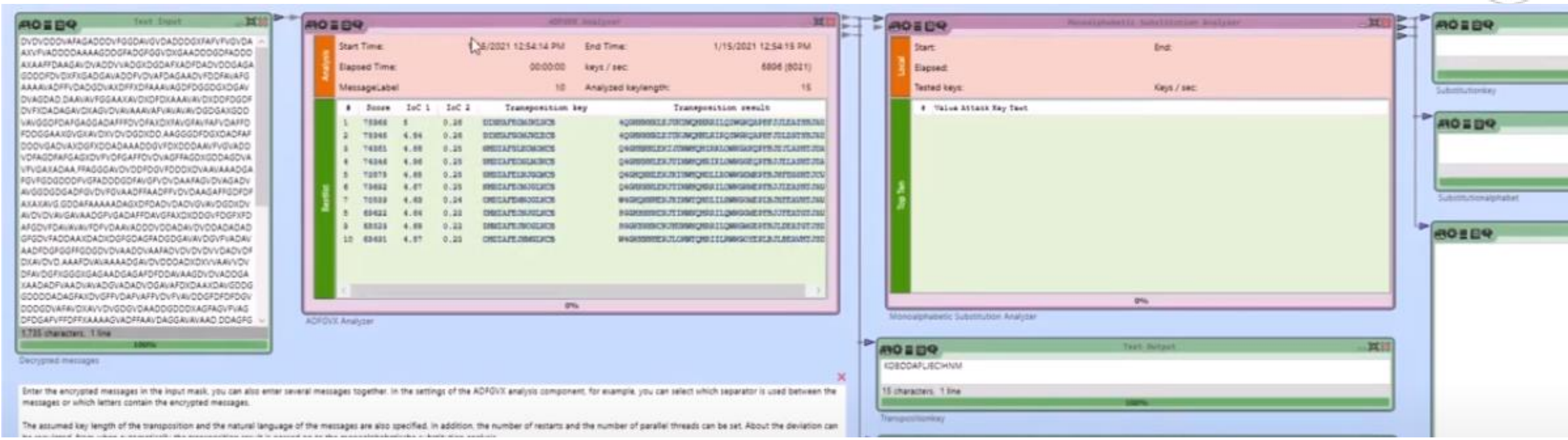
Friedman Test for classical and modern crypto



- Blocksize = 2
- Probability goes down!

Friedman Test for classical and modern crypto

Friedman Test for classical and modern crypto



- Blocksize = 2
- Probability goes down!

Friedman Test for classical and modern crypto

Analysis

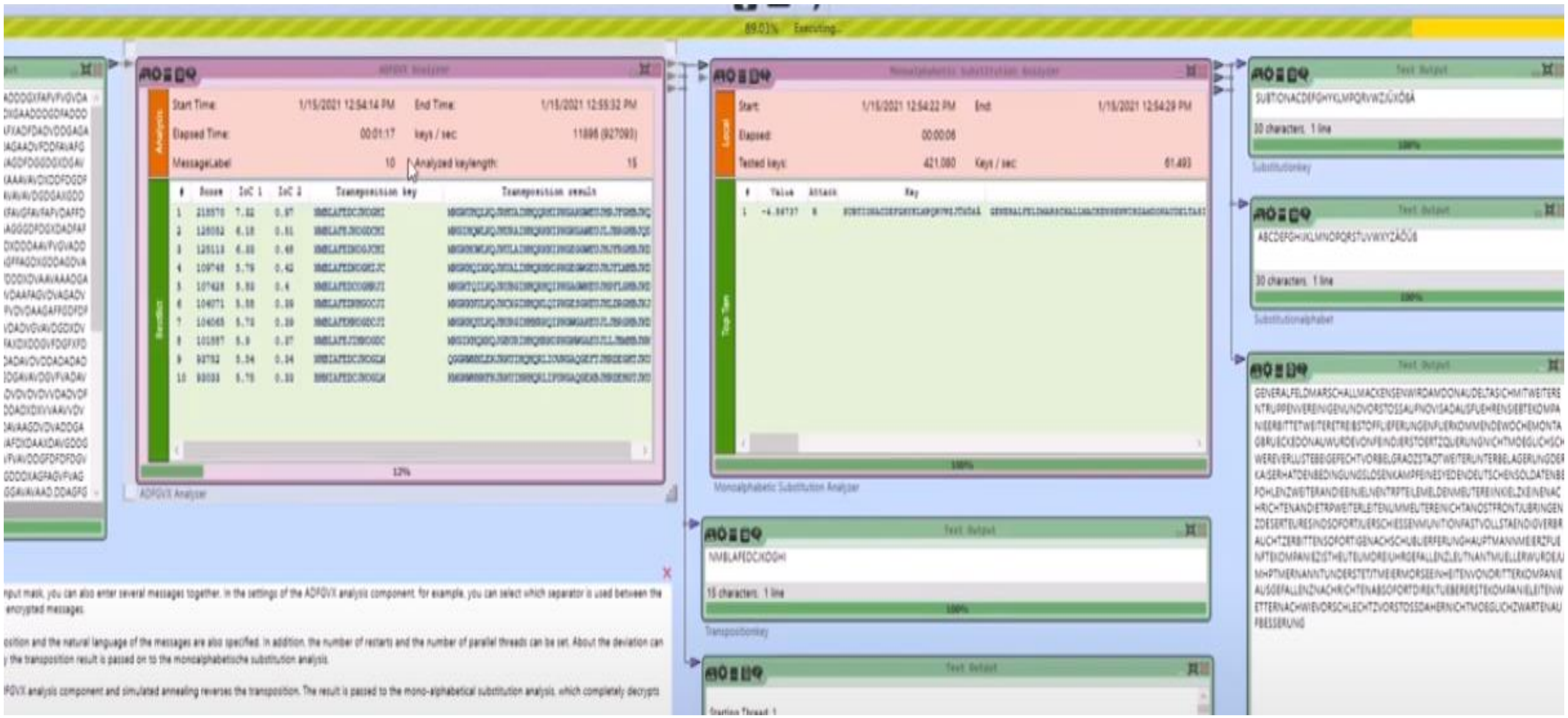
Start Time:	1/15/2021 12:54:14 PM	End Time:	1/15/2021 12:54:17 PM
Elapsed Time:	00:00:03	keys / sec:	9426 (30101)
MessageLabel	10	Analyzed keylength:	15

Bestlist

#	Score	IoC 1	IoC 2	Transposition key	Transposition result
1	93752	5.54	0.34	NHBIAFEDCJKOGLM	QGGKWNNLEKJRKUIHQHQRLIOVKGAQGEFTJHRDEGHTJKU
2	93033	5.75	0.33	BHNIAFEDCJKOGLM	KMGKWNNKFKJRKUINKHQRLIPUKGAQGEXBJHRDEHGTJKU
3	83665	5.23	0.29	BHNIAFEDCLMJKOG	KMGKTKNQFKJRIKUNKHQORLJUKGAEQGXBJHQLDBGTJKA
4	83304	5.4	0.28	BINHAFELMJKOGDC	GQGHKNQWLEJIKURQHHORLKPIWGEQGATFJKLDBNSHJAU
5	83067	5.42	0.28	BHNIAFELMJKOGDC	KMGHKNQWFKJIKURNKHORLKPUKGEQGAXBJKLDBNGTJAU
6	82310	5.31	0.28	BHNIAFEJKLMOGDC	KMGKNHQWFKJKIURNKHRIRKPUKGQEGAXBJLEJBNGTJUA
7	81538	5.31	0.28	BINHAFEJKLMOGDC	GQGKNHQWLEJKIURQHHRIRKPIWGQEGATFJLEJBNSHJUA
8	80481	5.3	0.27	BINHAFEJMLKOGDC	GQGKHNQWLEJIKURQHHROLKPIWGQEGATFJLKDBNSHJSC
9	76574	5.16	0.25	BINHAFEOMJKLGDC	GQGHKNQWLEJUKIRQHHRRIKPIWGKQAATFJJLEBNSHJAU
10	75966	5	0.26	DINHAFEOMJKLGCB	4QGHKNNKLEJUKIWQHHRRILQIWGKQAPBFJJLEATSHJAU

- See difference between (IoC) unigrams and bigrams

Friedman Test for classical and modern crypto



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Hill climbing for classical and modern crypto

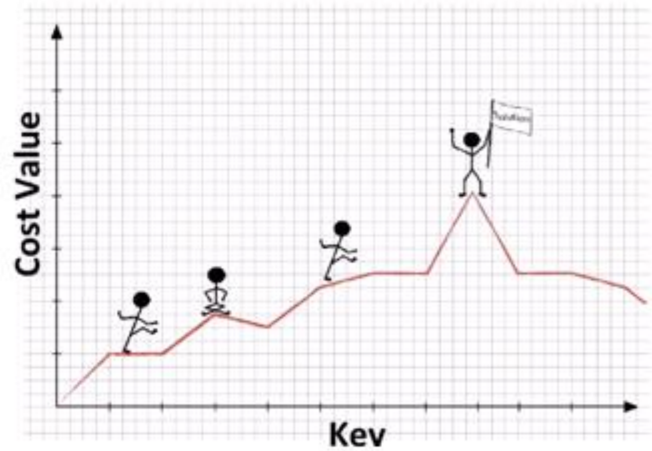
Cryptanalysis of Classic Ciphers Using Heuristics

. What is a Heuristic?

. Hill Climbing – Basics

. Genetic Algorithm

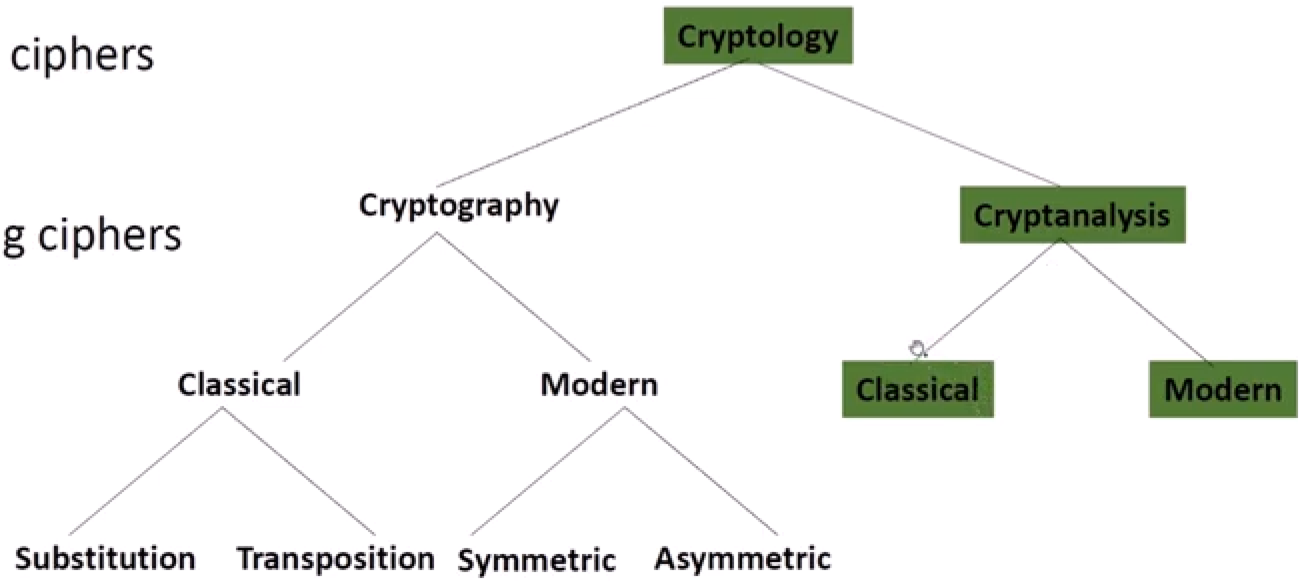
. Simulated Annealing – Improved Hill Climbing



Hill climbing for classical and modern crypto

Cryptography
Art of making ciphers

Cryptanalysis
Art of breaking ciphers



Sec

Hill climbing for classical and modern crypto

- A heuristic technique (/hjʊəˈrɪstɪk/; Ancient Greek: εὑρίσκω, "find" or "discover"), or a heuristic, is any approach to problem solving or self-discovery that employs a practical method that is not guaranteed to be optimal, perfect or rational, but which is nevertheless sufficient for reaching an immediate, short-term goal. Where finding an optimal solution is impossible or impractical, heuristic methods can be used to speed up the process of finding a satisfactory solution. (Englisch Wikipedia)
- Our problem: Finding the key of a classical cipher with brute-force is (mostly) impractical
- Can we speed up the search for the key using a heuristic, making the search practical? → Yes, of course ☺
- Hill climbing is a well suited heuristic to do so. Why? → On next slides ☺

Hill climbing for classical and modern crypto

- First, we need to know the vulnerabilities of classical ciphers we exploit with hill climbing
- I focus now on substitution ciphers, but transposition ciphers also work

1. Letter frequencies are still visible in ciphertext
2. Low diffusion after changing key or plaintext
3. We can measure "how good (even a wrong) key is"
4. Inventors of (historical/classical) ciphers didn't know computers ☺

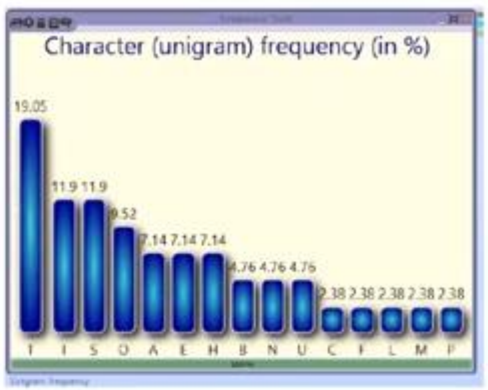
Hill climbing for classical and modern crypto

1. Letter frequencies are still visible in ciphertext

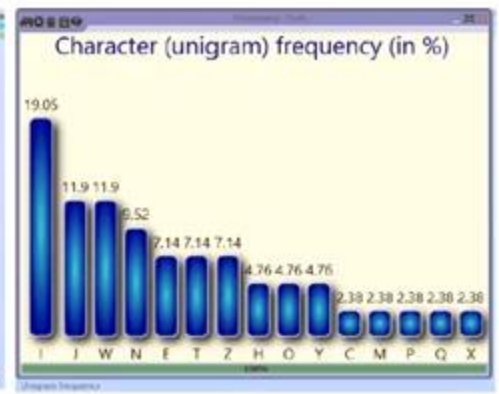
Example: Simple monoalphabetic substitution cipher

THIS IS A TEST OF THE MONOALPHABETIC SUBSTITUTION

ITWJ WJ Z IEJI NC ITE PNONZQMTZYEIWX JHYJIWIHIWNO



Plaintext Frequencies



Ciphertext Frequencies

Hill climbing for classical and modern crypto

2. Low diffusion after changing key or plaintext

THIS IS A TEST OF THE MONOALPHABETIC SUBSTITUTION

Key: ZY**X**SECRTWVUQPONMLKJ**I**HGFDBA

ITWJ WJ Z IEJI NC ITE PNONZQMTZYEIWX JHYJIWIHIWNO

51 characters 1 line

Ciphertext

Changed Key: ZY**I**SECRTWVUQPONMLKJ**X**HGFDBA

XTWJ WJ Z XEJX NC XTE PNONZQMTZYEXWI JHYJXWXHXWNO

51 characters 1 line

Ciphertext

In this example, only nine letters changed in the ciphertext. This is about 17% of the letters. Modern ciphers change on average about 50% of the bits when their inputs are changed.

Hill climbing for classical and modern crypto

3. We can measure "how good (even a wrong) key is"

- "The better a key the higher is its fitness"
- Example (bigram log2 cost function of CrypTool 2; performed on decrypted text)

```
EYISZWRTCVUQOPNMLKJAHGFDBX   193.24   <- start key
EYISZCRTWVUQOPNMLKJAHGFDBX   214.27
EYISZCRTWVUQPONMLKJAHGFDBX   218.16
ZYISECRTWVUQPONMLKJAHGFDBX   231.14
ZYISECRTWVUQPONMLKJXHGFDBA   271.28   <- final key
```

Hill climbing for classical and modern crypto

4. Inventors of (historical/classical) ciphers didn’t know computers

- 120,000 keys/sec with Vigenère analyzer (on a single CPU core)

- Enables optimization techniques (heuristics) to use vulnerabilities mentioned before
  - Hill climbing
  - Simulated annealing
  - Genetic algorithms
  - …

- Parallelization and distribution additionally speeds up the analysis ☺

Hill climbing for classical and modern crypto

- Why not just test every key (search for the correct one via a brute-force attack) ? (by rating all keys and the best should have the highest rating)

- Simplest cipher: Simple monoalphabetic substitution
  We can achieve ~120,000 keys/sec

- Computation time to search through all keys

$$26! = 2^{88.4} \text{ key}$$

$$\text{Search time} = \frac{2^{88.4}\, keys}{120{,}000\; keys/sec} \approx 10^{21.5} sec \approx 10^{14} years$$

- Maybe, brute-force is not a good idea... ☹

Hill climbing for classical and modern crypto

Step 1: Create an initial random key

Step 2: Decrypt ciphertext using the
initial key and compute fitness (e.g. trigram frequencies sum)

Step 4: Modify key (e.g. randomly swap letters)

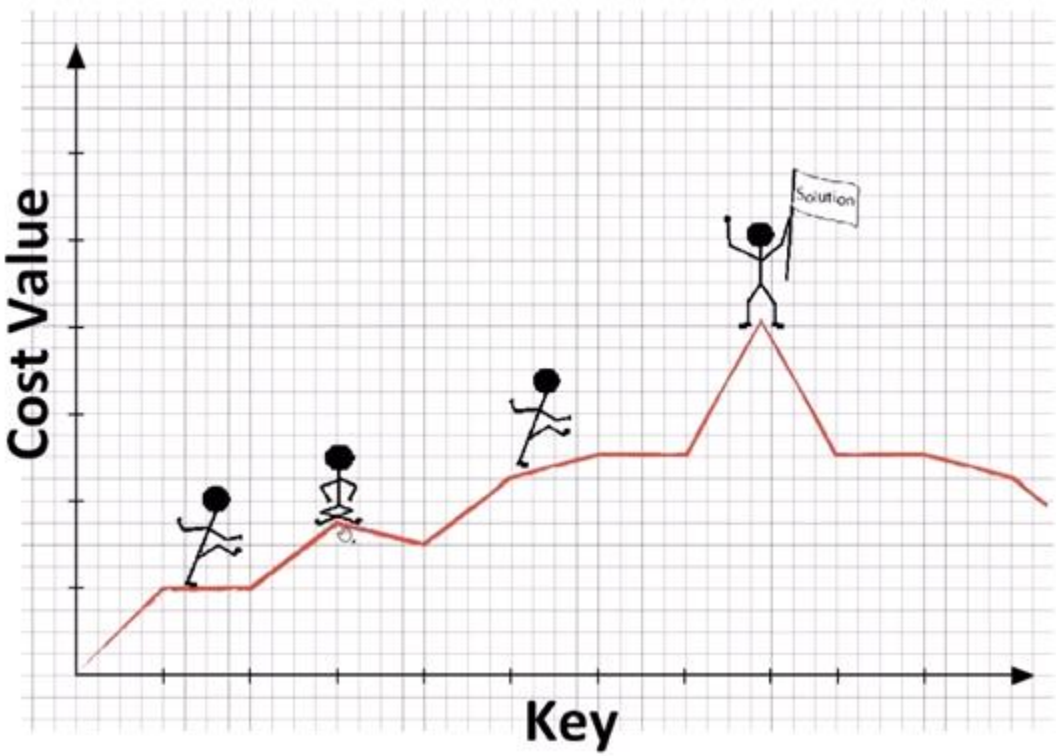
Step 5: Decrypt ciphertext using the modified key and compute fitness

Step 6: If fitness is worse than before revert modifications

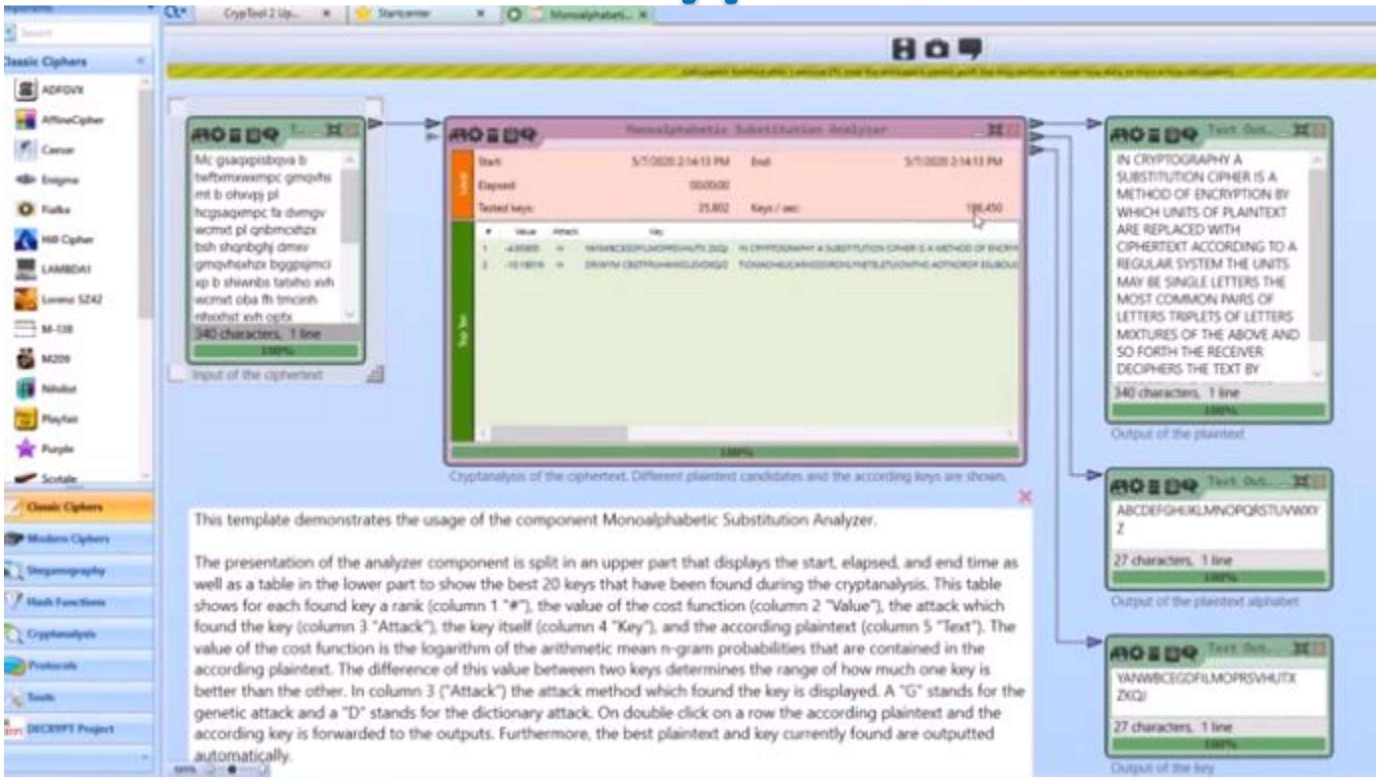
Step 7: Increment a counter;
If counter is above a defined value, we stop algorithm

Step 8: Jump to Step 4

Hill climbing for classical and modern crypto

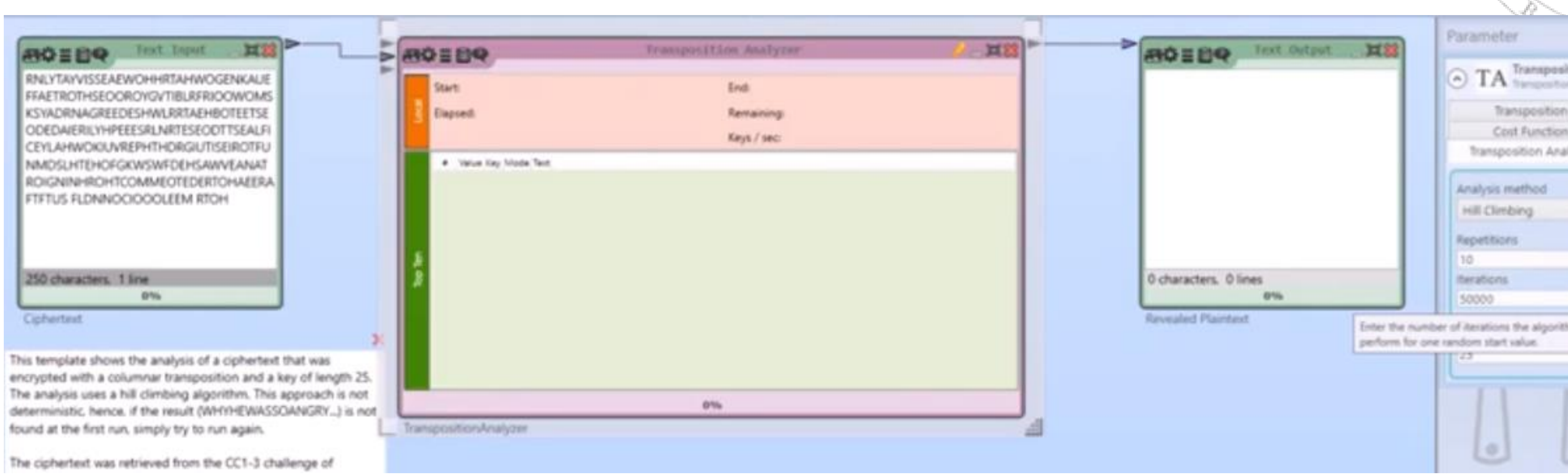


Hill climbing for classical and modern crypto



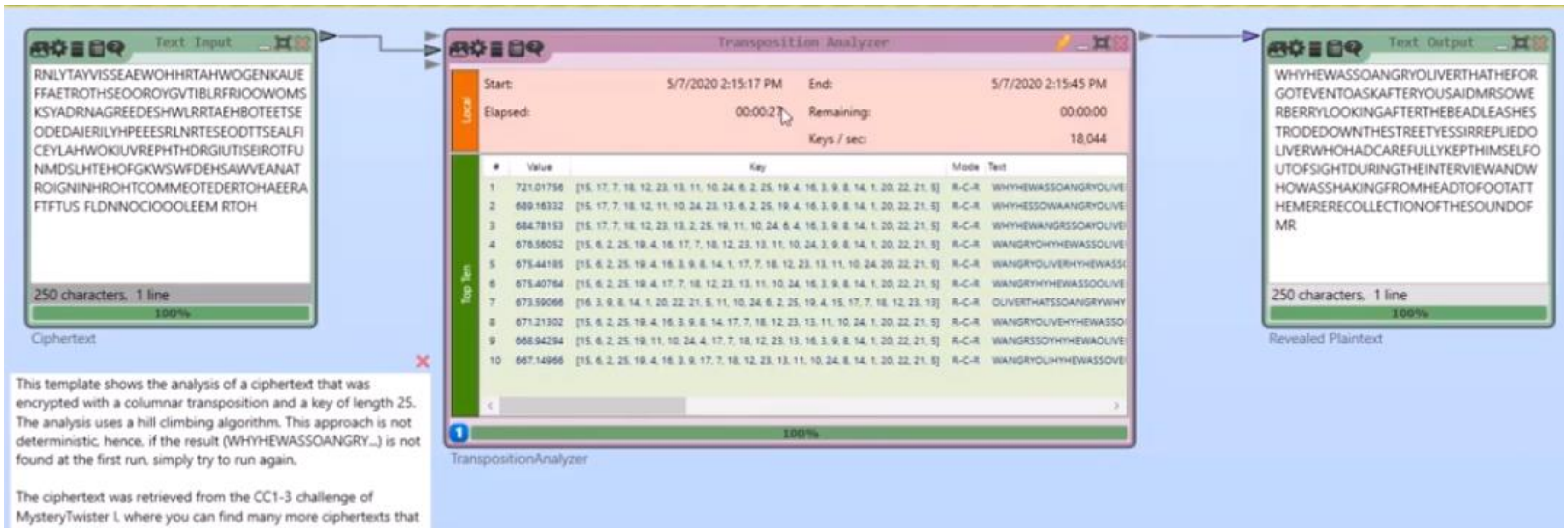
- Different uses of hill climbing
  - – Monoalphabetic substitution analyzer

Hill climbing for classical and modern crypto



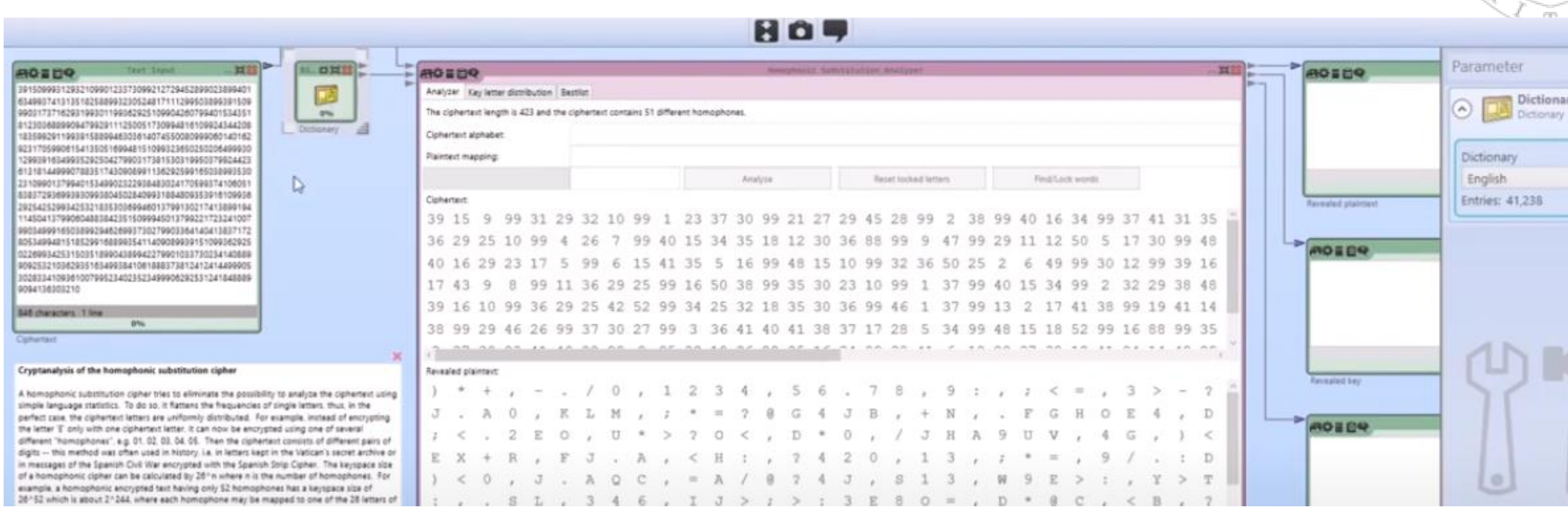
- Different uses of hill climbing
  - Transposition analyzer

Hill climbing for classical and modern crypto



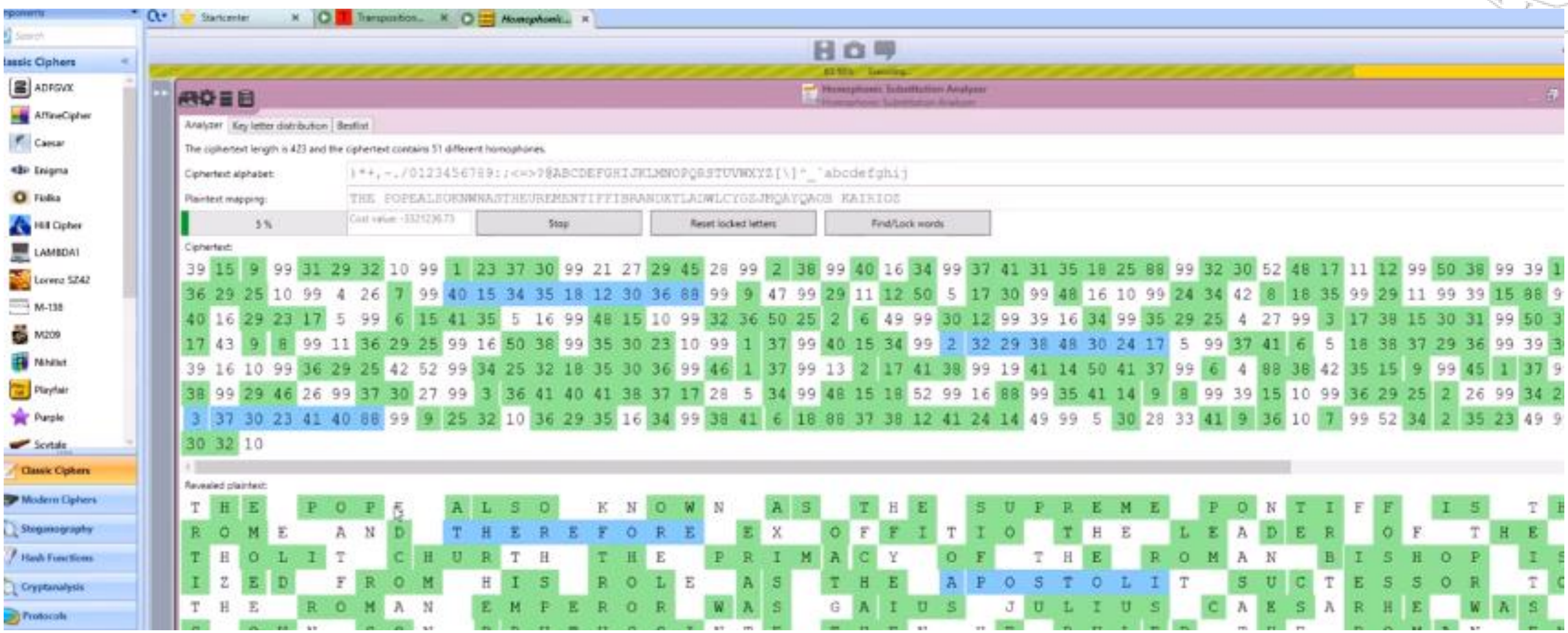
- Different uses of hill climbing
  - Transposition analyzer

Hill climbing for classical and modern crypto



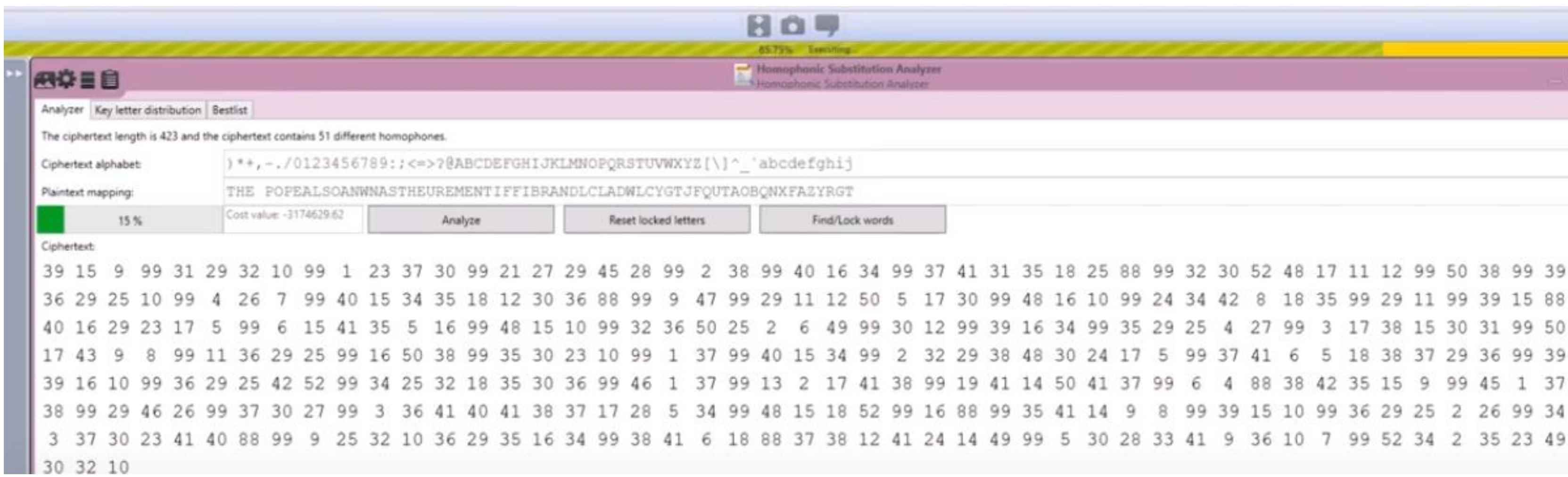
- Different uses of hill climbing
  - Homophonic Substitution analyzer

Hill climbing for classical and modern crypto



- Different uses of hill climbing
  – Homophonic Substitution analyzer

Hill climbing for classical and modern crypto



- Different uses of hill climbing
  - – Homophonic Substitution analyzer

Hill climbing for classical and modern crypto

- Different uses of hill climbing
  - Homophonic Substitution analyzer

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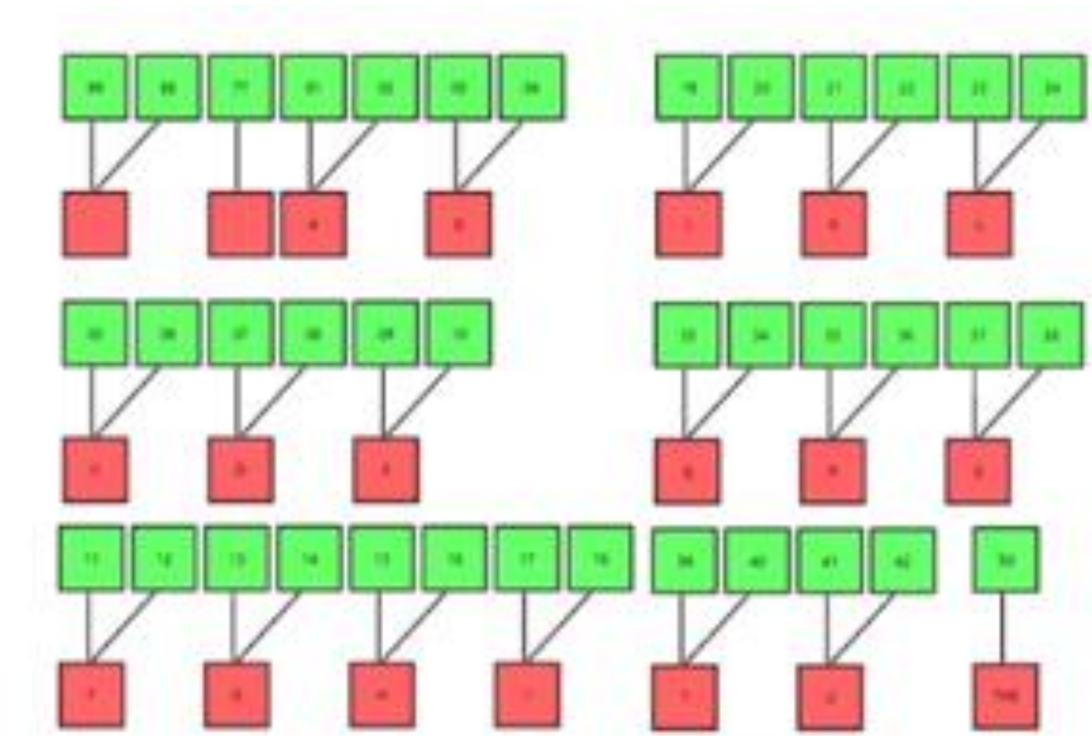
Homophonic Substitution



Visualization of a homophonic substitution cipher
Green boxes = ciphertext symbols
Red boxes = plaintext symbols

Homophonic Substitution

- A **simple substitution** replaces **single letters** by single letters, digit groups, or (in general) symbols
  - Examples: **Caesar** cipher, **Simple MASC**, **Pigpen** cipher
  - Simple substitution ciphers can be broken easily by hand (with frequency analysis)

Example encryption with a simple MASC*:
Key: H=01,E=02,L=03,O=04,W=05,R=06,D=07
HELLO WORLD → 01 02 03 03 04 05 04 06 03 07

- To make ciphers more secure, cryptographers invented **homophonic substitution** ciphers
- A homophonic substitution has more choices (**homophones**) for encrypting letters (or pieces of text)

Example encryption with a homophonic substitution cipher*:
Key: H=01,E=02,L=03|04,O=05|06,W=07,R=08,D=09
HELLO WORLD → 01 02 03 04 05 07 06 08 03 09

* To make it easy to "produce" many ciphertext symbols, we use digits

Module 6: Cryptology for IoT

Homophonic Substitution

- Example **plaintext**:
  IN CRYPTOGRAPHY A SUBSTITUTION CIPHER IS A METHOD OF ENCRYPTING IN WHICH UNITS OF PLAINTEXT ARE REPLACED WITH THE CIPHERTEXT IN A DEFINED MANNER WITH THE HELP OF A KEY THE UNITS MAY BE SINGLE LETTERS THE MOST COMMON PAIRS OF LETTERS TRIPLETS OF LETTERS MIXTURES OF THE ABOVE AND SO FORTH. THE RECEIVER DECIPHERS THE TEXT BY PERFORMING THE INVERSE SUBSTITUTION PROCESS TO EXTRACT THE ORIGINAL MESSAGE.

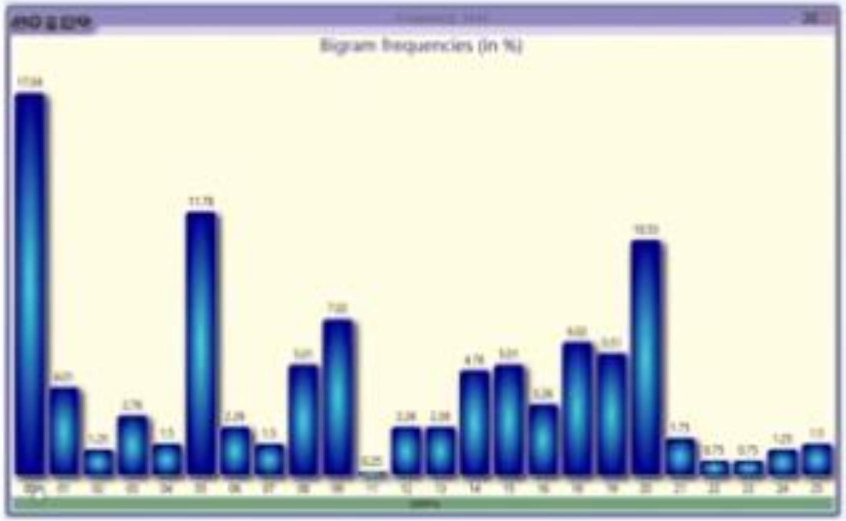
- Encrypted ciphertext using **simple MASC** (A=01, B=02, C=03, ..., Z=26):
  09 14 00 03 18 25 16 20 15 07 18 01 16 08 25 00 01 00 19 21 02 19 20 09 20 21 20 09 15 14 00 03 09 16 08 05 18 00 09 19 00 01 00 13 05 20 08 15 04 00
  15 06 00 05 14 03 18 25 16 20 09 14 07 00 09 14 00 23 08 09 03 08 00 21 14 09 20 19 00 15 06 00 16 12 01 09 14 20 05 24 20 00 01 18 05 00 18 05 16 12
  01 03 05 04 00 23 09 20 08 00 20 08 05 00 03 09 16 08 05 18 20 05 24 20 00 09 14 00 01 00 04 05 06 09 14 05 04 00 13 01 14 14 05 18 00 23 09 20 08 00
  20 08 05 00 08 05 12 16 00 15 06 00 01 00 11 05 25 00 20 08 05 00 21 14 09 20 19 00 13 01 25 00 02 05 00 19 09 14 07 12 05 00 12 05 20 20 05 18 19 00
  20 08 05 00 13 15 19 20 00 03 15 13 13 15 14 00 16 01 09 18 19 00 15 06 00 12 05 20 20 05 18 19 00 20 18 09 16 12 05 20 19 00 15 06 00 12 05 20 20 05
  18 19 00 13 09 24 20 21 18 05 19 00 15 06 00 20 08 05 00 01 02 15 22 05 00 01 14 04 00 19 15 00 06 15 18 20 08 00 20 08 05 00 18 05 03 05 09 22 05 18
  00 04 05 03 09 16 08 05 18 19 00 20 08 05 00 20 05 24 20 00 02 25 00 16 05 18 06 15 18 13 09 14 07 00 20 08 05 00 09 14 22 05 18 19 05 00 19 21 02 19
  20 09 20 21 20 09 15 14 00 16 18 15 03 05 19 19 00 20 15 00 05 24 20 18 01 03 20 00 20 08 05 00 15 18 09 07 09 14 01 12 00 13 05 19 19 01 07 05 00

- Encrypted ciphertext using **homophonic substitution cipher** (homophonicity = 3):
  09 14 00 03 18 25 16 20 15 07 44 01 42 08 51 88 27 99 19 21 02 45 46 35 72 47 20 61 41 40 00 29 09 68 34 05 70 88 35 71 99 53 00 13 31 46 60 67 04 88
  15 06 99 57 66 55 18 77 16 72 61 14 33 00 09 40 88 23 08 35 03 34 99 73 66 61 20 19 00 41 32 88 42 12 01 09 14 46 05 24 72 99 27 44 31 00 70 57 68 38
  53 29 05 30 88 49 35 20 60 99 46 08 31 00 55 61 16 34 57 18 72 05 50 20 88 09 40 99 01 00 56 31 58 35 66 57 04 88 39 27 14 40 05 44 99 75 61 46 60 00
  72 08 31 88 34 57 64 42 99 67 06 00 53 88 11 05 25 99 20 60 31 00 21 66 09 46 45 88 65 01 51 99 28 57 00 71 35 14 59 12 05 88 38 31 72 20 57 70 19 99
  46 08 05 00 13 15 45 72 88 03 41 39 65 67 40 99 68 27 61 18 71 00 15 32 88 64 31 20 46 57 44 19 99 72 70 09 16 12 05 20 45 00 41 58 88 38 31 46 72 57
  18 71 99 13 35 76 20 47 44 05 19 00 67 06 88 46 34 31 99 53 54 15 22 57 00 01 66 30 88 45 41 99 32 67 70 72 60 00 20 08 05 88 18 31 29 57 61 48 05 44
  99 56 31 55 09 42 34 57 70 71 00 46 60 05 88 72 31 24 20 99 02 77 00 68 57 18 58 15 44 39 35 14 07 88 46 08 05 99 61 40 74 31 70 19 57 00 45 44 99 75
  72 09 20 21 46 35 41 66 88 16 18 67 03 05 19 45 99 72 15 00 31 50 20 44 27 29 46 88 72 34 57 99 41 70 61 33 09 14 53 64 00 65 05 71 19 01 59 31 88

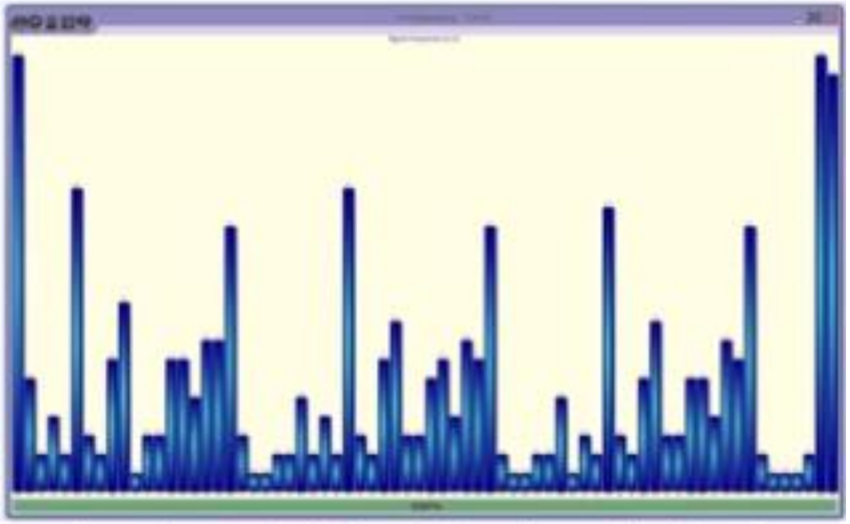
Sec

Homophonic Substitution

Frequencies of two digit combinations



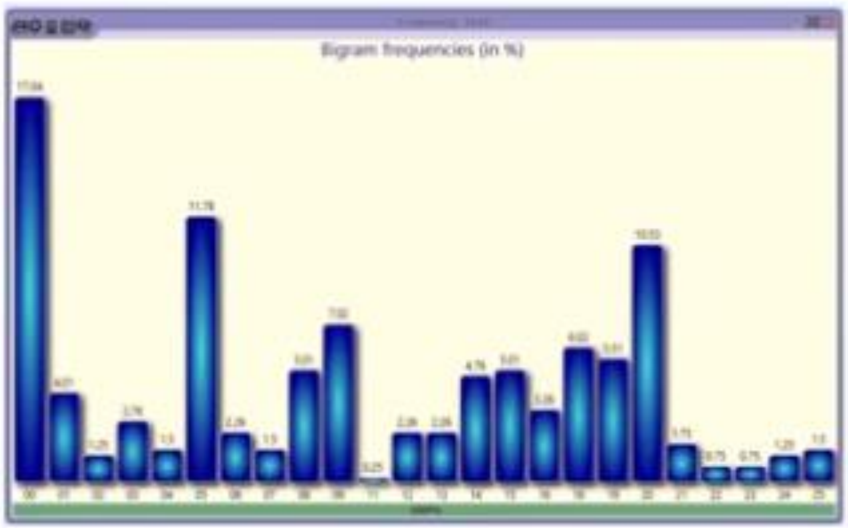
Simple substitution cipher
27 different ciphertext symbols in total



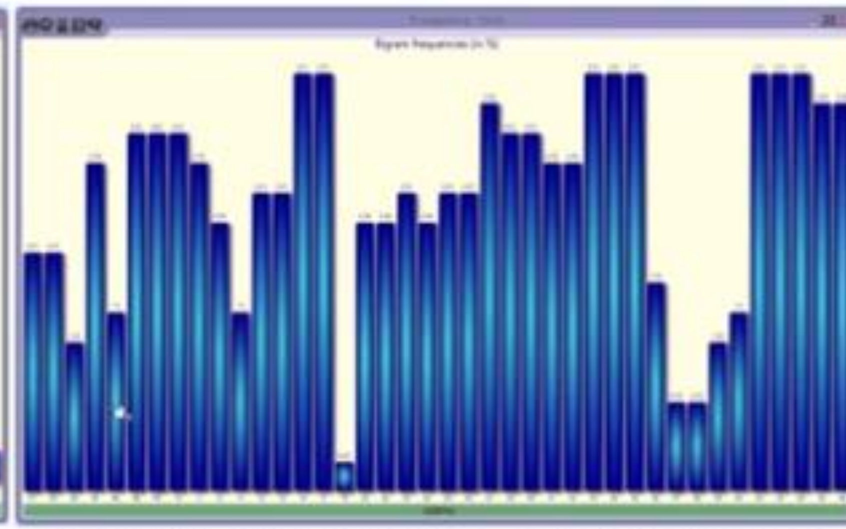
Homophonic substitution cipher – homophonicity = 3
70 different ciphertext symbols in total

Homophonic Substitution

Frequencies of two digit combinations



Simple substitution cipher
27 different ciphertext symbols in total



Homophonic substitution cipher – homophones based on language frequencies
41 different ciphertext symbols in total

Homophonic Substitution

- Homophonic substitution ciphers were not only built based on single letters
- To improve security, additional cipher elements were introduced

1. **Doubles / double letters** — AA, NN, TT, LL, SS, ...
2. Other **frequently used bigrams (or higher order n-grams)** — TH, HE, IN, EN, NT, RE, ..., ING, THE,
3. **Nulls** → Cipher elements that encode nothing to
   a) Further change frequencies
   b) Confuse attackers
   c) Mark "special" cipher elements, e.g. nomenclature elements (= code words)
4. **Complete Words** — THE, AND, WITH, TO, BE, OF, FROM, IN, ...
5. **Code Words** (in nomenclators) — The King, the Pope, London, Maximilian, ...

- **Encrypting** (or even showing unencrypted) **word separators** (spaces) **helps the cryptanalyst** to break a cipher
- Creating a code/cipher which **shows separations** of ciphertext symbols **helps the cryptanalyst** to break a code/cipher
- **Ordering in a code/cipher helps the cryptanalyst** to break a code/cipher

Homophonic Substitution

- Nomenclator (ciphers) contain a **nomenclature** (= code word table)

Example:

Cipher:

A	01|02|03	B	03|04|05	C	06|07|08	...
AA	11|12	LL	13|14	TT	15|16	

Nulls:

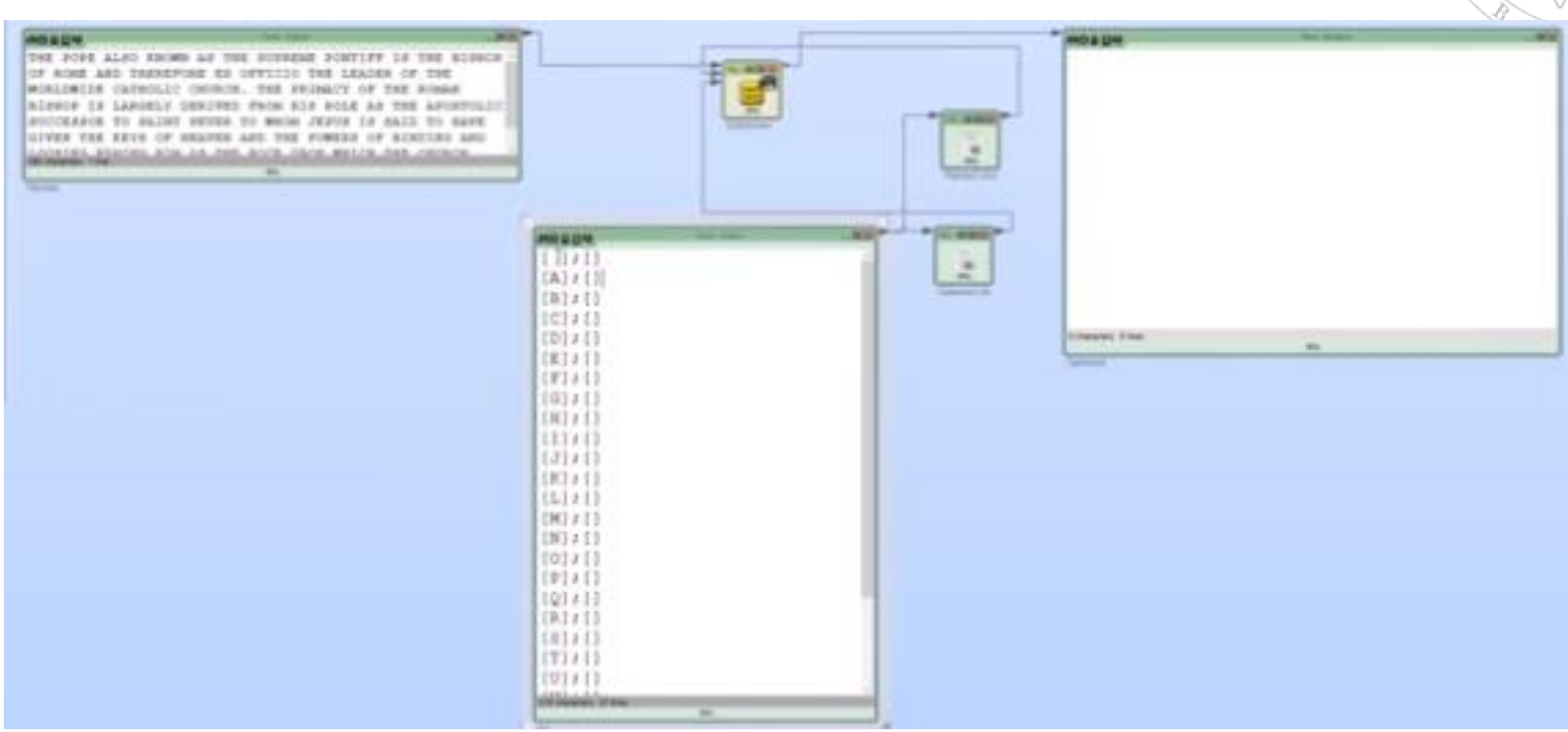
70|71|72|73|74|75|76|77|78|79

Nomenclature:

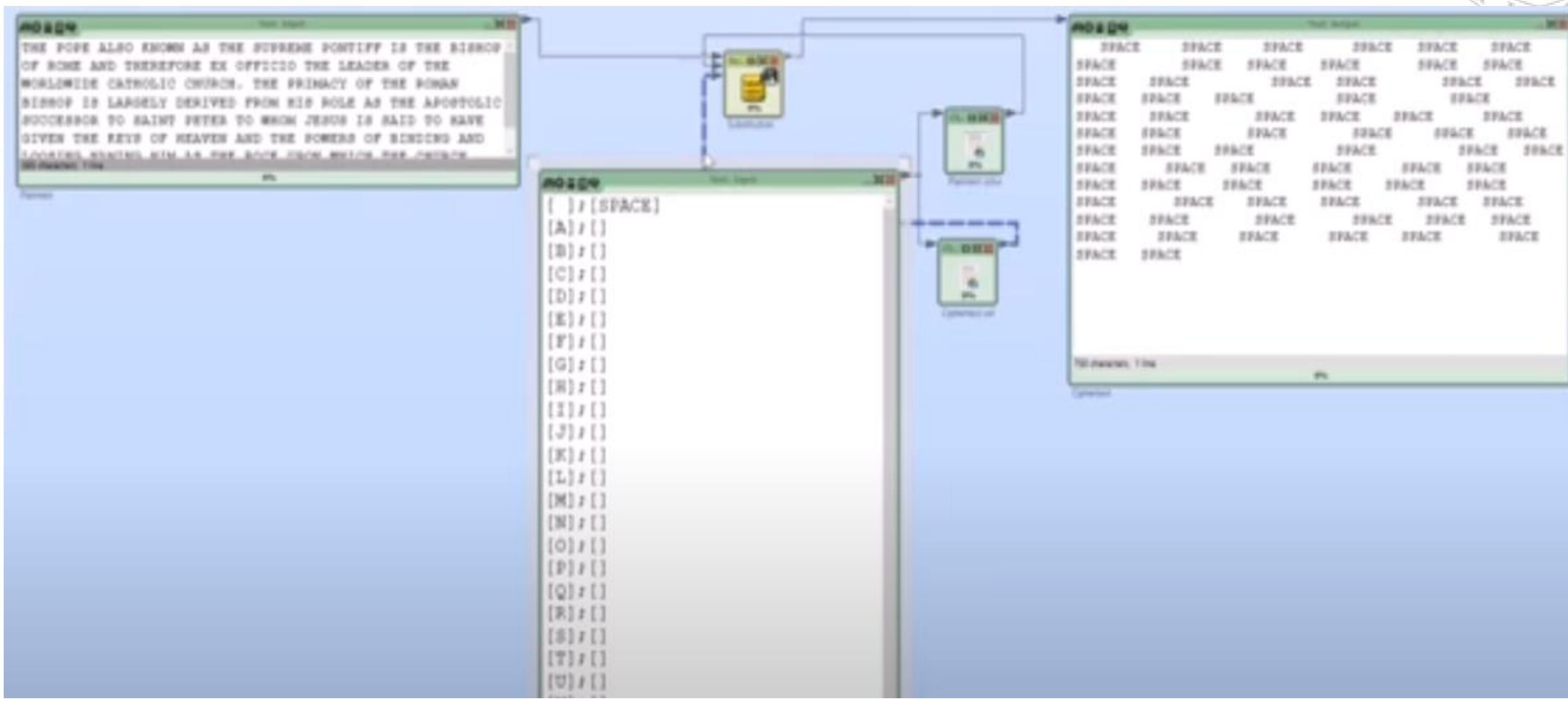
THE	840|841	AND	842|843	WITH	844|845	...

9100	The King	9200	One	We need help	9400
9101	The Pope	9201	Two	We attack at	9401
9102	Germany	9202	Three	The enemy is at	9402
9103	France	9203	Four	We will meet at	9403
9104	England	9204	Five	We need urgently	9404
9105	The Netherlands	9206	Six	We provide cover	9405
...	...	...	...	...	...

Homophonic Substitution



Homophonic Substitution



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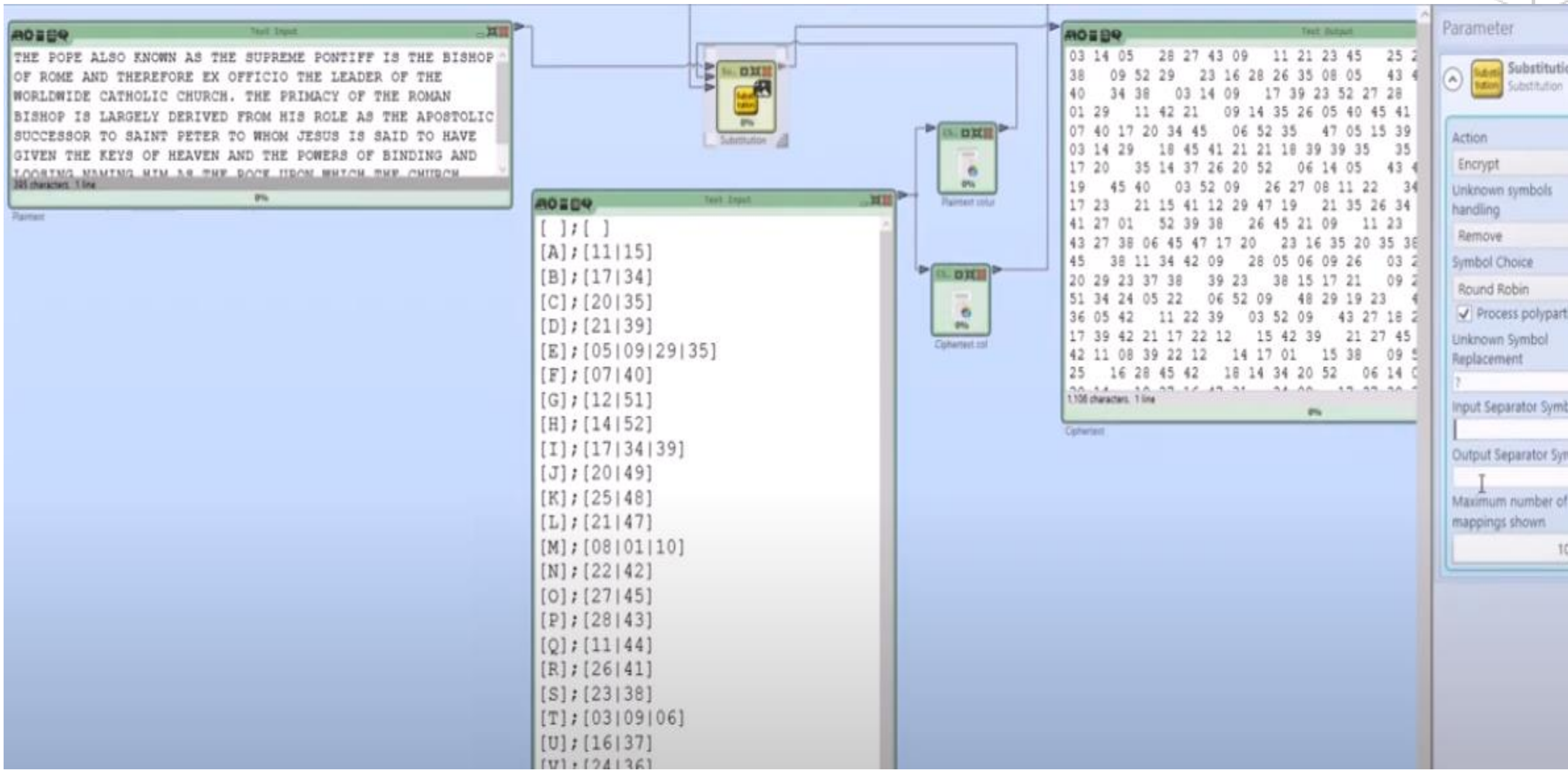
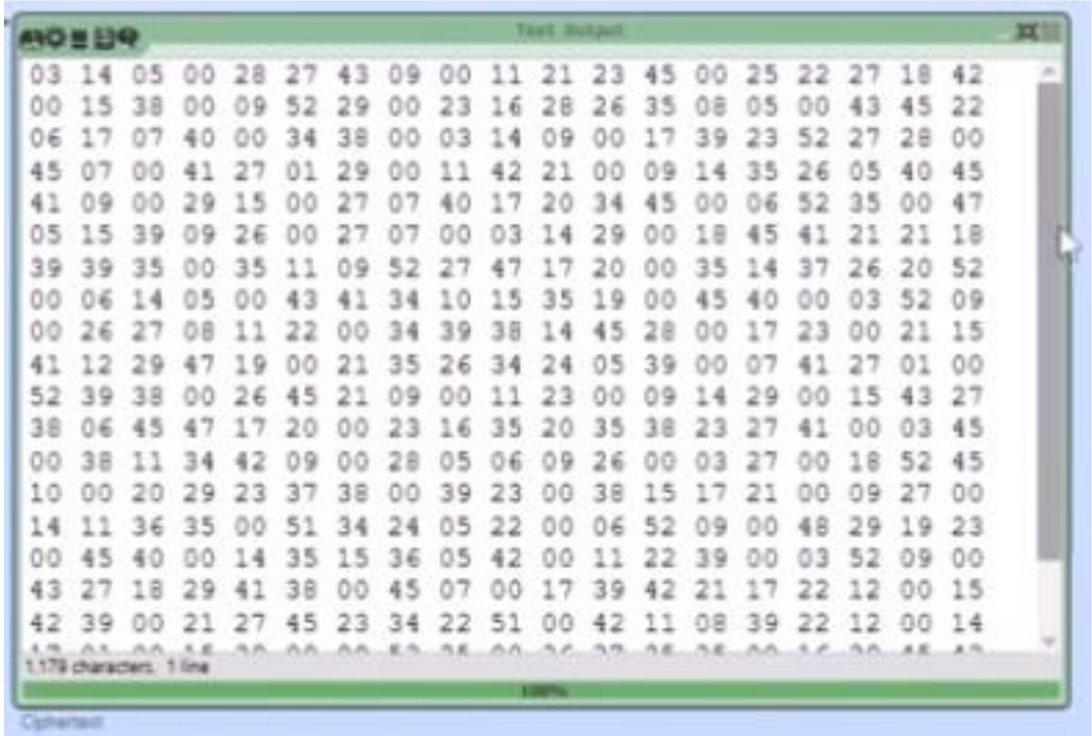


Homophonic Substitution

[ ] ; [00]



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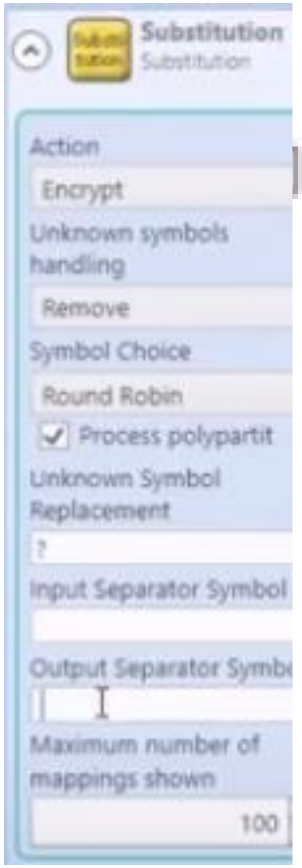

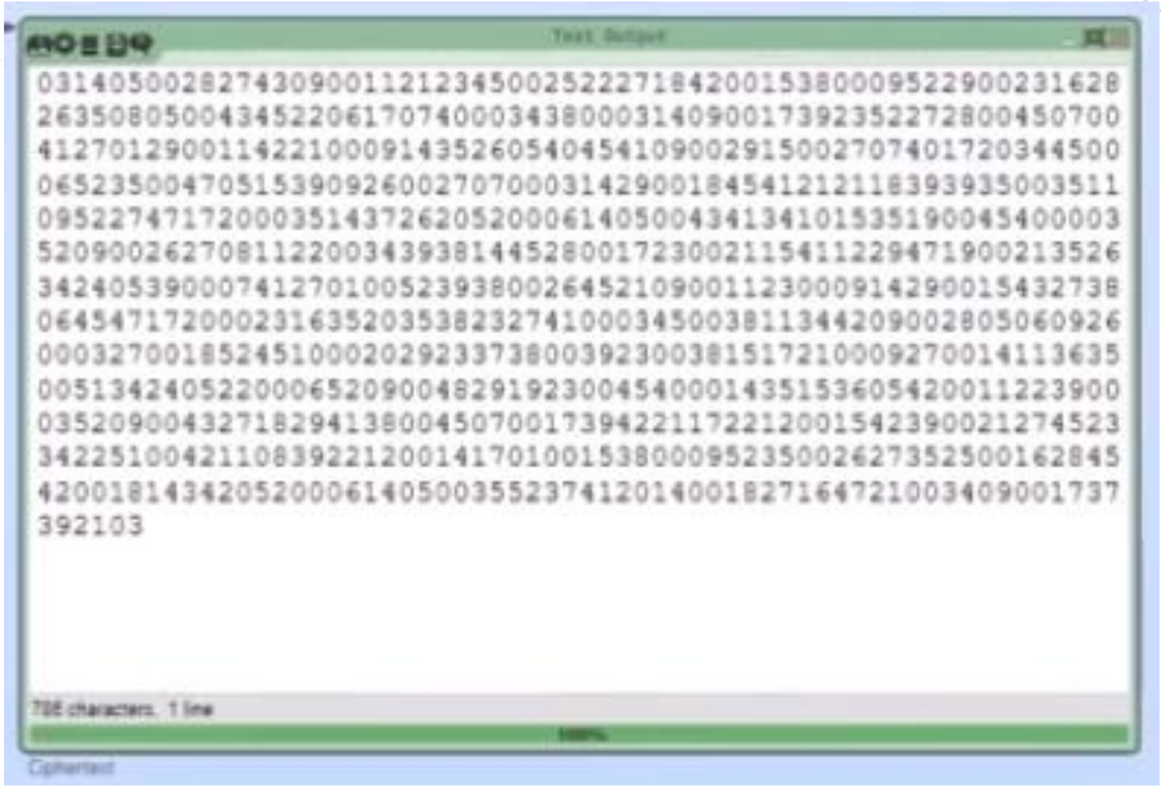

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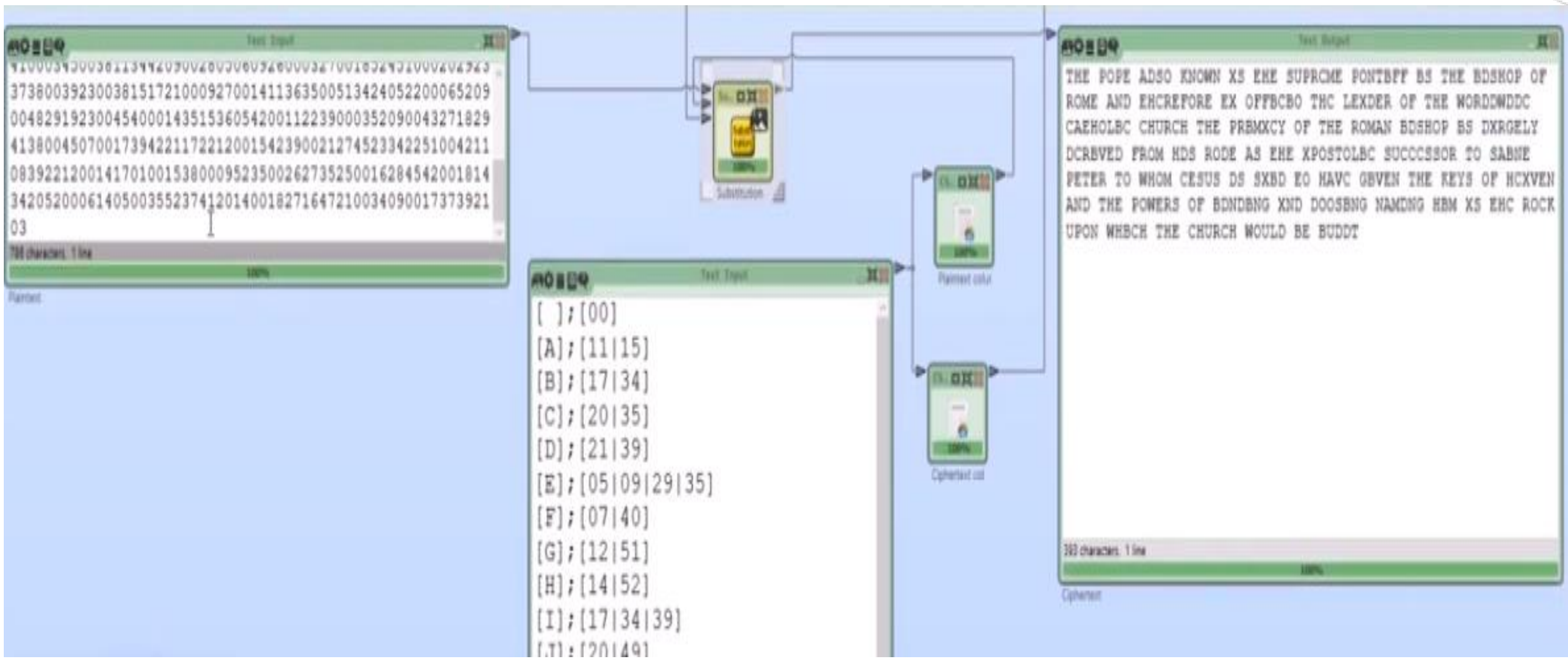

Homophonic Substitution

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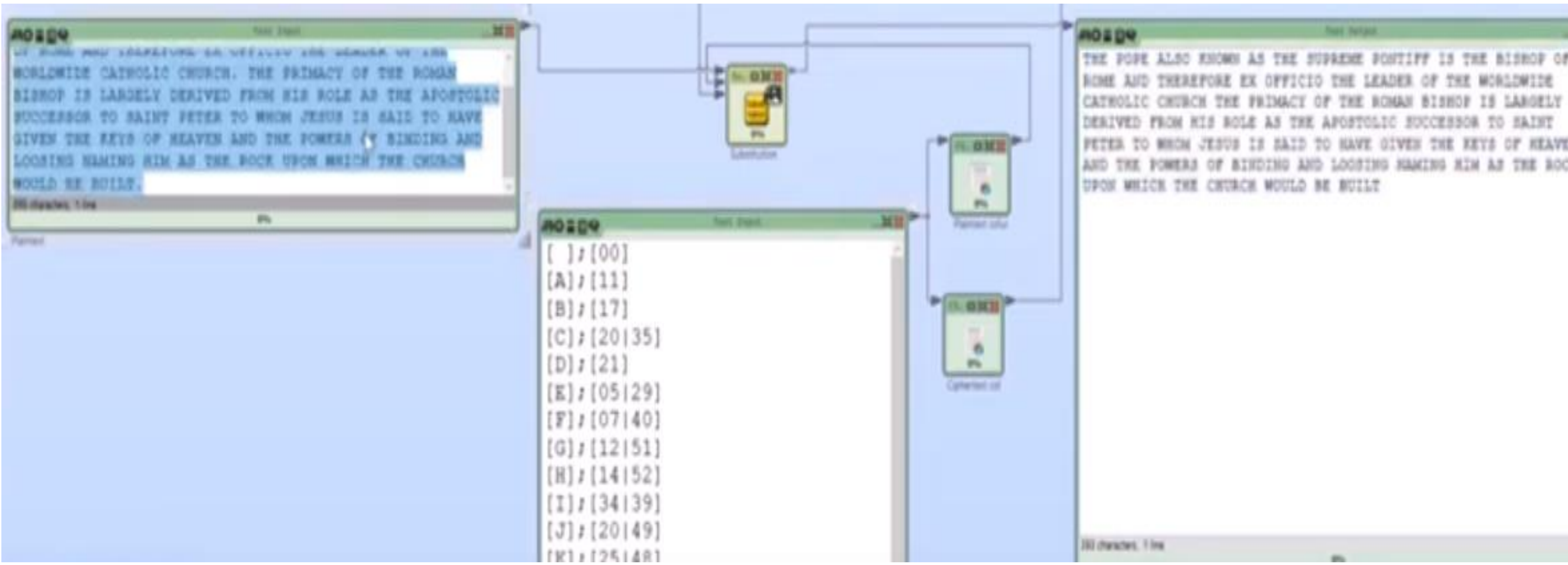
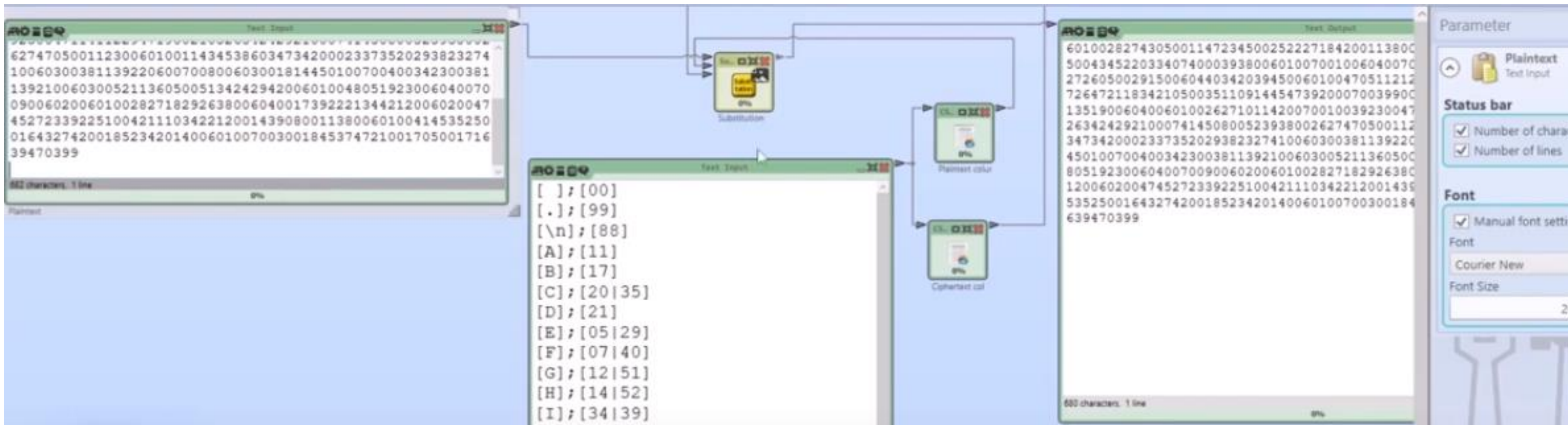
Homophonic Substitution



Homophonic Substitution



- Try to break your own code by using the Hill Climbing technique !

Cryptology for IoT

Modules M4, M6, M8
Session of 24th May, 2022.

M6.1 Briefing of the session
M6.2 Friedman Test
M6.3 Hill Climbing
M6.4 Final Exercise using Hill Climbing

Prof.: Guillermo Botella