

CSCI 241, Spring 2017, Project #1

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April 6, 2017

NOTE: this is incomplete.

Due date: April 28, midnight.

Caesar ciphers: Caesar ciphers are a simple way of enciphering messages and form the basis of the secret decoder ring (see Figure 1). A shift of the alphabet is used. For example, a shift of 3 (or, equivalently, shift to “D”) gives the following table:

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

To encipher a letter, look it up in the top row, but use the letter in the bottom row. For example, “HELLO WORLD” becomes “KHOOR ARUOG” (Klingon, I think).

To decipher a message enciphered with a Caesar cipher, you need to find the *key*, a number between 0 and 25 (or a letter between “A” and “Z”). Since there are only 26 Caesar ciphers, it would be easy to just try them all to break a message enciphered with one. But we need a little more sophistication for what follows.

Instead, we rely on *frequency analysis*. English text is not uniformly distributed among all 26 letters. “E”, for instance, is much more common than “Q”. If you take a large body of English text and count the occurrences of each letter, you get a distribution like that in Figure 2. There are clear patterns in the frequencies. E, for example, occurs quite a bit more frequently than any other letter. Further, the sequential letters UVWXYZ are all fairly infrequent, and so they create a noticeable “trough” of five sequential letters.

If you take any other work in English that has been enciphered with a Caesar cipher, and look at the letter frequencies, you will get something similar to Figure 3. The histograms are not exactly the same, but you can see the same patterns. The highest one is probably E. There is also a trough of five sequential letters, probably UVWXYZ, and its position relative to the supposed E is appropriate. We can be fairly confident that the key to this Caesar cipher is a shift of 8.



Figure 1: Magic decoder ring.

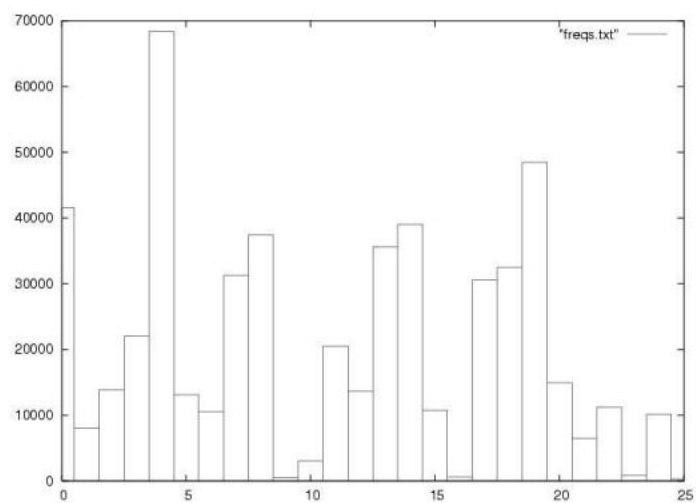


Figure 2: Letter frequencies for English.

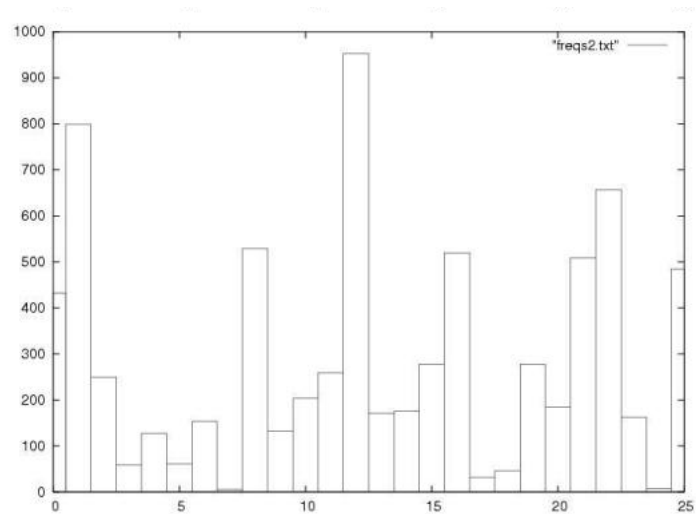


Figure 3: Letter frequencies for Caesar enciphered English.

Vigenere ciphers: Caesar ciphers are so easy to break that it is doubtful they were ever used (even by Caesar) to encipher important information. However, they form the basis for a much more sophisticated cipher that has been used: Vigenere square ciphers.

Vigenere squares were once thought to be unbreakable. It was Charles Babbage (the guy who invented the computer) who figured out how to break them (even without a computer).

Here's how they work. Let's suppose that we have a procedure to encipher with Caesar ciphers, `encipher(letter, key)` will encipher the character `letter` with the Caesar cipher with key `key`. Then (consulting the table above), `encipher('M', 'D') => 'P'`, for example. Note that `encipher(x,y) == encipher(y,x)`.

We can now encipher a long text and break up the frequencies of the output letters by using a different Caesar cipher for different letters in the text. Instead of a key being a single letter, a key is now a *keyword*. The letters of the keyword (repeated as necessary) tell us which Caesar cipher to use for each letter in the input.

For example, suppose the keyword is “fumble” and the plaintext is “meet me at midnight.” Then we encipher the message as follows:

Plaintext:	M	E	E	T	M	E	A	T	M	I	D	N	I	G	H	T
Keyword:	F	U	M	B	L	E	F	U	M	B	L	E	F	U	M	B
Ciphertext:	R	Y	Q	U	X	I	F	N	Y	J	O	R	N	A	T	U

Thus, we use `encipher('M', 'F')`, `encipher('E', 'U')`, `encipher('E', 'M')`, *etc.* as the ciphertext.

Letter frequencies and patterns are completely broken up with this strategy. For example, the double-e (a common pattern in English) in “meet” is *not* enciphered by a double letter. Further, since Es in general are enciphered by several different keys into several different letters, pretty much at random, and further since other letters will also be enciphered into the same letters that E is using, no one of encipherings of E will dominate and no one letter in the ciphertext will have a much larger frequency than the others.

A Vigenere Square: Historically, this cipher would have been used without computers, by a spy hiding in a closet with few materials. If all he or she knew was the keyword, they could still construct everything they needed quickly. A Vigenere square, such as the one in Figure 4, can be constructed by hand very quickly. Then you simply use the plaintext letter and the cipher key as the row and column to lookup your ciphertext letter.

A ruler or other straightedge would obviously be a big help.

Breaking Vigenere ciphers: What Charles Babbage realized, however, was that a Vigenere cipher is just n Caesar ciphers, where n is the length of the keyword, usually not very large. If we can guess the length of the keyword somehow, we can break the Vigenere ciphertext into n Caesar ciphertexts, and break each of them with frequency counts.

How do we guess the length of the keyword? If we have a longish ciphertext, and a relatively short keyword (the norm for human-generated ciphers), there are bound to be places where a common English word, like “the,” (or even a common *phrases* of English such as “on the” or “in the” or “when the”) lines up with the keyword at the same spot. For example, with the keyword “fumble,” you are likely to have this kind of thing happen:

Plaintext:	...	T	H	E	...	T	H	E	...
Keyword:	...	M	B	L	...	M	B	L	...
Ciphertext:	...	F	I	P	...	F	I	P	...

Note two things about this phenomenon: First, the ciphertext is identical. Second, the distance between the identical substrings must be a multiple of the length of the keyword.

The second fact must be true about virtually every pair of identical substrings in the ciphertext. Even a fairly short pair of identical substrings is unlikely to happen by accident. (What are the odds of a length-5 substring showing up twice by accident in a length-1000 string?)

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

Figure 4: A Vigenere Square.

These are the keys to breaking a Vigenere cipher (even without a computer):

1. Find pairs of identical substrings in the ciphertext.
2. Calculate the differences between their starting positions.
3. Find divisors of these differences.
4. The smallest, most common of them is the keyword length, n .
5. Break up the ciphertext into n subtexts, where the subtexts are letters with positions identical modulo n .
6. Each of these n subtexts is a Caesar cipher; use frequency analysis to decipher it.

Practical considerations for computers: With a modern computer, such sophistication is not necessary to decipher a Vigenere-enciphered text. For example, if the key is an English word, there are less than 500,000 of those, so just try them all.

If the key is a strong password (a fairly long string of essentially random letters), we can still brute force it by trying all possible lengths, n , for the keyword, and then using Babbage's trick of trying to solve n separate Caesar ciphers by frequency. Note that this will only work if the length of the ciphertext is many times longer than the length of the key. If we assume that we need at least 100 characters to do a frequency analysis, then the ciphertext needs to be at least 100 times longer than the key. We will assume that this is the case.

If the key is as long as the ciphertext, then this method amounts to a "one-time-pad" cipher, which is unbreakable even in theory. So we'll assume this is not the case.

If we are brute-forcing a solution with a computer, though, there are still some problems remaining. When we talked about deciphering a Caesar cipher, we spoke about examining the frequency table looking for the E, looking for the UVWXYZ trough, *etc.* This is easy to do as a human, but there's an easier (and better) approach if you're a computer.

Programmatically, we can detect these similar patterns in the frequency tables as follows. Looking back at Figures 2 and 3, if you shift the enciphered histogram to the right by 8 places, the alignment is nearly perfect. Any other shift will have large discrepancies between some of the columns. To decipher, we just need to find the shift with the smallest total discrepancies.

Suppose we make a frequency table of the ciphertext letters, and then shift this table by the value i , and match it up with a known table of English letter frequencies. We add up the absolute values of the differences in the frequency tables, which we will call the SAD value for the shift i (the Sum of the Absolute values of the Differences). The proper shift will be the i with the smallest SAD(i). This would be enough to crack a Caesar cipher.

However, in cracking a Vigenere cipher, we don't know if what we've found is a Caesar cipher or not. We search through various values for the length of the keyword, n , in order to find which n divides the text up into n Caesar ciphers. We need to know *whether or not* a given sequence of letters is a Caesar cipher.

We can solve this by using the following fact. If the distribution of letters in the ciphertext is *not* a Caesar cipher, the smallest SAD will not be *much* smaller than all the other SADs. It will only be *much* smaller than the others when the ciphertext is indeed a Caesar cipher.

We will use this to determine when we have the proper length for the keyword. Our Caesar solver routine will return two values, the best shift value (the i with the smallest SAD(i)), and also an estimate of "how good" this SAD is. The algorithm decides that it has found the proper length of the keyword when the Caesar solvers say their shifts are *very* good.

How should we measure the "goodness" of the SAD? If we assume (without real justification, as most statisticians do) that the SADs from bad partitions form an approximately normal distribution, then the SAD from the correct shift will be statistically unlikely.

For each possible Caesar ciphertext, we compute the standard score (z -score) for each SAD, with respect to the mean and standard deviation of the other 25 SADs. The z -score is computed from the raw number x by subtracting the mean and dividing by the standard deviation:

$$z = \frac{x - \mu}{\sigma}$$

Once we have a z -score for our shift, we can calculate a probability. Normally tables are used for this, but since we want to do this programmatically, we'll use an approximation:¹

$$\Phi(z) = 1 - 0.5e^{-1.2(z^{1.3})}$$

This is the probability for all values less than or equal to z , under the assumption of a normal distribution. This only works for positive values of z , so we take the absolute value of our z before calculating $\Phi(z)$. If this number, $\Phi(z)$, is greater than 0.95, then we have a significant match. This means that we probably have found our Caesar cipher. To be conservative, we will only say that our guess is "good enough" if *each* of the subclasses has a probability greater than 0.95 of being a Caesar cipher.

Note that this brute force method to find the length of the keyword does not rely on Babbage's insight about repeated strings.

Project: Write a Java program to automatically decipher a text enciphered with a Vigenere cipher using the ideas outlined here. Follow the pseudocode given at the end of this document. Note that the input and output files are given specific names. This will enable us to test your programs without responding to any prompts.

Use the table of English letter frequencies found in Wikipedia: https://en.wikipedia.org/wiki/Letter_frequency

General coding instructions: Follow decent style recommendations, such as that found in your CSCI 145 book or in <https://github.com/twitter/commons/blob/master/src/java/com/twitter/common/styleguide.md>

¹<http://web2.uwindsor.ca/math/hlynka/zogheibhlynka.pdf>

Pseudocode:

```
----- Vigenere main -----
// Initialize

Read ciphertext from file named "ciphertext.txt"
Convert ciphertext to upper alpha string: cipherletters

// Try all possible key lengths:
keylen = 1
solved = false
while (not solved and keylen <= 100) {

    // Partition cipherletters into their equivalence classes:
    assert classes[keylen] is an array of empty strings
    for (letter = 0 .. length(cipherletters)-1) {
        add cipherletters[letter] to classes[letter mod keylen]
    }

    // Find best shift for each letter of the keyword
    assert shifts[keylen] is an empty array of shifts and probabilities
    for (letter = 0 .. keylen-1) {
        shifts[letter] = bestShift(classes[letter])
    }

    // If we've found a significantly different solution, exit loop
    if (goodEnough(shifts)) {
        solved = true
    } else {
        keylen++
    }
}

// Output solution
print decipher(getKeyword(shifts), ciphertext) in file "plaintext.txt"
```

```
----- bestShift -----
bestShift(letters) {
    // Find frequency table of letters
    assert frequencies[26] is a table of frequencies for the letters

    // Find SAD for each shift
    assert sads[26] is array of SAD scores for each shift

    // Find minimum SAD score in array
    assert sadshift, sadvalue is smallest SAD and shift

    // Find significance of sadvalue
    find mean and sd for other 25 values
    find z-score for sadvalue
    find probability of z-score

    return sadshift, probability
}
```