Assignment 7
The Great Firewall of Santa Cruz: Bloom Filters, Linked Lists and Hash Tables

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1 Introduction

> *War is peace. Freedom is slavery. Ignorance is strength.*
>
> —George Orwell, 1984

You have been selected through thoroughly democratic processes (and the machinations of your friend and hero Ernst Blofeld) to be the Dear and Beloved Leader of the Glorious People's Republic of Santa Cruz following the failure of the short-lived anarcho-syndicalist commune, where each person in turn acted as a form of executive officer for the week but all the decisions of that officer have to be ratified at a special bi-weekly meeting by a simple majority in the case of purely internal affairs, but by a two-thirds majority in the case of more major decisions. Where it was understood that strange women lying in ponds distributing swords is no basis for a system of government. Supreme executive power derives from a mandate from the masses, not from some farcical aquatic ceremony. It was a very silly place, and so with Herr Blofeld's assistance you are now the leader of your people.

In order to promote virtue and prevent vice, and to preserve social cohesion and discourage unrest, you have decided that the Internet content must be filtered so that your beloved children are not corrupted through the use of unfortunate, hurtful, offensive, and far too descriptive language.

2 Bloom Filters

> *The Ministry of Peace concerns itself with war, the Ministry of Truth with lies, the Ministry of Love with torture and the Ministry of Plenty with starvation. These contradictions are not accidental, nor do they result from from ordinary hypocrisy: they are deliberate exercises in* ***doublethink****.*
>
> —George Orwell, 1984

The Internet is very large, very fast, and full of *badthink*. The masses spend their days sending each other cat videos and communicating through their beloved social media platforms: Twitter and Discord. To your dismay, you find that a portion of the masses frequently use words you deem improper—*oldspeak*. You decide, as the newly elected Dear and Beloved Leader of the Glorious People's Republic of Santa Cruz (GPRSC), that a more neutral *newspeak* is required to keep your citizens of the GPRSC content, pure, and from thinking too much. But how do you process and store so many words as they flow in and out of the GPRSC at 10 Gbits/second? The solution comes to your brilliant and pure mind—a *Bloom filter*.

A Bloom filter is a space-efficient probabilistic data structure, conceived by Burton H. Bloom in 1970, and is used to test whether an element is a member of a set. False-positive matches are possible, but false negatives are not—in other words, a query for set membership returns either "possibly in the set" or "definitely not in the set." Elements can be added to the set but not removed from it; the more elements added, the higher the probability of false positives.

A Bloom filter can be represented as an array of m bits, or a **bit vector**. A Bloom filter should utilize k different hash functions. Using these hash functions, a set element added to the Bloom filter is mapped to at most k of the m bit indices, generating a uniform pseudo-random distribution. Typically, k is a small constant which depends on the desired false error rate ϵ, while m is proportional to k and the number of elements to be added.

Assume you are adding a word w to your Bloom filter and are using $k = 3$ hash functions, $f(x)$, $g(x)$, and $h(x)$. To add w to the Bloom filter, you simply set the bits at indices $f(w)$, $g(w)$, and $h(w)$. To check if some word w' has been added to the same Bloom filter, you check if the bits at indices $f(w')$, $g(w')$, and $h(w')$ are set. If they are all set, then w' has *most likely* been added to the Bloom filter. If any one of those bits was cleared, then w' has definitely *not* been added to the Bloom filter. The fact that the Bloom filter can only tell if some word has *most likely* been added to the Bloom filter means that *false positives* can occur. The larger the Bloom filter, the lower the chances of getting false positives.

So what do Bloom filters mean for you as the Dear and Beloved Leader? It means you can take a list of proscribed words, *oldspeak* and add each word into your Bloom filter. If any of the words that your citizens use seem to be added to the Bloom filter, then this is very ungood and further action must be taken to discern whether or not the citizen did transgress. You decide to implement a Bloom filter with *three* salts for *three* different hash functions. Why? To reduce the chance of a *false positive*.

You can think of a "salt" as an initialization vector or a key. Using different salts with the same hash function results in a different, unique hash. Since you are equipping your Bloom filter with three different salts, you are effectively getting three different hash functions: $f(x)$, $g(x)$, and $h(x)$. Hashing a word w, with extremely high probability, should result in $f(w) \neq g(w) \neq h(w)$. These salts are to be used for the SPECK cipher, which requires a 128-bit key, so we have used MD5 [1] "message-digest" to reduce three books down to 128 bits each. You will use the SPECK cipher as a hash function, which will be discussed in §4.

2.1 `BloomFilter`

The following `struct` defines the `BloomFilter` ADT. The three salts will be stored in the `primary`, `secondary`, and `tertiary` fields. Each salt is 128 bits in size. To hold these 128 bits, we use an array of two `uint64_t`s. This `struct` definition *must* go in `bf.c`.

```
1 struct BloomFilter {
2   uint64_t primary[2];   // Primary hash function salt.
3   uint64_t secondary[2]; // Secondary hash function salt.
4   uint64_t tertiary[2];  // Tertiary hash function salt.
5   BitVector *filter;
6 };
```

2.2 `BloomFilter *bf_create(uint32_t size)`

The constructor for a Bloom filter. Working code for the constructor, complete with primary, secondary, and tertiary salts that you will use, is shown below. Note that you will also have to implement the bit vector ADT for your Bloom filter, as it will serve as the array of bits necessary for a proper Bloom filter.

[1] Rivest, R.. "The MD5 Message-Digest Algorithm." RFC 1321 (1992): 1-21.

```
BloomFilter *bf_create(uint32_t size) {
  BloomFilter *bf = (BloomFilter *) malloc(sizeof(BloomFilter));
  if (bf) {
    // Grimm's Fairy Tales
    bf->primary[0] = 0x5adf08ae86d36f21;
    bf->primary[1] = 0xa267bbd3116f3957;
    // The Adventures of Sherlock Holmes
    bf->secondary[0] = 0x419d292ea2ffd49e;
    bf->secondary[1] = 0x09601433057d5786;
    // The Strange Case of Dr. Jekyll and Mr. Hyde
    bf->tertiary[0] = 0x50d8bb08de3818df;
    bf->tertiary[1] = 0x4deaae187c16ae1d;
    bf->filter = bv_create(size);
    if (!bf->filter) {
      free(bf);
      bf = NULL;
    }
  }
  return bf;
}
```

2.3 `void bf_delete(BloomFilter **bf)`

The destructor for a Bloom filter. As with all other destructors, it should free any memory allocated by the constructor and null out the pointer that was passed in.

2.4 `uint32_t bf_size(BloomFilter *bf)`

Returns the size of the Bloom filter. In other words, the number of bits that the Bloom filter can access. Hint: this is the length of the underlying bit vector.

2.5 `void bf_insert(BloomFilter *bf, char *oldspeak)`

Takes `oldspeak` and inserts it into the Bloom filter. This entails hashing `oldspeak` with each of the three salts for three indices, and setting the bits at those indices in the underlying bit vector.

2.6 `bool bf_probe(BloomFilter *bf, char *oldspeak)`

Probes the Bloom filter for `oldspeak`. Like with `bf_insert()`, `oldspeak` is hashed with each of the three salts for three indices. If all the bits at those indices are set, return `true` to signify that `oldspeak` was most likely added to the Bloom filter. Else, return `false`.

2.7 `uint32_t bf_count(BloomFilter *bf)`

Returns the number of set bits in the Bloom filter.

2.8 `void bf_print(BloomFilter *bf)`

A debug function to print out a Bloom filter.

3 Hashing with the SPECK Cipher

You will need a good hash function to use in your Bloom filter and hash table (discussed in §5). We will have discussed hash functions in lecture, and rather than risk having a poor one implemented, we will simply provide you one. The SPECK[2] block cipher is provided for use as a hash function.

SPECK is a family of lightweight block ciphers publicly released by the National Security Agency (NSA) in June 2013. SPECK has been optimized for performance in software implementations, while its sister algorithm, SIMON, has been optimized for hardware implementations. SPECK is an add-rotate-xor (ARX) cipher. The reason a cipher is used for this is because encryption generates random output given some input; exactly what we want for a hash.

Encryption is the process of taking some file you wish to protect, usually called plaintext, and transforming its data such that only authorized parties can access it. This transformed data is referred to as ciphertext. Decryption is the inverse operation of encryption, taking the ciphertext and transforming the encrypted data back to its original state as found in the original plaintext. Encryption algorithms that utilize the same key for both encryption and decryption, like SPECK, are symmetric-key algorithms, and algorithms that don't, such as RSA, are asymmetric-key algorithms.

You will be given two files, `speck.h` and `speck.c`. The former will provide the interface to using the SPECK hash function which has been named `hash()`, and the latter contains the implementation. The hash function `hash()` takes two parameters: a 128-bit salt passed in the form of an array of two `uint64_t`s, and a key to hash. The function will return a `uint32_t` which is exactly the index the key is mapped to.

```
1 uint32_t hash(uint64_t salt[], char *key);
```

4 Bit Vectors

> *Symmetrical equations are good in their place, but 'vector' is a useless survival, or offshoot from quaternions, and has never been of the slightest use to any creature.*
>
> —Lord Kelvin

You will reuse much of the bit vector implementation from assignment 5 for this assignment. If there were any problems with your implementation, make sure to fix them here.

```
1 struct BitVector {
2   uint32_t length;
3   uint8_t *vector;
4 };
```

4.1 `BitVector *bv_create(uint32_t length)`

The constructor for a bit vector. In the even that sufficient memory cannot be allocated, the function must return `NULL`. Else, it must return a `BitVector *)`, or a pointer to an allocated `BitVector`. Each bit of the bit vector should be initialized to 0.

4.2 `void bv_delete(BitVector **bv)`

The destructor for a bit vector. Remember to set the pointer to `NULL` after the memory associated with the bit vector is freed.

[2] Ray Beaulieu, Stefan Treatman-Clark, Douglas Shors, Bryan Weeks, Jason Smith, and Louis Wingers, "The SIMON and SPECK lightweight block ciphers." In Proceedings of the 52nd ACM/EDAC/IEEE Design Automation Conference (DAC), pp. 1–6. IEEE, 2015.

4.3 `uint32_t bv_length(BitVector *bv)`

Returns the length of a bit vector.

4.4 `void bv_set_bit(BitVector *bv, uint32_t i)`

Sets the i^{th} bit in a bit vector. To set a bit in a bit vector, it is necessary to first locate the byte in which the i^{th} resides. The location of the byte is calculated as `i / 8`. The position of the bit in that byte is calculated as `i % 8`. Setting a bit in a bit vector should not modify any of the other bits.

4.5 `void bv_clr_bit(BitVector *bv, uint32_t i)`

Clears the i^{th} bit in the bit vector.

4.6 `uint8_t bv_get_bit(BitVector *bv, uint32_t i)`

Returns the i^{th} bit in the bit vector.

4.7 `void bv_print(BitVector *bv)`

A debug function to print a bit vector. Write this immediately after the constructor.

5 Hash Tables

> *To send men to the firing squad, judicial proof is unnecessary . . . These procedures are an archaic bourgeois detail.*
>
> Ernesto Ché Guevara

Armed with a Bloom filter, you now exercise the power to catch and punish those who practice wrongthink and continue to use oldspeak. It comes to mind however, that a Bloom filter is probabilistic and that it is better to exercise mercy and counsel the oldspeakers so that they may atone and use *newspeak*. To remedy this, another solution pops into your brilliant and pure mind—a *hash table*.

A hash table is a data structure that maps keys to values and provides fast, O(1), look-up times. It does so typically by taking a key k, hashing it with some hash function $h(x)$, and placing the key's corresponding value in an underlying array at index $h(k)$. This is the perfect way not only to store translations from oldspeak to newspeak, but also as a way to store all prohibited oldspeak words without newspeak translations. We will refer to oldspeak without newspeak translations as *badspeak*. So what happens when two *oldspeak* words have the same hash value? This is called a *hash collision*, and must be resolved. Rather than doing *open addressing* (as will be discussed in lecture), we will be using *linked lists* to resolve *oldspeak* hash collisions.

5.1 `HashTable`

Below is the `struct` definition for a hash table. Similar to a Bloom filter, a hash table contains a salt which is passed to `hash()` whenever a new oldspeak entry is being inserted. As mentioned in §5, we will be using linked lists to resolve oldspeak hash collisions, which is why a hash table contains an array of linked lists. The `mtf` field indicates whether or not the linked lists should use the *move-to-front* technique, which will be discussed in §5.6.

```c
struct HashTable {
  uint64_t salt[2];
  uint32_t size;
  bool mtf;
  LinkedList **lists;
};
```

5.2 `HashTable *ht_create(uint32_t size, bool mtf)`

The constructor for a hash table. The `size` parameter denotes the number of indices, or linked lists, that the hash table can index up to. The salt for the hash table has been supplied in the constructor as well.

```c
HashTable *ht_create(uint32_t size, bool mtf) {
  HashTable *ht = (HashTable *) malloc(sizeof(HashTable));
  if (ht) {
    // Leviathan
    ht->salt[0] = 0x9846e4f157fe8840;
    ht->salt[1] = 0xc5f318d7e055afb8;
    ht->size = size;
    ht->mtf = mtf;
    ht->lists = (LinkedList **) calloc(size, sizeof(LinkedList *));
    if (!ht->lists) {
      free(ht);
      ht = NULL;
    }
  }
  return ht;
}
```

5.3 `void ht_delete(HashTable **ht)`

The destructor for a hash table. Each of the linked lists in `lists`, the underlying array of linked lists, is freed. The pointer that was passed in should be set to `NULL`.

5.4 `uint32_t ht_size(HashTable *ht)`

Returns the hash table's size.

5.5 `Node *ht_lookup(HashTable *ht, char *oldspeak)`

Searches for an entry, a node, in the hash table that contains `oldspeak`. A node stores oldspeak and its newspeak translation. The index of the linked list to perform a look-up on is calculated by hashing the `oldspeak`. If the node is found, the pointer to the node is returned. Else, a `NULL` pointer is returned.

5.6 `void ht_insert(HashTable *ht, char *oldspeak, char *newspeak)`

Inserts the specified `oldspeak` and its corresponding `newspeak` translation into the hash table. The index of the linked list to insert into is calculated by hashing the `oldspeak`. If the linked list that should be inserted into hasn't been initialized yet, create it first before inserting the oldspeak and newspeak.

5.7 `uint32_t ht_count(HashTable *ht)`

Returns the number of non-`NULL` linked lists in the hash table.

5.8 `void ht_print(HashTable *ht)`

A debug function to print out the contents of a hash table. Write this immediately after the constructor.

6 Linked Lists

> *Education is a weapon, whose effect depends on who holds it in his hands and at whom it is aimed.*
>
> —Joseph Stalin

A *linked list* will be used to resolve hash collisions. Each node of the linked list contains *oldspeak* and its *newspeak* translation if it exists. The *key* to search with in the linked list is *oldspeak*. Each node will also contain a pointer to the previous node *and* the next node in the linked list. This is because you will be implementing *doubly linked lists*.

6.1 `Node`

A node is defined with the following `struct`:

```
1 struct Node {
2   char *oldspeak;
3   char *newspeak;
4   Node *next;
5   Node *prev;
6 };
```

If the `newspeak` field is `NULL`, then the oldspeak contained in this node is badspeak, since there is no newspeak translation. This `struct` definition and interface for the node ADT will be provided for you in `node.h`. The node ADT is not opaque in order to simplify the rest of the linked list implementation.

6.2 `Node *node_create(char *oldspeak, char *newspeak)`

The constructor for a node. You will want to make a *copy* of the `oldspeak` and its `newspeak` translation that are passed in. What this means is *allocating memory* and copying over the characters for both `oldspeak` and `newspeak`. There was a function `strdup()` that did precisely that, but it has been deprecated. You will find it helpful to implement your own function to mimic `strdup()`.

6.3 `void node_delete(Node **n)`

The destructor for a node. Only the node `n` is freed. The previous and next nodes that `n` points to *are not* deleted. Since you have allocated memory for `oldspeak` and `newspeak`, remember to free the memory allocated to both of those as well. The pointer to the node should be set to `NULL`.

6.4 `void node_print(Node *n)`

While helpful as debug function, you will use this function to produce correct program output. Thus, it is imperative that you print out the contents of a node in the following manner:

- If the node `n` contains oldspeak *and* newspeak, print out the node with this print statement:

```
printf("%s -> %s\n", n->oldspeak, n->newspeak);
```

- If the node `n` contains *only* oldspeak, meaning that newspeak is null, then print out the node with this print statement:

```
printf("%s\n", n->oldspeak);
```

6.5 `LinkedList`

The `struct` definition of a linked list is given below. A linked list, when constructed, will initially have two *sentinel* nodes, which will be further explained in §6.6 where the constructor function is discussed along with the rationale and usage of the sentinel nodes. The field `mtf` signifies the *move-to-front* technique, which will be further explained in §6.6 and §6.10. The linked list interface, defined in `ll.h`, will contain the declaration of two `extern` variables: `seeks` and `links`. These two variables should be defined in `ll.c`. You will use these variables to calculate statistics, where `seeks` tracks the number of linked list lookups performed, and `links` counts the total number of links traversed.

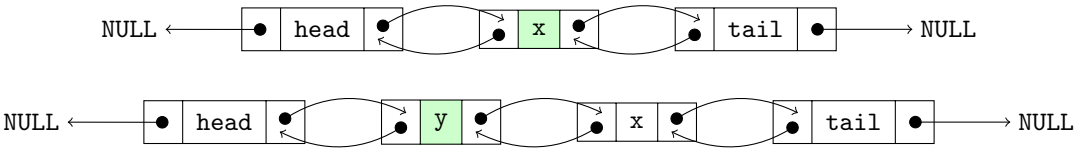
```
struct LinkedList {
  uint32_t length;
  Node *head; // Head sentinel node.
  Node *tail; // Tail sentinel node.
  bool mtf;
};
```

6.6 `LinkedList *ll_create(bool mtf)`

The constructor for a linked list. The only parameter that this function takes is a boolean, `mtf`. If `mtf` is `true`, that means any node that is found in the linked list through a look-up is *moved to the front* of the linked list. To simplify the code to insert nodes into the linked list, your linked lists will be initialized with exactly two *sentinel nodes*. They will serve as the head and the tail of the linked list.

A linked list that is not initialized with sentinel nodes exhibits two different cases when inserting a node. The first case is when the linked list is empty and contains no nodes. This means the inserted node becomes the head of the linked list. The second case is when the linked list contains at least one node, which means the inserted node becomes the new head of the linked list and must point to the old head of the linked list. The old head of the linked list must also point back to the new head to preserve the properties of a doubly linked list.

Using two sentinel nodes reduces the insertion cases down to one: every inserted node will go between two nodes. Why? Because there are already two nodes to start with. The following diagrams showcase, in order, a linked list when initialized, the linked list when a node containing `x` is inserted, and then the linked list when a node containing `y` is inserted. Note that inserting a node into a linked list means inserting it *at the head*.



6.7 `void ll_delete(LinkedList **ll)`

The destructor for a linked list. Each node in the linked list should be freed using `node_delete()`. The pointer to the linked list should be set to `NULL`.

6.8 `uint32_t ll_length(LinkedList *ll)`

Returns the length of the linked list, which is equivalent to the number of nodes in the linked list, *not* including the head and tail sentinel nodes.

6.9 `Node *ll_lookup(LinkedList *ll, char *oldspeak)`

Searches for a node containing `oldspeak`. If a node is found, the pointer to the node is returned. Else, a `NULL` pointer is returned. If a node was found and the move-to-front option was specified when constructing the linked list, then the found node is moved to the front of the linked list. The move-to-front technique decreases look-up times for nodes that are frequently searched for. You will learn more about optimality in your future classes.

6.10 `void ll_insert(LinkedList *ll, char *oldspeak, char *newspeak)`

Inserts a new node containing the specified `oldspeak` and `newspeak` into the linked list. Before inserting the node, a look-up is performed to make sure the linked list *does not* already contain a node containing a matching `oldspeak`. If a duplicate exists, a new node is not inserted into the linked list. Else, the new node is inserted *at the head* of the linked list. This means that the new node comes directly after the head sentinel node.

6.11 `void ll_print(LinkedList *ll)`

Prints out each node in the linked list *except* for the head and tail sentinel nodes. This will require the use of `node_print()`.

7 Lexical Analysis with Regular Expressions

> *Ideas are more powerful than guns. We would not let our enemies have guns, why should we let them have ideas.*
>
> —Joseph Stalin

Back to regulating your citizens of the GPRSC. You will need a function to parse out the words that they speak, which will be passed to you in the form of an input stream. The words that they will use are valid words, which can include *contractions* and *hyphenations*. A valid word is any sequence of one or more characters that are part of your regular expression word character set. Your word character set should contain characters from a–z, A–Z, 0–9, and the underscore character. Since you also accept contractions like "don't" and "y'all've" and hyphenations like "pseudo-code" and "move-to-front", your word character set should include apostrophes and hyphens as well.

You will need to write your own *regular expression* for a word, utilizing the `regex.h` library to lexically analyze the input stream for words. You will be given a parsing module that lexically analyzes the input stream using your regular expression. You are not required to use the module itself, but it is *mandatory* that you parse through

an input stream for words using at least one regular expression. The interface for the parsing module will be in `parser.h` and its implementation will be in `parser.c`.

The function `next_word()` requires two inputs, the input stream `infile`, and a pointer to a compiled regular expression, `word_regex`. Notice the word *compiled*: you must first compile your regular expression using `regcomp()` before passing it to the function. Make sure you remember to call the function `clear_words()` to free any memory used by the module when you're done reading in words. Here is a small program that prints out words input to `stdin` using the parsing module. In the program, the regular expression for a word matches one or more lowercase and uppercase letters. The regular expression you will have to write for your assignment will be more complex than the one displayed here, as it is just an example.

Example program using the parsing module.

```
#include "parser.h"
#include <regex.h>
#include <stdio.h>

#define WORD "[a-zA-Z]+"

int main(void) {
    regex_t re;
    if (regcomp(&re, WORD, REG_EXTENDED)) {
        fprintf(stderr, "Failed to compile regex.\n");
        return 1;
    }

    char *word = NULL;
    while ((word = next_word(stdin, &re)) != NULL) {
        printf("Word: %s\n", word);
    }

    clear_words();
    regfree(&re);
    return 0;
}
```

8 Your Task

The people will believe what the media tells them they believe.

—George Orwell

- Initialize your Bloom filter and hash table.
- Read in a list of *badspeak* words with `fscanf()`. Again, badspeak is simply oldspeak without a newspeak translation. Badspeak is strictly forbidden. Each badspeak word should be added to the Bloom filter and the hash table. The list of proscribed words will be in `badspeak.txt`, which can be found in the `resources` repository.
- Read in a list of *oldspeak* and *newspeak* pairs with `fscanf()`. Only the oldspeak should be added to the Bloom filter. The oldspeak *and* newspeak are added to the hash table. The list of oldspeak and newspeak pairs will be in `newspeak.txt`, which can also be found in the `resources` repository.

- Now that the lexicon of badspeak and oldspeak/newspeak translations has been populated, you can start to filter out words. Read words in from `stdin` using the supplied parsing module.
- For each word that is read in, check to see if it has been added to the Bloom filter. If it has not been added to the Bloom filter, then no action is needed since the word isn't a proscribed word.
- If the word has most likely been added to the Bloom filter, meaning `bf_probe()` returned `true`, then further action needs to be taken.
    1. If the hash table contains the word and the word *does not* have a newspeak translation, then the citizen who used this word is guilty of `thoughtcrime`. Insert this badspeak word into a list of badspeak words that the citizen used in order to notify them of their errors later.
    2. If the hash table contains the word, and the word *does* have a newspeak translation, then the citizen requires counseling on proper *Rightspeak*. Insert this oldspeak word into a list of oldspeak words with newspeak translations in order to notify the citizen of the revisions needed to be made in order to practice Rightspeak.
    3. If the hash table does not contain the word, then all is good since the Bloom filter issued a false positive. No disciplinary action needs to be taken.
- If the citizen is accused of thoughtcrime *and* requires counseling on proper *Rightspeak*, then they are given a reprimanding *mixspeak message* notifying them of their transgressions and promptly sent off to *joycamp*. The message should contain the list of badspeak words that were used followed by the list of oldspeak words that were used with their proper newspeak translations.

```
Dear beloved citizen of the GPRSC,

We have some good news, and we have some bad news.
The good news is that there is bad news. The bad news is that you will
be sent to joycamp and subjected to a week-long destitute existence.
This is the penalty for using degenerate words, as well as using
oldspeak in place of newspeak. We hope you can correct your behavior.

Your transgressions, followed by the words you must think on:

kalamazoo
antidisestablishmentarianism
write -> papertalk
sad -> happy
read -> papertalk
music -> noise
liberty -> badfree
```

- If the citizen is accused solely of thoughtcrime, then they are issued a thoughtcrime message and also sent off to *joycamp*. The *badspeak message* should contain the list of badspeak words that were used.

```
Dear beloved citizen of the GPRSC,

You have been caught using degenerate words that may cause
distress among the moral and upstanding citizens of the GPSRC.
As such, you will be sent to joycamp. It is there where you will
sit and reflect on the consequences of your choice in language.

Your transgressions:
```

```
kalamazoo
antidisestablishmentarianism
```

- If the citizen only requires counseling, then they are issued an encouraging *goodspeak message*. They will read it, correct their *wrongthink*, and enjoy the rest of their stay in the GPRSC. The message should contain the list of oldspeak words that were used with their proper newspeak translations.

```
Dear beloved citizen of the GPRSC,

We recognize your efforts in conforming to the language standards
of the GPSRC. Alas, you have been caught uttering questionable words
and thinking unpleasant thoughts. You must correct your wrongspeak
and badthink at once. Failure to do so will result in your deliverance
to joycamp.

Words that you must think on:

write -> papertalk
sad -> happy
read -> papertalk
music -> noise
liberty -> badfree
```

- Each of the messages are defined for you in `messages.h`. You may not modify this file.
- The list of the command-line options your program must support is listed below. *Any* combination of the command-line options must be supported.
  - `-h` prints out the program usage. Refer to the reference program in the resources repository for what to print.
  - `-t size` specifies that the hash table will have `size` entries (the default will be 10000).
  - `-f size` specifies that the Bloom filter will have `size` entries (the default will be 2^{20}).
  - `-m` will enable the *move-to-front rule*. By default, the move-to-front rule is *disabled*.
  - `-s` will enable the printing of statistics to `stdout`. The statistics to calculate are the total number of seeks, the average seek length, the hash table load, and the Bloom filter load. The calculations for the latter three statistics are as follows:

$$\text{Average seek length} = \frac{\texttt{links}}{\texttt{seeks}}$$

$$\text{Hash table load} = 100 \times \frac{\texttt{ht\_count()}}{\texttt{ht\_size()}}$$

$$\text{Bloom filter load} = 100 \times \frac{\texttt{bf\_count()}}{\texttt{bf\_size()}}$$

    The hash table load and Bloom filter load should be printed with up to 6 digits of precision. Enabling the printing of statistics should *suppress all messages* the program may otherwise print.

9 Deliverables

> *I would rather have questions that can't be answered than answers that can't be questioned.*
>
> —Richard P. Feynman

You will need to turn in:

1. `banhammer.c`: This contains `main()` and *may* contain the other functions necessary to complete the assignment.
2. `messages.h`: Defines the mixspeak, badspeak, and goodspeak messages that are used in `banhammer.c`. Do not modify this.
3. `speck.h`: Defines the interface for the hash function using the SPECK cipher. Do not modify this.
4. `speck.c`: Contains the implementation of the hash function using the SPECK cipher. Do not modify this.
5. `ht.h`: Defines the interface for the hash table ADT. Do not modify this.
6. `ht.c`: Contains the implementation of the hash table ADT.
7. `ll.h`: Defines the interface for the linked list ADT. Do not modify this.
8. `ll.c`: Contains the implementation of the linked list ADT.
9. `node.h`: Defines the interface for the node ADT. Do not modify this.
10. `node.c`: Contains the implementation of the node ADT.
11. `bf.h`: Defines the interface for the Bloom filter ADT. Do not modify this.
12. `bf.c`: Contains the implementation of the Bloom filter ADT.
13. `bv.h`: Defines the interface for the bit vector ADT. Do not modify this.
14. `bv.c`: Contains the implementation of the bit vector ADT.
15. `parser.h`: Defines the interface for the regex parsing module. Do not modify this.
16. `parser.c`: Contains the implementation of the regex parsing module.
17. You may have other source and header files, but *do not make things overly complicated.*
18. `Makefile`: This is a file that will allow the grader to type `make` to compile your program.
    - `CC=clang` must be specified.
    - `CFLAGS=-Wall -Wextra -Werror -Wpedantic` must be included.
    - `make` should build the `banhammer` executable, as should `make all`.
    - `make clean` must remove all files that are compiler generated.
    - `make format` should format all your source code, including the header files.
19. Your code must pass `scan-build` *cleanly*. If there are any bugs or errors that are false positives, document them and explain why they are false positives in your `README.md`.
20. `README.md`: This must be in Markdown. This must describe how to use your program and `Makefile`. This includes listing and explaining the command-line options that your program accepts. Any false positives reported by `scan-build` should go here as well.

21. `DESIGN.pdf`: This *must* be a PDF. The design document should describe your design for your program with enough detail that a sufficiently knowledgeable programmer would be able to replicate your implementation. This does not mean copying your entire program in verbatim. You should instead describe how your program works with supporting pseudocode. For this program, pay extra attention to how you build each necessary component.

22. `WRITEUP.pdf`: This document *must* be a PDF. The writeup must include the following:

    - Graphs comparing the total number of seeks and average seek length as you vary the hash table and Bloom filter size.
      - Do linked lists get longer?
      - How does the number of links followed without using the move-to-front rule compare to the number of links followed using the rule?
      - How does changing the Bloom filter size affect the number of lookups performed in the hash table?
    - Analysis of the graphs you produce.

10 Submission

> *We can and must write in a language which sows among the masses hate, revulsion, and scorn toward those who disagree with us.*
>
> —Vladimir Lenin

To submit your assignment through `git`, refer to the steps shown in `asgn0` Remember: *add, commit,* and *push*! Your assignment is turned in *only* after you have pushed and submitted the commit ID to Canvas. Your design document is turned in *only* after you have pushed and submitted the commit ID to Canvas. If you forget to push, you have not turned in your assignment and you will get a *zero*. "I forgot to push" is not a valid excuse. It is *highly* recommended to commit and push your changes *often*.

11 Supplemental Readings

> *The more you read, the more things you will know. The more that you learn, the more places you'll go.*
>
> —Dr. Seuss

- *The C Programming Language* by Kernighan & Ritchie
  - Chapter 5 §5.7
  - Chapter 7
- *Introduction to Algorithms* by T. Cormen, C. Leiserson, R. Rivest, & C. Stein
  - Chapter 10 §10.2 (Linked lists)
  - Chapter 11 (Hash tables and hash functions)
- *Introduction to the Theory of Computation* by M. Sipser
  - Chapter 1 §1.3 (Regular expressions)

Ynhtu abj juvyr lbh pna, zbaxrl-obl.