Project 0: Implementing a Hash Table

CS 165, Data Systems

Goal and Motivation. The goal of Project 0 is to help you develop (or refresh) basic skills at designing and implementing data structures and algorithms. These skills will be essential for following the class. Project 0 is meant to be done prior to the semester or during the early weeks. If you are doing it before the semester feel free to contact the staff for any help or questions by coming to the office hours or posting in Piazza.

We expect that for most students Project 0 will take anything between a few days to a couple of weeks, depending in the student's background on the above areas. If you are having serious trouble navigating Project 0 then you should reconsider the decision to take CS165. You can expect the semester project to be multiple orders of magnitude more work and more complex.

How much extra work is this? Project 0 is actually designed as a part of the fourth milestone of the semester project. So after finishing Project 0 you will have refreshed some basic skills and you will have a part of your project as well.

Basic Project Description. In many computer applications, it is often necessary to store a collection of key-value pairs. For example, consider a digital movie catalog. In this case, keys are movie names and values are their corresponding movie descriptions. Users of the application look up movie names and expect the program to fetch their corresponding descriptions quickly. Administrators can insert, erase and update movie descriptions, and they want to execute these operations quickly as well. In general, any data structure that stores a collection of key-value pairs is called an associative array. It implements the following interface:

```
allocate (size);
put (key, value);
get (key, values_array);
erase (key);
deallocate();
```

The allocate command initializes a hash table of a given size. The put command stores a new key-value pair in the associative array. The get command retrieves all key-value pairs with a matching key and stores their values in values_array. The erase command removes all key-value pairs with a matching key. The deallocate command frees all memory taken up by the hash table.

An associative array can be implemented in many different ways, and the implementation determines the time it takes the three different commands (i.e., put, get and erase) to execute. In project 0, you will implement an associative array as a hash table. Relative to other data structures that can be used to implement an associative array (e.g., sorted array, linked list, etc), the distinguishing characteristic of a hash table is that the time to put, get and erase a key-value pair does not increase asymptotically with respect to the number of key-value pairs inserted so far, i.e., their runtime is O(1).

Programming Language. For your implementation, you will be using the C programming language. C is considered to be a low-level programming language. Low-level programming languages give the programmer fine control over how the program is executed in hardware. This enables the creation of very efficient implementations. However, it also opens up various pitfalls that do not exist in higher-level

programming languages (e.g., Java or Python). Throughout the project, we will examine several common problems that can occur when programming in C, how to fix them, and how to avoid them altogether. A brief tutorial on C is located here[1].

Instructions. Below we provide a guideline for implementing a hash table and its basic operations, e.g., putting, getting and erasing. We also provide a description of common implementation problems that may come up. In addition, we provide test scripts that will help you test your hash table for correctness and performance.

Getting Started: Skeleton code for your implementation is provided within the repository for the semester project within the src/project0 folder[2]. To access the code, install the version control system Git, for which an installation guide is located here[3]. If you do not already have a public key set on code.seas, log into it (using your SEAS username and password, not your HarvardID) and set up your public key on it. Through the command line, you can then clone the repository onto your own machine. More details on how to run the code and get started are in the README file in the project0 folder.

If you are a DCE student or an extension school student, follow these steps to get a seas account so you can access code.seas. (1) Sign up for a SEAS account using the following form below[4]. (2) Under “Affiliation” select “Enrolled in a SEAS class”. (3) For sponsor choose Stratos. (4) Include the course number in the “Courses and Groups” field.

1 Basic Implementation

A hash table uses a hash function h to map from keys onto random yet deterministic slots in an array. Thus, a key-value entry with key K is stored at index h(K) of the array, and looking up a key K requires searching in slot h(K) for a key-value pair with key K. You may use a hash function of your choosing (many common choices can be found online, though be sure to cite your source). A reasonable starting point is modular hashing, which involves taking the key modulo the size of the array.

A general concern is that the hash function may map multiple key-value pairs onto the same slot in the array. These phenomena are called collisions, as multiple entries collide in the same slot. To handle collisions, each slot in the array should point to a linked list. All key-value entries mapped by the hash function onto the same slot should be inserted to the same linked list. A lookup should quickly find the appropriate linked list and then traverse it to find the target key. This is illustrated in Figure 1. Note that the amount of time to find or insert an entry with key K is proportional to the length of the linked list at slot h(K) of the array.

Ideally, the hash function should distribute keys uniformly across the slots of the array so that the sizes of the linked lists all have lengths of 0 or 1. However, if the workload is skewed, some linked lists may grow disproportionately larger than others. In particular, suppose the workload has the characteristic that most keys are divisible by some common factor of N, the number of slots in the array. For example, in the case of Figure 1, N is 10, so suppose most keys are divisible by 5, which is a common factor of
10. If so, then most key-value pairs would reside in the same small set of linked lists: the ones at slots 0 and 5. This would result in poor performance. To minimize the chance of this happening, a common strategy is to set N to be a prime number. The intuition is that this minimizes the number of factors that can be common to the keys in the workload and N.

Your implementation should allow the existence of multiple key-value pairs with the same key. Thus, the put command simply appends an entry to the appropriate linked list, the get command returns all entries with a matching key, and the erase command removes all entries with a matching key. You should implement these commands inside the hash_table.c file, which provides further instructions.

For this step of project 0, only implement the allocate, put, get and deallocate commands. The erase command is covered in the next step.

[1] C tutorial: http://www.cprogramming.com/tutorial/c-tutorial.html
[2] Project 0 skeleton code: https://bitbucket.org/HarvardDASlab/project0-cs165-2016/src/master/
[3] Git installation guide: https://confluence.atlassian.com/bitbucket/set-up-git-744723531.html
[4] https://password.seas.harvard.edu/itapps/apply/

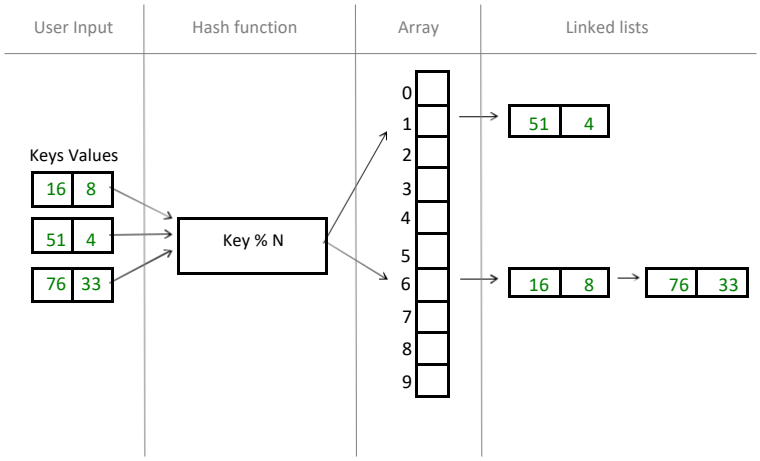


Figure 1: Illustration of a Hash Table with an array comprising 10 slots. The first key-value pair is mapped to slot 6 because the key is 16 and 16 mod 10 is 6. The second key-value pair is mapped to slot 1 because the key is 51 and 51 mod 10 is 1. The third key-value pair is mapped to slot 6 because the key is 76 and 76 mod 10 is 6. Note that since the first and third key-value pairs map into the same slot in the array, they are chained within the same linked list.

Implementation Details. A node of the linked list should be implemented as a C structure[5]. This structure contains one key-value entry as well as a pointer[6] to the next node in the linked list.

In Figure 1, each slot in the array contains only a pointer to the first node in each linked list. Alternatively, you may also make each slot in the array be the first node of the linked list (meaning that each slot in the array contains one or more key-value pairs belonging to the given slot). This latter design would have better performance as it reduces random access.

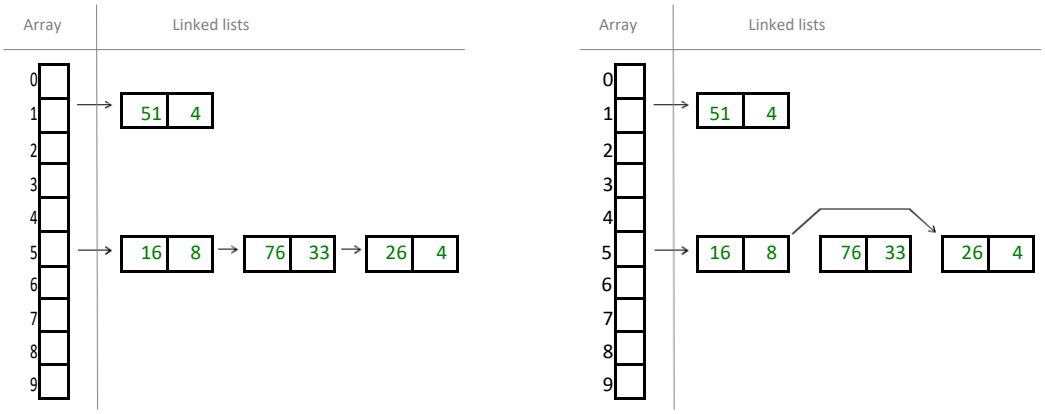
For the terminal node in the linked list, the pointer is set to NULL. When a new key-value pair is inserted into a linked list, a new node should be allocated using a call to malloc (the C memory allocator), and the pointer of the terminal node should be set to point at the new node. Thus, a new node becomes the new terminal node.

You may want to set the size of the array to be a multiple of the expected data size to reduce the chance of collisions taking place.

Common Problem. In the interest of speed, the programming language C does not perform bound-checking on arrays during runtime. This means that if a program accesses slot X + 1 of an array that only contains X slots, the program will not necessarily crash (unless you are lucky). Instead, the access will return the wrong data and thereby cause the program to behave unpredictably. Even worse, if the program updates an out-of-bound index, it may corrupt live data that belongs to other data structures in the program. This is known as a buffer overflow. Such errors are difficult to debug, and they should be avoided through vigilance while programming. However, there are tools that exist to profile a program to detect out-of-bound memory accesses. Valgrind is an example of such a tool. If your program crashes in an obscure way, we recommend running it with Valgrind to identify the problem. An example of using Valgrind is located here[7].

Debugging. While implementing a data structure or algorithm, it is common to make small logical mistakes that may cause the program to return incorrect results or even crash. If either of these things happen, you can use a debugger to try to identify the source of the problem. A debugger is a tool that allows stepping through the code, line by line, while showing the values of all the different variables at a given point in the execution. Thus, it can be used to track down the source of an error. GDB is an example of a debugger, and a tutorial on how to use it is located here: https://kb.iu.edu/d/aqsj.

[5]A tutorial on C structures can be found here: http://www.cprogramming.com/tutorial/c/lesson7.html
[6]A tutorial on C pointers can be found here: http://www.cprogramming.com/tutorial/c/lesson6.html
[7]Out-of-bound error detection with Valgrind: https://www.cs.swarthmore.edu/ newhall/unixhelp/purify.html



(a) Before erase (b) After erase

Figure 2: Illustration of before and after erasing a key-value entry with key 76. The erase involves changing the pointer from the predecessor node to to point to the successor node. This leads to a memory leak because the erased node still exists and is now not accessible by the application. To avoid a memory leak, we must inform the memory allocator that the node is no longer used.

Compilation. The C compiler, GCC, gives various options for how to compile a program. One important compiler option is the level of optimization. By default, the compiler's main goal is to minimize compilation time, and so it does not try to improve the performance of the code through compiler optimizations. However, we can tell the compiler using the -O3 flag to perform as much optimization as possible. While this improves the performance of the code, it increases compilation time. It may also change the order in which lines of the program are executed, which can make debugging confusing.

In the repository, there is a file called Makefile, which is a script for how the code should be compiled (instructions for how to use the Makefile are in the README file in the repository). The compilation command for all files uses the -O3 flag, because we want the code to run as fast as possible. It is possible to switch to the -O0 option, which tells the compiler to perform no optimization, and so we retain debugging ability. Another relevant flag is -Og, which performs as much optimization as possible while retaining debugging ability. You may experiment with these and other flags throughout the project.

2 Erasing Key-Value Pairs

Now implement the erase(K) function, which removes the key-value entry with key K from the hash table if such a key-value pair exists. The erase function should initially identify the node in the linked list that contains the key-value pair. It should then remove this node from the linked list by changing the preceding node to point to the target node's successor. This is illustrated in Figure 2.

Common Problem: The programming language C does not automatically delete unused data from memory. Thus, when the node is removed from the linked list, the memory is not automatically freed even if it is no longer reachable from the code. This phenomenon is known as a memory leak. Figure 2 illustrated a memory leak resulting from an erase. Memory leaks are undesirable because the memory taken up by inaccessible objects is no longer available to the application. If the amount of non-available memory accumulates over time (e.g. after many erases), the system will run out of available memory. This may cause the program to crash. Thus, it is imperative to delete data from memory as it becomes unused. To this end, use the free command of C to inform the memory allocator when a node is removed from the linked list[8]. This informs the memory allocator that the space taken up by the removed node is now available for future memory allocations.

[8]A tutorial on the free command is given here: http://www.tutorialspoint.com/c_standard_library/c_function_free.htm

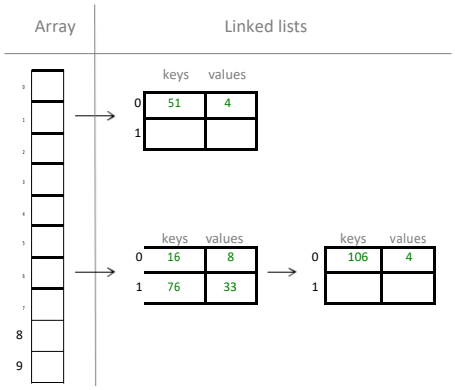


Figure 3: Using a linked list of arrays.

Valgrind, the tool already mentioned in the previous section, can be used to profile a program to identify memory leaks. A tutorial on using Valgrind for this purpose is located here9. It is a good idea to regularly check your program with valgrind to verify that there are no memory leaks.

The erase command will not be used in milestone 4 of your semester project, but we recommend that you implement it anyways for practice and completeness.

3 Modern Hardware Considerations

In modern computers, fetching data from memory into the processor takes a long time, typically much longer than actually using this data when it is already in the processor. In the context of your hash table implementation, traversing a linked list may involve multiple memory accesses, one for each node. These memory accesses become increasingly expensive as the length of linked lists grow.

To reduce this cost, we can take advantage of how modern computers are fast at sequential access. We can do so by placing multiple key-value pairs in each node of the linked list. This is shown in Figure 3, where each node of the linked list contains 2 key-value pairs. The effect of doing so is that the processor can fetch multiple key-value pairs through a single sequential access, reading an entire node at the same time. This reduces the overall number of memory accesses per traversal of a linked list, and so performance improves. This is known as having fat nodes.

On the other hand, you should not set the number of key-value pairs that fit into a node too large. The reason is that the amount of data that the processor can store in each of its cache lines is small, typically 64 or 128 bytes. If the size of a node exceeds this amount, then reading each node would involve more than one memory access. In your implementation, you can experiment to find the node size that results in the best performance.

Note that as long as and when we have a good hash function and the size of the hash table is set to some multiple of the data size, then collisions are unlikely to occur, and so the lengths of all linked lists would remain 0 or 1. In this case, fat nodes are less critical to performance. For milestone 4 of your semester project, we will know in advance the size of the data to be inserted into the hash table, and so having fat nodes will not be critical to performance, but we recommend that you implement fat nodes as a learning exercise.

4 Running out of Capacity

As more keys are added to the hash table, the average length of each linked list grows. Thus, the overheads of inserting or retrieving a key-value pair begins to increase because it takes a longer time

[9] Tutorial on valgrind: http://valgrind.org/docs/manual/quick-start.html

to traverse the appropriate linked list. To avoid such a degradation in performance, you should enlarge the size of the array in proportion to the number of key-value pairs inserted so far.

Implementation Details: First, implement bookkeeping within the hash table to keep track of the number of key-value pairs P. Whenever the number of key-value pairs grows beyond a threshold value, the size of the array should be enlarged. The threshold value is typically defined as Q.P/N, where P is the number of entries in the hash table, N is the number of slots in the array, and Q is a tuning parameter. You may experiment with different values of Q to find the one that results in the best performance.

To enlarge the hash table, allocate a new array that is larger than the original. The size of the new array should be some multiple of the size of the original array. Then iterate through every key-value pair of the original hash table and insert them into the new hash table. Finally, deallocate the original hash table to ensure no memory leaks have taken place.

Note that for your semester project you will know in advance the number of elements to be inserted into the hash table, but we recommend that you implement a policy for growing out-of-capacity anyways for completeness and practice.

5 Experimentation

We provide you with two scripts that automatically test the correctness and performance of your implementation. The correctness test ensures that your implementations of the put, get and erase commands return correct results. For example, after we insert a key-value pair, we should be able to retrieve the value associated with the key. Similarly, after erasing a key-value pair, we should no longer be able to retrieve a value that was associated with the key before.

The performance test measures the amount of time that it takes to insert 50 million key-value pairs into your hash table. You can use the performance test to iteratively improve your hash table, e.g., to lower response time for queries and inserting new data. You can also use it to experiment with alternative designs and see their effect. For the script to work you will need to support the following C API.

```
int allocate (hashtable** ht,  int size);
int put (hashtable* ht,  keyType key, valType value);
int get (hashtable* ht,  keyType key, valType values, int num_values, int* num_results);
int erase (hashtable* ht,  keyType key);
int deallocate (hashtable* ht);
```

Note that this API is expressed in terms of generic data types for keys and values. This is done to emphasize that much of the hash table infrastructure that you will create is applicable to any data types. However, for this project you may assume that keyType and valType are always integers.

View the README file in the repository for further details on how to implement this interface and how to run the correctness and performance tests.