Part X
Proto-mechanical ciphers

Unit 120
Disk ciphers (cipher clocks)

Consider a device that looks like a pocket watch. Around the outer rim are symbols like letters and digits. Inside that is another ring of symbols. The outer ring has *m* symbols equally spaced around it, while the inner ring has *n* symbols, also equally spaced. The device has two hands like a clock. When the longer hand moves from one symbol on the outer ring to the next, the shorter hand moves from one symbol on the inner ring to the next. In other words, the hands are geared in the ratio *m*:*n*. The device can be used to encipher a text by rotating one of the hands clockwise until it points to the first plaintext symbol; the ciphertext symbol is the one to which the other hand points. The first hand is advanced to the next symbol in the plaintext; the second ciphertext symbol is indicated by the other hand. This continues until the full text is enciphered.

The *Wadsworth cipher disk* uses the outer ring for ciphertext symbols. It holds 33 symbols, the letters A-Z and digits 2-8. They can be removed and replaced in any order. The inner ring is for plaintext symbols, of which there are 26 (just the letters). Rather than having hands, in this device the two rings that rotate in the same direction under a single pointer. To encipher a text, the inner disk is rotated until the plaintext letter is under the pointer. The gearing rotates the outer ring to bring the ciphertext letter to the pointer. This operation is equivalent to the “cipher clock” described in the previous paragraph. The disks are always rotated in the same direction, presumably counterclockwise.

There is no evidence that there was ever more than one Wadsworth disk in existence. We do not know if it was used more than once. It was invented by Decius Wadsworth in America in 1817, more than fifty years before Charles Wheatstone reinvented it in England (too slow, Britain!).

The *Wheatstone Cryptograph* is better documented, especially by Wheatstone himself. Its outer ring holds the plaintext symbols, which are fixed in place. There are 27 of them, the space and 26 letters. The inner ring has 26 ciphertext symbols, which are the 26 letters in any order. The initial position before the first letter is enciphered is for the longer hand to point to the space and the shorter hand to point to the first letter of the mixed ciphertext alphabet. The hands are always rotated clockwise. To encipher a text, the hands are rotated clockwise until the longer hand points to the plaintext letter. The shorter hand points to the ciphertext symbol.

Wadsworth cipher disk. Photo from NSA.

Wheatstone Cryptograph. Photo from eBay.

In his paper describing his device (citation below), Wheatstone introduces a novel way of mixing the ciphertext alphabet from a keyword. It goes like this:

1. Write the keyword in a row.
2. Take the 26-letter alphabet and delete any letters that appear in the keyword.
3. Add the remaining letters in the alphabet under the keyword in rows with the keyword letters at the top of each column.
4. Duplicate letters in the keyword are deleted.
5. The mixed alphabet is read off in columns.

Here is an example using the keyword `WHEATSTONE`:

```
W H E A T S T O N E
B C D F G I J K L M
P Q R U V X Y Z
```

The mixed alphabet is

```
WBPHCQEDRAFUTGVSIXJYOKZNLM
```

The procedure for encipherment on the Wheatstone disk is

1. Remove all punctuation from the plaintext. Keep only letters and spaces.
2. Either:
   a. Put an ‘X’ between any double letters in the plaintext. If the double letters are already ‘XX,’ then put a ‘Q’ between them.
   b. Replace the second letter of doubles with ‘X’ or ‘Q.’ Be sure not to accidentally get a doubled ‘X’ or ‘Q.’
3. If the plaintext does not end with space, then add one. The last ciphertext letter serves as a sort of checksum.
4. Position the longer hand of the device so that it points to the space on the outer ring of symbols and the shorter hand so that it points to the first letter of the mixed ciphertext alphabet.
5. For each plaintext symbol (letter or space):
   a. Rotate the longer hand clockwise until it points to the plaintext symbol. Do not go all the way around. Let the shorter hand move on its own, according to the gearing.
   b. Read the ciphertext symbol, which is indicated by the shorter hand.

Step 2 is necessary because there is no combination of ciphertext letters that the Wheatstone disk can decipher to a repeated letter, since the ciphertext alphabet is shorter than the plaintext alphabet. This is not true for the Wadsworth disk; for double letters on that disk, we would simply rotate 26 more steps for the second letter.

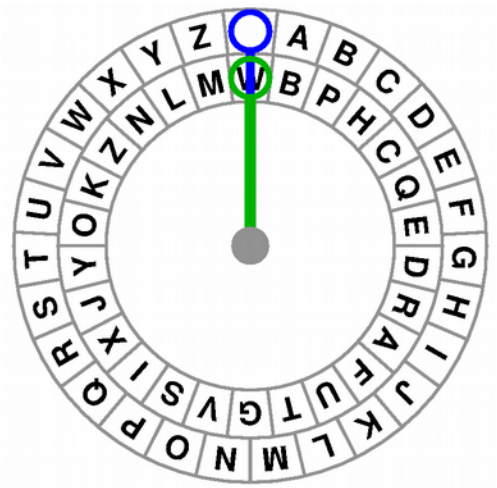
Let’s look at a short example and encrypt this message with the Wheatstone disk. We will use the mixed alphabet from the example above.

```
SECRET MESSAGE
```

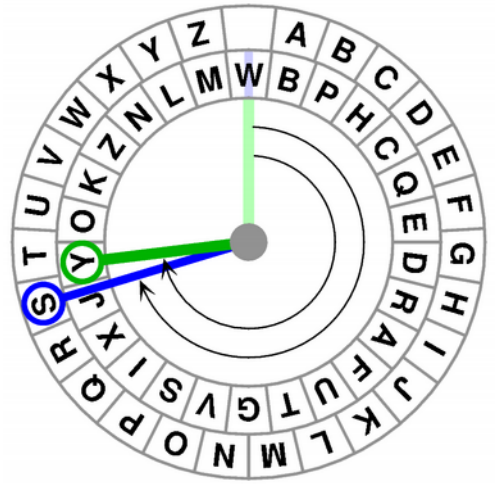
First, we have to prepare the plaintext:

```
SECRET_MESXSAGE_
```

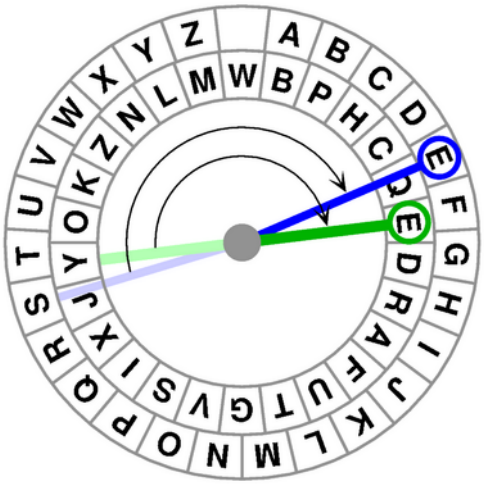
We begin the encipherment by putting the hands of the device in their initial positions.



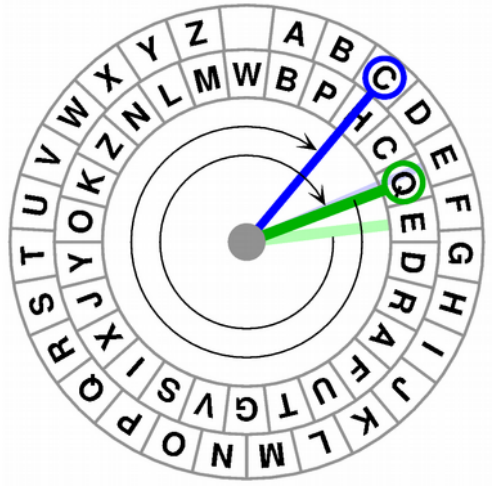
The first letter of the plaintext is ‘S,’ so we turn the large hand clockwise 19 steps until it points to ‘S.’ At the same time, because of the gearing of the device, the short hand also moves 19 steps and lands on ‘Y,’ which is the first letter of the ciphertext.



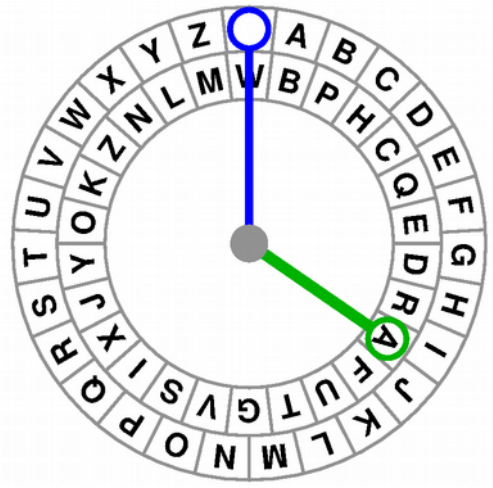
The second letter of the plaintext is ‘E,’ so we turn the large hand 13 steps clockwise to ‘E,’ while the short hand also moves 13 steps and lands on ‘E.’



Since we always rotate clockwise, to encipher the next letter, ‘C,’ we have to turn the large hand most of the way around the circle. The short hand indicates that the next ciphertext letter is ‘Q.’



The process continues, always clockwise, until the entire text is enciphered. By the time we get to the space at the end of the plaintext, the short hand has moved so far that it points to ‘A’ in the inner ring.



The full ciphertext is

YEQORNCXFLHMRVGA

The astute reader may have noticed that these two devices give us stream ciphers. Let's consider the Wheatstone disk. The internal state can be thought of as the positions of the two hands, (h_{long}, h_{short}). The initial state is (0, 0). The cipher is factored into a stream cipher that corresponds to the disk using the key ABCDEFGHIJKLMNOPQRSTUVWXYZ, followed by a monoalphabetic substitution cipher M that uses the mixed alphabet as its key. For each character p_i from the plaintext, which we think of as a series of integers (space = 0, 'A' = 1, 'B' = 2, ...), the action of the encryptor is

$$\begin{aligned} x &= p_i - h_{\text{long}} \mod 27 \\ h_{\text{short}} &= h_{\text{short}} + x \mod 26 \\ h_{\text{long}} &= p_i \\ c_i &= M(h_{\text{short}}) \end{aligned}$$

For the Wadsworth disk, exchange the rolls of h_{long} and h_{short}, and replace 26 with 33 and 27 with 26. For the Wadsworth disk, we also need to specify that if x is ever zero, it should be changed to 26; this allows for the encipherment of repeated letters, which is never done with Wheatstone.

Let's now redo our example encipherment with the Wheatstone disk as a stream cipher. Start with an internal state of (h_{long}=0, h_{short}=0). The first plaintext letter is 'S'=19, so x is 19 − 0 = 19. The internal state changes to (19, 19), and the output of the stream cipher is 19. Applying the monoalphabetic substitution gives us the first ciphertext letter, which is 'Y.'

W	B	P	H	C	Q	E	D	R	A	F	U	T	G	V	S	I	X	J	Y	O	K	Z	N	L	M
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

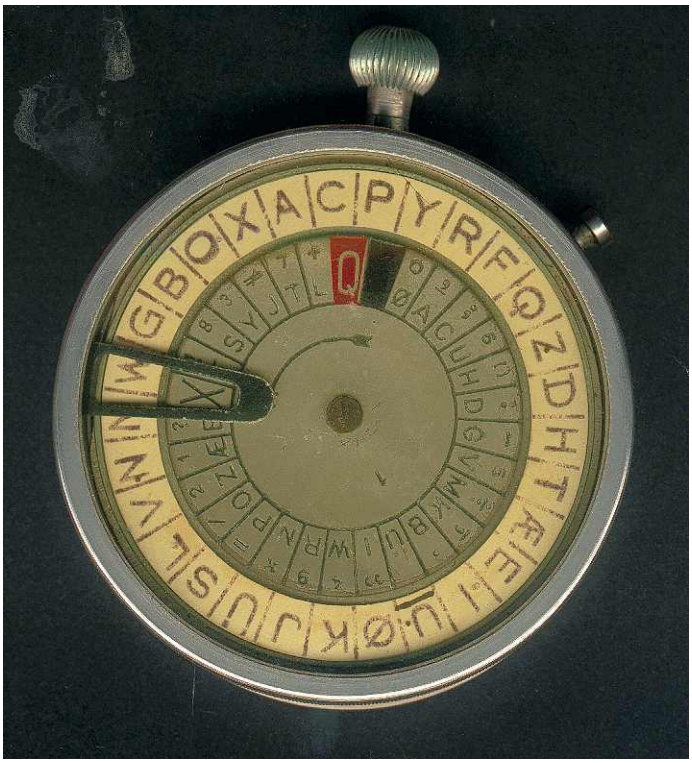
Next is 'E'=5, so x = 5 − 19 = 13 modulo 27. The internal state becomes (5, 19 + 13 mod 26) = (5, 6). The output is M(6) = 'E.' Then comes 'C'=3. The internal state becomes (3, 5). The next ciphertext letter is M(5) = 'Q.' Etc.

A more interesting way to define the internal state S is as the total number of steps taken. From this point of view, the encryptor does these things for each character that it enciphers:

$$\begin{aligned} x &= p_i - S \mod 27 \\ S &= S + x \\ c_i &= M(S \bmod 26) \end{aligned}$$

During World War II, the Danes used a derivative of the Wadsworth and Wheatstone devices, called *Urkryptographen* (Danish for “clock cryptograph”). Like the Wadsworth disk, it had two concentric rings of characters that rotated counterclockwise under a single fixed pointer, and the key was written on the outer ring. Like the Wheatstone Cryptograph, the plaintext alphabet contained a space which the ciphertext did not; therefore, double letters had to be disguised with ‘X.’ The letter ‘Q’ was used to indicate numbers, which appeared with some letters on the plaintext disk. The two letters ‘X’ and ‘Q’ are not used in native Danish words. Unlike either of the other two devices, Urkryptografen had three additional letters in each alphabet: ‘*Æ*,’ ‘*Ø*,’ and ‘Ü,’ so that the rings had 29 and 30 characters. The plaintext alphabet was also mixed, and there was a number of preprinted disks. One such plaintext alphabet was (where ‘_’ denotes the space)

```
_ØACUHDGVMKBÜIWRNPOZÆEXFSYJTLQ
```



Urkryptografen. Photo from Museum of Cypher Equipment in Fife, Scotland.

Reading and references

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Niels Faurholt, “Urkryptografen (The Clock Cryptograph),” *Cryptologia* 27:3 (2003) 206-208, DOI: 10.1080/0161-110391891874; this article is available also at www.jproc.ca/crypto/crypto_watch.html

Greg Mellen, “Cryptanalyst’s Corner,” *Cryptologia* 8:1 (1984) 55-57, DOI: 10.1080.0161-118491858773

David Kahn, *The Codebreakers: The Story of Secret Writing*, New York: Simon & Schuster, 1967, revised and updated 1996, pages 195-198.

Auguste Kerckhoffs, “La cryptographie militaire,” *Journal des sciences militaires* IX (1883) 5-39 and 161-191, www.petitcolas.net/kerckhoffs/crypto_militaire_1_b.pdf, www.petitcolas.net/kerckhoffs/crypto_militaire_2.pdf, section IV.

Programming Tasks

1. Write a function that mixes a ciphertext alphabet using the prescription of Wheatstone.
2. Implement an encryptor for the Wheatstone disk.
3. Implement a decryptor for the Wheatstone disk. Think about how to handle double letters in the ciphertext.
4. Implement a dictionary attack on the Wheatstone cipher.
5. Implement an encryptor for the Wadsworth disk.

6. Implement a decryptor for the Wadsworth disk. You do not have to worry about double letters in the ciphertext, since they cannot appear with this cipher. To handle double letters in the plaintext, advance the device 26 steps between them; the shorter hand will return to the same place, but the longer hand will point to a different ciphertext character.

7. Learn Danish and implement a simulation of Urkryptografen. Brug det for at skrive i sifer din favorite aventuren av Hans Christian Andersen. Skift din bakkeopstigningangreb på Wheatstone-kryptografen (Unit 123) at tilægge de tre nye bogstaverne, og brug angrebben din at løse siferteksten din.

Exercises

1. On average, how many characters are enciphered before the Wheatstone disk passes through its initial configuration? Use your monogram frequency table in your calculation.

2. Encipher this text with the Wheatstone cipher using keyword `CONVOLUTION`.

   > Viewing the Wheatstone Cryptograph as two rotating pointers is only one way of seeing this cipher. Another way is through the lens of modular arithmetic. The modulus for the plaintext is twenty-seven, while the modulus for the ciphertext is twenty-six.

3. This is the example ciphertext from Wheatstone's article. It was enciphered with the keyword `FRANCE`. Each paragraph is enciphered separately; i.e., the disk is reset to the starting position at the beginning of each paragraph. Decipher the message.

   ```
   PZLSPQREQAJDITFBUFZOHQOSUQUDIKITORTWEZACMTPLERAUESKGSO
   FGFDKHLSJIRKHFHMFADAYIVUOHAOBLNOGREJAIBKMPJZTMJABQCNFP
   OMYHYRCZDCWBXUBZ

   ZBILIJTEJYSPFDLCXETKQASOXOUNNODQJCWECLXPUYIEMMCMSYVCFP
   OKWCDEDVDAGLPEEKNAGVKMNUULSHXYXYVGFQPUYIORQKLPTCZHHK

   ZBKUPVSWZWXAQXDREKTKQASOXOUIRSKOMFSTIIXGWTQJJVDYFNAHLS
   IIXIAGQLZXVOGNHGRBUOHYZOOPWVYDDMQJKFMOBJPDYVRBAWKGWSJU
   RJGITOWTVEZBHSOSLVUNBCHQSOTEIEBDQMGWHGJAMISXFIFBBPAVPE
   SVCJUTAD

   PZLPTYVXQXDTGLTTAFCVMHOMBINJKWVYAZOCQLAIUKFEGFNCNFIZHH
   KVZYQUGLIVENKAHTRVFVEBWHWLRYCMLXWSYSYJHUFSFPOKEGZRXLUB
   FT
   ```

4. Break this ciphertext with a dictionary attack. The keyword is a ten-letter English word. The cipher is Wheatstones's.

   ```
   ZUKMNXQCDJKEADWCJVQHKCWNGGFVMAGQFEOCOWOIXTVIAKJPNIJJXU
   UQKCLBXVABOFIAATPQHIVKJQYUWZQRZKXWXYZVILALHDSSIGGMQQVK
   ZVYCVZUPMHRTCTJXCFXBIJGLNUVWEBTJZTOQLIKPRYEDCXIGDMETEY
   ```

```
YPOWFEBARSZZCOHWPABUIZCLWJJYQQKGPTTLWAIZUKXNGWDVHVDXUX
EXEBJWJPPSXPNEPUHRHTILXRKSGXKWMCZFZMBTVMNUDCDVLAFCQRRM
GGFOUWAHVXHNHABCUPXKZOABAWMMZGFVNOQCKYIOVGXDBUARIYSTJG
YVGWLPLKEWXHJSZVIMSYFPL
```

5. Decipher this text with the Wadsworth disk cipher in which the ciphertext alphabet is not mixed.

```
TABLV3BTJWYCVKNRCOXFLSD2GTL6JUBUJNQ7CUXZG4AK4NT2LBO7DM
XYLQDQVCK8OW3AL6T2GWOU3MCPR4ODKVZK56APHABIZ36JUBUN2J8Q
5M7XM3B2MUC2K8YH4TAK6BMXM6DXGL24EF7XHLV7KBE2M3FMZMOERU
3CZG5OSVDHZ46LAFPAYBVG4IOH4IL3S6WYADMXQ3CILMUKYOYQHULP
SAEWZ3I6CM6RBKXZN5P2DEHL56LBMOEJ6CHYGKPVCZQBZ2O5RARJQG
U78K6OBZDK6CKT4BMEUBYP38ZNFY27LYH26P3GKY7YG7OCPBPSDSFT
6XYFHMNSCQR7V8BY5RW3L2LPAOQ5FOUIU8H7K2LAFU8YRBZJYL5V5T
HVL5HITGXKRFRGJW
```

madness's book on classical cryptography
unit 121: attacking cipher clocks with cribs
last modified 2020-10-28

Unit 121
Attacking cipher clocks with cribs

If we know some part of the plaintext (a “crib”), we can use it to break the ciphertext. To make it easier, we will encrypt the crib with an unkeyed cipher clock before we compare it to the ciphertext, since the difference between a ciphertext and a text that was encrypted with an unkeyed device is a monoalphabetic substitution.

An example will make the technique more clear. This ciphertext was encrypted with a Wheatstone Cryptograph:

```
DGBRHDRYDURNFTWLOMIBLSPDZCIJNSMBZXCSHDYCVMGOAZSAEGNVQLJRFTX
CWJHACZZMPEHMZNPZJYKMRXQGOUIUCRBOYQLOTOBUNZGJTEQBOFYLEHBOBZ
RRGWOHWJKCUKPZCIQELLOUEJVAYVYPQWHEOBJNVGMAXRGLYYHNAHYCYFTGR
ILIJNSMHQFUWYYUEJVNFIXNSDMXZSAHCNFVDVXVZKMCJWLXTBKJJGHHDRSK
CIMACCWTUKZVSRDGZSKCNUQQGCDKWKHVHIIFIXUMYIPWYSOPCGGSGHZBFWW
XPCEWEQMISKVXEMIZXSHAZEWOMRGQUTKCTKMPEUQJYLHTIDHFPERYUKSKON
NCEPLARCSBLMKOBCBSEFGXN
```

We have this short bit of its plaintext:

```
never wear out no matter how long it may stand in times
```

Before we use the crib we will encipher it with an unkeyed Cryptograph. The ciphertext alphabet for this process is just the unmixed alphabet. Before encipherment we need to disguise the double `tt` by replacing the second with `q`.

```
never wear out no matqer how long it may stand in times
```

Enciphered this is

```
OGXHUDAJGXGVBBIWXJWLECRENVCKOADDXRALSFUSUNOWJAXGLYSIMFT
```

Notice that we did not add a space to the end before encipherment, as Wheatstone had recommended, since we do not know if the next character after the crib is a space.

Now we compare the enciphered crib to the ciphertext, one position at a time. Start at the beginning:

```
DGBRHDRYDURNFTWLOMIBLSPDZCIJNSMBZXCSHDYCVMGOAZSAEGNVQLJRFTX...
OGXHUDAJGXGVBBIWXJWLECRENVCKOADDXRALSFUSUNOWJAXGLYSIMFT
```

Notice that B in the crib matches up with F *and* T in the ciphertext. Also, A in the crib matches up with R, S, C, and Z. These things cannot happen with a monoalphabetic substitution, so we know that this is not the correct position.

The only acceptable line-up we can find is at position 107:

```
...TEQBOFYLEHBOBZRRGWOHWJKCUKPZCIQELLOUEJVAYVYPQWHEOBJNVGMAXRG...
   OGXHUDAJGXGVBBIWXJWLECRENVCKOADDXRALSFUSUNOWJAXGLYSIMFT
```

Now we can begin to reconstruct the key by tabulating the substitutions for the letters of the enciphered crib:

```
ABCDEFGHIJKLMNOPQRSTUVWXYZ
ERCLKABFGHIJMPQ??UVXYZWON?
```

The missing letters are D, S, and T. Missing three letters means that there are six possibilities. If the key is mixed in some less obvious way, then we would have to try all six. But in our example, we can guess immediately that the key is

```
WONDERCLKABFGHIJMPQSTUVXYZ
```

and the keyword is WONDERCLOCK. Usually, we also have to try all twenty-six ways of rotating the key before we find the correct key, since we do not know the position of the cipher clock's hands when the plaintext was encrypted at the point that the crib begins.

Deciphering with the reconstructed key gives us the plaintext, which you should recognize as a paragraph from *The Wonder Clock* by Howard and Katharine Pyle.

```
CLICK BUZQ WENT THE WHEQLS AND THEN TICK TOCK TICK TOCK FOR
THE WONDER CLOCK IS OF THAT KIND THAT IT WILQ NEVER WEAR
OUT NO MATQER HOW LONG IT MAY STAND IN TIMES GARQET DOWN I
SAT AND WATCHED IT FOR EVERY TIME IT STRUCK IT PLAYED A
PRETQY SONG AND WHEN THE SONG WAS ENDED CLICK CLICK OUT
STEPQED THE DROLQEST LITQLE PUPQET FIGURES AND WENT THROUGH
WITH A DANCE AND I SAW IT ALQ
```

Now let's work through a more complicated example. This ciphertext was also encrypted with a Cryptograph:

```
VDZYHDCDOFCLZSCPWTKEIVTTRNVGSYSCPUVEUJOWVFTZBLXDYXNZAU
NICZVYFHIKQFZLEMNLQIJHRCGOJSRODYLLCKDTWQUAOXTAVJOOYOGU
ZGBRZXZIRDXAGYBLHRGUINGCCNQHJSUWPLEUVDDAWVORXIRJBUOOYW
FQOTXDFRDYUJYEVXUAITGMLIIHKGAEFFVDAKXEHGSYXAVVAQCNECYK
ZOXWFXRRQIJYAZVCPZDUWSHHPAWLVFKDYNLRBTSCYREOBLPVVXZMCF
DUNQSXBXSRKAPMWCYHTBUERKAVCCARWYDNEHXSWXBPHRACQIWIOYBX
```

```
PFMNUKGEFFDNBXASYSXDHQFLDNWYTDGMCWLTPUXZFUIIALEKEILREZ
JHNPAEIBYHRNVGDLKUFECLXCGEWMEFVLCZBUONKUISJCSOFCLZTNES
DUWSXNLROKNNGWCHBOUIZZATRKNNPQHXJMONSMZDWKGTBZKPDQFTIJ
NVXJRKZP
```

This crib is known to be part of the plaintext:

```
information exists of course but it is scattered
```

After we replace the double `tt` with `tq` and encipher with an unkeyed Cryptograph, the crib is

JOHQTPEXNTTGLEQABBJYQLOAGEFSOQJJQZKRAKSLWVOMBOCC

The first position that does not give a contradiction in regarding the monoalphabetic substitution is 177. This is actually the only position that works.

```
...YEVXUAITGMLIIHKGAEFFVDAKXEHGSYXAVVAQCNECYKZOXWFXRRQI...
   JOHQTPEXNTTGLEQABBJYQLOAGEFSOQJJQZKRAKSLWVOMBOCC
```

We begin to reconstruct the key:

```
ABCDEFGHIJKLMNOPQRSTUVWXYZ
EFR?GSHU?VCKWLXTANYI?OZMDQ
```

There are three missing letters (`B`, `J`, and `P`) in the key, so there are six possibilities. Plus, there are twenty-six ways to rotate the key. That makes 26 × 6 = 156 total possibilites. But we don’t need to try them all. Let’s just try one and see what happens. Start with

```
EFRBGSHUJVCKWLXTANYIPOZMDQ
```

There are twenty-six ways to rotate this key, and we try them until we find something useful. Deciphering the ciphertext with the key as written above gives gobbly-gook:

```
IXUPCUFTPVDGPYCMDGBQIYDCPDVPQCPUDQSIPQCTPGUAHRSBVQTYR...
```

Next we try `FRBGSHUJVCKWLXTANYIPOZMDQE` and get more nonsense:

```
HWTOBTESOUCFOXBLCFAPHXCBOCUOPBOTCPRHOPBSOFT GQRAUPSXQ...
```

We continue to rotate the key, and soon we arrive at `TANYIPOZMDQEFRBGSHUJVCKWLX`, which gives this plaintext:

```
THE NEQD FOR INXORMATION OF AN EOACT AND RELSBCMFADIB...
```

Aha! We are getting close. Most of the key is correct, but now we need to find the correct placement of `B`, `J`, and `P`. By swapping `B` and `P` we get the true plaintext, which is from *The Modern Clock*, by Ward L. Goodrich.

```
THE NEQD FOR INFORMATION OF AN EXACT AND RELIABLE CHARACTER
IN REGARD TO THE HARD WORKED AND MUCH ABUSED CLOCK HAS WE
PRESUME BEQN FELT BY EVERY ONE WHO ENTERED THE TRADE THIS
INFORMATION EXISTS OF COURSE BUT IT IS SCATQERED THROUGH
SUCH A WIDE RANGE OF PUBLICATIONS AND IS FOUND IN THEM IN
SUCH A FRAGMENTARY FORM THAT BY THE TIME A WORKMAN IS
SUFQICIENTLY ACQUAINTED WITH THE LITERATURE OF THE TRADE TO
KNOW WHERE TO LOQK FOR SUCH INFORMATION HE NO LONGER FEQLS
THE NECESQITY OF ACQUIRING IT
```

Notice that instead of trying 156 possibilities, with this method we only need to try at most 26 + 6 = 32 possibilities.

Now that we have the plaintext, we can stop. But, no, we can't stop. Never stop solving puzzles. Let's go onward and get the keyword. The key we found was

```
TANYIBOZMDQEFRPGSHUJVCKWLX
```

It looks random, but notice the sequence `Q`, `R`, `S`, (`T` is missing), `U`, `V`, `W`, `X`, with one or two letters between them. Also see `F`, `G`, `H`, `J`, `K`, `L`. So the key was likely constructed with Wheatstone's prescription. We proceed by breaking the key into columns and getting the sequences each to appear on one row.

```
T I M E P     C
A B D F G H J K L
N O Q R S U V W X
Y Z
```

If we search our dictionary for `TIMEP??C?`, we find the only choice is `TIMEPIECE`.

Programming tasks

1. Implement a boolean function that detects whether two (short) texts could be related by a monoalphabetic substitution.

2. Implement the attack that uses a crib to break a ciphertext encrypted with the Wheatstone Cryptograph.

Exercises

1. Break this ciphertext that was encrypted with the Cryptograph. Use the crib "the average collector would be bored." What is the keyword?

```
XRIHAOZJMWGRABONYAJXBGPMWMFDHLGBDBYDPVHTBKATCDNUIXEENO
LSUHVCLRCFHRVUQFKBMLMSFGLHMAIAYSWAMNEOPTSJQJBPGITLRYLA
YCRJTGPWAKWAZXSZKONBVNHLXFQDKSPUONMFEGQGBQBCNXNUHUXXTM
```

```
RVXPVUQFKCQLMNYXQUIKNGPHANTBVKIVDBAVWONAZGVEJAMSJKXLHQ
TDZFFPJMSFLKMVXGYSKBTBIWTYDNGXOCNUYOHEDACVHXYPKUGNDOIJ
GQRLSFQEOMMXHQSPRYUMBIFYCVFYGAQJWSJOISLFVESKJNIVMXQXEK
YMYXRVELATVXPNBOMEABVQNUUBVIVUYOZQXYETDKKGGWWDEIPXNEXT
MUFXNESNZXUNJIHVAPMFKYZBKWSXIZVMSCDZEQVCBIGGWUAPMGWMZK
BIZPJURNLOKMUAQJGSNVKAODZMYJGJIMCNUCYKMVVLZCQFSLNWWDYA
KQHQGQRVELDBYSGONJEREYNPKEXSAEUCRQJREGWOIOIUKLADDEZQRO
NHZALWJPEYHMDKIYVYDPFZBSFNMDVEOSQTKDNYIAXUDYAKNQECUULN
LCJICNOOHMVBTCYQLSXSIWBNESKTPOYCXOCOLMKHXYFKCNWIPRDGMW
Q
```

Challenge

crib: NOT A SOUND BROKE THE SILENCE OF THE STILL NIGHT

```
DOW#GLGHUJ#VOWNQJLPNWBDZQDAQ$R@CVZIXRMEFP#HIGNPAMGCIKGJTPCI
DQTCSLF$UHAXNE#VNGJUK@WDITNJXNHYRKIYQGEQ$NE@IUVHRT#$KCWLVKS
JEOXCLESNBFKFMJAS$LIOSCNVKLFKMWN@#GHPJOXEYVLOST#RHGOMFASYRT
F#AVPHFGUS@TQHUBIXYB#JLTCJRDUS#QND$UEKBTCTAZPWLCXQYPSLUPG#J
@AMPXB@JI$VYJRTZAFRZU$MNOKASVKABVTBHK#ELPYF$KXQSUJDOCHFLESG
CBZLDHXCRZFENO#BC@YPGW@TGJVTANFVIYFKGYOIZSV@JCSLUPG#BUV#LNS
GHILJZTYNVZUFCPQHRKCESL$ATUZE@IUOUKCWYKBHVOAUPF$PSGSADHP@ZQ
M#TGJ#H$N$UQRHDFN$JXE@IOQLMKRYJNWNQBSW@DROQT#VPENJ@YJIU$R@C
VHUXRIYABOYQZGJDKZJ@QIDQTCH#PHXAHKQSTEUO#N@RSTYPBZTFWLZ$CSZ
@CLVDP@RXE$ZGKXJADKWITE@JMJPCTLYOAZXAQRBOWRIJSNDJ@YRXEFEHXO
HYR@Y$ZCDKMRLAGJFTIEBNK#LIWNCXQYP#YJNWZKTBGOPTGBHPLI
```

Unit 122
Digram-counting attack on cipher clocks

This attack only applies if the length of the ciphertext alphabet is at least two more than the length of the plaintext alphabet. The reason that it works, if the text is long enough, is that when we encipher the next letter of a text, then the hands on the cipher clock move at most *m* steps (remember that m is the length of the plaintext alphabet, and *n* the length of the ciphertext alphabet). So if *n* is one greater than *m*, there are no double letters in the ciphertext, but all other digrams are possible. If *n* is two or more greater than *m*, then the missing digrams indicate what letter(s) is found on the key just before the last ciphertext letter that we wrote down.

To show how it works, we will work through three examples.

example 1: n = m + 2

Below is a ciphertext. It was encrypted with a cipher clock that uses this plaintext alphabet:

ABCDEFGHIJKLMNOPQRSTUVWXYZ

and this ciphertext alphabet, before it is mixed:

ABCDEFGHIJKLMNOPQRSTUVWXYZ◊○

And here it is . . .

XAYIHVBS○URMXE◊○WBQPSTGXECXCXPA◊OCATLXVBEQSZYB◊DTAJSNEKGJDV
WEAXA◊GBNGQWJQXOJEGPXJLFXFESFMWDOWEKEJFPWE◊CABSYUWSKOLZDMH○
BIBYTJQYUECVAUEOCSPKWLGM◊HIEWNEJKCUBSXMSEQVALMNTUBSNBMD○OJE
QGADBPGYPHYQJVHBHIBTDKTAPCEUMI○WEHNGZIDVQXZENWAQBPFHJKMSYOB
UORLGNBLZ◊○QAWPRIEOVY○◊RVYUFCHO◊UZJ○DVUNAT○NF◊UPXKOPYRSZ◊ST
JHKNSMPRDVXTGEKITAPLUEJ○OVR○SUPJPZKGNGDWCXIPJDIXCPBYOQMSLZU
JVNXED○QG○WENUGCN◊OFEPATLMPDWLCDEOATAP◊D○Z○CFORQLUZPXQ○ZGOK
TA◊NKMPG○MQLZUJVNB◊ADBNALQ◊E◊KLND○XUF◊BL○E◊GOBHDA◊DTAGXPXIY
UVBCYOJ◊TQD○WDLIO○NJKB○TDRUZRNG◊H○JW○PSE◊NRD○XUSLHZSRNXSDXZ
GKIJEUYXCPVOMHGHSLNULRZPU○UNO◊EGEAPEXUFWEACWJYIEMLHJXNOWLIQ
YXKVXV○GRCMPYKOJDP◊DJZGVPOVUBIQGAZIHUYX◊RLWBSL◊DSGTBEV○PSKE
DLGRLORQYVJQWBGBZMDAWCUQ○IKET◊PISD◊QPVSZGTLTDZODTUO○MEKO◊FX

OMXCOGZIDVUNAXKRENOQ◊FHVAW◊UIVPSKGJVRNGQVMDJYBPQBQ◊FHOMSFEC
WORYQSZLMK○ZFPSIJQCEHXSEDHNJQJGZOBPSBQMGUJOMSFECWORYQSZLMK○
ZFPSIJQCEHXUJ◊MHMPAEGBNXEIDUWCDK○OQYXKMSIVOPBZKQDRGWZSHBYTA
PLXB◊CSF◊SMAYMEJPTHJWGNBYN○UCZMBL○WCSMTGYJOUBHJQZF○ILIESECK
◊FXIVRXMSENJGQJQDVXECSJU○UKSPAUFBOYVJVJMRVJ○BWCUQKXEJPA◊ELV
JS○QR◊VSEASOGUIMCGDEUYXVYJYLNETQEZO◊PQRO○NKMXZOSVASNKLZJFAP
WCE○FJVGMKMXDZ◊RXMSNSMJNB◊XB○JEMNDI◊YSKWAP◊SRU◊H○JABHNQEOLE
DASYTCPYOSGMIVGOJQAKUCLXJRNUCPAIHVBDU◊LMR○OTLGIZUF○KGXNRDLU
MIDZLCOBGZIJHGCYPEGTJ◊DUAVAVH○MJRJEYQDRGLHXT○BVF◊KSREJCXC◊R
V○RLGBQNBYTAPDNDKMXSLHUJHKHJBDGIUNTWBV○KTAJVGMK◊AUYFZSNOGKR
HBTXUJNKDT◊JRFEUMIHOBXAEILWTCZSJ○KTAPGIFI◊GD◊FS○VZLZGJBTCXB
○JEMNDUPKXEVL○E○MDWDGHIEWTAPGAZVR○SUGL○EYSWTBI○JZFAVFV◊N◊R◊
FSFPJOWJ◊ILMIXVZOPBPS◊PA◊○KBSZ◊GPELOROXOHYNEHTJZ◊T○J◊TPKVZD
BPD◊OJHEJDHDGQEAWGNBJ◊OPCMKBR○IVSCOHYQJUGQ○XZKDGEGXGAZVR○SU
XAEYGZIULT○XNXBPJNFUI○UTGLGKOYBLJWMKDFJWBVDRE◊FHVYBLSCSZSNK
◊XHQDEAGNBTJDVZUZF○EUVYPKBSDJXAGAYSLUZG○VIAOHESYJT○HIWOXBCL
VQNR◊AXUXZNPBRQ◊XFHIEWDA◊QUDHIXYFZS○JYSPKBDHJSNOACE◊KECUIHV
YDNHVJDWXHMKDYPGEN◊FHJBEVCXUOELYJWMKDTETDSAUCUIECXF◊CXPHSZL
V○KVUXBJ○EKPKDHLH○PX○TGWTK○HBLXECTJO◊VZSVAWQJAUSZKXHSIJOZF○
EW◊UNKP○XQJUJEYLMNPSWIWBUSPFJUBDVZVFTXCFEGWP◊SNBMDWBC○QNPHO
BJRTBPUZJHCGQJBZ○DTQYXCKMXDGRMPYJRLRNG◊DJZVLICVHEJKPAVF◊EM○
VYQDUBDXUJWBYDUGYXFCOFEBLGJHUYQJHLT◊DTETPRI◊PJFC◊VF◊RVXAHUY
◊WQEUGWCJ◊EIAGVB◊AIDORQYOQZLGMLVQXYXTXBQYNRDJ◊BZ○FZSY◊LZOTL
MDAPILIPYUI◊HBFSR○RVAV◊L○OMKVUZENUAQBPFHDIVXDJSUYFOROSXMATL
GXPZ◊DSCLUXUIMPKECUGTLRXSTYGZIF○PEWPIFYGOIJVAWDVL○UZPOWDLHE
XZT○EQLXCZDJUVCOPBHYMBZBZHXGEUGPNDW◊HSE◊MXJRBSRNDGZH○JQCPE○
SUIMNDKVEXUFCPTLDHMB◊V◊GW○UAPXNSZPGSAYPVHYXJWMLFZF○◊Y◊○CUZI
○ACVBSMAYQJVUGQMDXBPECUQ○NJVXVGBCP◊LIUWSZYXTQYUJ◊LXCVCWOUZT
○IZJBNYSBDIPSXCZTXLEMNYQJVLIEANOKEBQYXFCXYVQWPDOALM○NGTJFPY
BLIPGCKMJDWEALHPHOROVGHIEWDYJNDUZSYOS○DLXMAJHJL○OMK○CDECD○K
TFPDXCOMPVHC◊YSMOKSZRXLTHJOE○UPKRUCGLUXBEAORXPHEQSHRXMKL◊IS
◊TDUG○PCDIVAI○WZ◊BMJ◊LSROUKL◊I◊LOXQTJUGCX◊SR◊CPYTLQDUBZDEVL
I◊FHFLFAEBSTPY○UK◊OWJLTDJZF○QP◊LUEHXVMCWJYQJNB◊○WGBCTQGKUGL
PFXOASABRZ◊KMKDZTXSTAPYXJFXAEBSNGZIB◊IBFPSIPQUIJBJ◊HFCPNVEJ
◊YJHSEXBEQEQ○RVKXYVFSY○U○OQRMVWDQBWQUQPY○LNR◊FXEOJWJALFJGT◊
SL○TABIE○FNREJKVXPIV○RTXNOHJLSZJBDKVHIBTAIUQNUIPA◊ORQRZLDUB
THZOXSMJQYXCZPIEOJWJALSXHDHMGCJQZF○ME○BIFECUSYOTQXAVUZDTAG◊
HTBTCUKOQGDLFZC◊SMNEQSHFJMKL◊○XGWJUXSURVKX◊CEGMAUILWOSGAWOW
CENO◊FHJKPYR◊EMZDVZ◊○NOVB◊HIBY○UY○PFNA◊○SY

The first step in the attack is to tabulate all of the digrams in the ciphertext. Remember to count *all* of them. The first four letters are XAYI; from them we get XA and AY and YI; don't forget that one in the middle. We don't need to count the digrams, just make a table of all the ones that exist.

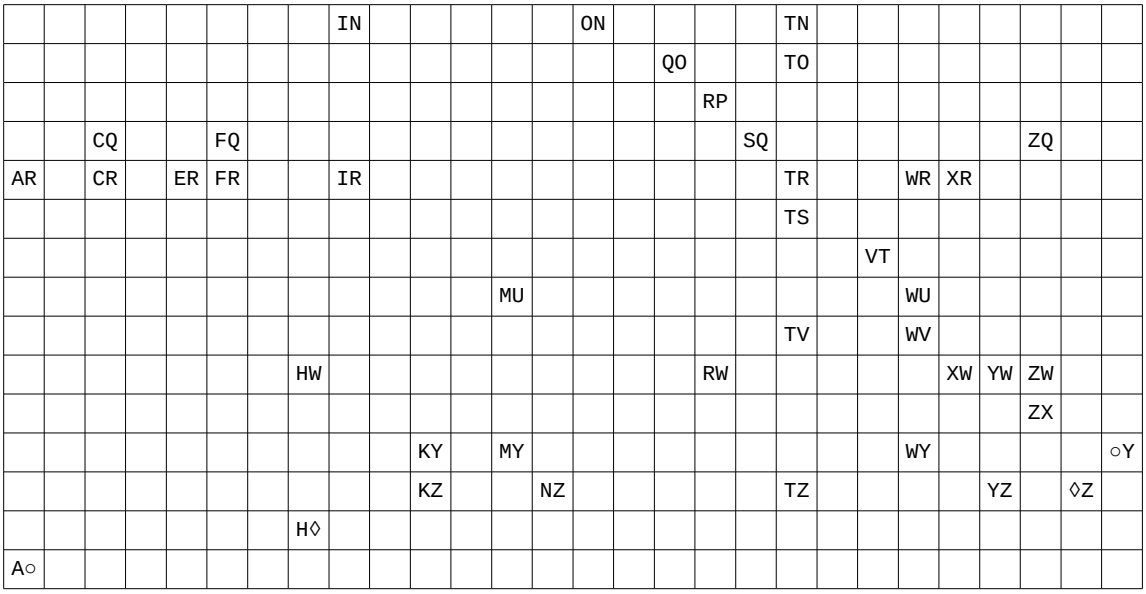
AB			DB	EB	FB	GB	HB	IB	JB	KB		MB	NB	OB	PB	QB	RB	SB	TB	UB	VB	WB	XB	YB	ZB	◊B	○B
AC	BC			EC	FC	GC	HC	IC	JC	KC	LC	MC		OC	PC	QC	RC	SC	TC	UC	VC	WC	XC		ZC	◊C	○C
AD	BD	CD		ED		GD	HD	ID	JD	KD	LD	MD	ND	OD	PD	QD	RD	SD	TD	UD	VD	WD	XD	YD	ZD	◊D	○D
AE	BE	CE	DE		FE	GE	HE	IE	JE	KE	LE	ME	NE	OE	PE	QE	RE	SE	TE	UE	VE	WE	XE		ZE	◊E	○E

	BF	CF	DF				HF	IF	JF		LF		NF	OF	PF		RF	SF	TF	UF	VF		XF	YF	ZF	◊F	○F
AG	BG	CG	DG	EG			HG		JG	KG	LG	MG	NG	OG	PG	QG	RG	SG	TG	UG	VG	WG	XG	YG	ZG	◊G	○G
AH	BH	CH	DH	EH	FH	GH		IH	JH	KH	LH	MH	NH	OH	PH		RH	SH	TH		VH		XH	YH	ZH	◊H	○H
AI	BI		DI	EI	FI	GI	HI			KI	LI	MI		OI	PI		RI	SI		UI	VI	WI	XI	YI	ZI	◊I	○I
AJ	BJ	CJ	DJ	EJ	FJ	GJ	HJ	IJ			LJ	MJ	NJ	OJ	PJ	QJ	RJ	SJ	TJ	UJ	VJ	WJ	XJ	YJ	ZJ	◊J	○J
AK		CK	DK	EK		GK	HK	IK	JK			MK	NK	OK	PK	QK		SK	TK	UK	VK		XK	YK	ZK	◊K	○K
AL	BL	CL	DL	EL	FL	GL	HL	IL	JL	KL		ML		OL	PL	QL	RL	SL	TL	UL	VL	WL	XL	YL	ZL	◊L	○L
	BM	CM	DM	EM	FM	GM	HM	IM	JM	KM	LM			OM		QM	RM	SM		UM	VM	WM	XM	YM	ZM	◊M	○M
AN	BN	CN	DN	EN	FN	GN	HN		JN	KN	LN	MN			PN	QN	RN	SN		UN	VN	WN	XN	YN	ZN	◊N	○N
AO	BO	CO	DO	EO	FO	GO	HO	IO	JO	KO	LO	MO	NO		PO		RO	SO		UO	VO	WO	XO	YO	ZO	◊O	○O
AP	BP	CP	DP	EP	FP	GP	HP	IP	JP	KP	LP	MP	NP	OP		QP		SP	TP	UP	VP	WP	XP	YP	ZP	◊P	○P
AQ	BQ		DQ	EQ		GQ	HQ	IQ	JQ	KQ	LQ	MQ	NQ	OQ	PQ		RQ		TQ	UQ	VQ	WQ	XQ	YQ		◊Q	○Q
	BR		DR			GR	HR		JR	KR	LR	MR	NR	OR	PR	QR		SR		UR	VR			YR	ZR	◊R	○R
AS	BS	CS	DS	ES	FS	GS	HS	IS	JS	KS	LS	MS	NS	OS	PS	QS	RS			US	VS	WS	XS	YS	ZS	◊S	○S
AT	BT	CT	DT	ET	FT	GT	HT	IT	JT	KT	LT	MT	NT	OT	PT	QT	RT	ST		UT		WT	XT	YT	ZT	◊T	○T
AU	BU	CU	DU	EU	FU	GU	HU	IU	JU	KU	LU		NU	OU	PU	QU	RU	SU	TU		VU		XU	YU	ZU	◊U	○U
AV	BV	CV	DV	EV	FV	GV	HV	IV	JV	KV	LV	MV	NV	OV	PV	QV	RV	SV		UV			XV	YV	ZV	◊V	○V
AW	BW	CW	DW	EW	FW	GW		IW	JW	KW	LW	MW	NW	OW	PW	QW		SW	TW	UW	VW					◊W	○W
AX	BX	CX	DX	EX	FX	GX	HX	IX	JX	KX	LX	MX	NX	OX	PX	QX	RX	SX	TX	UX	VX	WX		YX		◊X	○X
AY	BY	CY	DY	EY	FY	GY	HY	IY	JY		LY		NY	OY	PY	QY	RY	SY	TY	UY	VY		XY		ZY	◊Y	
AZ	BZ	CZ	DZ	EZ	FZ	GZ	HZ	IZ	JZ		LZ	MZ		OZ	PZ	QZ	RZ	SZ		UZ	VZ	WZ	XZ				○Z
A◊	B◊	C◊	D◊	E◊	F◊	G◊		I◊	J◊	K◊	L◊	M◊	N◊	O◊	P◊	Q◊	R◊	S◊	T◊	U◊	V◊	W◊	X◊	Y◊	Z◊		○◊
	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○	◊○	

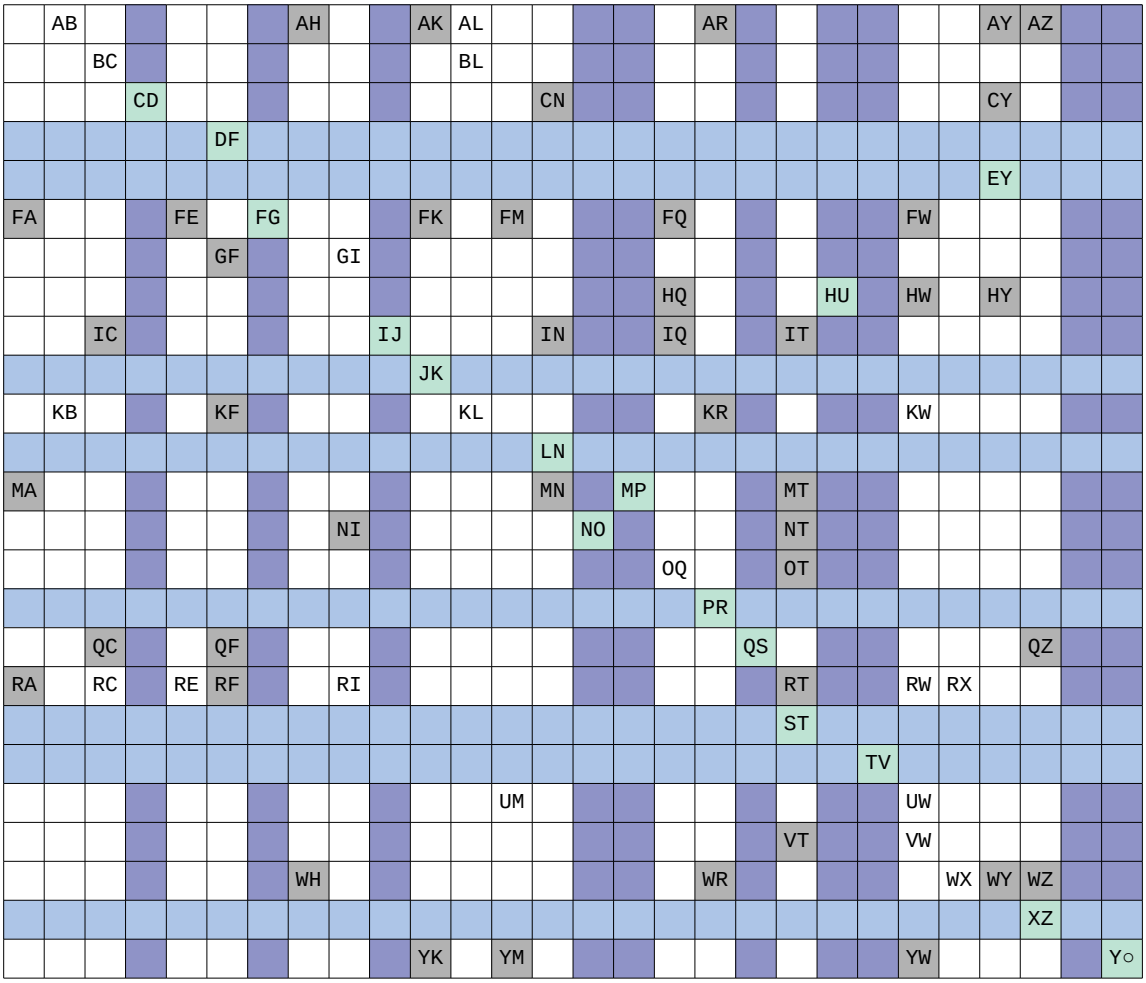
What is important to us now is which digrams are *missing*. Of course, all of the diagonal entries are missing, since double letters cannot occur in the ciphertext for a device with this configuration. But look at the `J` column. The digram for `JI` is the only other one missing. Therefore, we know that `I` comes immediately before `J` in the key.

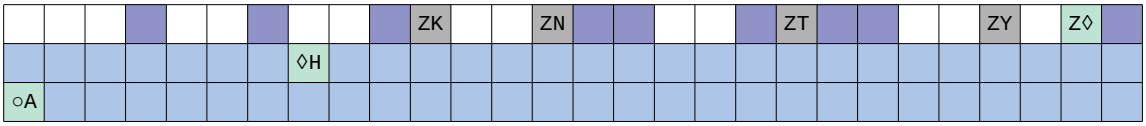
Here are all of the missing digrams, except for the doubles:

	BA						HA			KA	LA						RA							YA	ZA		
		CB									LB																
			DC										NC											YC			
					FD																						
																								YE			
AF				EF		GF				KF		MF				QF						WF					
					FG			IG																			
																QH				UH		WH		YH			
		CI							JI				NI			QI			TI								
										KJ																	
	BK				FK						LK						RK					WK					
													NL														
AM													NM		PM				TM								

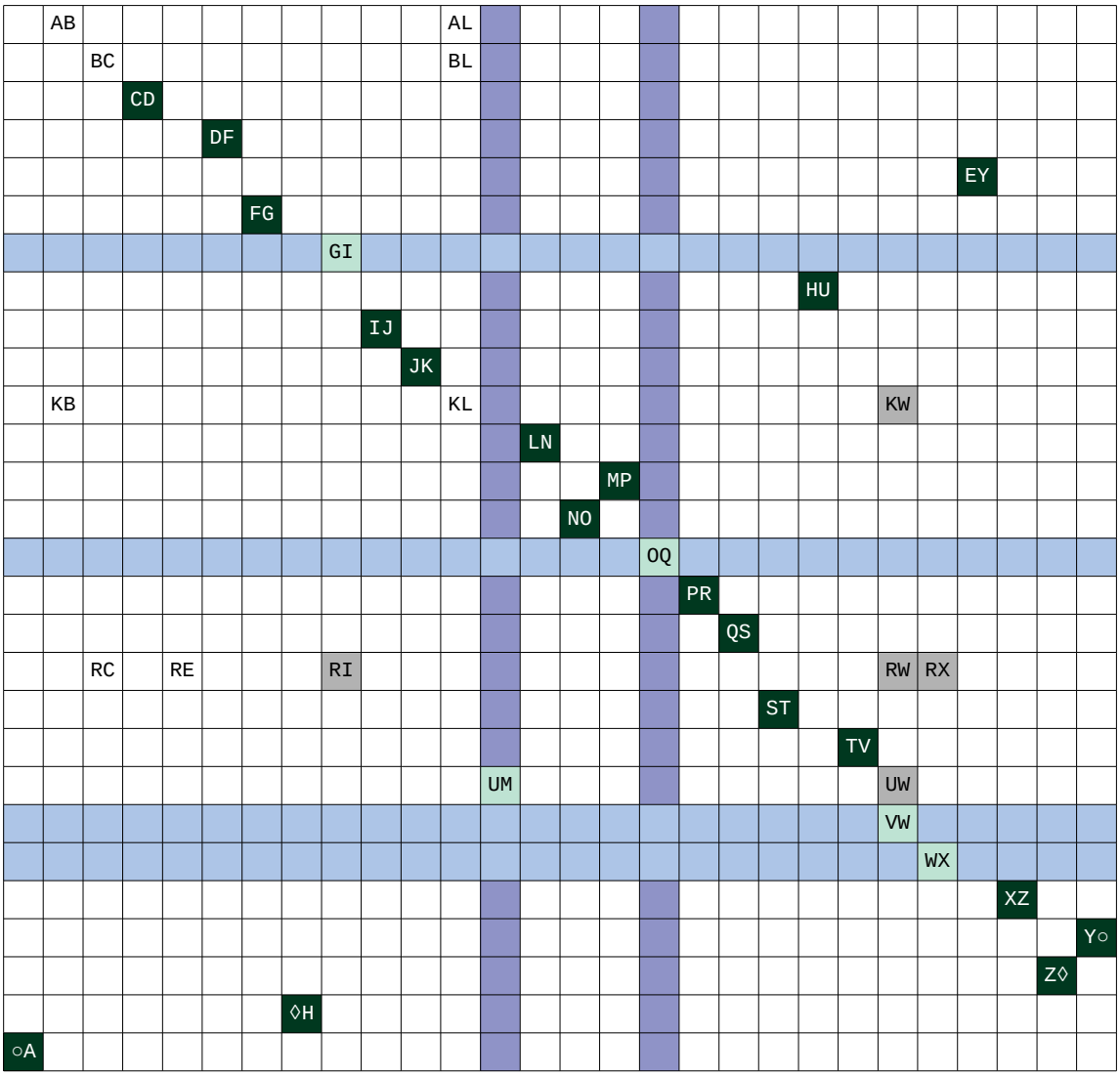


Now don’t get confused, but to make things easier, we reverse each missing digram so that it is written in the way it might appear in the key. Here is the new table:

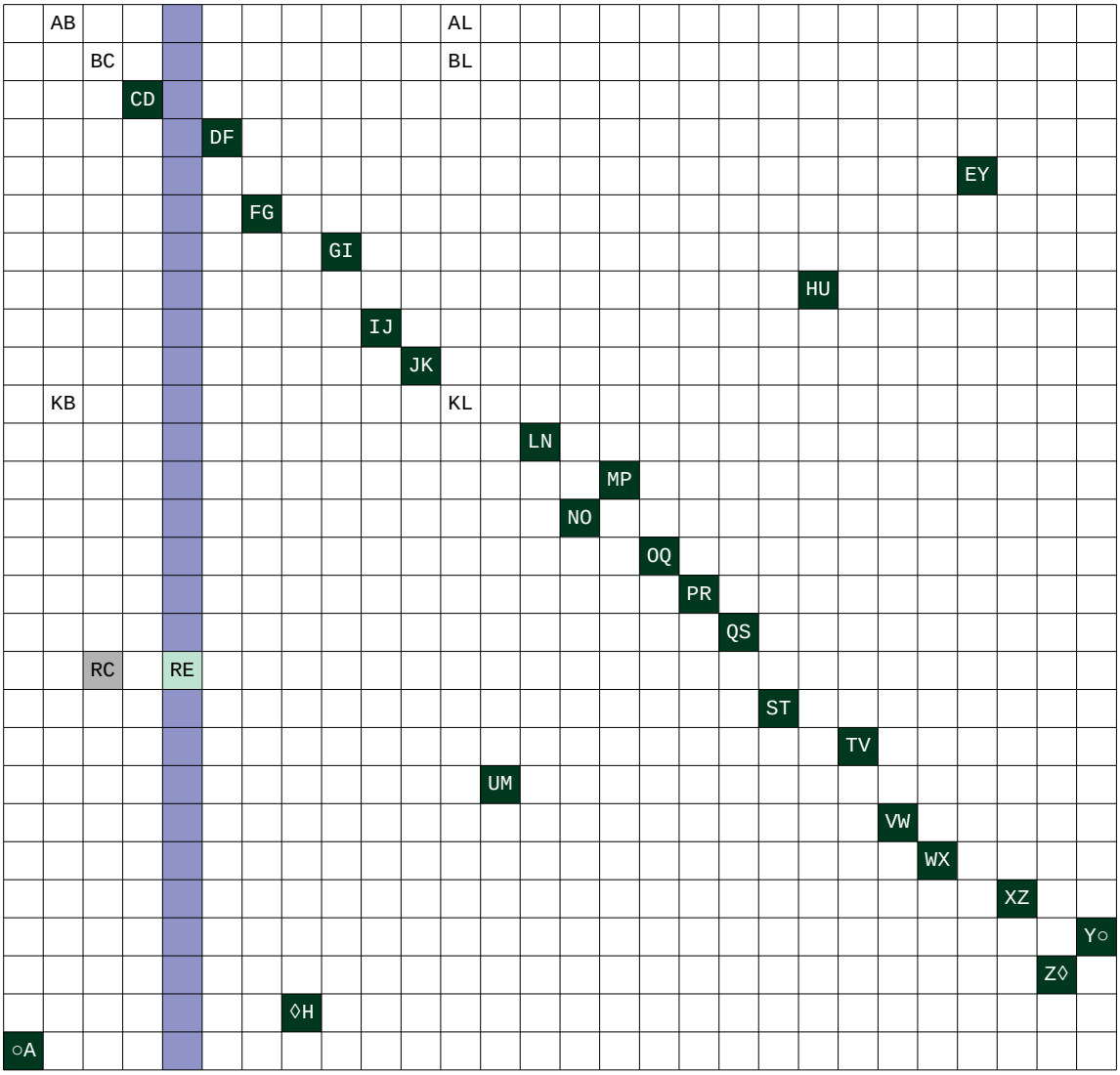




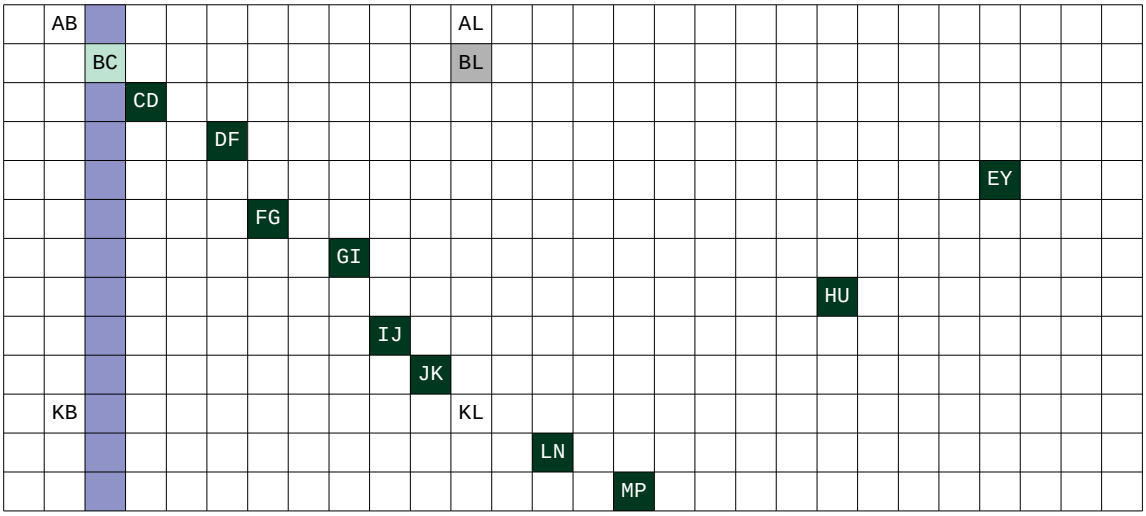
Now we look for any digram that appears alone in a row or column. Such a digram must be in the key. We find CD, FG, IJ, NO, MP, QS, HU, TV, Z◊, Y○, DF, EY, JK, LN, PR, ST, XZ, ◊H, and ○A. Once we decide to keep a digram in a row, we can eliminate the other digrams in its column; similarly, once we keep a digram in a column, we can eliminate the others in the same row. We can also eliminate the reversal of any digram that we keep. Here is what is left after we make those deletions:

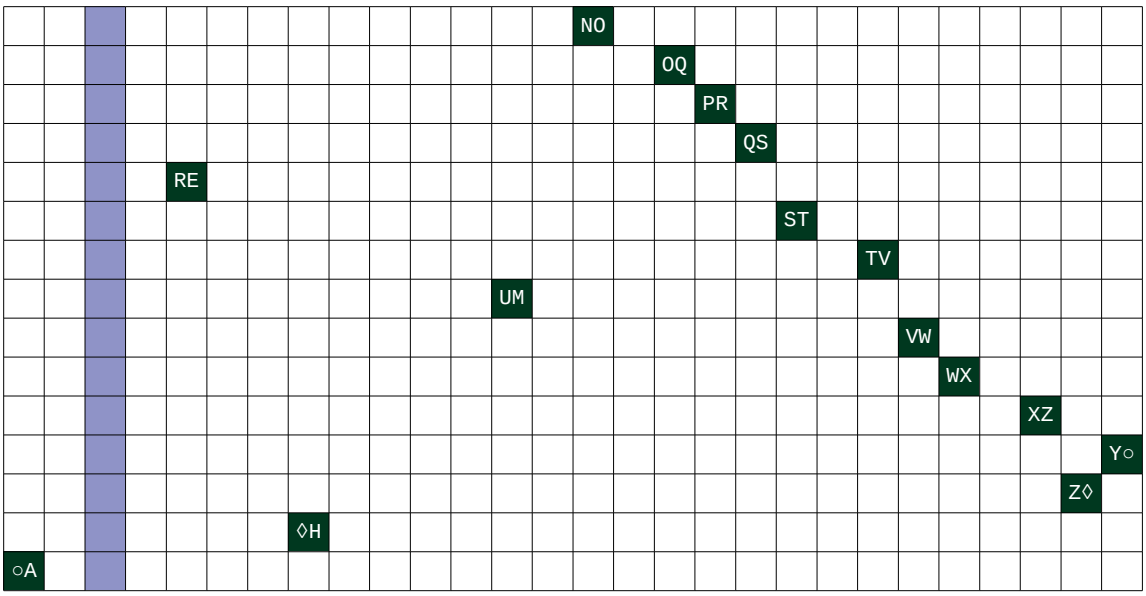


Now we play the same game and look for digrams that are alone on a row or column in what remains in the table. We find GI, OQ, UM, VW, and WX. Eliminate those rows and columns to get an even smaller table:



Now we get RE and eliminate RC. One more time:





Now we keep BC and eliminate BL. One more elimination won't gain us anything, so we stop.

Here are all of the key's digrams that we have found to definitely belong:

```
BC CD DF EY FG GI HU IJ JK LN MP NO OQ
PR QS RE ST TV UM VW WX XZ Y○ Z◊ ◊H ○A
```

But remember that AB, AL, KB, and KL are still possibilities.

If we chain the definte key digrams together, we get these key fragments:

```
BCDFGIJK
LNOQSTVWXZ◊HUMPREY○A
```

There are two ways to combine them, but it doesn't matter, since the key goes on a ring. So now we know that the key is something like

```
LNOQSTVWXZ◊HUMPREY○ABCDFGIJK
```

To find the final key, we need to roll this key to each possible position on the ring and decipher the ciphertext. When we find a recognizably English plaintext, then we have found the correct key. It turns out that the correct key is

```
◊HUMPREY○ABCDFGIJKLNOQSTVWXZ
```

and the plaintext is (broken into words)

```
ALL THESE SORROWS ARE PAST MY GLANCING AT THEM MAY NOT BE
WITHOUT ITS USE FOR IT MAY HELP IN SOME MEASURE TO EXPLAIN
WHY I HAVE ALL MY LIFE BEEN ATTACHED TO THE INANIMATE
OBJECTS THAT PEOPLE MY CHAMBER AND HOW I HAVE COME TO
```

```
LOOKUP ON THEM RATHER IN THE LIGHT OF OLD AND CONSTANT
FRIENDS THAN AS MERE CHAIRS AND TABLES WHICH A LITTLE MONEY
COULD REPLACE AT WILL CHIEF AND FIRST AMONG ALL THESE IS MY
CLOCK MY OLD CHEERFUL COMPANIONABLE CLOCK HOW CAN I EVER
CONVEY TO OTHERS AN IDEA OF THE COMFORT AND CONSOLATION
THAT THIS OLD CLOCK HAS BEEN FOR YEARS TO ME IT IS
ASSOCIATED WITH MY EARLIEST RECOLLECTIONS IT STOOD UPON THE
STAIRCASE AT HOME I CALL IT HOME STILL MECHANICALLY NIGH
SIXTY YEARS AGO I LIKE IT FOR THAT BUT IT IS NOT ON THAT
ACCOUNT NOR BECAUSE IT IS A QUAINT OLD THING IN A HUGE
OAKEN CASE CURIOUSLY AND RICHLY CARVED THAT I PRIZE IT AS I
DO I INCLINE TO IT AS IF IT WERE ALIVE AND COULD UNDERSTAND
AND GIVE ME BACK THE LOVE I BEAR IT AND WHAT OTHER THING
THAT HAS NOT LIFE COULD CHEER ME AS IT DOES WHAT OTHER
THING THAT HAS NOT LIFE I WILL NOT SAY HOW FEW THINGS THAT
HAVE COULD HAVE PROVED THE SAME PATIENT TRUE UNTIRING
FRIEND HOW OFTEN HAVE IS AT IN THE LONG WINTER EVENINGS
FEELING SUCH SOCIETY IN ITS CRICKET VOICE THAT RAISING MY
EYES FROM MY BOOK AND LOOKING GRATEFULLY TOWARDS IT THE
FACE REDDENED BY THE GLOW OF THE SHINING FIRE HAS SEEMED TO
RELAX FROM ITS STAID EXPRESSION AND TO REGARD ME KINDLY HOW
OFTEN IN THE SUMMER TWILIGHT WHEN MY THOUGHTS HAVE WANDERED
BACK TO A MELANCHOLY PAST HAVE ITS REGULAR WHISPERINGS
RECALLED THEM TO THE CALM AND PEACEFUL PRESENT HOW OFTEN IN
THE DEAD TRANQUILLITY OF NIGHT HAS ITS BELL BROKEN THE
OPPRESSIVE SILENCE AND SEEMED TO GIVE ME ASSURANCE THAT THE
OLD CLOCK WAS STILL A FAITHFUL WATCHER AT MY CHAMBER DOOR
MY EASY CHAIR MY DESK MY ANCIENT FURNITURE MY VERY BOOKS I
CAN SCARCELY BRING MYSELF TO LOVE EVEN THESE LAST LIKE MY
OLD CLOCK IT STANDS IN A SNUG CORNER MIDWAY BETWEEN THE
FIRESIDE AND A LOW ARCHED DOOR LEADING TO MY BEDROOM ITS
FAME IS DIFFUSED SO EXTENSIVELY THROUGHOUT THE
NEIGHBOURHOOD THAT I HAVE OFTEN THE SATISFACTION OF HEARING
THE PUBLICAN OR THE BAKER AND SOMETIMES EVEN THE PARISH
CLERK PETITIONING MY HOUSEKEEPER OF WHOM IS HALL HAVE MUCH
TO SAY BY AND BY TO IN FORM HIM THE EXACT TIME BY MASTER
HUMPHREYS CLOCK MY BARBER TO WHOM I HAVE REFERRED WOULD
SOONER BELIEVE IT THAN THE SUN NOR ARE THESE ITS ONLY
DISTINCTIONS IT HAS ACQUIRED I AM HAPPY TO SAY ANOTHER
INSEPARABLY CONNECTING IT NOT ONLY WITH MY ENJOYMENTS AND
REFLECTIONS BUT WITH THOSE OF OTHER MEN
```

You might recognize the text from *Master Humphrey's Clock* by Charles Dickens.

example 2: n = m + 3

For this example, we need to add another character to the ciphertext alphabet. This time, for each character in the key, we should find two missing digrams for the two characters that follow it. In which

order those two occur can be deduced from the choices of what characters might follow them. For example, if we have missing digrams AB, AC, BC, and BD, then we know that B and C are after A. Since C is after B, the order is ABCD.

Here is a ciphertext for us to break:

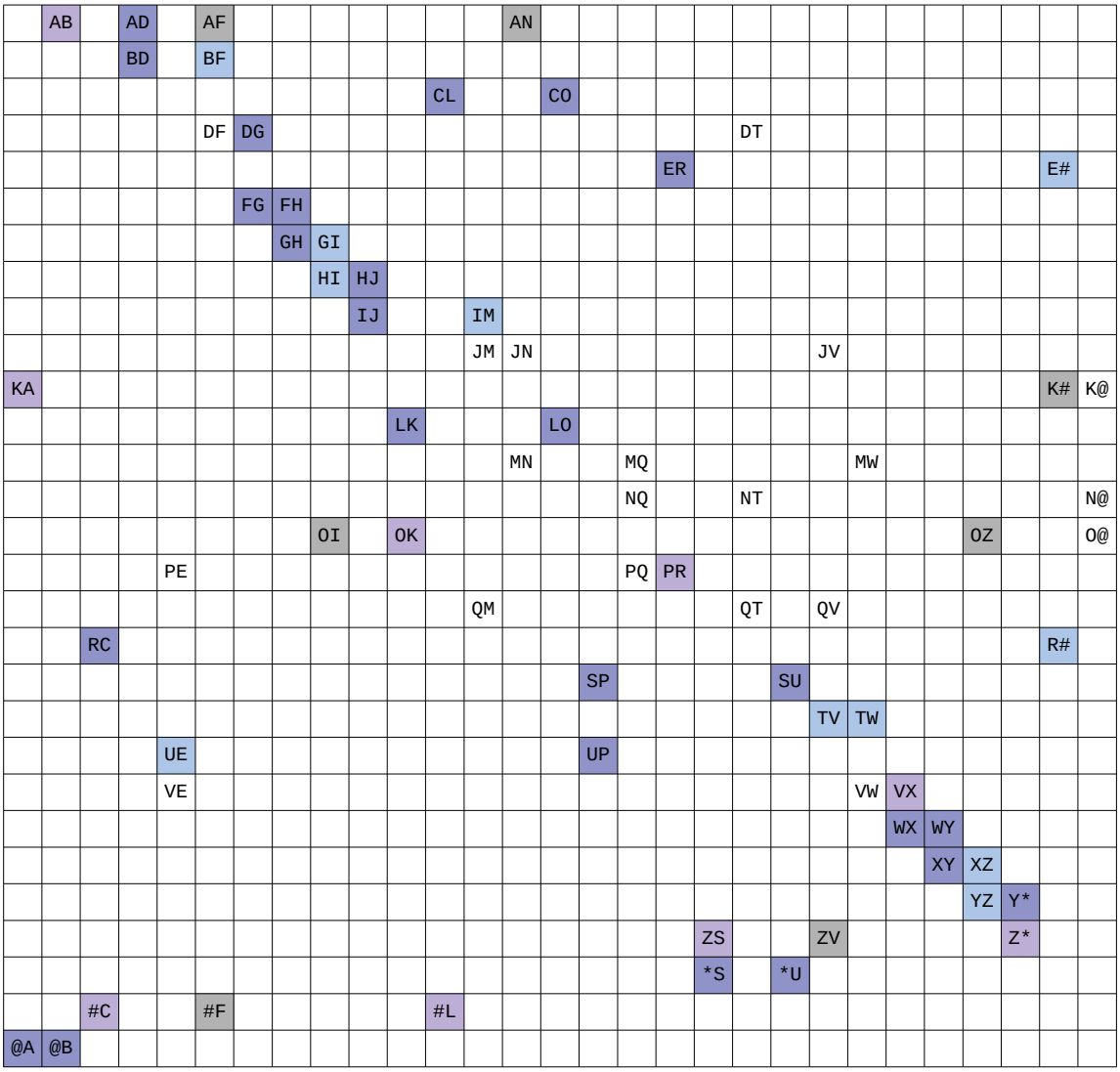
```
JEY@VHRIECWIBIRMBSVECN*LOTHSDIZ*DLPAF*LHUN@XCFXLACYUTHBPTCT
KVDENVWEXBVKMVGK#WG*GJVYSI@WAHOMY@YDZQ#JTERJBLHMRBQCXGUAMUB
HAPZG@AV#WSPDINPX#HEKEHVLSQID#HVLV@WJZMUHYIMTCWH@CXKVDYOWUE
QZGRN#CA#QVECN*ISCVBL@FME#AWOA#TZVMPOZR*CHXKICFSEHXZL@WELWK
VW#W@SYOQV*HPIPQAFTXGJV*#MDHVSWLXLU@PHNKIJPBPXPZDJOTIXLRD#H
CEIZAOJEBGSOBOXFYPOMERWYSTFMKXRLYSP#@PBZQIB*B#GL*IJXGBVE*QY
RSAXYJCGQGWOWSWEO#YUAHVNFSA#HDPQFMRG*DHSKPGPIXGXLGERSCNF*SA
TJWNHEWXJPJFSI@CUR*VFKQXLQ*#IJUZBCWDHLXSMTJUXFSQRI#FUPM*BMA
XYPQOBUZNCLSMROPRW@WJYAWRGTLPG@RIYUCBYN#DXFIWUXOYKN#BOXCVOT
HUDOIN#DQSDS@AHZLVIUNG*GHYLBPGUEDUEYMANSDFZRSQIE#Z@BOF*MDR#
BXBITBYJSDSHZ#PXUNTRLJOZBCQCLBCFLWZKW#IQEIAWRLUFR*BCBLENRKN
*NX@SMA#VWK@IJ*TEJBO@DTFODY@DYRAVYNHZF*NQYFIJY#FGQR#XQWEJPQ
CBJD*NGS@U#HMOADZWXC@QTXGUTYZ#TWN*VRK*MEFCNQYHLYRGBN#*UBXJO
JEHKQVAFXQA#*W*K@PX#*BEMXHBRKGLBLFWSMEWKRVEOZIBQS#MDV#IYS#D
@HWEHETUZRB*@DX*XQBKNWKEADIJAY@WNGESGMOBCN#*BXFTCMBXLBIAORI
U@XZPLD*EQGJRLGBQZBPQU@DZCTCTKVIPRV#QZSJWBUX*VCP@V*FHBI*PCW
X@RJN@LOD@WJDTX@JZBPQW*BJSXAVNWSMEW#QZK#PKIPQAYN#MK*OIN#DLY
BKWRQIRXFKWPJT*HJSDLWH#IBWNLKUMNBGIPXTYQT#MYFCMAHQTSDMG#OH*
@DPOXFKXKPBLJFSVHRCDYD@GOBVKMCAIPED@RVENPVA#@AFEA#LZ*N*@WXU
TRSHQZKAT@QYJETBRSIXZUVGN@*GQRWF*TCDSCSFCJAFZSIAILVGPOTZRJB
V#VN*#SCUAOFULUBIJQ@WOIUFUWSFXKFJCJONZDRNYNKYKCJE#ALQSXJKSH
THURK*VLWSCNFOR#*MPT*@BCUVRHXYP*NOINCUHD#P#IJPRJBLMPDNW*NST
BUH#CJZV@RLB#QVCIPF*TKZDSDNIESDSYZKNO@TP#LQG*OHMU#SNQ*JR@CZ
ENOIUIL*OP#PAFJEFXJMSM#YBDOFCLGZJUO*HZ*MWXCLQGVX*BHXT@Q*JRK
*BRL@SCKZTGJOTUNIPXAERSILVSVWJRUYNRNLQGWUT@DJ#WCSKNLDLNDGNE
IAXYRVKGAIPQAHEKGEHPHY@LMVSIMUFGOXIUQ*#*UTMC*HLNL@BROKRZQJR
GJFRK*EDGKTSD#MDPDNFRTYQVLVNFLFTB#CMXQDMGAZMNCNFOQJACAUKYVY
IM#BVMFMKTFJACWP#MFXMAHTZ#J#QCSKGLAGMXTIUBLWOG#MHCMCPOS#MDW
IET#FIKEFK@XULTYGUTYKCQCSG@MZETUZRSLXKJQVOPBIPXKNSGRUVA#FIP
@JMRZT#SY*WX*OMU#SNWH@CXJZUGVPEIAPRQ#OZGLETLRHXYEGHRNY*AHEM
RZCFCILRJBVXMNCMLBJSDITRAMEMUYBFWZSEGCOUVP*#MCBRK#PH@JVACLM
Y@YAWYA*FRGUGKIPNYDMZTRUWCDYD#QZHKR#IRG@AJLAMYVPYRXINRCNOVD
WI*PZFXQZMFUXGVDKFULHZ@QJYABTFGNEGKRJPDRHVFIZDJNXAWRJZIDXOP
YASBQYKMLPMGNBRKVIBQWKIBVMPKSMCBFJPO#YF@LFTLYHMUN@QKJPVOEBP
IFSKNLDYHOIDWNOVOPGEZ*AOTV*J@RFXEHEMRVDR#J*FYG@#JPQJXZEGLIR
@#ZGLWRTBGB#S#WOSNPFVYCMUNRMNFL*KMPZDG*QK#QCXGNLDENOIUDZARH
JCUBEOZJPJFYTZ@TYLHTAWQOFNOQUPLITEAYVM@GQE*NLDMOYKN@SYA#NC@
*EDQ#QOTHJNSNY@QFOUGMZ#P@WJDTX@JDJWKE*RKUCXLUZT*LPTUIQZGI*B
LJLO#OY@SXUIVSIU@AHYZTW*BQIBCZBDVSHTKBDQGSMKH#DX@SYOQGESQVA
YOZCUP@DZNGRTRZAWJQL@JGWQDJC*B*GYCZEKVIFPANBILZAZBXRTUHMENX
G*DETZFN@AHPTWNFEADPXDMXNULHZH#ABMEJNCN@SYA#SKBY#IQ@E*VLFVY
*RJAHVMUGKNK@TPOPJXPXY#AMSHTARLXRIMTPWRIQE*ANOQLKPHWOWKTLSC
SADZCMCXF@YZAZ#DXLI*GSHZDISNE@UALAON#P@BQWKIYAUNEBGYKRLSVFK
```

```
*@CVD*ALGWR@XPZATHZE#J#DLPEGSVHRCIDJV@ATOIR#FSPYKGEQYLTSCVB
*DFMDCOQUBO*R@CL*AWCZBDJOYEJ*RFWLFVLNHQYEIACAQGABLXACVFKNIA
HRYGVCWOQLTYGYHKRC@Q@STFVO*LGNEWOALOTKJPZTBOISXUIK@VLEYGVBW
PTFHRMWFLMGTB*DH#ZKW#JRQJQKBIV#JPHIWOWDJCVHPLIDLSISA*NEIUPZ
DGRGTBP#*U@DZCGSMKVIR*ALVGMZTIQ@EN*SJYVKXISDWALWQAHJSRJMVSB
M@ECUXHAVYNKDPEIAQIBX@WOI*CBPJMER#YVKFX@RJY#YPDHNKIUJODGTMK
JWRDHUKXKXLENCN@S#QZCJWBUIPKBCBWXSDJMUHXBSQIDZIDJ#ADIULJFUT
GJMZ@QJ@SMAN#CLHQF@GYTMXHI*LQ#CBORNBDYJACLMZUZNKX*BYMSMK#SV
RGZL@ZEOKHSGINFEQZGRMZTI*TPV#UPYFHLQ#OPHZWRIUIRJBG#J#NF@UCB
KUCKIYEOTGNZV#MDWDFXET@M*NTXY#I*FWEMVSIMUFHOW*VWLQTEADZPOHQ
Z#JRCNCLFQRGSBYHCGWZBNTUXYCOQVUKFKTPQDTWY@M*MNWKTCKZEHTSCUA
JZADZQH#*STXEMENEHNSDVDKCNFHZARVEOZGLQTCBOZ@FVYAMFWATJFZ#*I
J*J#W@BXZ#DJWS@QWDHCFLESUXFSFQLYOZI*HXK
```

Here is our table of digrams present in the ciphertext:

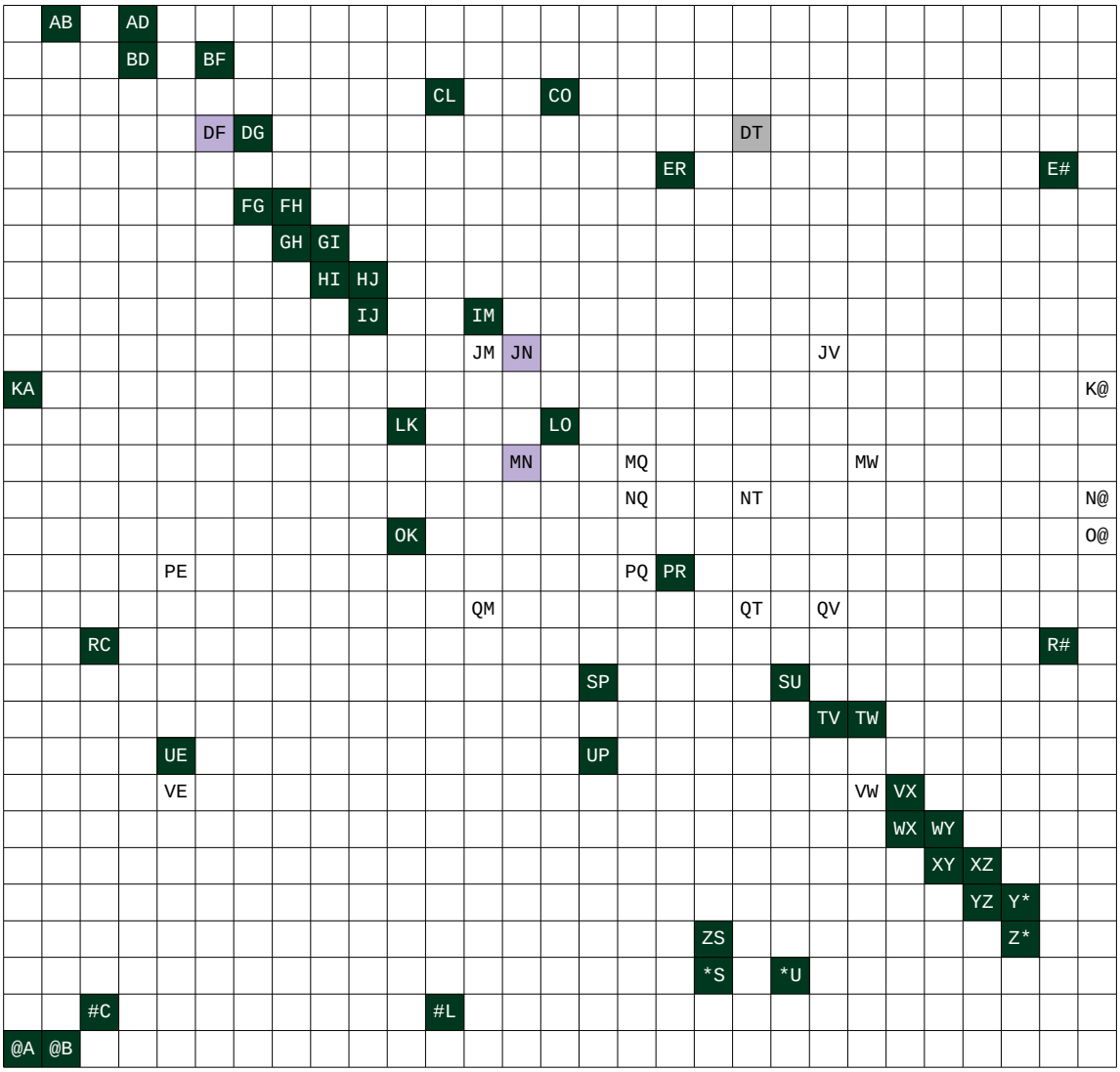
		CA		EA		GA	HA	IA	JA	KA	LA	MA		OA	PA	QA	RA	SA	TA	UA	VA	WA	XA	YA	ZA	*A	#A	@A
AB		CB		EB		GB	HB	IB	JB	KB	LB	MB	NB	OB	PB	QB	RB	SB	TB	UB	VB	WB	XB	YB	ZB	*B	#B	@B
AC	BC		DC	EC	FC	GC	HC	IC	JC	KC		MC	NC		PC	QC	RC	SC	TC	UC	VC	WC	XC	YC	ZC	*C	#C	@C
AD	BD	CD		ED			HD	ID	JD	KD	LD	MD	ND	OD	PD	QD	RD	SD		UD	VD	WD	XD	YD	ZD	*D	#D	@D
AE	BE	CE	DE		FE	GE	HE	IE	JE	KE	LE	ME	NE	OE	PE	QE		SE	TE	UE	VE	WE	XE	YE	ZE	*E	#E	@E
AF	BF	CF	DF	EF				IF	JF	KF	LF	MF	NF	OF	PF	QF	RF	SF	TF	UF	VF	WF	XF	YF	ZF	*F		@F
AG	BG	CG	DG	EG	FG				JG	KG	LG	MG	NG	OG	PG	QG	RG	SG	TG	UG	VG	WG	XG	YG	ZG	*G	#G	@G
AH	BH	CH	DH	EH	FH	GH				KH	LH	MH	NH	OH	PH	QH	RH	SH	TH	UH	VH	WH	XH	YH	ZH	*H	#H	@H
AI	BI	CI	DI	EI	FI	GI	HI			KI	LI		NI	OI	PI	QI	RI	SI	TI	UI	VI	WI	XI	YI	ZI	*I	#I	@I
AJ	BJ	CJ	DJ	EJ	FJ	GJ	HJ	IJ		KJ	LJ			OJ	PJ	QJ	RJ	SJ	TJ	UJ		WJ	XJ	YJ	ZJ	*J	#J	@J
	BK	CK	DK	EK	FK	GK	HK	IK	JK		LK	MK	NK	OK	PK	QK	RK	SK	TK	UK	VK	WK	XK	YK	ZK	*K		
AL	BL	CL	DL	EL	FL	GL	HL	IL	JL			ML	NL		PL	QL	RL	SL	TL	UL	VL	WL	XL	YL	ZL	*L	#L	@L
AM	BM	CM	DM	EM	FM	GM	HM	IM	JM	KM	LM			OM	PM		RM	SM	TM	UM	VM		XM	YM	ZM	*M	#M	@M
AN	BN	CN	DN	EN	FN	GN	HN	IN	JN	KN	LN	MN		ON	PN		RN	SN		UN	VN	WN	XN	YN	ZN	*N	#N	
AO	BO	CO	DO	EO	FO	GO	HO		JO		LO	MO	NO		PO	QO	RO	SO	TO	UO	VO	WO	XO	YO		*O	#O	
AP	BP	CP	DP		FP	GP	HP	IP	JP	KP	LP	MP	NP	OP				SP	TP	UP	VP	WP	XP	YP	ZP	*P	#P	@P
AQ	BQ	CQ	DQ	EQ	FQ	GQ	HQ	IQ	JQ	KQ	LQ		NQ	OQ	PQ		RQ	SQ		UQ		WQ	XQ	YQ	ZQ	*Q	#Q	@Q
AR	BR		DR	ER	FR	GR	HR	IR	JR	KR	LR	MR	NR	OR	PR	QR		SR	TR	UR	VR	WR	XR	YR	ZR	*R		@R
AS	BS	CS	DS	ES	FS	GS	HS	IS	JS	KS	LS	MS	NS	OS		QS	RS		TS		VS	WS	XS	YS	ZS	*S	#S	@S
AT	BT	CT	DT	ET	FT	GT	HT	IT	JT	KT	LT	MT	NT	OT	PT	QT	RT	ST		UT			XT	YT	ZT	*T	#T	@T
AU	BU	CU	DU		FU	GU	HU	IU	JU	KU	LU	MU	NU	OU		QU	RU	SU	TU		VU	WU	XU	YU	ZU	*U	#U	@U
AV	BV	CV	DV		FV	GV	HV	IV	JV	KV	LV	MV	NV	OV	PV	QV	RV	SV	TV	UV				YV	ZV	*V	#V	@V
AW	BW	CW	DW	EW	FW	GW	HW	IW	JW	KW	LW	MW	NW	OW	PW	QW	RW	SW	TW	UW	VW				ZW	*W	#W	@W
AX	BX	CX	DX	EX	FX	GX	HX	IX	JX	KX	LX	MX	NX	OX	PX	QX	RX	SX	TX	UX	VX	WX				*X	#X	@X
AY	BY	CY	DY	EY	FY	GY	HY	IY	JY	KY	LY	MY	NY	OY	PY	QY	RY	SY	TY	UY	VY	WY	XY				#Y	@Y
AZ	BZ	CZ	DZ	EZ	FZ	GZ	HZ	IZ	JZ	KZ	LZ	MZ	NZ	OZ	PZ	QZ	RZ		TZ	UZ		WZ	XZ	YZ			#Z	@Z
A*	B*	C*	D*	E*	F*	G*	H*	I*	J*	K*	L*	M*	N*	O*	P*	Q*	R*		T*		V*	W*	X*	Y*	Z*		#*	@*
A#	B#		D#	E#		G#	H#	I#	J#	K#		M#	N#	O#	P#	Q#	R#	S#	T#	U#	V#	W#	X#	Y#	Z#	*#		@#
		C@	D@	E@	F@	G@	H@	I@	J@	K@	L@	M@	N@	O@	P@	Q@	R@	S@	T@	U@	V@	W@	X@	Y@	Z@	*@	#@	

Here are the missing digrams, reversed:

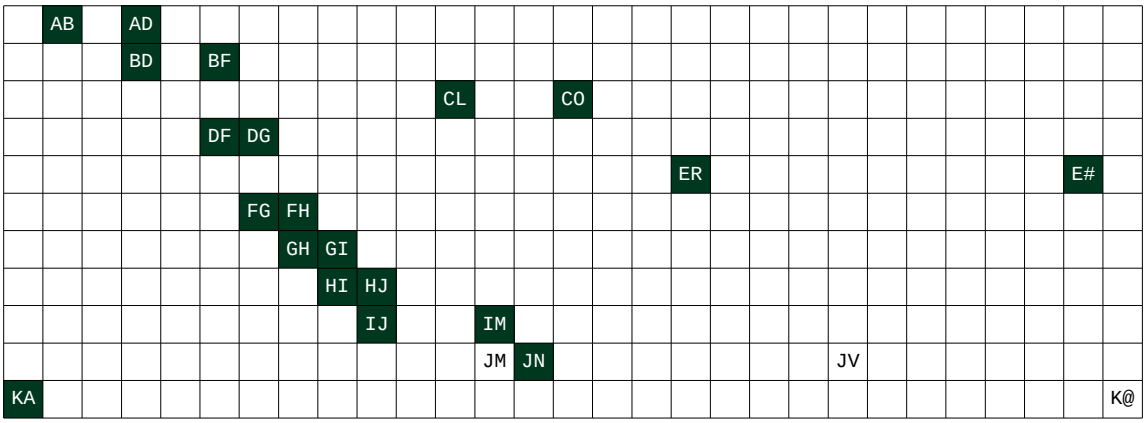


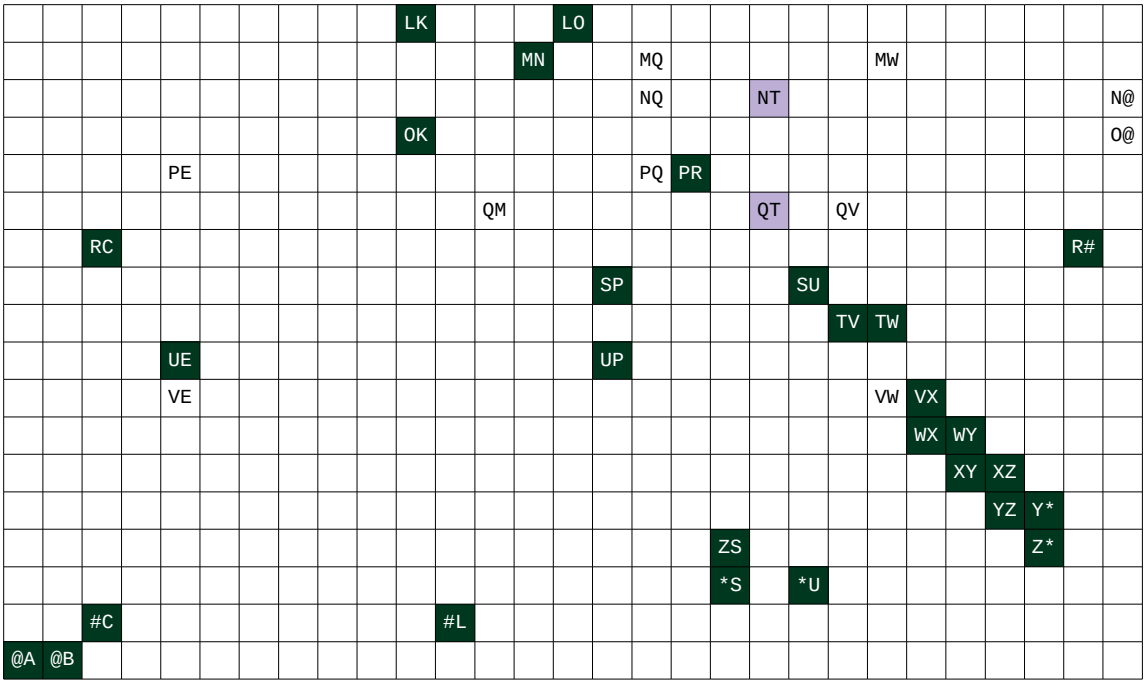
This time, we are looking for rows and columns that have exactly *two* digrams (some are in both), since there are two characters that we cannot reach when we encipher the next letter. From rows we get BD, BF, CL, CO, ER, E#, FG, FH, GH, GI, HI, HJ, IJ, IM, LK, LO, RC, R#, SP, SU, TV, TW, UE, UP, WX, WY, XY, XZ, YZ, Y*, *S, *U, @A, and @B. From columns, we add AB, #C, AD, DG, KA, OK, #L, PR, ZS, VX, and Z*.

We can eliminate all non-listed digrams from rows and columns that contain two of the digrams in our list, since we know that any other digrams in such a row or column is accidentally rather than necessarily missing. One such column contains GI, HI, and OI; since GI and HI are in our list, we know that OI cannot be. The table becomes



Now there are some new rows and columns with only two digrams. This allows us to add `DF`, `JN`, and `MN` to our list. Moving onward, we can eliminate a few more from rows and columns that already have two listed digrams, such as `DT`.





Now we can also add NT and QT. We have reached the end of this path. The key diagrams we have are

```
AB AD BD BF CL CO DF DG ER E# FG FH GH GI HI HJ IJ IM JN KA
LK LO MN NT OK PR QT RC R# SP SU TV TW UE UP VX WX WY XY XZ
YZ Y* ZS Z* *S *U @A @B #C #L
```

We see that A is followed by B and D, and B is followed by D. So the order must be ABD. Using this logic, we can construct this key:

```
@ABDFGHIJMNQTVWXYZ*SUPER#CLOK
```

We have to roll the key and try each option until we get a readable plaintext. The true key that we find is ultimately

```
*SUPER#CLOK@ABDFGHIJMNQTVWXYZ
```

and the plaintext is (with spaces added)

```
THERE ARE TWO KINDS OF CLOCKS THERE IS THE CLOCK THAT IS
ALWAYS WRONG AND THAT KNOWS IT IS WRONG AND GLORIES IN IT
AND THERE IS THE CLOCK THAT IS ALWAYS RIGHT EXCEPT WHEN YOU
RELY UPON IT AND THEN IT IS MORE WRONG THAN YOU WOULD THINK
A CLOCK COULD BE IN A CIVILIZED COUNTRY I REMEMBER A CLOCK
OF THIS LATTER TYPE THAT WE HAD IN THE HOUSE WHEN I WAS A
BOY ROUTING US ALL UP AT THREE OCLOCK ONE WINTERS MORNING
WE HAD FINISHED BREAKFAST AT TEN MINUTES TO FOUR AND I GOT
TO SCHOOL A LITTLE AFTER FIVE AND SAT DOWN ON THE STEP
OUTSIDE AND CRIED BECAUSE I THOUGHT THE WORLD HAD COME TO
```

AN END EVERYTHING WAS SO DEATHLIKE THE MAN WHO CAN LIVE IN THE SAME HOUSE WITH ONE OF THESE CLOCKS AND NOT ENDANGER HIS CHANCE OF HEAVEN ABOUT ONCE A MONTH BY STANDING UP AND TELLING IT WHAT HE THINKS OF IT IS EITHER A DANGEROUS RIVAL TO THAT OLD ESTABLISHED FIRM JOB OR ELSE HE DOES NOT KNOW ENOUGH BAD LANGUAGE TO MAKE IT WORTH HIS WHILE TO START SAYING ANYTHING AT ALL THE GREAT DREAM OF ITS LIFE IS TO LURE YOU ON INTO TRYING TO CATCH A TRAIN BY IT FOR WEEKS AND WEEKS IT WILL KEEP THE MOST PERFECT TIME IF THERE WERE ANY DIFFERENCE IN TIME BETWEEN THAT CLOCK AND THE SUN YOU WOULD BE CONVINCED IT WAS THE SUN NOT THE CLOCK THAT WANTED SEEING TO YOU FEEL THAT IF THAT CLOCK HAPPENED TO GET A QUARTER OF A SECOND FAST OR THE EIGHTH OF AN INSTANT SLOW IT WOULD BREAK ITS HEART AND DIE IT IS IN THIS SPIRIT OF CHILDLIKE FAITH IN ITS INTEGRITY THAT ONE MORNING YOU GATHER YOUR FAMILY AROUND YOU IN THE PASSAGE KISS YOUR CHILDREN AND AFTERWARD WIPE YOUR JAMMY MOUTH POKE YOUR FINGER IN THE BABYS EYE PROMISE NOT TO FORGET TO ORDER THE COALS WAVE AT LAST FOND ADIEU WITH THE UMBRELLA AND DEPART FOR THE RAILWAY STATION I NEVER HAVE BEEN QUITE ABLE TO DECIDE MYSELF WHICH IS THE MORE IRRITATING TO RUN TWO MILES AT THE TOP OF YOUR SPEED AND THEN TO FIND WHEN YOU REACH THE STATION THAT YOU ARE THREE QUARTERS OF AN HOUR TOO EARLY OR TO STROLL ALONG LEISURELY THE WHOLE WAY AND DAWDLE ABOUT OUTSIDE THE BOOKING OFFICE TALKING TO SOME LOCAL IDIOT AND THEN TO SWAGGER CARELESSLY ON TO THE PLATFORM JUST IN TIME TO SEE THE TRAIN GO OUT AS FOR THE OTHER CLASS OF CLOCKS THE COMMON OR ALWAYS WRONG CLOCKS THEY ARE HARMLESS ENOUGH YOU WIND THEM UP AT THE PROPER INTERVALS AND ONCE OR TWICE A WEEK YOU PUT THEM RIGHT AND REGULATE THEM AS YOU CALL IT AND YOU MIGHT JUST AS WELL TRY TO REGULATE A LONDON TOMCAT BUT YOU DO ALL THIS NOT FROM ANY SELFISH MOTIVES BUT FROM A SENSE OF DUTY TO THE CLOCK ITSELF YOU WANT TO FEEL THAT WHATEVER MAY HAPPEN YOU HAVE DONE THE RIGHT THING BY IT AND THAT NO BLAME CAN ATTACH TO YOU SO FAR AS LOOKING TO IT FOR ANY RETURN IS CONCERNED THAT YOU NEVER DREAM OF DOING AND CONSEQUENTLY YOU ARE NOT DISAPPOINTED YOU ASK WHAT THE TIME IS AND THE GIRL REPLIES WELL THE CLOCK IN THE DININGROOM SAYS A QUARTER PAST TWO BUT YOU ARE NOT DECEIVED BY THIS YOU KNOW THAT AS A MATTER OF FACT IT MUST BE SOMEWHERE BETWEEN NINE AND TEN IN THE EVENING AND REMEMBERING THAT YOU NOTICED AS A CURIOUS CIRCUMSTANCE THAT THE CLOCK WAS ONLY FORTY MINUTES PAST FOUR HOURS AGO YOU MILDLY ADMIRE ITS ENERGIES AND RESOURCES AND WONDER HOW IT DOES IT I MYSELF POSSESS A CLOCK THAT FOR COMPLICATED UNCONVENTIONALITY AND LIGHTHEARTED INDEPENDENCE COULD I SHOULD THINK GIVE POINTS TO ANYTHING YET DISCOVERED IN THE CHRONOMETRICAL LINE AS A MERE TIMEPIECE IT LEAVES MUCH TO BE DESIRED BUT CONSIDERED AS A SELFACTING CONUNDRUM

```
IT IS FULL OF INTEREST AND VARIETY I HEARD OF A MAN ONCE
WHO HAD A CLOCK THAT HE USED TO SAY WAS OF NO GOOD TO ANY
ONE EXCEPT HIMSELF BECAUSE HE WAS THE ONLY MAN WHO
UNDERSTOOD IT HE SAID IT WAS AN EXCELLENT CLOCK AND ONE
THAT YOU COULD THOROUGHLY DEPEND UPON BUT YOU WANTED TO
KNOW IT TO HAVE STUDIED ITS SYSTEM AN OUTSIDER MIGHT BE
EASILY MISLED BY IT FOR INSTANCE HE WOULD SAY WHEN IT
STRIKES FIFTEEN AND THE HANDS POINT TO TWENTY MINUTES PAST
ELEVEN I KNOW IT IS A QUARTER TO EIGHT HIS ACQUAINTANCESHIP
WITH THAT CLOCK MUST CERTAINLY HAVE GIVEN HIM AN ADVANTAGE
OVER THE CURSORY OBSERVER BUT THE GREAT CHARM ABOUT MY
CLOCK IS ITS RELIABLE UNCERTAINTY IT WORKS ON NO METHOD
WHATEVER
```

The text is from *Clocks* by Jerome K. Jerome.

example 3: both alphabets mixed

For this example, we use a cipher clock with the twenty-six-letter modern-English plaintext alphabet and this twenty-eight-letter old-English ciphertext alphabet (before mixing):

```
abcdefghijklmnopqrstuvwxyzðþ
```

To make things easier, we also specify that mixing is done like this:

```
keywordðþabcfghijlmnpqstuvxz
```

Both alphabets will be mixed, so after the digram-counting attack, we need to break a monoalphabetic substitution cipher.

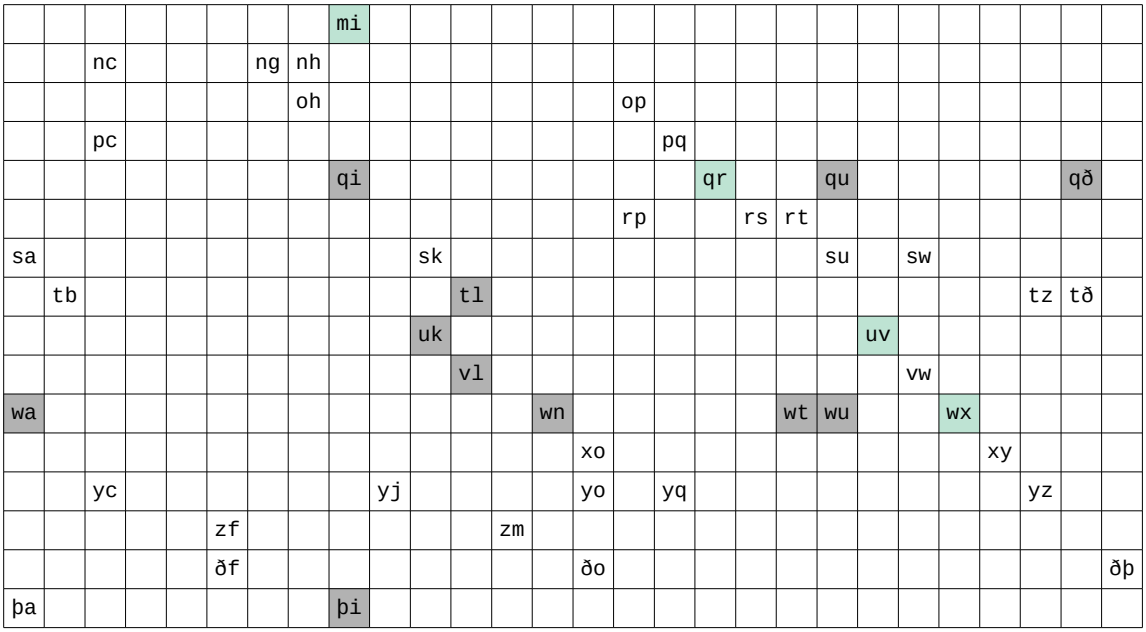
Here is the ciphertext:

```
ienbzuvcuvxpðykyozkpujwajbpblqþdgjhvtxðwitskourixmjtgqwdnah
tþtkpevznyðatzjkfwkxzþaðvtnudhaoþdbþcjuxdmðpkefigyoctdnþpaz
bifwxhvþpðynrdekzdzbðeuhðrxðpinojwzðefwmbmvdujknizpðcucðhlm
nlbmdxixjwhdxkpamþceufbqlcigvjuxzlhqjhticlacxubrcienþdbuzmj
sgarsoenupzvsvrtpqwjnðaizbnvtxqjosotarctauðinzikefgþxnvtxrj
þuctðvtðadedofkezhxþvpukonmirafnðfvstmiozbiezosvþjdukwnywzg
þcleuvrlyeopnxþmsqdsuxvkmszpeghtspclnrxydxþyþzomqoelqclehðs
pqbynqiwmþdwglsugvþopjkbxuadwnjebzmnjrþvwpslfilojueueðctlðz
evzhuyqvzbgvoeþajwkðrfqbknðziomþvþfvtoqhdpmqarcðrnðdþrexlwm
þsuyþphqjekiyzpakabdeqdzbiczdtyþsyudumnrjmfþpbudnjhcmngxiuv
tvþzpuguowlþkcarhiyzmngxczbsjsomodpbkwpjvrnþnlnðbzuvculðyko
iozklþmþcsarnhpweitbwlbiswglbrfoepwzlbgbrcmnkiedwnxfsysjreb
dvchlðptzpydbwctvðyrdrkþaxþghsnjhunzðþvnuvfvtsjupdkxfwðjrve
tnlzbizmutlqdwqdfgetaragxhðwkryzlyiujðvomrfpvkyfþerpmdqreiw
xzgmsxiutðedqvxoirsfjþaukþpihagxiuvtxstcsgkonmirarcjrvetþpa
nsxienrzwyrknfwkpwjtgðeþlrhmikhfgtxrðugvðkcedncmteufduþegpx
```

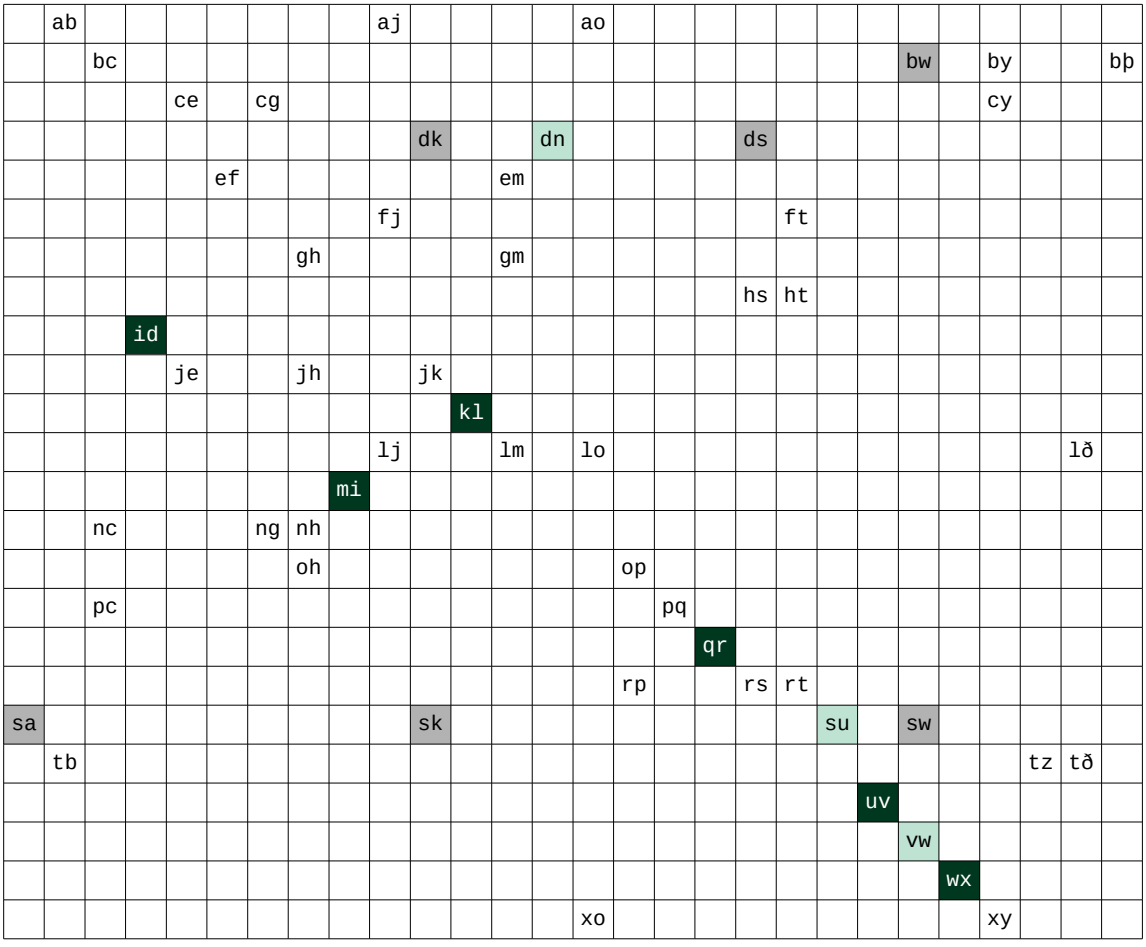
þfwrjvgdpdnþmrzbðpahdkntbdexdytstzqdtkcfkþpmþhlðdkomniozbvd
atsuxnofbcufmtcvjblqþdezmiðzmuvþivqwnjocufciðdnðpþnktvtxmta
yrofkbþacuruaeðmygyrvctaðryhlfwkcwkauðpanjxzeozbsvatlhwfwkg
faophfghvhtlðktvtxðvydugoupykþlewaqðpizbitxupqðykyobkxjgtca
qbqkpgydvxkxtlqrscqudrdbiyfpesðphþduixþvtxrwqjodvirufjigrvb
fdaykngjwfguabvlugvgtywfgjvypcmrmneuyigfhbvovomqgibþckarðny
oþpwzehreydugrjelyqcsarnhpdhsnyuzmrypðbpwqnubcklqtyvmagphsn
yvtxtvljkyogbkzpðpðdchsitixrþaqrvyðpxqvqkrzbfahdþmykgxmsvat
eqkywþqbjmrðeþpapnyjzsewghðoqhdzlpucwcgðrnjhkgjpwgwxespðylo
þmpjeufhiypwixbymtayrþjodvbdlrewagrhzpdbcfvxcþjdsqmioepdbgl
ðplhagwdgbfdwxpyutqiomcfyarceghtspqkitdbdcisysjnulwpxugsnjh
uiwiyvþiðyupbcfwflehlðmhþojhxbkxþqsðgkypczpðpaqðbjtlitdbzrm
wþsnqdfwlþyþcgarnðcqlnktvtxðapqougkrmkafyqxlwtsalhkyrzvtcjs
iaexokyorezgweufjslnozxrexamsjupdkxfwðewuðþdyzknzsgvmqlefri
xmuajbnðcohþegjzgmþvþfvtoqhdlmityaxðpaðudopngjcxnitvwisjofw
kbjukgswgweoeidðzcdðwydqgqipjcwodanpqidtþnbduixvtyhþdskcðpa
gqbgwxidhrzkagboqhdnubdlrcgeþrhknjxucuamomqkefynfwðavrhphrm
klivtcjngqdsujklnmixclerepsbgpkriwznzlweukqjtufcrbrcfqvhmji
hipyþvlwrgozkyauabckaxhbhegðnzxþvguvhlrfosfylraubjsgmhsnydb
dxþqbpqsjsouiekarclðgmitplidwmbmvðyhþlumnrjþdcsyghrsygðjhtm
widwzkvpvzlohlbirarcvtðkhpqbzbigbfdwypsomreqkfwtykfhyznðnrw
zdxþqrvlsuluyobzwðpalhmiomufghxyrstzrdsiylrauadðþpaozbiwmrs
uatðnoupyzlpucwcgbjnðdzbzulxpdudmuiearclðgmizifijwzrxþqvcqx
qdrkaxtpvmhlþizbzursarjqjutjkigbwtbfuehafnqiegxfgsgvþslgocd
msqsanjnkezcdqdszlqrfrwfxfþegsemþinjgzsgwowriouezvahdohainq
dbfwxhvþqðþdrbpmfxmxþhbrnrtmxzeacuxrvysgkvohkwzmvcuhdqbnjiw
hxqsylugvfwkrzdwkbnhqlyktvtxrhðxedpzfpþcðagbewghqumkisxlwzm
þtqdsnhlqeiofleyganþpcjnðzezosuvmwxgjqgoftkþrerpenlðxþzacrs
vðbðpkrdfpmqfjþrðadngðehmnjgzrsaqdsþjqnucufveouanhbþofldurv
þqdsbqefkcþfcsghlþinlmnqzuxbnqdsmoefiefkþxlepsbgukymdensgvh
uzgqfkrpzvyegdnjhyntkeuxnxrwoqhdeirmfþwanutjkozikenxfsysjip
þmbxiakadqknfpgþezxivzsaovompf

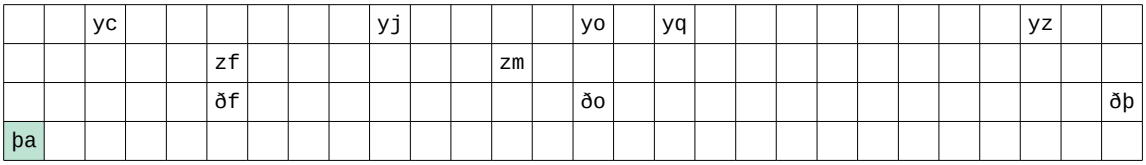
Here is our table of missing digrams:

	ab								aj					ao												
		bc																				bw		by			bþ
				ce		cg																		cy			
										dk			dn					ds									
					ef							em															
									fj										ft								
							gh					gm															
																		hs	ht								
			id																								
			jd	je			jh			jk																	
											kl																
									lj			lm		lo											lð		

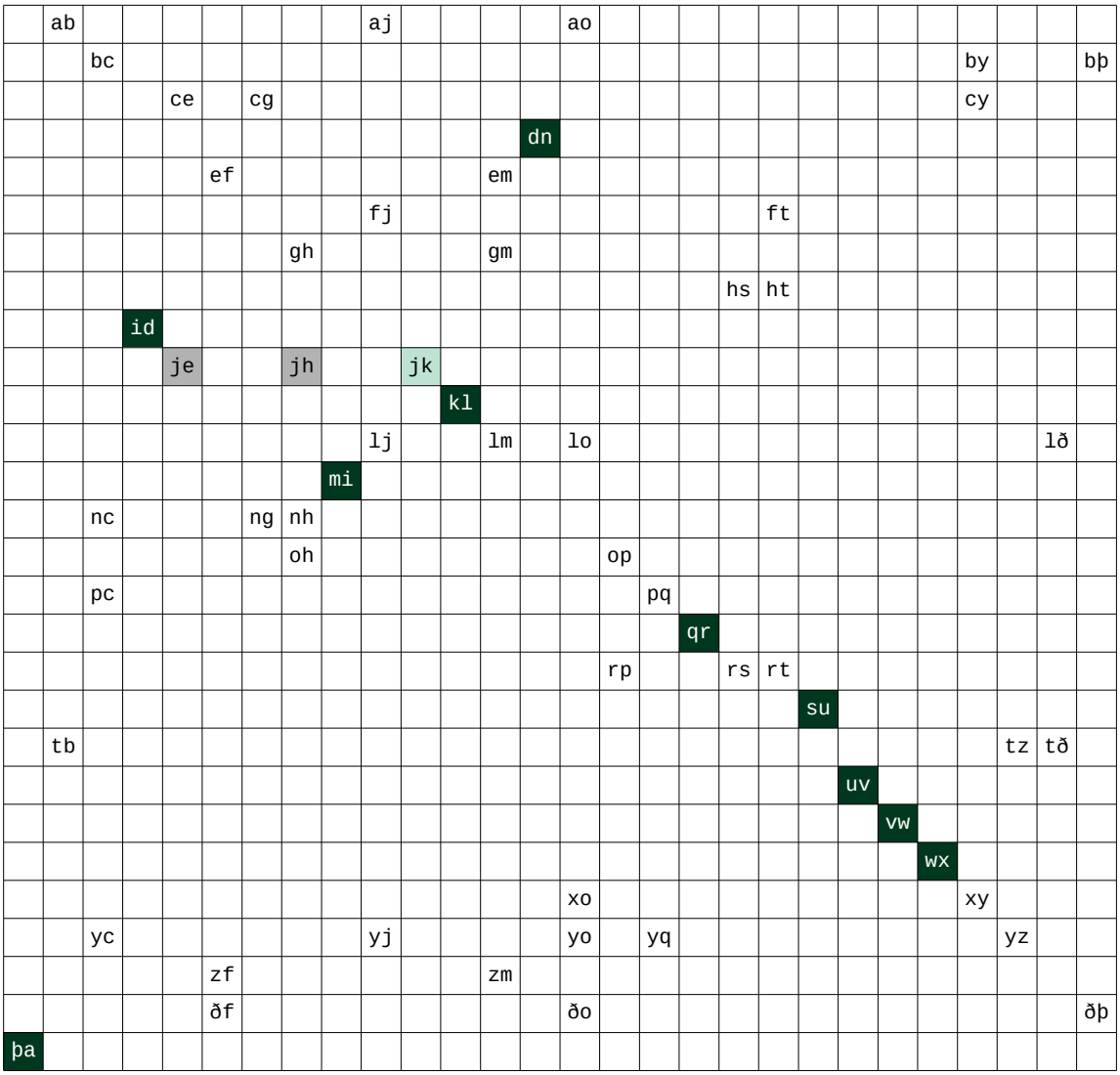


Remember that for $n-m=2$ we are looking for singles on rows and columns. On the first pass, we get `id`, `kl`, `mi`, `qr`, `uv`, and `wx`. Eliminate the digrams that conflict with them.

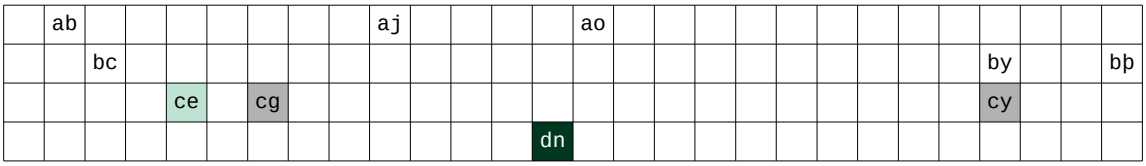


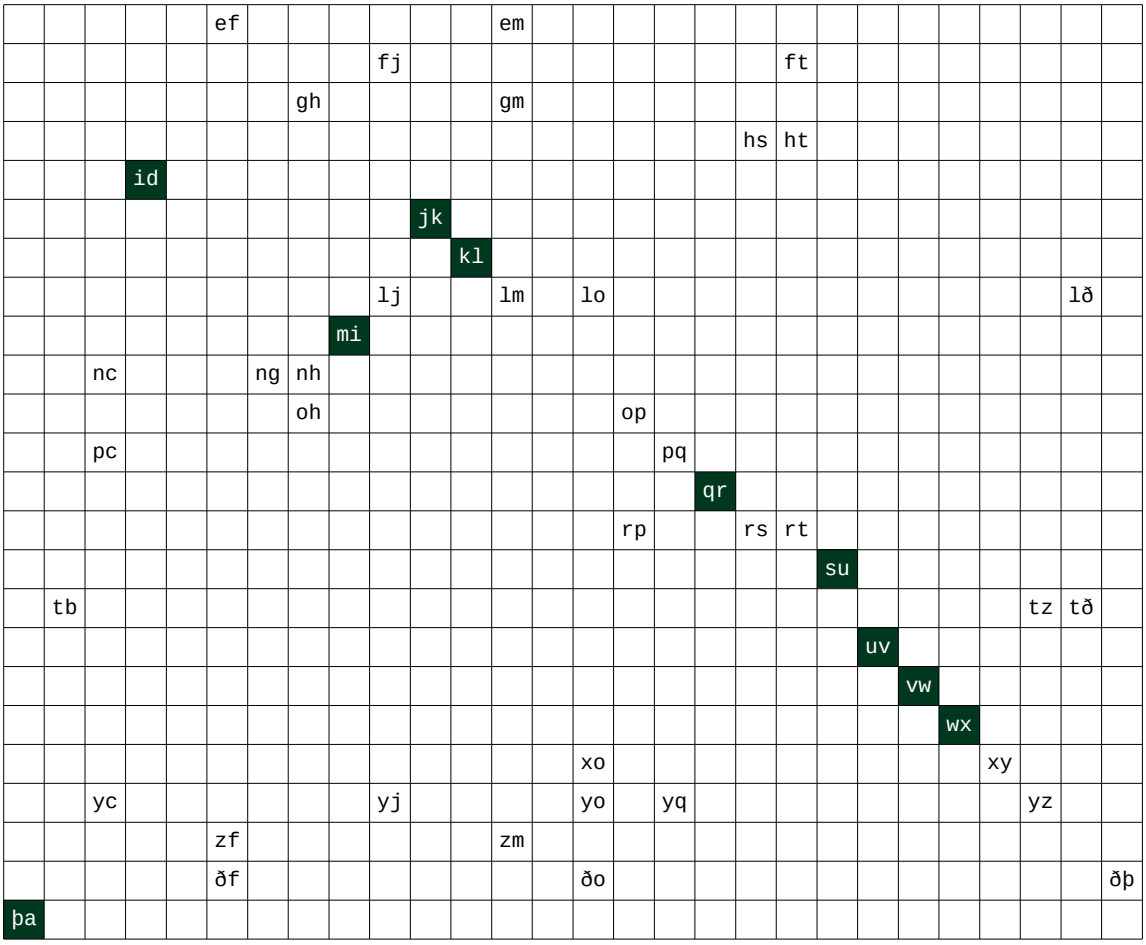


Now we add dn, su, vw, and þa and eliminate the conflicts.

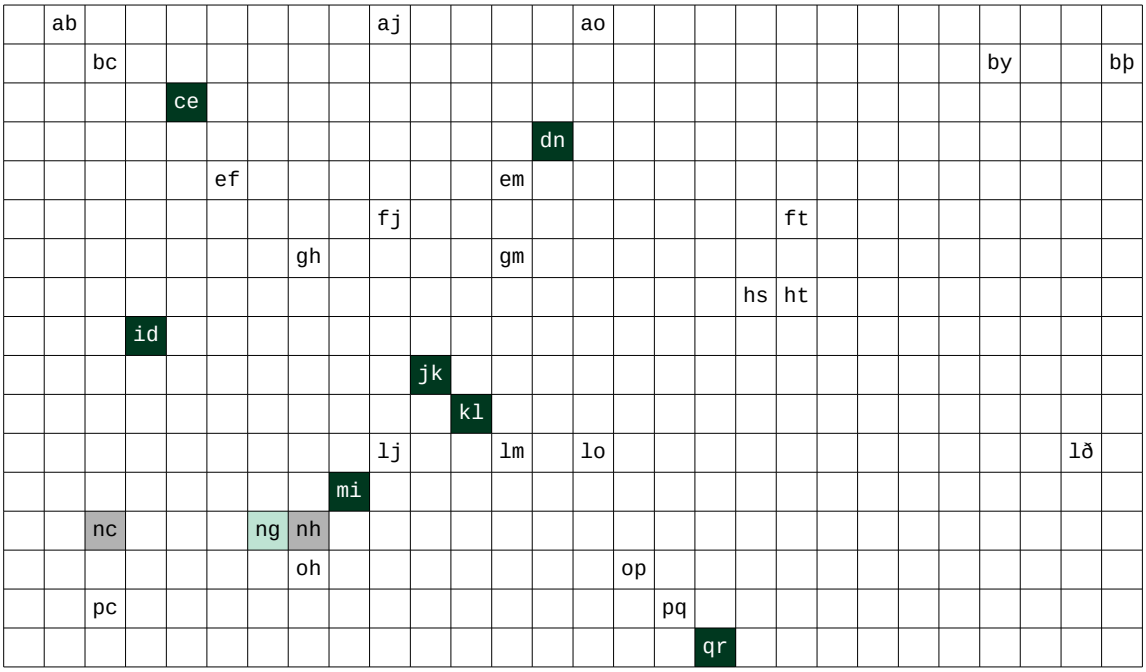


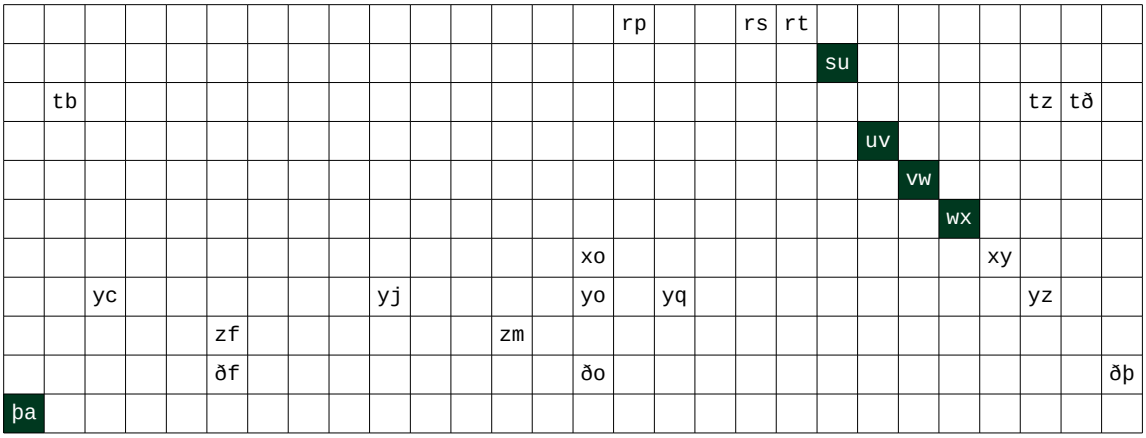
We can add jk, and eliminate je and jh.



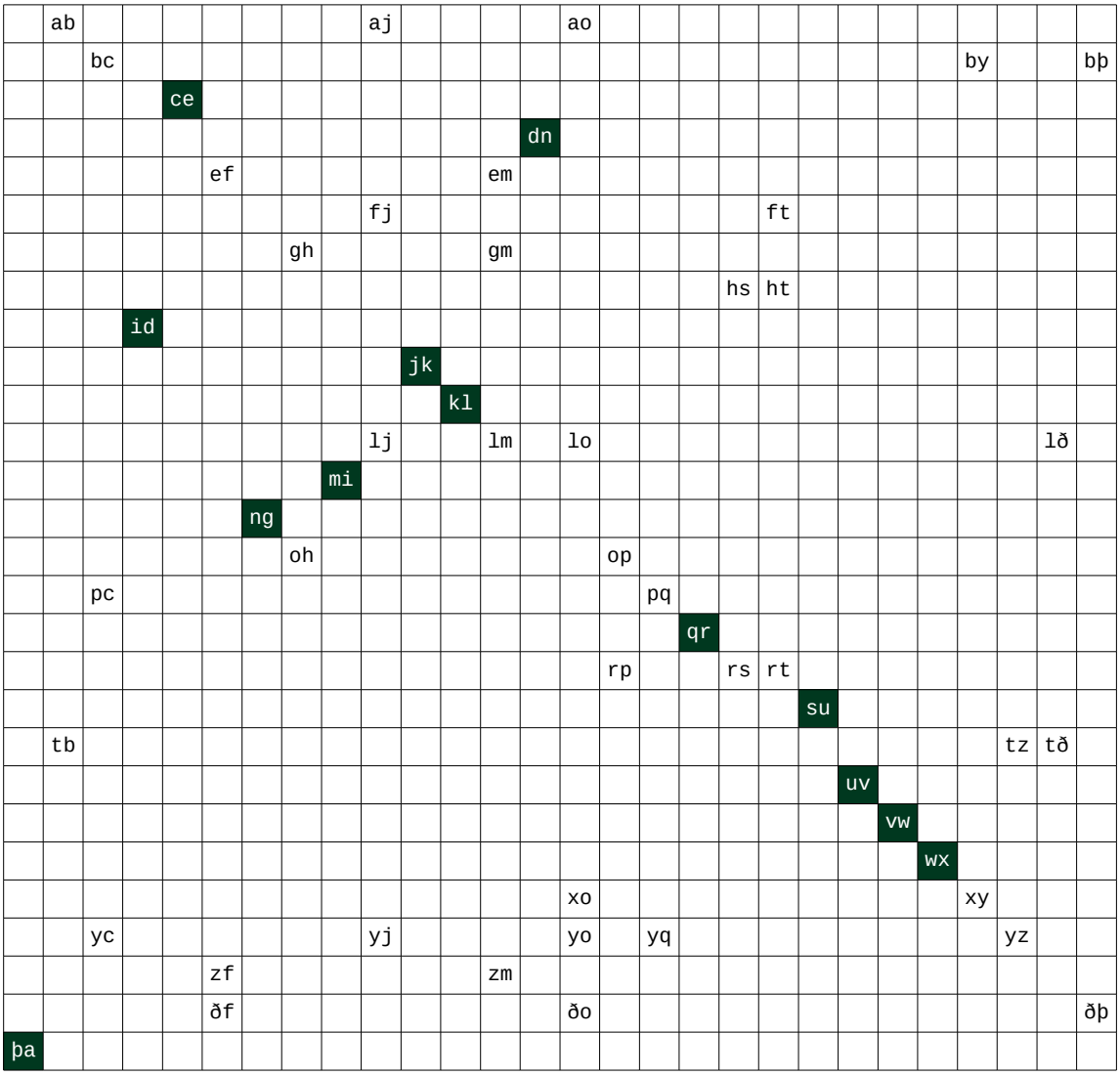


Now we pick up ce and eliminate cg and cy.





That allows us to get ng and eliminate nc and nh.



Looks like we’re stuck. Let’s see what we can do with this list of key digrams:

```
ce dn id jk kl mi ng qr su uv vw wx þa
```

We can get these key fragments:

```
ce jkl midng qr suvwx þa
```

Remember the form of the mixed alphabet. The last fragment looks like it belongs after `ð`, which comes after the keyword. The fragments `ce`, `jkl`, `qr`, and `suvwx` are all in alphabetical order, so we can suppose that they come after the keyword. Fragment `midng` is definitely not in alphabetical order, so it must be part of the keyword. So far, we have

```
...midng...þa...ce...jkl...qr...suvwx...
```

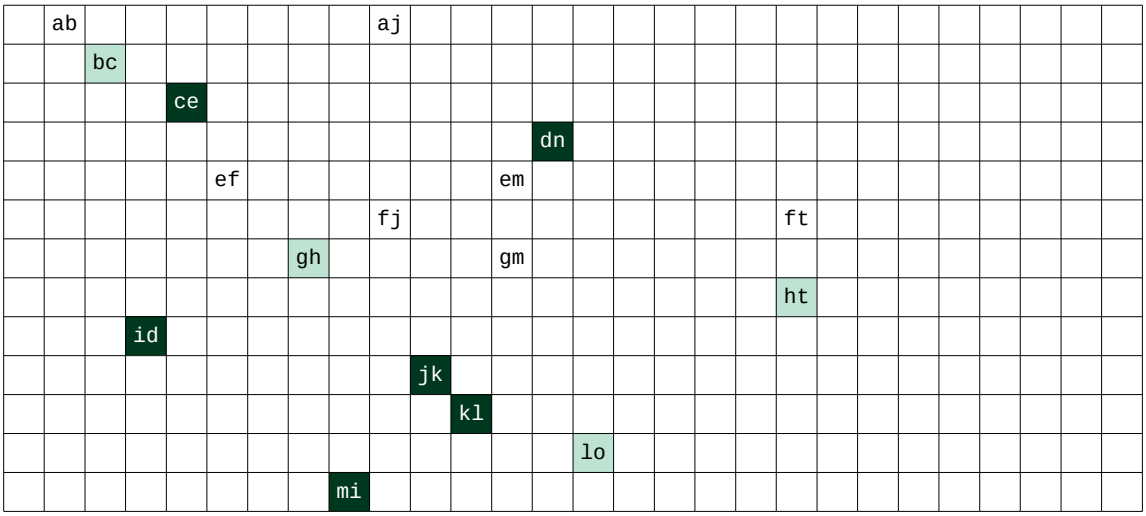
Since `t` is missing from `suvwx`, we can suppose also that `t` belongs in the keyword, but we do not know if it comes before or after `midng`. Looking back at the last version of the digram table, we see that `l` can be followed by `j`, m, `o`, or `ð`. We already know it cannot be `j`. Since `m` is in the keyword, it should not be `m`. And since `ð` comes between the keyword and the rest, it cannot be `ð`. So we can, with good reason, decide to put `o` after `l`. Furthermore, the table contains only `op` and `rp` in one column. So `p` is in the ordered part of the key, since `o` and `r` are. The table also has `pc` and `pq`. So let’s put `p` between `o` and `q`. And in the ordered part of the key, nothing should come between `r` and `s`.

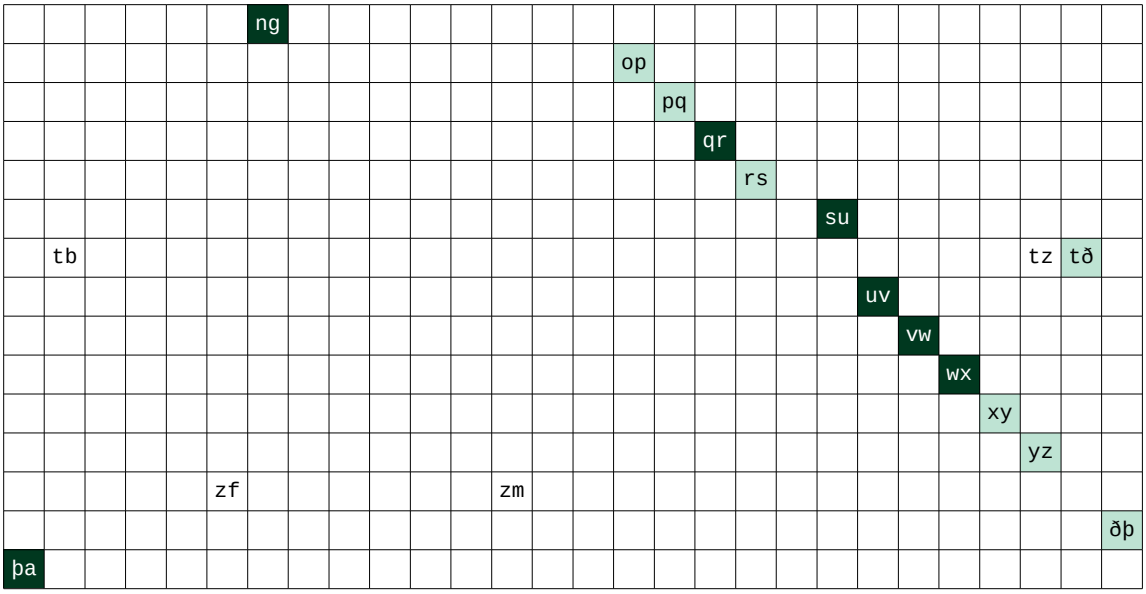
```
...midng...ðþa...ce...jklopqrsuvwx...
```

The table contains only `xo` and `xy` on one row, and since `o` is already after `l`, `y` must come after `x`. But we can’t yet place `z` safely at the end.

```
...midng...ðþa...ce...jklopqrsuvwxy...
```

Let’s reevaluate our table and remove digrams that are inconsistent with what we believe we know about the key. Does this remind you of the game Clue™?





We have some new singles: `bc`, `gh`, `ht`, `tð`, `yz`, and `ðþ`. We can now add `ht` after `g`. At this point we have

```
...midnghtðþabce...jklopqrsuvwxyz...
```

The only letter left to place is `f`, either between `e` and `j` or between `z` and `m`. Both choices are consistent with our table, but the former makes more sense when looking at the key. Finally we have

```
midnghtðþabcefjklopqrsuvwxyz
```

and the keyword is `midnight`.

Now, decipher the ciphertext with this key. The “plaintext” is this:

```
BMFMDABRCDFARKBMFPFIMGQDIGOIORIEGQJBMFPGLQFBDIIRPSGAAPUABHF
GIIRUQBFJGPRQLABBMFPRABBRCBUCFJRKGOORUCFKKRCBABRUQJFCABGQJB
MFRCDLDQARKPGQADPSRCBGQBDQVFQBDRQADLQRCGQIFMGABRRRKBFQHFFQC
FSOGIFJHYIRQNFIBUCFGQJIRQNFIBUCFHYPDATURBGBDRQGQJBMFKGOAFGU
BMRCDBYRKIRPPRQEQRWOFJLFFQLFQJFCFJHYBMFCFSFBDBDRQRKOFLFQJGC
YMDABRCDFAKCRPRQFLFQFCGBDRQRKBFXBHRREABRBMFQFXBDQWMGBKROORW
ADIGQRQOYMRSFBMGBBMFGJJDQLRKGABCRQLQFWBCGDOGQJBMFFCGJDIGBDR
QRKAFVFCGOKGOAFGQJWFGEFCRQFAWDOOOFGJUAQFGCFCBRGHGOGQIFJGQJD
QBFLCGBFJUQJFCABGQJDQLRKPFJDFVGODQVFQBDRQGQJBMFDQBFCIUOBUCG
OBCGQAPDAADRQRKDJFGAKRCBMFPFIMGQDIGOIORIESFCMGSABMFLCFGBFAB
MDQJCGQIFMGAHFFQDBABCFGBPFQBWDBMDQGAFOKIRQBGDQFJMDABRCYRKBD
PFPFGAUCFPFQBDQWMDIMAUQJDGOAWGBFCIORIEAGQJADPDOGCJFVDIFAGAA
UPFBMFQGBUCGOCROFRKGQIFABRCABRBMFWFDLMBJCDVFQFAIGSFPFQBIORI
EDQBMFFGCOYBMIFQBUCYBMDAVDFWPUABSCFAUPFBMGBGLFQFCGOOYARSMDA
BDIGBFJEQRWOFJLFRKLFGCDQLGQBFJGBFABMFDQVFQBDRQRKBMFIORIEGQJ
FXBFQJAHGIEBRBMFIOGAADIGOSFCDRJRKMFCRGQJVDBCUVDUAGQJAUIMGUB
MRCAWFOOEQRWQKRCBMFDCPFIMGQDIGODQLFQUDBDFAKUCBMFCPRCFFVFQDK
```

```
RQFGJPDBABMFUAFRKIORIEODEFLFGCDQLHFKRCFBMFFXDABFQIFRKBMFIOR
IEDBDAABDOOQFIFAAGCYBRORREKRCBMFDQJFSFQJFQBDQVFQBDRQARKBMFW
FDLMBJCDVFGQJRKBMFPFIMGQDIGOFAIGSFPFQBBMFKDCABRKBMFAFPGYAFF
PIRPSGCGBDVFOYBCDVDGOGQYRQFKGPDODGCWDBMBMFCGDADQLRKMFGVYORG
JAHYPFGQARKCRSFAGQJSUOOFYIRUOJAUCFOYCFIRLQDZFBMFSRAADHDODBY
RKUADQLAUIMGQGCCGQLFPFQBDQCFVFCAFGAGARUCIFRKABFGJYSRWFCQFVF
CBMFOFAABMFUAFRKBMDAJFVDIFDAQRBCFIRCJFJHFKRCFDBAGAARIDGBDRQ
WDBMMYJCGUODIGQJSFCSFBUGOPRBDRQPGIMDQFADQBMFPGQUAICDSBARKCD
WQIGGQJDBAUAFDQGIORIEUADQLAUIMGSFCSFBUGOPRBDRQWMFFOPFCIUCYK
DOOFJGAGIORIEFAIGSFPFQBDQBMFGABCRQRPDIGOIRJDIFARKGOKRQARBMF
WDAFEDQLRKIGABDOFIGBMFAFIRQJDQVFQBDRQBMGBRKBMFPFIMGQDIGOFAI
GSFPFQBMGASCFAFQBFJRQFRKBMFPRABBGQBGODZDQLRKSCRHOFPAWDBMRUB
JRUHBBMFICRWQGQJKRODRBBYSFRKFAIGSFPFQBGSSFGCABRHFBMFKDCABIR
PSODIGBFJPFIMGQDIGODQVFQBDRQEQRWQBRBMFFUCRSFGQPDJJOFGLFADBM
FCGOJARUCWMROFGLFRKPGIMDQFPGEDQLYFBQRBCGIFMGAHFFQKRUQJFDBMF
CRKGABFGJYFVROUBDRQRKAUIMFAIGSFPFQBARCRKBMFDCDQVFQBDRQDQFUC
RSFBMRULMBMFGABCRQRPDIGOIORIESRWFCFJHYGWGBFCWMFFOGQJLRVFCQF
JHYGQFAIGSFPFQBODEFJFVDIFMGJHFFQFOGHRCGBFJDQIMDQGKRCAFVFCGO
IFQBUCDFAHFKRCFBMFKDCABGSSFGCGQIFRKRUCIORIEAWFPUABQRWCFMFGC
AFGCFVDAFJABRCYRKBMFRCDLDQRKBMFIORIEGADBMGAHFFQAULLFABFJHYC
FIFQBCFAFGCIMFARQBMFMDABRCYRKLFGCDQLGQJRQIMDQFAFGQJRBMFCGAB
CRQRPDIGOPGIMDQFAGKBFCBMDAWFAMGOOKRCBMFKDCABBDPFSCFAFQBFVDJ
FQIFBRAMRWBMGBBMDAABRCYDAIUCDRUAOYCFOGBFJBRBMGBRKBMFSFCSFBU
UPPRHDOFRQFRKBMFLCFGBIMDPFCGARKAIDFQIFBMGBIGPFKCRPDBAPFJDFV
GORCDLDQBRSOGYGQDPSRCBGQBSGCBDQPRCFCFIFQBJFVFORSPFQBARKFQFC
LFBDIAGQJBMFKRUQJGBDRQARKBMFCPRJYQGPDIADBDAGIUCDRUAPDXBUCFG
OOBMFPRCFARHFIGUAFBGQLOFJDQFXBCDIGHOYDQDBWFAMGOOKDQJBMFPRAB
DPSRCBGQBGQJFGCODFABCFKFCFQIFABRBMFUAFRKBMFPGLQFBDIIRPSGAAD
QBMFWFABDBAFFPABMGBDQCFVDADQLBMFMDABRCDFARKIORIEWRCEGQJBMFP
GLQFBDIIRPSGAABMFAFIRQADJFCGBDRQARKSFCSFBUGOPRBDRQJFVDIFAPG
YSCRVDJFARPFPUIMQFFJFJFVDJFQIF
```

We have to break this text as a monoalphabetic substitution. When we do, the plaintext is

```
THE HISTORIES OF THE MECHANICAL CLOCK AND THE MAGNETIC
COMPASS MUST BE ACCOUNTED AMONGST THE MOST TORTURED OF ALL
OUR EFFORTS TO UNDERSTAND THE ORIGINS OF MANS IMPORTANT
INVENTIONS IGNORANCE HAS TOO OFTEN BEEN REPLACED BY
CONJECTURE AND CONJECTURE BY MISQUOTATION AND THE FALSE
AUTHORITY OF COMMON KNOWLEDGE ENGENDERED BY THE REPETITION
OF LEGENDARY HISTORIES FROM ONE GENERATION OF TEXTBOOKS TO
THE NEXT IN WHAT FOLLOWS I CAN ONLY HOPE THAT THE ADDING OF
A STRONG NEW TRAIL AND THE ERADICATION OF SEVERAL FALSE AND
WEAKER ONES WILL LEAD US NEARER TO A BALANCED AND
INTEGRATED UNDERSTANDING OF MEDIEVAL INVENTION AND THE
INTERCULTURAL TRANSMISSION OF IDEAS FOR THE MECHANICAL
CLOCK PERHAPS THE GREATEST HINDRANCE HAS BEEN ITS TREATMENT
WITHIN A SELFCONTAINED HISTORY OF TIME MEASUREMENT IN WHICH
SUNDIALS WATER CLOCKS AND SIMILAR DEVICES ASSUME THE
```

NATURAL ROLE OF ANCESTORS TO THE WEIGHT DRIVEN ESCAPEMENT CLOCK IN THE EARLY TH CENTURY THIS VIEW MUST PRESUME THAT A GENERALLY SOPHISTICATED KNOWLEDGE OF GEARING ANTEDATES THE INVENTION OF THE CLOCK AND EXTENDS BACK TO THE CLASSICAL PERIOD OF HERO AND VITRUVIUS AND SUCH AUTHORS WELL KNOWN FOR THEIR MECHANICAL INGENUITIES FURTHERMORE EVEN IF ONE ADMITS THE USE OF CLOCKLIKE GEARING BEFORE THE EXISTENCE OF THE CLOCK IT IS STILL NECESSARY TO LOOK FOR THE INDEPENDENT INVENTIONS OF THE WEIGHT DRIVE AND OF THE MECHANICAL ESCAPEMENT THE FIRST OF THESE MAY SEEM COMPARATIVELY TRIVIAL ANYONE FAMILIAR WITH THE RAISING OF HEAVY LOADS BY MEANS OF ROPES AND PULLEY COULD SURELY RECOGNIZE THE POSSIBILITY OF USING SUCH AN ARRANGEMENT IN REVERSE AS A SOURCE OF STEADY POWER NEVERTHELESS THE USE OF THIS DEVICE IS NOT RECORDED BEFORE ITS ASSOCIATION WITH HYDRAULIC AND PERPETUAL MOTION MACHINES IN THE MANUSCRIPTS OF RIWN CA AND ITS USE IN A CLOCK USING SUCH A PERPETUAL MOTION WHEEL MERCURY FILLED AS A CLOCK ESCAPEMENT IN THE ASTRONOMICAL CODICES OF ALFONSO THE WISE KING OF CASTILE CA THE SECOND INVENTION THAT OF THE MECHANICAL ESCAPEMENT HAS PRESENTED ONE OF THE MOST TANTALIZING OF PROBLEMS WITHOUT DOUBT THE CROWN AND FOLIOT TYPE OF ESCAPEMENT APPEARS TO BE THE FIRST COMPLICATED MECHANICAL INVENTION KNOWN TO THE EUROPEAN MIDDLE AGES IT HERALDS OUR WHOLE AGE OF MACHINEMAKING YET NO TRACE HAS BEEN FOUND EITHER OF A STEADY EVOLUTION OF SUCH ESCAPEMENTS OR OF THEIR INVENTION IN EUROPE THOUGH THE ASTRONOMICAL CLOCK POWERED BY A WATER WHEEL AND GOVERNED BY AN ESCAPEMENTLIKE DEVICE HAD BEEN ELABORATED IN CHINA FOR SEVERAL CENTURIES BEFORE THE FIRST APPEARANCE OF OUR CLOCKS WE MUST NOW REHEARSE A REVISED STORY OF THE ORIGIN OF THE CLOCK AS IT HAS BEEN SUGGESTED BY RECENT RESEARCHES ON THE HISTORY OF GEARING AND ON CHINESE AND OTHER ASTRONOMICAL MACHINES AFTER THIS WE SHALL FOR THE FIRST TIME PRESENT EVIDENCE TO SHOW THAT THIS STORY IS CURIOUSLY RELATED TO THAT OF THE PERPETUUM MOBILE ONE OF THE GREAT CHIMERAS OF SCIENCE THAT CAME FROM ITS MEDIEVAL ORIGIN TO PLAY AN IMPORTANT PART IN MORE RECENT DEVELOPMENTS OF ENERGETICS AND THE FOUNDATIONS OF THERMODYNAMICS IT IS A CURIOUS MIXTURE ALL THE MORE SO BECAUSE TANGLED INEXTRICABLY IN IT WE SHALL FIND THE MOST IMPORTANT AND EARLIEST REFERENCES TO THE USE OF THE MAGNETIC COMPASS IN THE WEST IT SEEMS THAT IN REVISING THE HISTORIES OF CLOCKWORK AND THE MAGNETIC COMPASS THESE CONSIDERATIONS OF PERPETUAL MOTION DEVICES MAY PROVIDE SOME MUCH NEEDED EVIDENCE

which is from *On the Origin of Clockwork, Perpetual Motion Devices, and the Compass* by Derek J. de Solla Price. The key for this substitution is

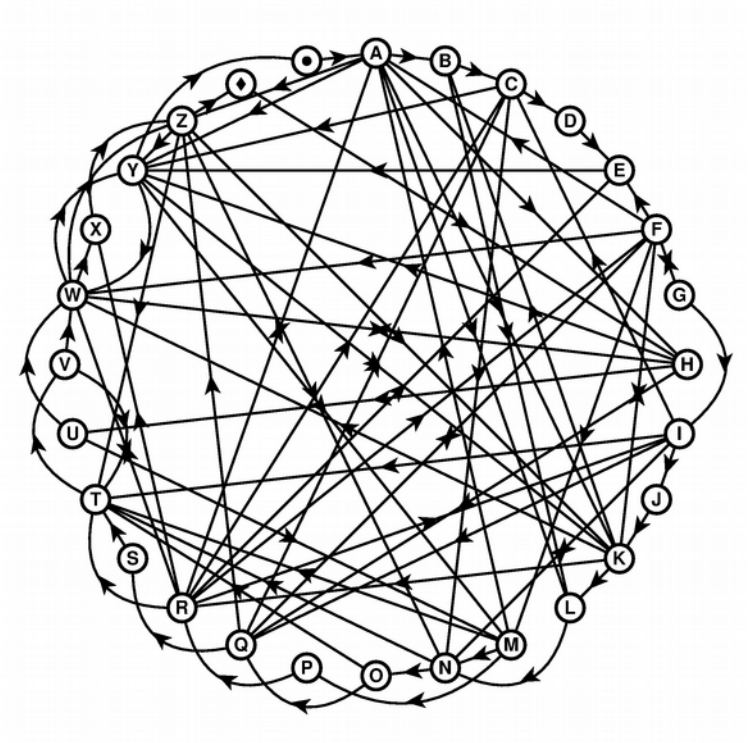
GHIJFKLMDNEOPQRSTCABUVWXYZ

If we invert this key, we obtain the mixed plaintext alphabet:

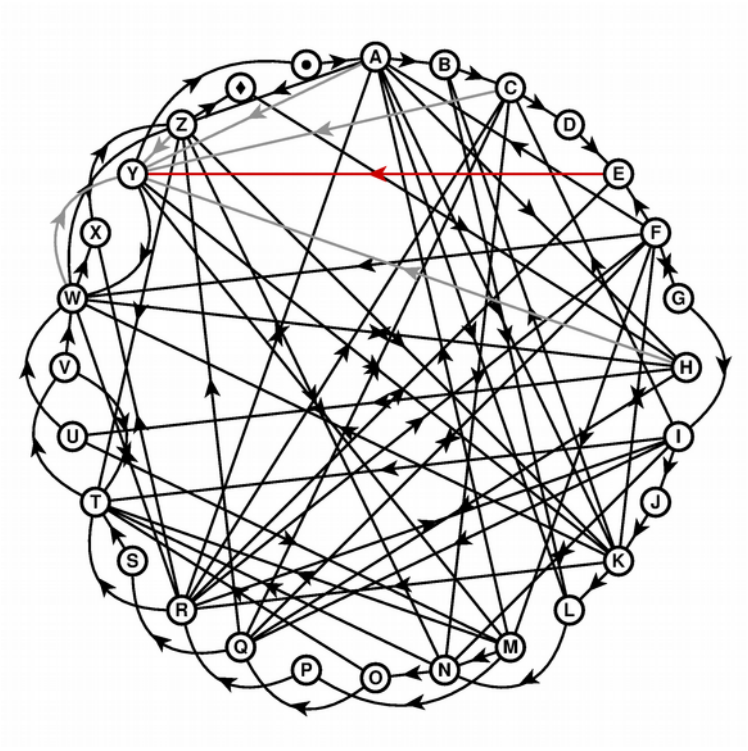
STRIKEABCDFGHJLMNOPQUVWXYZ

When working with pen and paper, it may be easier, especially when $n=m+2$, to do this attack with a directed graph. A *directed graph* is a graph whose edges are directed (have a direction). A *graph* is a set of vertices and a set of edges. A *vertex* is a point, but it can be drawn anywhere; we don't care about coordinates in this kind of graph, and vertices can be slid around on the page. An *edge* is a line from one vertex to another. In a directed graph, each of those lines has an arrow on it to show its direction. Think of a map in which cities are connected by one-way roads.

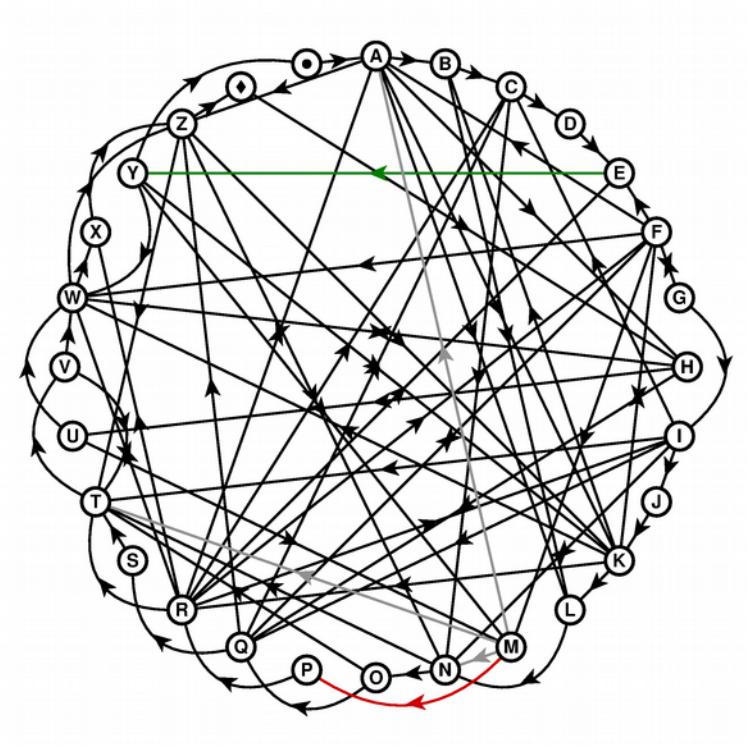
Let's redo the first example with a directed graph. If we take the reversed missing digrams and use each to define a directed edge, we have this graph:



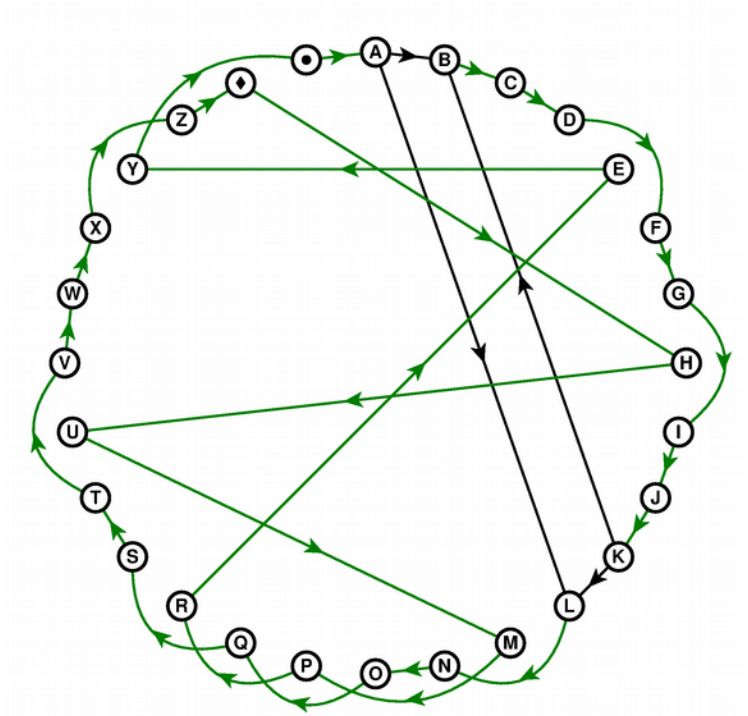
It is quite a mess. But notice that E has only one line directed outward from it. That line ends on Y. Since E must come immediately before Y in the key, we know that no other letter comes immediately before Y, so all other lines that end on Y can be removed.



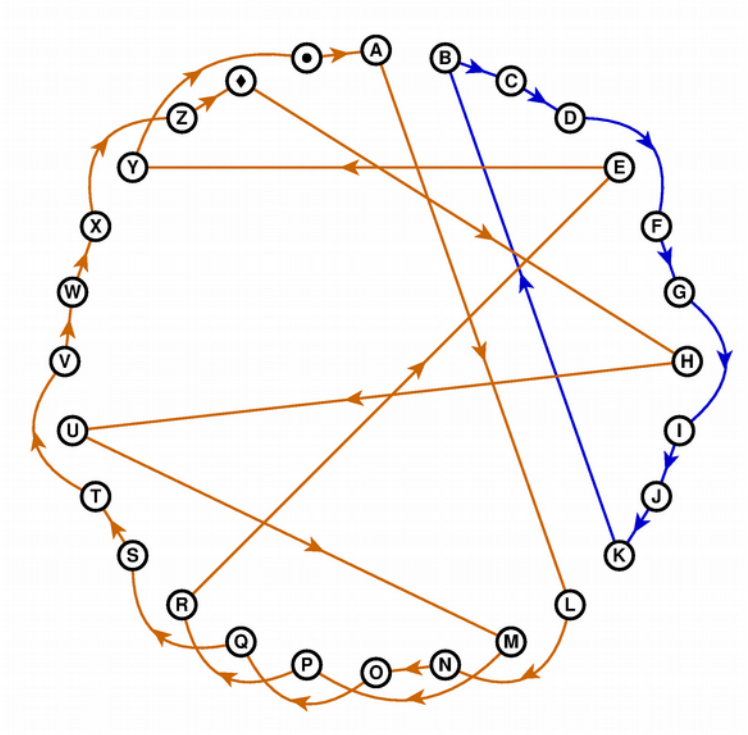
Also notice that `P` has only one edge that ends on it, from `M`. Therefore all other lines that start on `M` can be removed.



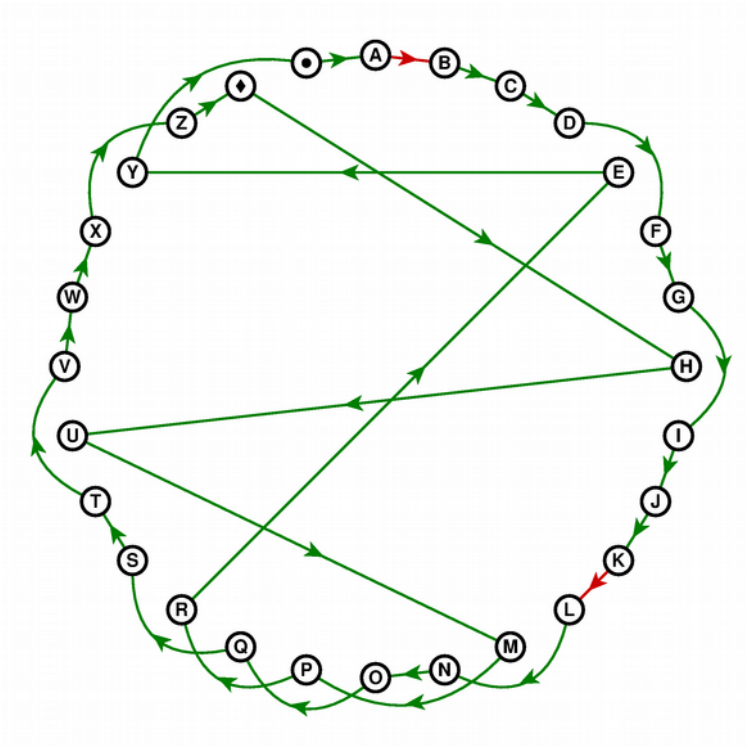
After a lot of this sort of work, we eventually get to the following graph, in which we can make no more eliminations. Did I say “pen and paper”? I meant “pencil.” The kind with an eraser.



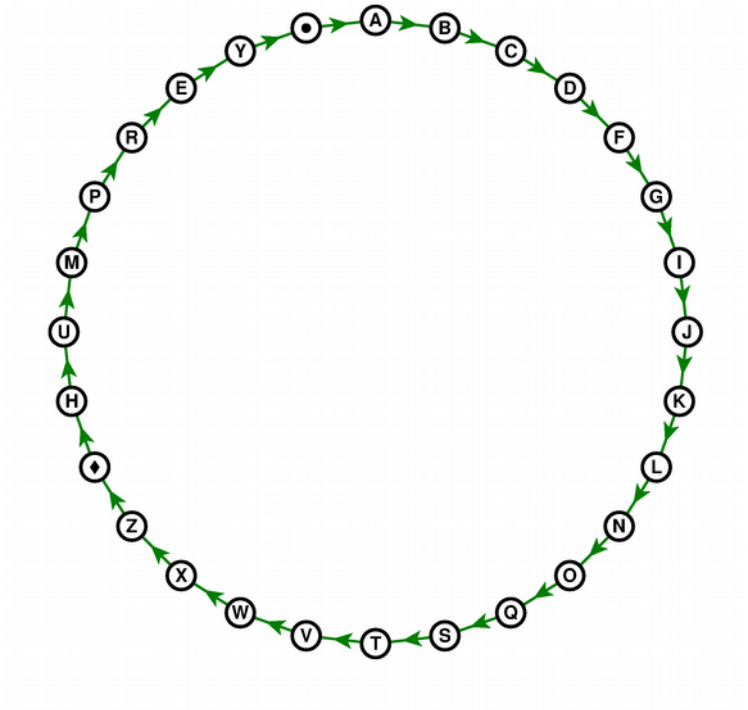
At this point, we have a choice to make. Either we keep A to B and K to L, or A to L and K to B. If we choose A to L and K to B, we see that the graph has two separate circuits (loops):



We can’t have two loops, since we want one key to fit on the outer ring of the cipher clock. With the other choice, we get that one loop:



If we untangle the graph (remember that coordinates of vertices don't matter, and so vertices can be slid around), we see the key just as it would be set into the ring of the device:



Programming tasks

1. Implement the attack in the case $n=m+2$. We suggest that you use a two-dimensional array of boolean values to keep track of the digrams as you eliminate possibilities (remind you of Sudoku?). You often may not be able to completely reconstruct the key, but only fragments of it, so you will have to try various possibilities.

2. If you are so inclined, extend your attack for $n=m+1+k$, with $k \geq 1$. (It will become obvious why we write it that way.)

Exercises

1. You know what to do.

```
BT2QLFQDZSUYQBKQROWL1YFEZFOU3SEDPYFIA1XADSLHWZACIDGLVZ
DFMEJT3PXZPH1TC1GTIV2FOQHEYAQVD3JWYM2UX3KEZPGVQC13QVBM
VPGUKMLZLFJBLG1MQROSIW1BVNCMEUXLDXCO2BYDBCREZVZUJMLHZF
DACID2XGAXH2KIRLXJGSVOET3NP1ROWFHZIG2TWLPOULTMPYRNATJ2
AYJE2CXBSFLSVODFTENRZPO1SWR3YKTF1MG2IAHUNPYI1KBH2DJVA1
RACWSWU2NCIRB1GB1BVOWPL2GZLYP1S2RUMPQG2MCXKGPUFTXPOUAJ
FYMNUFR2BPYMLHJQMYAKZBCZJKBJ2RLYJUMTMQSVGYQRWFLC3KSWEJ
RUXRZCMD1QW2T2XWUEM1HMTF3BF3FYLSAKPUKCE1UYLGVNBQVGORJT
CUSWEJSWLMI3SEKV2G2W2AYDNQFUQVIL2QTHOZ1C2UM2VDTAROFXC2
JCWAQAIAREY2GCZLHT2DRWLRORCHMFYATFEVPKTDNX23JVNLFSEXMB
JLJSYCTPUHWBUPH12Y1CAORSWTJMEHI1AC3B3FLIROPQKSUNDZMCVY
1STBQTWB2QFIPBPROHUEZRNCU3AI12YQAWHOUJ1UXMA3JMZLYCERWZ
LYP1SUYVOMUL3YBKPTCWXP3SDCKVJCXYC3J1QWNI12DUROYNRGISMX
23JVNLFSEXMDUPBC2KGPUEZFD3LILBLJNTLXSYM3UIABVCLYCE2DIP
FDB3NVRKMZNGOZCUGPEILZD3IOSKIVNZSGTJKRCFYDABUG1BZTKT3B
ECNUIDQFPDPU1HVRXJEDYWPOM13WJ1QW2TLSKZNUH2NCJMKQITIRBK
MLZ3AF1EIUVDXQ1AMSTOR2MNBVNCMERTXANPI1CZBPXETYZMBUEXEC
HI1JAY1GB1IEGKTDNJ3KBH1SCZPDIKHKOBYIEZFD3NJHDV12UWCROL
GUJAUWRAY1MTGITJES2RLYAUM3CZMB3OVRXJEBCZLHMVNC3FOZQ2TF
1UJQVI3WM3AXTLDBPJUKTIZMC1TNQXWDMYDWPXMGA1EZFD3JFGTV2G
2W2AYJENMB3MZBOQJ2RL3WHUACEDVDMRN2WLKWHKPVSWVBKMOY2CDB
DC2BZO3HI1JA3JBOLGUVKIMOWQZFKUKTLY1OVIJ2MBC3G2IANSLRTB
QYC3TWDWXJSB3M3QFTGBOWPL2F1CUXIAYT1P2IRA2J2PTCSZVNUJ1M
KQOMZRSWPQEGJATUIRAPGCLXZPF2RFXYULGMYAQVQMFOQR2KEGVZEF
TXZNW3DKQR12LHYMNUER2BPYMRHQEM3A1FEGHGL2GHZPO1SCZWBEJ2
MBEHDXYWRUNJPSL1PLBZ2TWSGXSHJQYVKAOFYBOAFTUVKI3OWZ2NOF
J3UYGLB1STLV2RBKMCWDRMTUQTKQLCGTDYPYOEKY2QSFGRLQWECFPE
S2GRZEMX23INCTUOVMD3FWXFHZ12DSGNYG2QYLMVOHTF1UHJVIEMA3
ULQGNSUPNXWJUNFSYRGIMD3FKJZSWEBL3T3KINYMNZKBRACRTZBXLU
2YKACK1LYCERWZ1J3UJTA1WBEIYTZI3GVFWGO1R12BGVDZSWZNUH2Y
IDYSYWVBMHZFKUH2VMTJOLSBWP2IWUDGLQOF2KVIDRBYSHOWF3KAX1
D1HGKEQUGHI3PWVLSDWYKDI3OFOQHEY1QNPS3KI1DCZOLBXFRTCHWP
XOX3SCLQ3JLYCE23TNJYN1SBLTRMBYIEZFD3QOZGVHJER2WPZGLHI3
1B1FT1LERPXNH2FIREFAUCEFOSILSJGHDXZFNO3RD3KI2UWRVQHJXL
```

HWRIDHMYZ1LSVOVAWZM3YGLUMNSFOQH1CWRUNCT3JFKVXYHDNCGSHN
ZNB3MUROQD2RL3U1TACZMNLILSJG2JRANWDUYLOFYMRATCHUSUDLUE
MAYGZXWBES2IOXJKYQGP3RFNOC2GVKCXWLQ3NACXLI1CKIOYKSWPVO
EJETMA23GYZLEVGKSIZOYHUGZXMDUHOBKMCW1BPFOYROYF1POTHWRI
DFEVYCUKMRKGRZKF3IUDGHSWR3TIJFMTMICXAQLD3JWYCGZROZNAEQ
CSYA3JBOWRP3PNCPXCLTVYQWUILSJGUCLUDTU3RS2MYAPZNTWXADJR
KQOCNPFLQSYFQJ2IOXJKYQVPLDUFTZBYUCWGO13H2AKVXGRTCXWAZP
1QCJSJHBVGPWE23HKXYIUH23BQDNDJLT1XGP1EZFD3JFGTVBZB2LTJ
ETFNAQ2DSBWUXR3KCNXZSUVDQSES2TPLFEQRCMEJYWERXB3EAXO3VX
GYRFZDXJYMABTRLGPSEIKTGFNXWIUIOC1NPDRZBFKJPNSDZAE3NY1P
L12FZSNPGX2QCLPQBJLIXODNBHZ2R1G3AUVHSESGTLAJL1KRH1EGNW
RWTLQUDFOVP3XWPSUEGMX3HOWF3KAYGZXOVAWZB3HNX3ROMDUVWFTN
BIYUCWE3NBKUDFOVXTFXNUDQKNQCPSEICLEYOTBEDRZ1CND1FSTVAW
GEIJFNORIFWL2CT3VDQWVBKILBDJMEHWRIDFTAXOZABNDZEMXDVNXQ
VHPRDZBFPC3KGAUBW1DTU3KINYWCIOSDWBQ3JK1CWI1LDHMYQOUXPJ
FJPIUFEQRGMD3FIPBM2HCWBUPH12BGVMKTGQGXK1CFYHDCMZ12VLNJ
NWZPO1SCVKTEP3KPBHAUEZFDM3JFGTVDAMZR2WPGVQC1TGTBOQD2FN
JWZNTLQROSIVWFJCUSCGNO3SMZBJOITKECFGCKS3EHI1JAQ2D1HGKP
RGF1JUXOBHGOEY1RIV2WLKWVHU2EFTXWPDKRTMLBKTJ1L3SHPFD2DK
HIPGKWHMNBQZB3VFIAVMDUPTKB3NBFPKJYHRMT3RHA2TIXGJPVZNSH
DS3I2DGYBOUVRWR3L3ZSHVDAYPHXUEGACZTYVNUGOYNCZJCRLVJETM
A3FRBXEQRE2IPZPO1SDKPRTIGSJ2HEDSWHPOAL1HNVI3XPDGMWHUOC
PZ3UFAOL2KTDNXBXOYTAV2JWNBYUCWRG3SEKVPKBXAPRUZNUHU1CNP
FLQFLOCNXBHUEYA1SYJ2FOQHETZFDST3KQOYPHZ1HNPGKHZMB2KYBO
VAWZKEMPYAY1SEXMDUPB3KAZEDYWHXNOQMQHZ2W2HTUEVP3SIEMKA3
JBOMERGKEYAUVDXQAXRFYCPXPFNHQA3MHTKIVOGXBXQDSLHWRIDGVT
WTEJT2FIREFAUVDXQNP1RWFTOB3VER1DFNDKRDKIVIDRLRDSWGQCFI
FKYEYGJ2

Unit 123
Hill-climbing attack on cipher clocks

There is a hill-climbing attack that we can perform on a ciphertext that was encrypted with the Wheatstone Cryptograph. It relies of the fact that we can factor the Wheatstone cipher into one with an unmixed ciphertext alphabet followed by a monoalphabetic substitution. We therefore start with the attack on the monoalphabetic substitution from Unit 28. To avoid becoming trapped in a local maximum, we need to use a margin of error that allows downward steps some of the time. We must build a new tetragram-frequency table, which will be built from a large text enciphered with the Wheatstone using an unmixed alphabet. Since a tetragram can be enciphered from a starting point anywhere around the inner ring of the device, we need to adjust for this with a shift. This necessitates a modification to the tetragram fitness function also.

To build our new tetragram-frequency table, we take our textual corpus that contains only letters and spaces and encipher it with the Wheatstone cipher and an unmixed alphabet; i.e., the keyword is “” (an empty string) or “A” or “ABCDEFG....” The resulting ciphertext contains only letters. We run through this ciphertext and look at each tetragram. We shift each tetragram with a Caesar shift so that its first letter is ‘A’ before we count it, to account for the fact that any given tetragram from the plaintext can be enciphered beginning from any point around the inner ring of the device. Because of this shift, the table with have 26^3 entries rather than 26^4.

Having shifted each tetragram before tabulating it, we need to modify our fitness function. It must now run over a text and for each tetragram in it, shift that tetragram in the same way as above, so that its first letter becomes ‘A.’ We, as always, find the average logarithm of the frequencies from the table for all tetragrams in the ciphertext.

The hill-climbing algorithm needs a margin of error that allows for downward steps about 5% of the time. A good margin to use is δ=0.1. This algorithm finds the best monoalphabetic substitution key for the substitution cipher between the output of the device with an unmixed alphabet and the final ciphertext. Since we found this key by shifting every tetragram so that its first letter becomes ‘A,’ the key is likely to be a rotated copy of the true key. In the example that we looked at earlier, the key was

```
WBPHCQEDRAFUTGVSIXJYOKZNLM
```

We can expect that the attack will find a key such as

```
JYOKZNLMWBPHCQEDRAFUTGVSIX
```

which, as you can see, has been rotated right by eight places. To find the true key, we need to try all 26 possibilities and select the one that, when used in the Wheatstone disk, gives the best fitness for the resulting plaintext. Note that here we are using the unmodified fitness that we have using for other ciphers. Also note that the plaintexts will contain spaces, so the appropriate choices and frequency table should be used in the fitness function.

Here is the full algorithm for the attack. Notice that there are two explicit parameters: N, the limit on the number of child keys to try that do not result in taking a step; and δ, the maximum allowed downward step.

1. Set the parent key k_{parent} equal to the unmixed ciphertext alphabet
2. Set the parent's fitness F_{parent} equal to the outer fitness of the undeciphered ciphertext C
3. Set the counter to 0
4. While the counter is less than N...
    a. Increment the counter
    b. Set the child key k_{child} equal to k_{parent}
    c. Swap two randomly selected characters in k_{child}
    d. Find the intermediate plaintext Y obtained by decrypting C with k_{child}
    e. Set the child's fitness F_{child} equal to the outer fitness of Y
    f. If ($F_{\text{child}} > F_{\text{parent}}$) or [($F_{\text{child}} > F_{\text{parent}} - \delta$) and (we roll a 20 on a 20-sided die)]...
        i. Copy k_{child} into k_{parent}
        ii. Copy F_{child} into F_{parent}
        iii. Set the counter to 0
5. Output k_{parent}

An attack on the Wadsworth disk is similar. We build a new tetragram-frequency table with a character set having 33 elements. However, we also need to add a modification to the algorithm. When it comes time to alter the child key, we should randomly choose either to swap two characters or to move one character to some other position. In the algorithm above, we replace step 4c with

    c. Flip a coin...
        i. If heads, then swap two randomly selected characters in k_{child}
        ii. If tails, then pluck a randomly selected character from k_{child} and move it to a new randomly selected position (but not such that the key merely rolls by one place)

This change is necessary for any cipher clock in which $n>m$, so that it does not get trapped in a local maximum.

Reading and references

Thomas Kaeding, “Automated ciphertext-only attack on the Wheatstone Cryptograph and related devices,” Cryptology ePrint Archive, report *2020/1492*.

Programming Tasks

1. Implement the hill-climbing attack on the Wheatstone cipher. Start by building a new tetragram-frequency table, as described above. Make a modified fitness function. Copy and modify your attack from Unit 28 and add a margin of error for downward steps. Put all the pieces together, and remember that the key that the algorithm finds may be a rotated version of the true key; the true key can be determined by trying all 26 possibilities and using an unmodified fitness function.

2. Implement the hill-climbing attack on the Wadsworth disk cipher. Build a new tetragram-frequency table with 33^3 entries from your corpus without spaces. Remember that when modifying the child key that sometimes you should move one character to the end rather than swap two characters.

Exercises

1. Break this ciphertext with a hill-climbing attack. The cipher is Wheatstone’s. Reconstruct the keyword.

```
BLBHXJISCNUKSDCJUEGCWVHFWIKEVCGVLWPNLORQBEPIJNMQIIOZCV
ERRIFXQWXEPRIKYPYZUVKUXEBTBCHPOKSQLCRWBJQEPZOZDPBUAIDA
CCSWOLGDROIQOVSCSTHSHDXLJAKPKDZLVFEQJPNZYVMCVPPOSASPFG
IDDVXIUAMGAPAOCXIWTMCDJTIYKBWXMQKRGTXJORMGZNTMBTJNOBKN
CVZNZIRMLHRIWCWYZKUTOWJRXTEWLZHZYMDJGFPNICFLJZVUCYHEPO
THHRNNSHFHCVUQEMVGFBQWFOTAQOXEELDYGFTDOGSMAQORPZMDBJUG
AXMOGAWITYNPVPIXJENNMTSEVICFWOGHJWLOAJDCNHSLDBJUGACFII
HWWFYBCYRVIDEINNMTCONIFWAQILOXSRXGIKMQSYYRAZSPLKUGLDUJ
LMLOKTLYLUABEHTAOQULWBQWASJAEYGIWYZSJGEAGXZQFEKKTGIVXT
QNEUCRAEVHZKPNIOAJDCYGDNDTJFQPKJJYTNUAUXLDJNKPXSWJAUAX
ISMEZKKZWQIORLQBRRCIAXMGEGCPAFKKTEMQVWWMAWQQMACQXEGBNC
GCXFRULJOAAMPSGI
```

2. Break this ciphertext with a hill-climbing attack. The cipher is Wadsworth’s. Can you see the keyword?

```
27FWH46PQO2IYLZDT5XH5NS8CMCWSPVX23XK8IAMRTXTGRV45YZOGN
ELOL3IO7P8UYHJAKQW8BNV8EOKPQRTQG5MOISESKNV8BVBABRTQHKU
E38NUZE3PEFXOEW8QT4MAEUTU7ENZN6JMPHX57AQGKM6VYZ3YTL4E3
4CTBW7KNQ2Y6MO2J24IOTHEQT6YOUDLOL3L7Q3CKTMW8M5W47ANPRC
VKY5ERKMNVD8J2I4KALU8Q2YCAOM3IQSCWRLRKBX8DO4W3KRC2UDRT
F2WD4AT37LORP4YAGUO45A8USCZ5C2ACJH38CFQV7UBEIJNY4EONSV
OFOLOQXCGW7DRCWJTBFKQ7PHX7OT6LQVRHMTPU3YBIL5DSBHGZNA8I
```

```
5UGIZ8GRV7KD3J6EW5U6WLBAJAEFOK8FATNPQYOCL4M67U2NU4LTZK
DJ6NTF2Z3IJ278GNTVW4SRBF2PXBCOHI3MTJZ6A8NY5IJV7PTKM6M3
Y3BUEI2V4W5SVZIA8GQCQUZREM5ACT8YBHYJ3L7J4AD8DGJKZHM6XR
2LSPVGSE2J5FDE3NBAGRQ67IWCYI4VJ5WOUYJ3L7EKUTBIZNALURGO
7GWLMWTN27FMRU3JZJHV8KD2I2JS3Y6QEY4NTH5EVSLCNUX5PRCX3X
YSU34I7LUFP5BIP8XCL8ZMT6O
```

Challenge

```
ILCYRCVHRNFYTEJERTYO_*JEWIBDQZGHPX_CZWORCAZOFJQJGXEP_DIR*_Q
YDG#JUM*QAMISUODBDMOUHKWBDRZNYLV_AJTK*VRHM*EVHSLNZ_DOQJTI*U
H*VMNLZOBYA*LAPWIUPTCXO_JDB*KWLTKUMXHSLUDERAVNL*SZQ#UIRBQAM
XDJERL_RVRFIXAJRCMXDP*_DNYAOVRPXRXMSY*_HCUMI_IOUWKAUIHBPTSX
OXOCEXOAFKWBDRZMYELC_*QCLOUHREHQIYUSRCESRPG*#HDWSB_IZCVJTCH
CLMIRPIKWOXDPIOXEMVJ#WOVMPRHIMHFGTBSDCY*QE#U#E_MRNWMSUOB#MO
ULRFI_FREZNYLVHYWCUQHKYAZGQN#CATMGYNOJUGHT#UMTFDCOI#OVRKEPN
#RHXJ*DUBVODRHWRXHTESLUDERAVNL*_HYOCZRBGI#QCGCNQUOHJYKZBEJZ
FVXMIAL*#GAOXM_PFEBVFGXBSDC#IBYOBUVRKVDODOU#W_BYAZ*NJEYS#AR
OXJ*DLKR_OFVWE#M#PVJYEV_K#FA#YRFYT#JEZBDMFKSCJL#DJIXG*UWYZH
IOKNREPZKFQYEAWHZBQCGODTSIW*#VYRFSODK_VYTC_BXJNRHABU#_*OXEM
HTVYKIOQNDWMXA#LBCPQOQKPMKOZRBZDTDOQGHYJ_ZFAOSKZPFVDCMYQCUL
MECE#BVBGEXFIT*QE#U_CUMQ*IOXGNF#_Z*LPMIC#N*SPK#LKQHP_PVPIFG
IAUESBLNPE_TEMJOYBUW#VGPV*QZSM#GJPQKVBVN_AUALAPWI_VPGEMOGYQ
CLOBRKFHL*YR*SME_KODRIZLZ#SRUWF#EXM#GKOWM_*TKMQYS#EUCGXMIYF
WO#MENHXRUJSRCERLE*IFJ#_
```

Unit 124
Cylinder ciphers

The first cylinder cipher is the *Jefferson cypher wheel*, invented by Thomas Jefferson. It had 36 disks, each with a mixed alphabet of 40 letters printed around its edge. It was intended for the encryption of French correspondence, since French was the language of international diplomacy at the time.

Somewhat later, Bazeries reinvented the cylinder cipher, so it is sometimes called a *Bazeries cylinder*. His had 20 disks of 26 letters each. The key for this device is the ordered list of the disks on the cylinder. Bazeries proposed a method for deriving the key from a keyword, and this method was adopted later by the United States military (we explain it below).

Bazeries cylinder. Photo courtesy of Étienne Bazeries.
The cylinder is set to encipher the phrase “I am indecipherable.”

Below are the mixed alphabets on the disks of the Bazeries cylinder (the French have no need for `W`, it seems). Notice that many are built from French phrases.

disk	mixed alphabet
1	`ABCDEFGHIJKLMNOPQRSTUVXYZ`
2	`BCDFGHJKLMNPQRSTVXZAEIOUY`
3	`AEBCDFGHIOJKLMNPUYQRSTVXZ`
4	`ZYXVUTSRQPONMLKJIHGFEDCBA`

5	YUZXVTSROIQPNMLKEAJHGFDCB
6	ZXVTSRQPNMLKJHGFDCBYUOIEA
7	ALONSEFTDPRIJUGVBCHKMQXYZ
8	BIENHURXLSPAVDTOYMCFGJKQZ
9	CHARYBDETSLFGIJKMNOPQUVXZ
10	DIEUPROTGLAFNCBHJKMQSVXYZ
11	EVITZLSCOURANDBFGHJKMPQXY
12	FORMEZLSAICUXBDGHJKNPQTVY
13	GLOIREMTDNSAUXBCFHJKPQVYZ
14	HONEURTPAIBCDFGJKLMQSVXYZ
15	INSTRUEZLAJBCDFGHKMOPQVXY
16	JAIMELOGNFRTHUBCDKPQSVXYZ
17	KYRIELSONABCDFGHJMPQTUVXZ
18	LHOMEPRSTDIUABCFGJKNQVXYZ
19	MONTEZACHVLBDFGIJKPQRSUXY
20	NOUSTELACFBDGHIJKMPQRVXYZ

The *M-94* (also known as *CSP-488*) was a cylinder with 25 disks. The disks of the M-94 were identified by a number or by the letter that followed ‘A’ in their mixed alphabets. Here is a list of them. Notice that disk 17 begins with “ARMY OF THE US.”

disk	mixed alphabet
1 or ‘B’	ABCEIGDJFVUYMHTQKZOLRXSPWN
2 or ‘C’	ACDEHFIJKTLMOUVYGZNPQXRWSB
3 or ‘D’	ADKOMJUBGEPHSCZINXFYQRTVWL
4 or ‘E’	AEDCBIFGJHLKMRUOQVPTNWYXZS
5 or ‘F’	AFNQUKDOPITJBRHCYSLWEMZVXG
6 or ‘G’	AGPOCIXLURNDYZHWBJSQFKVMET
7 or ‘H’	AHXJEZBNIKPVROGSYDULCFMQTW
8 or ‘I’	AIHPJOBWKCVFZLQERYNSUMGTDX
9 or ‘J’	AJDSKQOIVTZEFHGYUNLPMBXWCR
10 or ‘K’	AKELBDFJGHONMTPRQSVZUXYWIC
11 or ‘L’	ALTMSXVQPNOHUWDIZYCGKRFBEJ
12 or ‘M’	AMNFLHQGCUJTBYPZKXISRDVEWO
13 or ‘N’	ANCJILDHBMKGXUZTSWQYVORPFE
14 or ‘O’	AODWPKJVIUQHZCTXBLEGNYRSMF
15 or ‘P’	APBVHIYKSGUENTCXOWFQDRLJZM
16 or ‘Q’	AQJNUBTGIMWZRVLXCSHDEOKFPY
17 or ‘R’	ARMYOFTHEUSZJXDPCWGQIBKLNV
18 or ‘S’	ASDMCNEQBOZPLGVJRKYTFUIWXH
19 or ‘T’	ATOJYLFXNGWHVCMIRBSEKUPDZQ
20 or ‘U’	AUTRZXQLYIOVBPESNHJWMDGFCK
21 or ‘V’	AVNKHRGOXEYBFSJMUDQCLZWTIP

22 or ‘W’	AWVSFDLIEBHKNRJQZGMXPUCOTY
23 or ‘X’	AXKWREVDTUFOYHMLSIQNJCPGBZ
24 or ‘Y’	AYJPXMVKBQWUGLOSTECHNZFRID
25 or ‘Z’	AZDNBUHYFWJLVGRCQMPSOEXTKI

The key for the M-94 is a list of 25 disk numbers, indicating their order on the cylinder. As we mentioned earlier, the key can be generated from a keyword. The procedure, taken from Bazeries, is as follows: First, write the keyword as many times as necessary to have 25 letters. Then, in alphabetical order, from left to right, number them. For example, if our keyword is CYLINDERCIPHER, then we proceed as below. Since ‘C’ is alphabetically first, we number the ‘C’s first. Then the ‘D’s, etc.

C	Y	L	I	N	D	E	R	C	I	P	H	E	R	C	Y	L	I	N	D	E	R	C	I	P
1	24	15	11	17	5	7	21	2	12	19	10	8	22	3	25	16	13	18	6	9	23	4	14	20

The key is 1, 24, 15, 11, 17, 5, 7, 21, 2, 12, 19, 10, 8, 22, 3, 25, 16, 13, 18, 6, 9, 23, 4, 14, 20. Notice that the lowest number is not zero.

To encipher a message with the M-94, the 25 disks are placed on the cylinder in the order given by the key. The message is broken into blocks of 25 letters. Each block is enciphered by rotating the disks until the block is written in a straight line down the cylinder. Then, some other line of letters is taken as the ciphertext block. It is required that that line not be immediately above or below the plaintext on the cylinder. The offset between the plaintext and ciphertext lines should change from one block to the next in some random fashion. This makes the cipher probabilistic, but also makes decipherment nondeterministic. During decipherment, since the offset is not known, we must choose the best line on the cylinder.

Let’s continue with our example, and encrypt the message

THIS MESSAGE WAS ENCRYPTED WITH A CYLINDER CIPHER

The first block is THISMESSAGEWASENCRYPTEDWI. We line up this block on the cylinder by rotating the disks:

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

P J C W Z Q T W T K O F C N F V Y L S D L M K Z J
W P X D J U W T L X J J V R Y G A D D Y P L M C W
N X O I X K A I M I Y G F J Q R Q H M Z M S R T M
A M W Z D D H P O S L H Z Q R C J B C H B I U X D
B V F Y P O X A U R F O L Z T Q N M N W X Q O B G
C K Q C C P J V V D X N Q G V M U K E B W N Q L F
E B D G W I E N Y V N M E M W P B G Q J C J V E C
I Q R K G T Z K G E G T R X L S T X B S R C P G K
G W L R Q J B H Z W W P Y P A O G U O Q A P T N A
D U J F I B N R N O H R N U D E I Z Z F J G N Y U
J G Z B B R I G P A V Q S C K X M T P K D B W R T
F L M E K H K O Q M C S U O O T W S L V S Z Y S R
V O A J L C P X X N M V M T M K Z W G M K A X M Z

The ciphertext for this block can be any of the rows other than the ones immediately before or after the plaintext. Let's just pick IQRKGTZKGEGTRXLSTXBSRCPGK. In the same way, we encipher the remainder of the message (we only need 17 letters for the second block). The full ciphertext can be

IQRKGTZKGEGTRXLSTXBSRCPGKLIIBEVOOJNUBBYNAS

The M-94 cylinder cipher. Photo from robbo@ev1.net.

Reading and references

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Programming tasks

1. Implement an encryptor for the M-94.
2. Implement a decryptor for the M-94. Use tetragram fitness to choose the best offset for each block.

Exercises

1. What is the size of the key space for a cylinder cipher with *n* disks with 26 letters on each disk, if the offset is not specified in the key (i.e., the offset can be different for each block)? What if the offset is specified and has the same value for each block?

Unit 125
Hill-climbing attack on cylinders

We can build a hill-climbing attack on the M-94 by using the parent/child key paradigm that is familiar to us already. The key is a permutation of the numbers 1, 2, ... , 25. To generate a child key from its parent, we randomly swap two of those numbers. If the tetragram fitness of the best decryption (remember that the offset is not determined a priori) exceeds that of the parent, the child takes the parent's place. To avoid being trapped in a local maximum, we can allow downward steps some of the time. A good maximum for the allowed distance downward is 0.15 or thereabouts. If we cannot find a child with a higher fitness that its parent in the last 1,000 children, then we output the parent key and quit.

Programming tasks

1. Implement the attack on the M-94.

Exercises

1. This ciphertext was encrypted with M-94. Break it. It may take a while.

```
UHMBVYKDKYSFBEQSVLZRQURQNPCJNKKBHSNIQUYJDSKSHQJPBKBTAG
JYPLKHGBMAOYUPYGPKVUFKWDBFBUJKWGVAYXKDJWONHFCYPIXPSBQV
FCRFYTKGJNWJDIDEPHVUWWVUJOTNKXMUCQZXLOMWUMYEDNWEWUJJFX
DLUSQPTFCCHUVBABRECUCQIPHJAPFGMGBYBOEMWXXZJUKSVLVVMNGG
UQVWSNKFQTYXOAUHWYNDSUQWSOMSAFQJMTWPOMWTAVSYDEXMDZUXPB
ZOXNNUEKZDMMGGMAFMUOZOGSAWIQMHJVQUYYYUNXTEULNWIRINTIVZ
CALTXXHUOUGBNUYFHZHFGCBNOIJWRWSXLILBGCTDWQWTNPHXNUQEHU
OMPNKWDRBRWYSWFILNYTDOUKDKIFIQDLQIJTLBRQKNTPEZUZPODHBL
LGKHZWKYJPZSJSURDSSOHCUXZVIKOUYEADDOXILPQQAHRAOVSBETQR
ZAGXRRDTYSVIKBTIQBNXJKHVSZJJZSWNJZMKXJKIHJIFCMWKIXXQZG
YRPPEFTXOUDQOVRCXABHKHDENXJIHHCAWFWXDEFAMCCKHQMTWPHXYK
AILDRIWBWLPSURPYDSYKWVWORCHMJJPPHJLLYEYNRHIQZLKASYAQJO
HIOKDZJLHBCAWTOSMFLVSDXHZKVOELRXBGPWXHAGPZCJUKNZCOGLNT
NVLKVFIOUIZCPXEGZHDLMVFYDZHMMKMOLGOVSYYVHMQNREOYPTCVLX
RCSAVPNHYPXHIVIKOSNFQQHCANYJDHNZHACDUIHCAWYETOOAQLYEUU
```

```
VTCHSYPGIZCRBVLTQBHRLKTPTXMPYBNTOHAGKOQIZRCRAOTSYCUOYX
HVZAYSPNHAKYAJCSFWLHHNNKORVYHPFCXQAAYJJSERNPDOSSBINUIL
ASPUDPRNWGWRDNYUCBSSJPMAKSKQQXFEPYWMMEDVCKMBWUXMJXOCAB
YHYODHCIVTRIXOXRSNUNKSJXSWKWVVASXMNQOHCSVMGSJXRLCZQVCC
TDUJXIXRRZTMXMBGTGHTCOSOFZAFJMIXRZZTIVKMLMQPQUNOGGXYKR
DLYOEAHNHVEORHVIKEGMVMXDWBBMXUNBIPBBIJAMRQFOQCRRUDWVXR
MOWJCLXUFMFEYGPMUVKBUUUZPRFUJWQEOOWYMEGXNMWNDIWNJTNDPZ
FYXAGXSVGQWKJRSPERDGYEPRBPZUAIFXRQIMGWABUWGCWWGRIIQJXL
XLQTRQTICGIZRCLIJSMWXWWCYQHAGKYUGTETXPNGAPCKABBUDFWGZT
CMWBRBQKUVMUYSGTNSCLVCJBMKY
```

2. This ciphertext is from the 2009 British National Cipher Challenge. It uses the set of 26 disks listed here, and the same offset is used for each block. The first two words of the plaintext are in French, but that should not stop you from decrypting it.

disk #	letters
1 and 14	HIMQEBNYULWTASCVOJPRXZFGDK
2 and 15	BLAXCVSHIRWPFYQODETMNJKZGU
3 and 16	EADZMIJYKSRXVQTLPUCHNWGBOF
4 and 17	LHRTSOUAZKXEDIBWYVPFNGMJCQ
5 and 18	AOEBMUNWJYCGXQZVHLSTKRDPFI
6 and 19	HBTWOSIVQRDPYGNXUZLAFCKEJM
7 and 20	OBQZGRLKXATPNSYEWVDFIJUMCH
8 and 21	IMRWVULBDKOQHAETPGZSYFCNJX
9 and 22	RUHCESJAXMNZOGVBQTKDWILPYF
10 and 23	SAZORCIETFYKXMDPGWQVUHLBNJ
11 and 24	QUAIHJMCEZTKYFVLPBXOSGRWND
12 and 25	MUCATPJZOXEWIFQHBSRGLYDKNV
13 and 26	QWLCKUETDIVPHFAMZOYBRSGXNJ

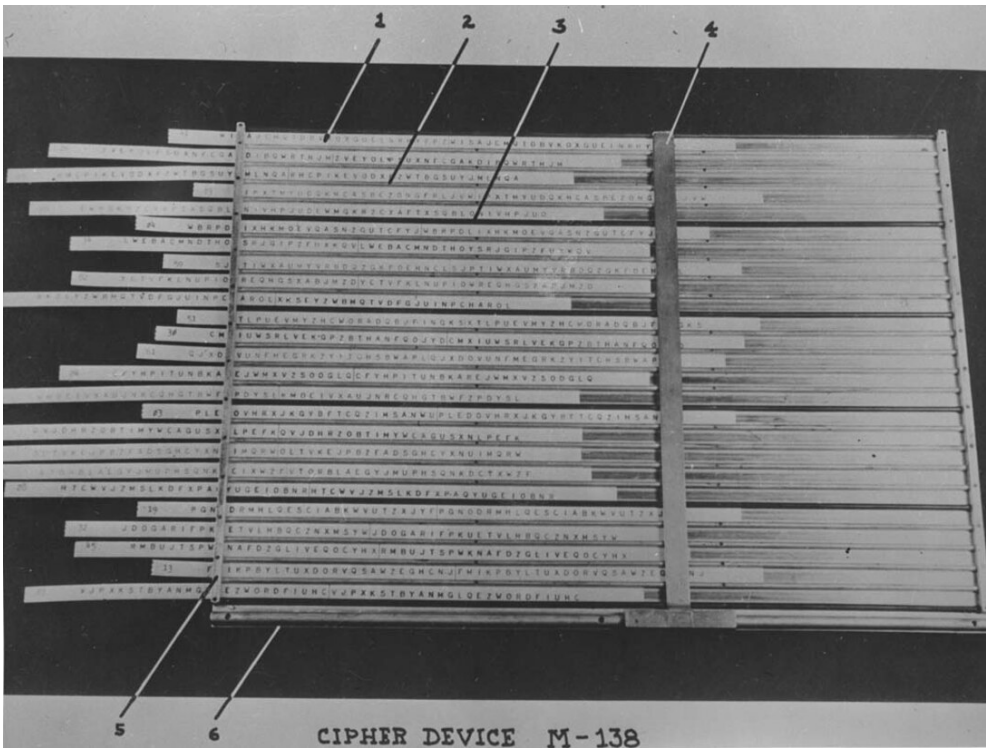
```
WUUHB SSCGG YRMIK JLNPL ZBGCI UJDUK FBHCU KZNVA EBXGA
AGBGD GLZAJ ELSDV EPTMI USOSW WARIZ PBRCA LZJNI CNFAF
VXLCO CMMOF LCTII HEEWY IZAKZ MEAGV XXOOA ZYULB CIFEW
DJPWJ MYGJB VVGPE SGKCP MAGZG OQKDG JKIML DTXXT CDDVZ
XRJDP FIFKD GJKIV AUAJM NBZXD VKEYD DTJAF CBXAI JUSPM
PPAAW LZZNJ USTCK DFERT CJCMJ IUVQQ LNCTL CBAFI YIPWI
LBEZG JAMWG ECDCR CWUGK JDQNH FAKAP AYCBH EUNDY PODNG
KCASC GPMEA DYJYB HKURJ KCRIZ YHYZM DIITU ACGAV FXRUZ
YVFIL ZDIND KCBZL IODDN XXXRU EJOIL CSVWS QQUOJ YLVAI
YDNXR USBVO LCUQE ASYWB ICIRA RBVHK ESDTZ XLRTK XCHXM
FGUXC NFBQK IMOFZ FDTDA GKCBG VFDUJ OSKIQ ORABK BNDCA
WCRCL MUWZI KJEQO JZUEQ EZAMI LZDEY BYEWJ VRMDC CLWMC
BXJVG WRRKW ADJZT PNWLR JNDNP ZUDNX IGLBA EFSKC EBUYS
IKZLN PESGK CPMZF JUENI XHFAB SCJNG XXRUX JMPID HUWZL
QDKTX MFFGC OBIAA EGNKR JDVGZ BDCND VKJPK PMXYA QWXCL
```

IUUVE FSMWA KHIGC RCWSP EQFYW FYIUD UFRGE EPXNA EJBMF
YAJUY ARTIU SUFQQ KNPCL ANQZV ATEBW GNDEX ROBGH QVOUN
RLLVC IFKEY IHHDJ BWIWI HXZKF MTGCK VOOAO SRTZX WHWCW
SQGNO OPGOJ BZXEU ESFZN XBOIB FQGAF PCTUA XDMYW RARWW
CFMAQ GGIHC ZXVKJ KRJTM FYAEI KNORL EEIXA GNCII REBQZ
MGTEG WKFNR CBSES BRTXD CUALD NXXVC LFDYF IROKC FBHCS
RTJCE JBVKP IWRLM DUCDY GSBIN EQVBL AUCLM HAYFZ MDBCZ
YEFSD AXIKJ KWSSK CMAIW GCLBC WUIXS CYBGP JOBVJ DCLAA
UZRBI LZDSC DKZUJ PGOJB YBZUF EDSVK JRDDB CDXKW IKIJI
GFMCH BEICO PVZBJ GXAMP ODXWC CKSMG AGECB ULIDW GECVF
NFKTE DOQBM CXGBE QCFFH EJLBN VNOEZ JPRFB MCDAR GSHPI
UULSJ FACHK HPOCM YIFYO QNSHD EATQE FASZA JYRGR UOXKP
GANPC JLJRK RMSVH WZHIJ LDOMX LAMED YPLIF JXBSJ JWICR
EFKIX LPVWU SFITU UCUYH YCBNZ RCWSL KBRAT IKNOL ZISEO
HMNWT PEFIK OKOXF ERNUN OXFAG ZSAAF GYRQU SPMKU MJFDQ
KJROK JJZRZ KOKRL

Unit 126
Strip ciphers

Strip ciphers involve paper strips that are laid in horizontal tracks on a tray. Each strip has two copies of a mixed alphabet. The strips can be slid relative to each other, and a block of plaintext is enciphered by lining up the strips so that the plaintext letters appear in a column. The ciphertext is then read from a different column. Essentially, a strip cipher is a flattened version of a cylinder cipher. We can see now that the reason each strip has two copies of its mixed alphabet is so that we do not run past the end of one when using the device.

The *M-138* is the flattened version of the M-94 and was used by the United States in World War II. It had 25 strips in 25 tracks. We cannot say with confidence at this time whether the strips had the same mixed alphabets as the M-94 or whether there were more strips (but only 25 were used at one time).



M-138. Photo from U.S. Department of Defense.

M-138-A was an improved version of M-138 with 30 tracks and 100 strips (only a subset of 30 are used for any one message). The U.S. Navy renamed it *CSP-845*.

To attack a strip cipher which has more strips than tracks, we can modify our hill-climbing attack on the cylinder cipher by extending the key. Suppose the device has *m* tracks but *n* strips. Then the key is a permutation of the integers 1, 2, ... , *n*, but only the first *m* entries in that permutation are used in decipherment. When we generate a child key from a parent key, we randomly choose one of those first *m* entries and swap it with any other entry. If the offset is the same for all blocks, then it is possible, for a sufficiently long ciphertext, to break it, even without allowing for downward steps. If the offsets are random, then this attack is likely not to converge to a solution.

Reading and references

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Greg Goebel, *Codes, Ciphers, & Codebreaking*, chapter 5, vc.airvectors.net/ttcode_05.html

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Programming tasks

1. Copy your routines for the M-94 and rename them for the M-138.
2. Implement an encryptor for the M-138-A. Allow it to read the strip set from a text file.
3. Implement a decryptor for the M-138-A. Allow it to read the strip set from a text file. Use tetragram fitness to find the best offset for each block.
4. Implement the attack on the M-138-A. Allow it to read the strip set from a text file.

Exercises

1. Encrypt this text with M-138-A and key 55, 37, 85, 10, 30, 9, 73, 91, 61, 4, 17, 64, 81, 94, 67, 1, 28, 75, 98, 90, 52, 48, 8, 11, 6, 45, 14, 38, 60, 5. Choose the offset randomly for each block, but do not use columns adjacent to the plaintext, as we avoided adjacent rows with the M-94. Use the randomly generated strip set below.

Are the mixed alphabets on the strips of the M-one-three-eight the same as the mixed alphabets on the disks of the M-nine-four? We do not know. We have contacted the museum holding one such device, and await an answer.

2. Decrypt this text with M-138-A and key 11, 93, 98, 52, 74, 89, 43, 41, 3, 58, 28, 23, 31, 14, 90, 82, 86, 44, 62, 34, 22, 12, 35, 91, 60, 13, 48, 29, 78, 40. Use the randomly generated strip set below.

```
SHJRQBJIMRHFLLVACMUMCILVCXYUKVPBVXSBUNBQXSCPGEXCHZNOZU
PKZRJPXCPRDQPMPJWHDTVGVUQYYHWZUCAFXRUWWDFWULXHSDSFUYNW
IVCCSMMLJKGLHEPNNEHZBGNEJGGSCXUTLLSJTIGPRCPFJSSXASCPXJ
VZIJLLIAMXIUQZFKALIBPHIGKOCERQGGQNKNXKVBHGOESHPJUBLZLB
LLXBWMRYXVBSHNVDIASJXAGXQRNAAMPABJDGFOYGIGBAOSGCCUWUQU
OFCYDUHYOUDYTQRPBEULPRJAHYSJDZGLROPGFZFMRCDAEGPQAYKNJP
R
```

3. Break this ciphertext that was encrypted with an M-138-A. The key was randomly generated. The offset is the same for each block. Use the strip set below.

```
KYIVOVMFBHRWPYJWITPDERWOXZJSYRWXIXTVTVRWOLMYIREFXAKNNA
QHTMYPPEMNGVMPTHHZTRDCDEFOUVOEITEZOHVAMGYTXTFOVYZURNJC
KJMKFYBCEUMGPVSHBHYHNVULAIGNWQJZMKJDLFJMKJEHSHMVHVVGVC
DPJMYXRLPKJDXUTTYXPLWOWUVETWYZKSVIJPBBUDRKLQJMVVTFDBMU
HNKYDKCAIILFMKKNNYKZQLNPWJZCVMHJHDQZTBLVFVRKXPPZLPXMVY
WFHGKHLVSGIOAUWAFAIOCCPDOOFYKJEIGLMHXXSLIFCMQCDEFOUVVN
URYBUVSOLWVHPVRPXLAFNBBOJXFJTVJRMYKPLIDNWUKKDHYZPBLVDJ
FDSIXYGPUUUQWOLGGQNFUBMDPZRODJLJMHWJLCSKOHXWVBMIAYVFYH
EBLVDJAXCOMYIGJIIQWXIITJLRKEGOLJGADIHWKJRQGUKQARVVVYSX
JZTTVCZYJIOSLBIGBAGCCUNZOLVNYMEZUSXYPMIIMVGZMDQRTZJULT
PXVBMJKNSYYHEBLVDJSKIPXOXUZCMONLGVIAUYQGOCIPWNRISOUJPM
XTESOJAVSNGMUIQODOQRQIOQAPSVPOIGFYKHURYMJRUVBDQDZRNDIF
ZKEJTMCRPZYQKFGIVKORVHUOWNGEFSPCLWIAGUYRWZVDMVMEMTTVEZ
TRONRGLIECZYIRYNNJSVWHBHUYGYYQTZSMJJLOUVRTQZZAZWAOVBMP
NZFKIGONGSYEKJMJPTKWYHBZKOWGPKJZTQHMWBIVILJTFDBZJKYLMI
PDMGULJZTQHGZRYRMVKKKNNYKZAFFQWOLNGMLFSYMYVAITDIKJMGNE
XUQIWQYLVBKIASNVVBKIIXWYQYCATKBGXUKJYHQODPJEQFOLVVGNDE
PVJPUYQACZQQEVEOKIANFEHEPZRAJGLIECFNQRQUSYIZQMKITINWIN
CPWTGPXCLVTKQATCZJEUVGSMUVVYNLVRITGPIKMXNELVJNJHVDLYCG
HHIPXEKMINDELJMSPALVUUL
```

Challenge

```
KHXPKMDWGKBDHUXWVBHKQOOKVTETXTQSBHDLWRFNPAOAEOPMRLHBIINPKQA
ZGPGXNUXMJBKPROCAFZPYQPARZQLYWUZGUJMYRWAORPFJZFPJQNSMBJZXSL
HYZGRBTDOVPCRZSYEPPPGLKUAFWKLXZCKKRBZXTAKRSPBIVJRKNZXUAFLGS
LEUKYNDNVGLPWAXNPNXYCQRLTWENBKRXUACAEUZBBZCMMIWCLUCKUUNRZGS
GWJABUZSVJWHYXYXDUFTJYYKPWLGNHPRXHESOBCTWFNYTOXSGNQOKJIFVMD
```

```
PEGNEVIYPLPLOMSMXGGZZLPUOPOHXIXTUGCOUATFVUYLTNSYMKWUZSIFCMQ
XUZARVITBEJWOOKVYQAZCFKUQAJQOTETTFBGNGPGPDBZLFSDZHHAMFOYQFB
WIMZKMKMMUOFAYSCQREZWVNDWDRMBXRBIEJIZFXMALJECOIPWFSHUAWISLW
VONCIORJOVVGYINUPLGEVCIXWFNRDXXAOSSUHPAWQEXQNACFBXAKOJGLJTU
KAOCZZFHWXSKNGEVIKQTQYQDLCDQJNANFCJRTFQCHBJSZFHRGMYVYPGQULD
ZCDWGHXNXFHFPXNSDTSWZFKOFHGNTOHPOOZRWXAUEFUMWKLAOTWQZUJZFIE
FPDRLQBBZEJHKSVJQCPZNHNEMVTOQVGXHASBHVSRULXKMMOMJKGLMFIRHCH
OTIKYDSPXSFWNLYJNAELCGVGVXQNIHRNSWJFCNXDCMXSFFHTCVMFVUDASHU
NJJYYMWHNPOBJZVFNHKLYXBVVHIJCHSNDDBBTOEDJIVMCQPXGCMBQPZXXZZ
NOKMJZWMACNNRFFVDUBMEGEVGQDQJVAWYOPJXQACAHFIYZJVZPASQVBIDNR
TALWMGXXALPLTSZQKKYVHBXGHOZOVEPEDRURQEUAPPZBJDAJJDSNNMSJOXR
CTNPCFDCHREAQMJXGGBYKLGSVVOUOBCXMAAQKYYQFJBSKHKPBWKFLAKOHZO
UURKFVFKENXWULACWRESAWYXKKSEPYPKLZWTZGJENDTZJU
```

This is the randomly generated strip set for the exercises and the challenge. It should not be considered an historically accurate list. They were generated solely for the ciphertexts in this unit.

strip #	mixed alphabet	strip #	mixed alphabet
1	EBCNRTKUZOQWMFGAPXVYHDIJLS	51	JSATWPRYNFOUVMZXGDHIEKCLQB
2	HIVQZUYJNSRLEXBPOTAGDWCMFK	52	ABXJMZTQOIKVHEDFYCLPRSWNUG
3	VSHTUPZIRWMGQOEALBYJDCNKFX	53	JBYOXPHGVZQLWSDMTKRFCNIEAU
4	HGYENUCRPZWMIQTKAXJBDLVSOF	54	RLKMQABOWHNFSVCXYPEIDZGJUT
5	ZBPGTUVCOWJLEISDHYNRKAXMQF	55	ETLMUZYWOCGIRDBFPKAVJSQHXN
6	YWXHKRZUOBJSFGNAPLQCEDVMIT	56	VMRIUJFKEBOPWTYSADCXNHQZGL
7	DMBNORVFCSAWGIQYKJTZXHPELU	57	ZAMDJFNUHKYPWVRXLIBGQOCTSE
8	XBQFAGITLEHZUDKSOWPCRYNJVM	58	DXYLJAQKUFRPITVNOHSZMGBWCE
9	RPJSWFBUTHEDQMKGOIANYVCZLX	59	XRMNJATKOBFZCPWUVQELGDYISH
10	FSOCELBPVAQKIXWZGTMDNYUHJR	60	SYPITVMJZKLEUHOBFRQNGDCWXA
11	ACPIDOYSRTUHBKQGVNXWFELJMZ	61	DABHQKMWXLICPZSTNEGFVRYUJO
12	YLXTMNVZEJUKDPBHQAFSRWGIOC	62	QFTJLICAZROBEKNUPSWYHVGMDX
13	TBDECYZPNLGUFOJRKQSIWHXVAM	63	OJELKXUHSPIWQMYDNBGTFVZRCA
14	FLNYCMEWSXHIABGQRPOJUKZTVD	64	IEWDCNOLZJHFGBPUQVMYTSKARX
15	FTHXADWIUNYJOMBCQPVSEZLGKR	65	SGKYVNLIUZEAQJMFXOWTDPRCBH
16	UHNYCAOTLMZDGIERJQXPVWFSKB	66	DRHPWCGYVUEXZQALIONMSJFTBK
17	JDGQBOZCVMHAWYKRSTPFXUNELI	67	FTNZQAOEUXYVPWHKRSIDBJLMGC
18	GMJUBTIAVYRHPOECDNKLXZQSWF	68	DIBHXALWQCNZGKVSFUJMPRYTOE
19	INYVECOHBDAFQZLWJMKGTRUPXS	69	KUDQXRFHLISACBTPYNWVJGOEMZ
20	BZAXDNSYWGHCRMEPLUFJIVTOQK	70	MIWEFSCPATKVLORQHXBYJNZUGD
21	HLZUEXJNRTQCKWOYBDMPFIGVAS	71	ZQTNYKHCVXIUMGAJPODEBRSLFW
22	AUEPVHSGMJFRCWDBXOTYILQKNZ	72	UKMHBAJSFWGCDXQYORVTZPELNI
23	FDIJMAGVWLNQKECZOXUSTRPBYH	73	WXYUVKNMADRGCTHLEFPZQOSJIB
24	HOANLPTXQDWYJRGKFBSCZMUVIE	74	BHEPRZTOVDGKMJQUIYNWFXLSAC
25	XTLSZCDFJEYUOPNBARWHVKQIMG	75	ORVUICMBNDXLAJYZSKGFEPTHQW
26	YCJWQUNIHOVPFSLZMGATDKERXB	76	HVJOKXSRFIQUACYNTMPGEWLDZB
27	RECXJZDGIAPKMYHQNOFLTVWSBU	77	KNGAOIYBHWEQMPJZLDSUFRTCVX

28 JDFSECBXZMWPNRHUGAOVLKQITY
29 EQHMOGUIYVACWTJZNKFPXRLSBD
30 DIFAHKGXWPVTRQSJLBZOEYNMCU
31 FJRBXNIGVOUPKWHYLDQESZAMTC
32 AKEFBDJPUIGVNWZHOSQRYCXLTM
33 ZMPKSAUBLWVQDNTGOFEXHCJYRI
34 JISEFBDYAMRTLPCQHXKGUNVZWO
35 CNDTUSILPVFYHMZWRBAKGOJXEQ
36 MATXNJLHVZUKCDBIPQFEWOGYRS
37 IMVEJAFZHQRGLKUPWTNCSYDOBX
38 NYJQLMDARHGOFKBPETWZXUVSIC
39 ZAVEPUWSOKCHNLRTQMJDYFXGBI
40 MFKTUREJYOCGXIZLQPNBVHDAWS
41 RQICZOHVMNWELSUGXYTJKABFPD
42 CPJMODWQXIFYLRNUKBGZVTESHA
43 LZMACJPOSQTKGINXVFWRHUBYED
44 VNTAYRIPFEDMGKWBQJUXLSOHZC
45 ZIWKNJMSVXFEUDGQACHLYBTRPO
46 FEWRDMLBNATKGVCSZJYOQIXPUH
47 NVEHYGLSTBIFXUZPCQRDAMWOJK
48 ALEGPMUOSDFYCHTWQIVNJXKBZR
49 DJNGOUHQYAELRWBMTXSVCIPFKZ
50 VQSEGULNCBMZJOWRYXPAKDTFHI
78 WIRBXALHKJZYQSVGDUNOPETCMF
79 SVYPXTINHZAKBRGMOLJDCUQEFW
80 OJFWITSPNDAMZXLYERUQBGVCHK
81 UJFQCGPAMTLEKRXBOYSDIVWZNH
82 QTEWPORKXCIZYJVBMFULANGDHS
83 TLCGDRXFSZIAJUPMEVOHKNQWYB
84 XKTJDPWLVOEZGRUCYANQFHBIMS
85 TBUFMIHRAGCWPVJLXZQYDOSNKE
86 WMLHSAGZEPKYJUIXVQBCRNFDOT
87 VLNTRGHDUIKEFMSWZJQOYAXBPC
88 YUVBSKNOPEIQDMCWAHJZFGLTRX
89 LYPFDHWBZNCTXROGKQIEUSJAVM
90 EKAQCSILMFJYUZBTXWDPGVHRNO
91 LRQJSDPTYWGBMAINKEVFOXUHCZ
92 AJNRXTMZKHBGOSLEFVCUPDIQYW
93 TCEWPVDIQBJONKYLRZGMFUAXSH
94 BMAOCFRZDWVTGXSHQJEINKUYPL
95 XKVDFJOPIWZQNHAGLERBSCYUTM
96 HZNUGFQRWCEADVSPMOBJYKLITX
97 BPTLKUHZMFADEVOXGSRQIWNJYC
98 MTCISYWNVKOZJELUFPGQBXRDAH
99 BANGXEZSMJPTDWCOHRYFIVLQKU
100 YVTSFOXPBRMKDIELGAQHWCNUZJ