CS 419 Project 3

Due Tuesday, April 12, 2022 11:59pm

Introduction

This assignment contains three parts:

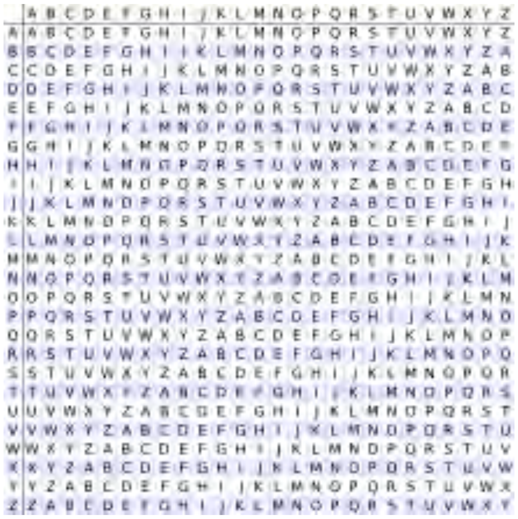
1. In part 1, you will implement a binary version of the Vigenère polyalphabetic substitution cipher.

2. In part 2, you will implement a stream cipher that uses a linear congruential keystream generator and a hashed key as a seed.

3. In part 3, you will modify the cipher in part 2 to operate as a block cipher that will shuffle pairs of bytes within each block based on the keystream and will apply cipher block chaining (CBC) between blocks.

Part 1: Binary Vigenère Cipher

We covered the cipher in class. This was a cipher that was created in the 1500s and used through the late 1800s. It was designed for field use (that is, you could encrypt and decrypt using only a pencil and paper with no need for special equipment) and used a repeating key. The cipher requires arranging multiple substitution alphabets in a grid.



	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
A	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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

Each row of the grid contains the alphabet shifted by one position to the left compared to the previous row. To encrypt, you:

1. Find the row indexed by the plaintext letter.
2. Find the column indexed by the next character of the key
3. The ciphertext letter is the intersection.

The key is repeated to make it the same length as the message.
It is also common to index the row by the key letter and the column by the plaintext letter.
Either way produces the same result.

Your program will create a *binary* version of this cipher.
The key can be either text or, preferably, binary data and is stored in a key file. A longer binary key allows the encryption to use a greater variety of substitution alphabets.

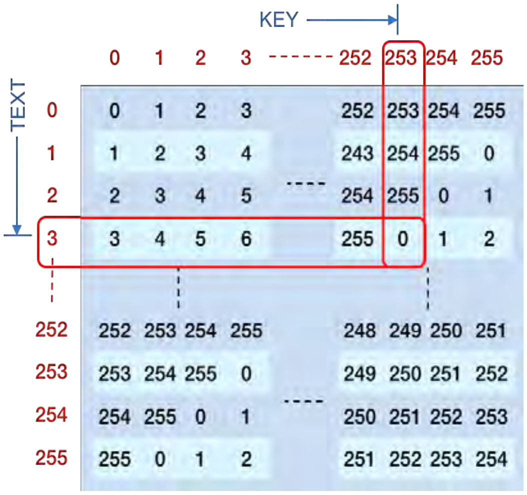
The usage of the command is:

```
vencrypt keyfile message ciphertext
```

This encrypts the *message* file using the key in *keyfile* and produces the file *ciphertext*.
Here's what you need to do (logically):

1. Create a 256x256 grid.
   a. Row 0 contains `00` .. `0xff`
   b. Row 1 contains `01` .. `0xff`, `00`
   c. Row 2 contains `02` .. `0xff`, `00`, `01`
   d. Row 255 contains `0xff`, `00`, `01` .. `0xfe`

2. To encrypt each byte of plaintext:
   a. Look up the value of the ciphertext in the table `ciphertext[n] = [`*`row=plaintext[n]`*`][`*`column=key[i]`*`]`
   b. `n = n+1`
   c. `i = (i+1) % length(key)`



	0	1	2	3	------	252	253	254	255
0	0	1	2	3		252	253	254	255
1	1	2	3	4	----	243	254	255	0
2	2	3	4	5		254	255	0	1
3	3	4	5	6		255	0	1	2
252	252	253	254	255		248	249	250	251
253	253	254	255	0	----	249	250	251	252
254	254	255	0	1		250	251	252	253
255	255	0	1	2		251	252	253	254

These steps are illustrative only. If you think about the operations that take place, you will realize that you don't need to build a table since you can easily derive the value of the ciphertext from the key byte and plaintext byte.

Then, create a decryption function

```
vdecrypt keyfile ciphertext message
```

This reads the key from *keyfile* and decrypts the contents in *cipherfile* into the file *message*.

Hints & testing

If you find this program getting long, you might be approaching it incorrectly. The entire encryption can be one `while` loop with one line of code within it! You can implement a table if you'd like, but it's not necessary.

Test your programs thoroughly. Come up with different test cases and validate them.

With this cipher, a key with bytes of 0 will always produce plaintext. A key with bytes of 1 will produce shifted data. For example, the string `ABC` will produce the ciphertext `BCD`.

Your program should not assume any maximum size for files being encrypted. That is, it should handle multi-gigabyte files without a problem. Hence, reading a stream of data is a more reasonable implementation than trying to read the file into memory all at once.

You cannot assume a maximum size for the key file but may assume that it's a reasonable size where you can allocate a memory buffer and read in the entire key file.

There is no distinction between text and binary data: a file is just a stream of bytes. You should not attempt to read lines or take any special actions for, say, newline characters, carriage returns, or null characters.

Printing input & output of data (as hex #s, for example) can help you see what's going on in your program.

The Linux (and macOS) *od* command dumps binary data and may be useful for inspecting your output. The command

```
      od –t xC keyfile
```

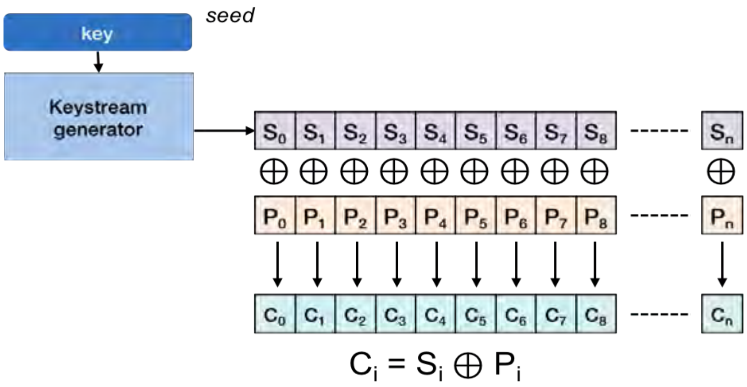
shows the contents of `keyfile` as a series of hexadecimal bytes.

Part 2: Stream cipher

We also covered stream ciphers in class. These simulate the one-time pad by using a *keystream generator* to create a keystream that is the same length as the message.

The keystream generator is simply a pseudorandom number generator, and the seed is derived from the password. You will always see the same sequence of numbers for the same seed.

To implement this cipher, you will:


seed
key
Keystream generator
S0 S1 S2 S3 S4 S5 S6 S7 S8 ------ Sn
P0 P1 P2 P3 P4 P5 P6 P7 P8 ------ Pn
C0 C1 C2 C3 C4 C5 C6 C7 C8 ------ Cn
Ci = Si ⊕ Pi

(a) Implement a linear congruential generator

It is a trivial formula that is described here:

https://en.wikipedia.org/wiki/Linear_congruential_generator

This is one of the best-known and widely used pseudorandom number generators. Each pseudorandom number is function of the previous one and defined as:

$X_{n+1} = aX_n + c \bmod m$

where:

X_{n+1} is the next pseudorandom number in the sequence
X_n is the number before that in the sequence
m is a modulus. We will be working only on bytes in this assignment, so you will use 256 for the modulus (since that is 2^8 and will produce a range of values that fit within a byte).

The values *a* and *c* are magic parameters. Certain values were found to produce better sequences of data. You will use the same parameters that are used in ANSI C, C99, and many other places:

Modulus, $m = 256$ (1 byte)
Multiplier, $a = 1103515245$
Increment, $c = 12345$

Implementing it is only three lines of code! By using a well-known formula, your output should be the same regardless of the programming language or operating system you use.

(b) Convert the password to a seed

The seed for a pseudorandom number generator is just a number. For this program, instead of asking users to use a number as a key, you will let them use a textual password. You will then apply a hash function to this password to create a seed for the keystream generator.

To create the seed, we will use a hash function that works well and is easy to implement. This is the *sbdm* hash that is used in gawk, the *sbdm* database, Berkeley DB, and many other places. You can find the C code for it here: http://www.cse.yorku.ca/~oz/hash.html

```
static unsigned long
sdbm(unsigned char *str) {
      unsigned long hash = 0;
      int c;
      while (c = *str++)
            hash = c + (hash << 6) + (hash << 16) - hash;
      return hash;
}
```

You should be able to translate it to whatever language you're programming in pretty easily. This implementation is also three lines of code!

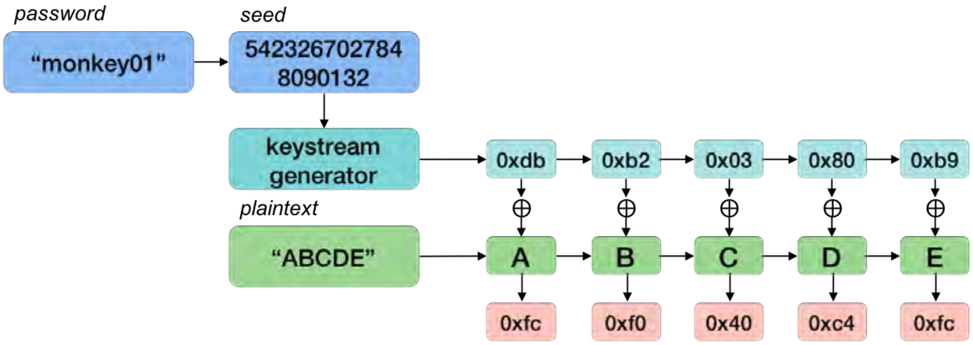
As with the previous step, this implementation should ensure that your output will be the same regardless of the programmer, programming language, or operating system.

(c) Apply the stream cipher

The ciphertext is generated byte by byte and is simply:

$$ciphertext_i = plaintext_i \oplus keytext_i$$

Each byte of plaintext is XORed with the next byte from the keystream generator to produce a byte of ciphertext. Because applying an exclusive-or of the same key a second time undoes the first exclusive-or, you only need to implement one command.



Usage:

```
scrypt password plaintext ciphertext
scrypt password ciphertext plaintext
```

The *password* is a text string. The parameters *plaintext* and *ciphertext* are files. The same program can be used to encrypt or decrypt.

Hints & testing

Before you even start implementing your cipher, you should test that your seed and keystream generation works as expected. It's important that different cipher implementations are all compatible – even if they are written by different people in different languages and on different platforms.

You are provided with a program called `prand-test` that lets you enter a password and see the seed and enter either a password or seed to get a pseudorandom stream of bytes.

The usage is:

```
prand-test [-p password | -s seed] [-n num]
```

If you supply a password, then you can see the seed:

```
$ ./prand-test -p monkey01
using seed=5423267027848090132 from password="monkey01"
```

It's possible that the seed may be different if you're using python, which implements arbitrary-precision arithmetic instead of 64-bit integers, but your sequence should be the same since we're taking the modulus of the results.

To see a sequence of pseudorandom bytes, use the `-n` parameter. Here are the first five bytes from the password `monkey01`:

```
./prand-test -p monkey01 -n 5
using seed=5423267027848090132 from password="monkey01"
189
178
3
128
185
```

You can also test the sequence from a seed number. Here are the first four bytes from the seed 85:

```
./prand-test -s 85 -n 5 using seed=85
106
91
248
209
54
```

Part 3: Block encryption with cipher block chaining and padding

This is an enhancement of Part 2 to use the concepts of:

- Processing data in 16-byte blocks
- Padding – adding it and removing it correctly
- Shuffling bits within a block
- Cipher block chaining.

We modify the stream cipher above to have it operate on 16-byte blocks instead of bytes. This turns it into a form of block cipher. A block cipher generally uses multiple iterations (rounds) through an SP-network (substitutions & permutations) to add confusion & diffusion. Confusion refers to changing bit values as a function of the key so that each bit of the ciphertext is determined by several parts of the key. Diffusion refers to the property that a change in one bit of plaintext will result in many bits of the ciphertext changing within the block (about half).

In this implementation, we will not use multiple rounds of an SP network. Instead, we will keep the mechanisms of the stream cipher in place but enhance it in two ways: cipher block chaining and shuffling bytes within the block.

Padding

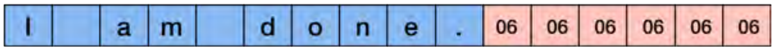
Block ciphers work on a block (a group of bytes) of data at a time. In our case, we will be processing 16-byte blocks.

Not every file is an exact multiple of 16 bytes so we may encounter a partial block at the end. To support this, every block cipher needs to support padding, which is the mechanism for adding extra bytes to fill the block. Padding must be added in such a way that we can detect and remove the padding when decrypting a message.

The way you will implement padding is by adding between 1 and 16 extra bytes at the end of the file. Each byte of the padding data is a number that tells you how many bytes were added. This is a technique that allows you to know how much padding needs to be removed when decrypting and writing the plaintext output.

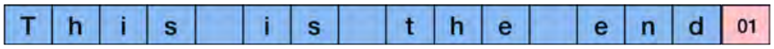
In the case that the file was an exact multiple of 16 bytes, we add an entire extra block of padding. Otherwise, we would never know if we had padding. Simply looking at the last byte of the last block of the file will tell us how much padding to ignore.

Here are a few examples. In the first, the text "`I am done.`" takes up 10 bytes so we have 6 bytes left over. Each of those bytes will contain a pad byte with a value of 6. Note that this is not the ASCII character 6 but the number 6.



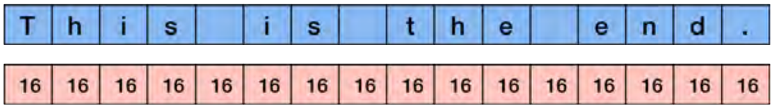
I		a	m		d	o	n	e	.	06	06	06	06	06	06

In this example, we have the text "`This is the end`". It takes up 15 bytes, so we need to add one byte of padding. This padding byte contains the value 1.



T	h	i	s		i	s		t	h	e		e	n	d	01

In the final example, we have the text "`This is the end.`" with a period at the end. This message takes up exactly 16 bytes. Because of this, we need to add an extra block filled with bytes containing the number 16.



T	h	i	s		i	s		t	h	e		e	n	d	.
16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16

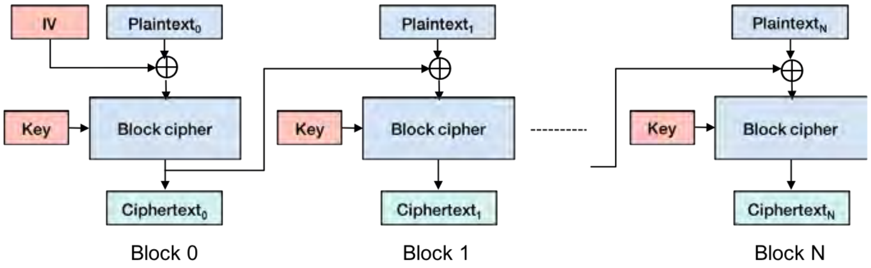
When you decode the message, you will need to remove the padding.

We will not use multiple rounds of an SP network. Instead, we will keep the mechanisms of the stream cipher in place but enhance it in two ways: cipher block chaining and byte shuffling within a block (a simple form of permutations).

Cipher block chaining

Stream ciphers have no diffusion. The change of a bit in plaintext will generally affect only that bit in ciphertext. We will add diffusion across the output by adding cipher block chaining (CBC). With cipher block chaining, we exclusive-or the previous block with the next block.

$$c_i = E_K(m_i) \oplus c_{i-1}$$



Byte shuffling

Confusion is roughly determined by the seed and the pseudorandom output of the keystream generator in this implementation, but we will enhance the degree of confusion by shuffling bytes of the block.

We will use the key to determine which sets of bytes in the block to exchange (swap). For each 16-byte block, do the following:

```
for (i=0; i < blocksize; i=i+1)
      first = key[i] & 0xf  (lower 4 bits of the keystream)
      second = (key[i] >> 4) & 0xf  (top 4 bits of the keystream)
      swap(block[first], block[second])  (exchange the bytes)
```

Cipher operation

The flow of the cipher is the following

Start by creating an initialization vector (IV) for applying CBC to the first block. This will be the first 16 bytes read from the keystream generator. These bytes will not be used for anything else.

Then, for each 16-byte plaintext_block *i*:

1. If it is the last block, add padding. This will be an amount from 1 through 16 bytes (e.g., finish up a block or add a new block). The padding is added before any encryption or shuffling takes place.
2. Apply CBC: $temp\_block_N = plaintext\_block_N \oplus ciphertext\_block_{N-1}$
   Use the initialization vector if this is the first block.
3. Read 16 bytes from the keystream.
4. Shuffle the bytes based on the keystream data.

5. $ciphertext\_block_N = temp\_block_N \oplus keystream_N$.
6. Write $ciphertext\_block_N$.

You need to use the same password hashing and keystream generator as in Part 2.

You will need to write two programs for this part, one to encrypt and another to decrypt:

```
sbencrypt password plaintext ciphertext
sbdecrypt password ciphertext plaintext
```

As with Part 2, the program will take a `password` string, which will be hashed and used as a seed for the keystream generator. The parameters `plaintext` and `ciphertext` are both file names.

Reference programs

It's important that encryption software works consistently across multiple systems regardless of author, programming language, or operating system. I should be able to encrypt a message on my Mac and expect you to be able to decrypt it with your program on your Raspberry Pi running Linux.

You are provided with reference versions of the programs that you can use to compare with yours and, perhaps, help debug your code. The `linux` directory contains intel architecture linux versions of the executables and the `macos` directory contains macOS versions (arm64 and i386 universal binary). The `samples` directory contains some sample files you can use for testing, but you should also create your own files and keys to test your program thoroughly. Be sure to test edge cases, such as empty files, one-byte files, and files that require different amount of padding (for the block cipher).

Here are the programs provided:

Binary Vigenère Cipher

```
vencrypt [-d] [keyfile | -k key] plaintext ciphertext
```

Encrypt a *plaintext* file to create a *ciphertext* file using key data stored in *keyfile*. Alternatively, you can specify a textual keyfile with the -k option. For example,

```
vencrypt -k monkey01 file.txt file.enc
```

Will use the bytes in the string "`monkey01`" as the key. This limits the key space but may be useful for debugging.

The `-d` flag turns on debugging information and shows you what lookups are taking place (note that you do not need to implement a table but can do so if you find that easier).

Stream Cipher – keystream test

Before you test your cipher, make sure that your password hash and pseudorandom number generator are producing the proper results. You can test this with the `prand-test` program:

```
prand-test [-p password | -s seed] [-n num]
```

If the program is supplied a password with the `-p` parameter, the password will be hashed and the result shown.

The `-n` parameter lets you specify the number of pseudorandom numbers to be printed. The default is 0.

If you just want to see the list of pseudorandom numbers generated from a specific seed, you can specify a seed number instead of a password with the `-s` parameter.

Stream Cipher

```
scrypt [-d] password plaintext ciphertext
```

Encrypt a *plaintext* file into a *ciphertext* file using a keystream derived from the *password* string. The same command decrypts a *ciphertext* file into a *plaintext* file.

```
scrypt [-d] password ciphertext plaintext
```

The `-d` flag turns on debugging mode and shows the series of xor operations from the source file to the output file.

Block Cipher

```
sbencrypt [-d] password plaintextfile ciphertextfile
```

Encrypts a *plaintext* file into a *ciphertext* file using a keystream derived from the *password* string. The command:

```
sbdecrypt [-d] password ciphertextfile plaintextfile
```

Decrypts a *ciphertext* file into a *plaintext* file using a keystream derived from the *password* string.

For both commands, the `-d` flag enables debugging, showing the sequence of shuffling per block.

What to submit

Place your source code into a single *zip* file. If code needs to be compiled (i.e., Java, C, or Go), please include a `Makefile` that will create the necessary executables.

We don't want to figure out how to run your program. We expect to:

1. unzip your submission
2. run make if there's a Makefile
3. Set the mode of the programs to executable:
   ```
   chmod u+x vencrypt vdecrypt scrypt sbencrypt sbdecrypt
   ```
4. Run the commands as:
   ```
       ./vencrypt keyfile plaintext ciphertext
       ./sbencrypt password plaintext ciphertext
   ```

If you are using python, you can submit either:

A. A `vencrypt` shell script that runs the program or

B. (preferably) a program named `vencrypt` that that contains your source and starts with the line:

```
#!/usr/bin/python3
```

If you are using Java, you will have a simple `makefile` that compiles the Java code to produce class files. The `vencrypt` program will be a script that runs the *java* command with the necessary arguments. The file vencrypt will contain content like this:

```
#!/bin/bash
CLASSPATH=. java Vencrypt "$@"
```

Test your scripts on an iLab machine to make sure they work prior to submitting.