CS121 Parallel Computing Lab 2

Cuckoo Hashing using CUDA

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Abstract

In computing, hash table is a widely used data structure that implements an associative array abstract structure, a structure that maps keys to values. Cuckoo Hashing is one among the hashing techniques which provides high memory usage with constant time access [1]. At the same time, GPU makes high throughput hash table possible. In this lab, I implement Cuckoo Hashing use CUDA as well as testing correctness and doing experiments to analyze performance.

1 Introduction

1.1 Compile & Build

You need a C++ compiler which supports at least C++ 17 standard and nvcc which supports at least C++ 17 standard for CUDA C++.
I use CMake to build the project, so you also need to have CMake with version at least 3.21 to compile our codes.
Compile by:

```
mkdir build
cd .\build
cmake ..
cmake --build . --config Release
```

Run the benchmark by main target under tests:

```
cd .\build\tests
.\main.exe
```

It will automatically run the four experiments with an additional correctness test.

1.2 Interface

We provide a function insert_and_lookup to use our hash table.
It will first insert the given keys into the hash table and then do the lookup and store the result according to the given lookup key sequence.

1.3 Benchmark Configures

I run my code on my own computer. The detailed information is:

Config	Value
CPU	AMD Ryzen 7 3700X
GPU	NVIDIA GeForce RTX 2060 SUPER
Memory	32 GB DDR4 3000 MHz 2 of 4 slots
GPU Memory	8 GB GDDR6
OS	Windows 11 Pro 22000.37
Compiler	MSVC 19.30.30706, nvcc V11.5.119
Optimize	MSVC: /O2, nvcc: -O3
CUDA Cores	2176
CUDA Version	11.5
Driver Version	GeForce Game Ready Driver 497.29

To test scalability, I also run my code on a cloud virtual machine provided by tencent cloud. The detailed information is:

Config	Value
CPU	AMD EPYC ROME™ 7k62 (16 vCPU)
GPU	NVIDIA TESLA A100 40GB PCIe
Memory	96 GB
GPU Memory	40 GB HBM2e
OS	Ubuntu 20.04 LTS
Compiler	gcc 11.1.0, nvcc V11.1.105
Optimize	gcc: -O2, nvcc: -O3
CUDA Cores	6912
CUDA Version	11.1
Driver Version	450.102.04

2 Implement Details

2.1 Cuckoo Hashing Algorithm

Cuckoo Hashing is one of the hash table schemas which provides high memory utilization and constant access time [1]. It is named after a type of bird who lays its eggs in other birds' nests, and

whose chicks push out the other eggs from the nest after they hatch.
Unlike many other hash tables, Cuckoo Hashing uses t hash functions where $t > 1$. Cuckoo hashing maintains t tables, each key k can be stored into t locations corresponds to the location that uses hash function h_i. In the insertion process, suppose we want to insert a key k into the hash table and we have t hash functions $h_0, h_1, \cdots, h_{t-1}$ while the tables are $T_0, T_1, \cdots, T_{t-1}$. We will first use hash function h_1 to try to insert k into $T_1[h_1(k)]$. If the cell is already occupied, then we will evict the key in that slot k', put the k into that cell and try to insert k' into tables after circularly. If we still need to evict key after a bound times, then we need to choose some other functions and rehash.

Algorithm 1 Cuckoo Hashing Insert

```
h_1, h_2, ..., h_t are t hash functions
T_1, T_2, ..., T_t are corresponding tables
C is the size of the table (capacity)
input: a key k
for i = 0 → iter-bound do
  loc ← h_{i mod t}(k) mod C
  if T_{i mod t}[loc] = empty then
    T_{i mod t}[loc] ← k
    return
  else
    swap(k, T_{i mod t}[loc])
  end if
end for
rehash()
insert(k)
```

The lookup process is much simpler, we just need to loop through all t possible locations and compare the key with the stored key in the table whether they are equal. Obviously, this process is done in $O(t)$ and since t is a constant, then Cuckoo Hashing provides constant time access.

Algorithm 2 Cuckoo Hashing Lookup

```
h_1, h_2, ..., h_t are t hash functions
T_1, T_2, ..., T_t are corresponding tables
C is the size of the table (capacity)
input: a key k
for i = 0 → t − 1 do
  loc = h_i(k) mod C
  if T_i[loc] = k then
    return true
  end if
end for
return false
```

We can find that the lookup time in Cuckoo Hashing is $O(t) = O(1)$, which is very good. But the worst case exists when key is not inserted into the hash table, it will loop through all t hash functions.

2.2 Table Storage

Since Cuckoo Hashing needs to maintain t tables where t is the number of hash functions. From the algorithm, it is obvious that the tables are independent to each other. So, instead of storing all the t tables into a big linear array, we choose to store t linear arrays, which performs better because of good pipeline and cache utilization.

2.3 Memory Management

For hash table, we mainly need some big linear arrays. Although unified memory can greatly decrease the difficulty for memory management between device and host. But it needs some techniques to achieve good performance and it may still perform a little bit worse than directly manage host and device memory. Therefore, I create a class to encapsulate cuda array. By overloading assignment operator, I can make copy operation between device and host simpler. Also, by encapsulation, I can allocate and free the memory by some class methods easily.

2.4 Random Set Generation

We need to generate random set to test our hash table. Since it is a set which means it cannot contain the same value, then I choose to first generate a such set on CPU and then copy it to GPU. I use std::mt19937, a mersenn twister engine, as our random number engine. To make the generation faster, I create a bitset whose size is 2^{32}, which will cost 0.5 GB memory but provides much better performance than using a hash table to filter out duplicates.
For the lookup set generation, I first generate a totally different set respected to the original random set with the same size. Then, I implement a random shuffle kernel function to support shuffle operation on a device array. For the lookup set, I will first shuffle it randomly then overwrite some keys using elements from the different set according to the given percentage. This is much faster than using bitset or hash table to filter and create another set.

2.5 Multi-level Table

One possible method to improve the performance of our GPU hash table is to use multi-level table [2]. The bottleneck of Cuckoo Hashing is memory access, uncoalesced global memory access will greatly influence our perfor-

mance. So, we may create multi-level tables. For example, two-level Cuckoo Hashing, we first hash the elements into different buckets and then perform Cuckoo Hashing locally inside those buckets.
This often performs better than single-level table when rehashing is needed. However, in our experiments, we do not need to rehash that much and according to the result in [2], the multi-level table performs even worse than single-level. Therefore, I choose to not use multi-level table and in my experiments, I compared my code with an existing multi-level cuckoo hashing code and I performs much better than him.

2.6 Parallel d-Pipeline

During researching, I found another way to increase the throughput, which is parallel d-pipeline [3]. Consider the insertion process of one key k, it will go through tables like a pipeline:

$$\text{input} \to T_0 \to T_1 \to T_2 \to \cdots \to T_{t-1} \to \text{rehash}$$

If success at one table in the middle, it will jump out the pipeline. Therefore, when a key failed at T_0 and evict one to try to insert in T_1, another new key can start to insert at T_0 without any race condition. And this forms a pipeline.
However, implement this directly is hard in coding. Hopefully, by taking advantage of modern compiler and C++ we can form the pipeline using template metaprogramming to expand the code and finally form a good pipeline through compiler optimization.

2.7 Hash Function

Since Cuckoo Hashing has a constant lookup time, then we just need to focus on insertion. A good hash function can cause less collisions and thus we can perform fewer evictions and finally gain a better performance in insertion.

2.7.1 Universal Hashing

Universal Hashing takes advantages of randomness. No matter what n input keys are, every operation takes $O(n/m)$ time in expectation, for a size m hash table, which is optimal if no randomness. Instead of using a fixed hash functions, universal hashing uses a random hash function, chosen from a universal hash family H that satisfied:

$$\mathbb{P}_{h\in H}(h(x) = h(y)) = \frac{1}{m}$$

We can construct hash function h_{ab} by choosing a prime number p s.t. $p > m$ and $p >$ all keys:

$$h_{ab}(k) = ((ak + b) \bmod p) \bmod m$$

Let $H_{pm} = \{h_{ab}|a \in \{1, 2, \cdots, p-1\}, b \in \{0, 1, \cdots, p-1\}\}$, then H_{pm} is a universal hash family. We can randomly choose h_{ab} from H_{pm}. However, we need to ensure $p > m$ and $p >$ all keys. In our experiments, the maximum value of key is the maximum value of 32-bit integer, which means we need to choose a prime $> 2^{32}$ and store it in 64-bit integer. 64-bit integer calculations are too slow in GPU, and if we use smaller p within 32-bit integer, the performance is not good. Therefore, I do not use this hash function at last.

2.7.2 Perfect Hashing

This is the ideal hash function because it maps different key to exactly different values. However, minimal perfect hashing costs too much time during construction [1] while some other variants of perfect hashing like achieving this by take two level universal hashing, are hard to use in Cuckoo Hashing and cannot support newly come keys.

2.7.3 xxHash

xxHash is an extremely fast Hash algorithm, running at RAM speed limits [4]. Besides extremely high performance, it provides excellent quality which passes Google hash tests. After testing different hash functions, xxHash performs better in most cases. So, I use xxHash as the hash functions at last.

2.8 Template metaprogramming

Template metapgrogramming is good way to transform some dynamic process into static process as well as gaining further optimization by compiler and thus have a better performance.
We pass the seed of xxHash through template, by doing this, all the multiplication involving the seed will be determined at compile time and after compiler optimization the code will become extremely small and simple and will be inlined.
Similarly, we create a template for insert and lookup, the recursion in template will be expand at compile time and form a pipeline, we can do this because the maximum eviction bound can be chosen as a constant.
By taking advantage of modern compiler, we gain a much higher performance with less cost at coding level.

2.9 Timer

To measure the time precisely, I use cudaEvent to measure the time. I record two cuda events before and after invoking the kernel function, respectively. Before calculating the time elapsed, we need to first synchronize the event to ensure the kernel function has already finished. Then use cudaEventTimeElapsed to calculate the time elapsed. To obtain reliable results, I perform each experiment 5 times.

2.10 CUDA Block Size Tuning

I tuned the CUDA block size with NVIDIA nsight compute. From Figure 2.10, we can see that we reach highest occupancy with block size of 512 or 1024. After further benchmark test, I finally choose 512 as the block size, which obtains a little bit better performance than choosing 1024. Because we may have more registers per thread to use when choosing 512 as the block size.

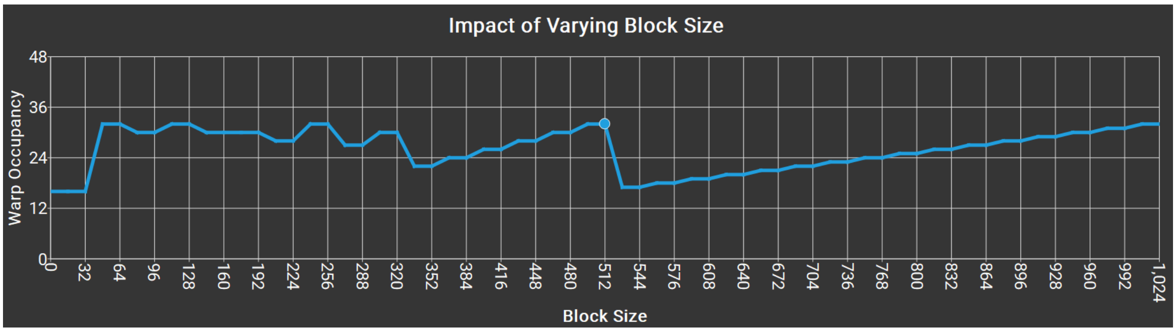
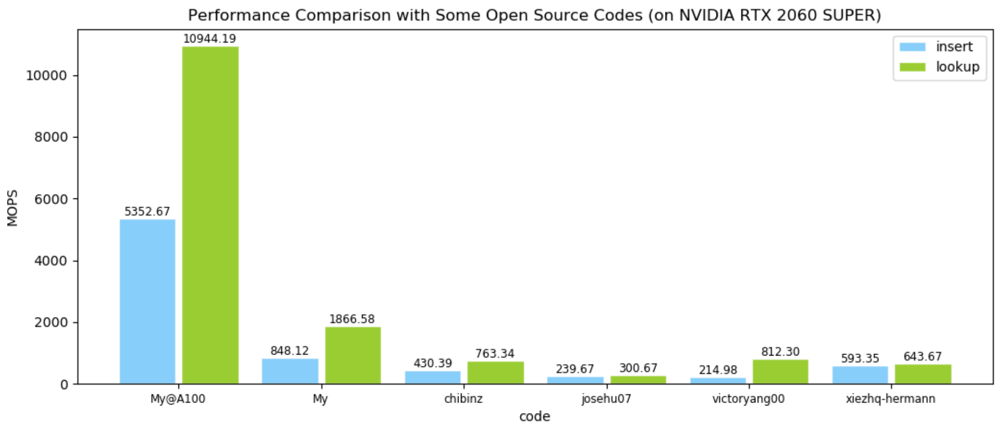


Figure 2.10: Impact of varying block size to warp occupancy

3 Results

After running experiments, the benchmark result is listed as follows:



Performance comparison with some open source codes

3.1 Experiment 1: Insertion

In this experiment, I create a hash table of size 2^{25} in GPU global memory, where each table entry stores a 32-bit integer. I insert a set of 2^s random integer keys into the hash table, for $s = 10, 11, \cdots, 24$. And I test for both using $t = 2$ hash functions and $t = 3$ hash functions. To produce reliable result, each experiment are repeated 5 times.

We can find that using 3 hash functions performs better than using 2 hash functions in most cases because fewer evictions are needed when using 3 hash functions. 3 hash function performs especially better when s is larger, when $s = 24$ the difference is extremely obvious.

With NVIDIA TESLA A100, we get our peak insertion performance of **5352.674049** millions of insertions per second. The result between different number of hash functions stays the same, that is $t = 3$ performs better than $t = 2$ also due to the decrease in the number of evictions.

We generally get more than **6**$\times$ speedup on TESLA A100 with respected to RTX 2060 SUPER, which shows that our implementation ob-

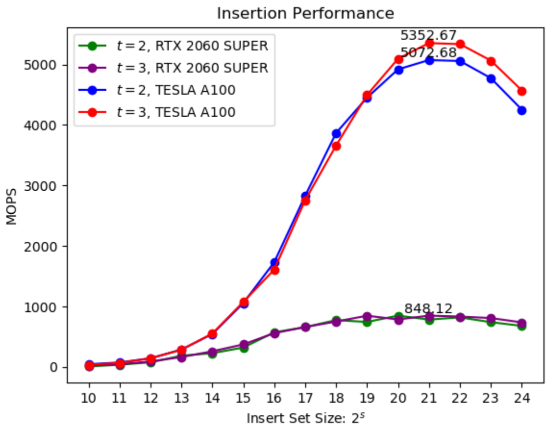


Figure 1: Experiment 1 Performance

s	t	MOPS	Time (ms)	StdDev
10	2	7.446709	0.137510	0.063818
11	2	37.200651	0.055053	0.027095
12	2	76.472696	0.053562	0.016374
13	2	185.561035	0.044147	0.015856
14	2	227.859371	0.071904	0.013538
15	2	320.661368	0.102189	0.049058
16	2	572.194902	0.114534	0.009390
17	2	658.499736	0.199046	0.009860
18	2	773.983850	0.338694	0.005635
19	2	743.422896	0.705235	0.137846
20	2	**848.028746**	1.236486	0.004866
21	2	782.824122	2.678957	0.274631
22	2	818.832553	5.122298	0.240417
23	2	740.279704	11.331674	0.807136
24	2	678.550312	24.725088	0.903823

Table 1: Insertion test on NVIDIA GeForce RTX 2060 SUPER using $t = 2$ hash functions

s	t	MOPS	Time (ms)	StdDev
10	3	21.214532	0.048269	0.009736
11	3	44.071065	0.046470	0.002681
12	3	90.026727	0.045498	0.004228
13	3	164.018451	0.049946	0.009279
14	3	258.638111	0.063347	0.005503
15	3	371.984887	0.088090	0.015388
16	3	559.348878	0.117165	0.003982
17	3	659.666305	0.198694	0.017240
18	3	750.733137	0.349184	0.026919
19	3	846.473374	0.619379	0.001562
20	3	784.772035	1.336154	0.234942
21	3	**848.118706**	2.472710	0.099679
22	3	832.881107	5.035898	0.234401
23	3	807.912957	10.383059	0.109445
24	3	736.136639	22.790899	0.155948

Table 2: Insertion test on NVIDIA GeForce RTX 2060 SUPER using 3 hash functions

s	t	MOPS	Time (ms)	StdDev
10	2	44.211108	0.023162	0.003254
11	2	73.613987	0.027821	0.002437
12	2	143.465591	0.028550	0.002464
13	2	286.802600	0.028563	0.002506
14	2	545.028746	0.030061	0.000516
15	2	1055.452489	0.031046	0.000901
16	2	1730.606726	0.037869	0.002185
17	2	2829.120113	0.046330	0.001364
18	2	3867.799868	0.067776	0.003297
19	2	4452.415964	0.117754	0.001905
20	2	4918.495447	0.213190	0.001987
21	2	5072.681438	0.413421	0.001089
22	2	**5057.063274**	0.829395	0.002853
23	2	4773.093010	1.757478	0.002250
24	2	4252.760722	3.945018	0.004734

Table 3: Insertion test on NVIDIA TESLA A100 40GB PCIe using $t = 2$ hash functions

tain an excellent scalability because we mainly benefit from the GPU memory bandwidth and the HBM2e is 3.47 times as fast as GDDR6 while A100 takes 2.7 times higher in TFLOPS.

3.2 Experiment 2: Lookup

In this experiment, I insert a set S of 2^{24} random keys into a hash table of size 2^{25}, then perform lookups for the following sets of keys $S_0, \cdots, S_{10}$. Each set S_i contains 2^{24} keys, where $(100 - 10i)$ percent of the keys are randomly chosen from S, and the remainder are random 32-bit keys. To produce reliable result, each experiment are repeated 5 times.

From table 5 and 6 we can find that for the lookup test, time increases as i increases because more elements are not in the hash table as i becomes bigger. The lookup time in Cuckoo Hashing is $O(t)$ when the element we try to lookup is already in the hash table, then it will take less than t steps to find that key. Otherwise, it will take the whole t step to give a not found.

Therefore, the performance of lookup reaches the peak when all the lookup keys are in the hash table. While all the keys are not in the hash table, it takes the longest time but the time complexity is still a constant because the number of hash functions t is a constant. And when t is smaller, the performance is better. However, smaller t may increase the number of evictions in insertion. So, in practice we need balance between insertion and lookup.

According to Table 6, we get a peak performance of **10944.190395** millions of lookups per second with NVIDIA TESLA A100, which is

s	t	MOPS	Time (ms)	StdDev
10	3	34.453057	0.029722	0.001653
11	3	67.100022	0.030522	0.001605
12	3	142.793397	0.028685	0.003427
13	3	283.248506	0.028922	0.000490
14	3	551.724145	0.029696	0.001909
15	3	1073.600350	0.030522	0.001782
16	3	1609.303782	0.040723	0.001657
17	3	2755.651233	0.047565	0.002297
18	3	3661.065435	0.071603	0.003161
19	3	4495.664528	0.116621	0.004782
20	3	5094.368927	0.205830	0.003153
21	3	**5352.674049**	0.391795	0.003084
22	3	5335.417389	0.786125	0.001248
23	3	5063.862307	1.656563	0.004728
24	3	4570.751084	3.670560	0.005147

Table 4: Insertion test on NVIDIA TESLA A100 40GB PCIe using $t = 3$ hash functions

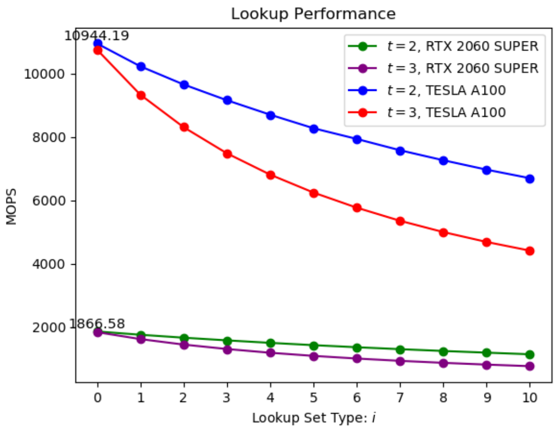


Figure 2: Experiment 2 Performance

extremely fast while in the worst case all the lookups are done in 2.51ms when $t = 2$. In addition, our implementation still obtains an excellent in the lookup, reaching a speedup of more **6**× with respected to RTX 2060 SUPER.

3.3 Experiment 3: Size

In this experiment, I create a fixed set of $n = 2^{24}$ random keys and measure the time to insert the keys into hash tables of size sn where $s = 1.01, 1.02, 1.05, 1.1, 1.2, \cdots, 2$. I terminate the experiment if the insertion takes too long which means the insert process of Cuckoo Hashing is hard to complete. To produce reliable result, each experiment are repeated 5 times.

According to Figure 3, we can see that generally, the performance increases as the size increases because there will be less evictions and rehashes.

i	t	MOPS	Time (ms)	StdDev
0	2	**1866.584072**	8.988192	0.107335
1	2	1761.835282	9.522579	0.007990
2	2	1668.597444	10.054682	0.004976
3	2	1584.623803	10.587507	0.003354
4	2	1506.272597	11.138234	0.001299
5	2	1433.399665	11.704493	0.008614
6	2	1367.833913	12.265536	0.005892
7	2	1306.748787	12.838899	0.005308
8	2	1249.908829	13.422752	0.004688
9	2	1197.400414	14.011366	0.002645
10	2	1146.550585	14.632774	0.057043
0	3	**1843.989880**	9.098323	0.002369
1	3	1625.353454	10.322195	0.002685
2	3	1452.115347	11.553639	0.010561
3	3	1311.857373	12.788902	0.005694
4	3	1194.372580	14.046886	0.010308
5	3	1095.647198	15.312608	0.003277
6	3	1011.771790	16.582016	0.004829
7	3	939.055437	17.866055	0.005416
8	3	875.845898	19.155443	0.005154
9	3	820.318196	20.452083	0.006410
10	3	771.261283	21.752960	0.007894

Table 5: Lookup test on NVIDIA GeForce RTX 2060 SUPER using 2 and 3 hash functions

i	t	MOPS	Time (ms)	StdDev
0	2	**10944.190395**	1.532979	0.001634
1	2	10225.301127	1.640755	0.033481
2	2	9652.516268	1.738118	0.039536
3	2	9155.470175	1.832480	0.039523
4	2	8699.132169	1.928608	0.042077
5	2	8272.762610	2.028006	0.048818
6	2	7935.005113	2.114330	0.025525
7	2	7577.905498	2.213965	0.029892
8	2	7263.175951	2.309901	0.026111
9	2	6966.356637	2.408320	0.027162
10	2	6697.239074	2.505094	0.027777
0	3	**10752.596504**	1.560294	0.019172
1	3	9331.956724	1.797824	0.045214
2	3	8307.342176	2.019565	0.055082
3	3	7482.538448	2.242182	0.065040
4	3	6810.226405	2.463533	0.072663
5	3	6244.869361	2.686560	0.083055
6	3	5768.100057	2.908621	0.093335
7	3	5354.653074	3.133203	0.101179
8	3	4998.941599	3.356154	0.112646
9	3	4687.387080	3.579226	0.121195
10	3	4413.198677	3.801600	0.130535

Table 6: Lookup test on NVIDIA TESLA A100 using 2 and 3 hash functions

When size is $1.7n$, we get a performance drop because we encounter one rehash in this test

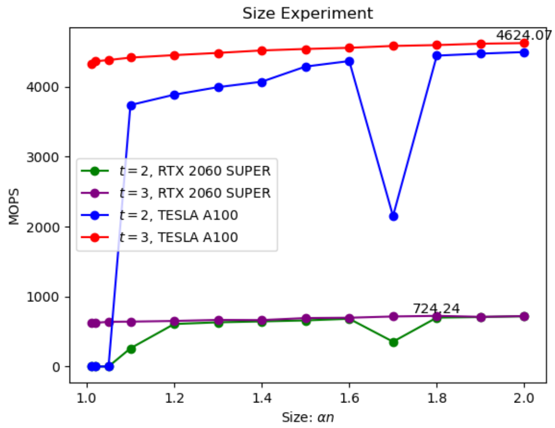


Figure 3: Experiment 3: Size Test

s	t	MOPS	Time (ms)	StdDev
2.0	2	**718.569511**	23.348077	0.526595
1.9	2	707.180415	23.724096	0.583006
1.8	2	699.033878	24.000576	0.654333
1.7	2	354.465352	47.331046	1.299906
1.6	2	682.258901	24.590688	0.316653
1.5	2	658.699933	25.470195	0.726411
1.4	2	644.583205	26.028007	0.887359
1.3	2	631.628612	26.561837	0.594943
1.2	2	607.410984	27.620864	0.922161
1.1	2	259.893430	64.554214	1.874496
1.05	2	N/A	N/A	N/A
1.02	2	N/A	N/A	N/A
1.01	2	N/A	N/A	N/A

Table 7: Size test on NVIDIA GeForce RTX 2060 SUPER using 2 hash functions

s	t	MOPS	Time (ms)	StdDev
2.0	3	**720.760163**	23.277113	0.823124
1.9	3	710.266831	23.621004	0.795786
1.8	3	724.240721	23.165248	0.162821
1.7	3	715.366934	23.452602	0.253312
1.6	3	697.417215	24.056211	0.665444
1.5	3	692.596413	24.223654	0.630849
1.4	3	663.355432	25.291443	0.560652
1.3	3	665.923213	25.193920	0.797485
1.2	3	651.055876	25.769241	0.822991
1.1	3	641.431637	26.155891	0.766913
1.05	3	639.108578	26.250964	0.603821
1.02	3	624.410461	26.868890	0.688250
1.01	3	622.909822	26.933619	0.796268

Table 8: Size test on NVIDIA GeForce RTX 2060 SUPER using 3 hash functions

s	t	MOPS	Time (ms)	StdDev
2.0	2	**4495.988473**	3.731597	0.047658
1.9	2	4473.218103	3.750592	0.043783
1.8	2	4444.836303	3.774541	0.045024
1.7	2	2150.872191	7.800192	0.070234
1.6	2	4367.152402	3.841683	0.043648
1.5	2	4288.401832	3.912230	0.090330
1.4	2	4071.855181	4.120288	0.041169
1.3	2	3994.070087	4.200531	0.038393
1.2	2	3886.171126	4.317158	0.040137
1.1	2	3738.228285	4.488013	0.003802
1.05	2	N/A	N/A	N/A
1.02	2	N/A	N/A	N/A
1.01	2	N/A	N/A	N/A

Table 9: Size test on NVIDIA TESLA A100 using 2 hash functions

s	t	MOPS	Time (ms)	StdDev
2.0	3	**4624.068615**	3.628237	0.044546
1.9	3	4615.325053	3.635110	0.045759
1.8	3	4595.526630	3.650771	0.045174
1.7	3	4583.313615	3.660499	0.048979
1.6	3	4556.363571	3.682150	0.045424
1.5	3	4539.911130	3.695494	0.052675
1.4	3	4518.867180	3.712704	0.049443
1.3	3	4483.699920	3.741824	0.043908
1.2	3	4452.022667	3.768448	0.038733
1.1	3	4416.581690	3.798688	0.038431
1.05	3	4381.700577	3.828928	0.044611
1.02	3	4364.069773	3.844397	0.044340
1.01	3	4328.415614	3.876064	0.053024

Table 10: Size test on NVIDIA TESLA A100 using 3 hash functions

key set. When the size $\leq 1.05n$ and if we choose 2 hash functions, the hash table will infinitely rehash.

When we choose 3 hash functions, there will not be any rehash and the performance increases as the size increases due to fewer evictions.

According to Figure 3 and Table 10, on NVIDIA TESLA A100, we get our peak performance of **4624.068615** with 3 hash functions and size of $2.0n$.

3.4 Experiment 4: Bound

In this experiment, I use $n = 2^{24}$ random keys and a hash table of size $1.4n$. I test Cuckoo Hashing with different bounds of $l \log n$ on the maximum length of eviction chain before restarting.
I terminate the experiment if the insertion takes too long which means the insert process of Cuckoo Hashing is hard to complete. To produce reliable result, each experiment are repeated 5 times.

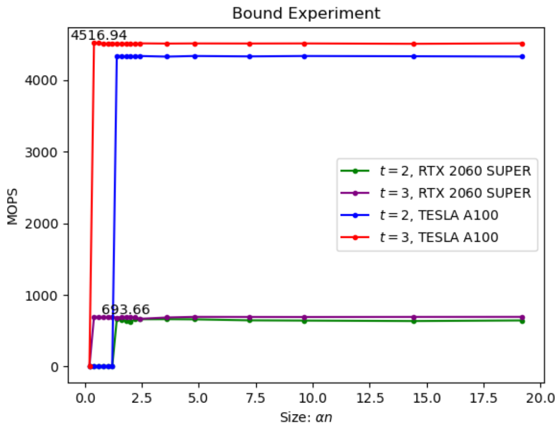


Figure 4: Experiment 4: Bound Test

l	t	MOPS	Time (ms)	StdDev
0.2	2	N/A	N/A	N/A
0.4	2	N/A	N/A	N/A
0.6	2	N/A	N/A	N/A
0.8	2	N/A	N/A	N/A
1.0	2	N/A	N/A	N/A
1.2	2	N/A	N/A	N/A
1.4	2	4336.226983	3.869082	0.040889
1.6	2	**4336.965930**	3.868422	0.041448
1.8	2	4329.588092	3.875014	0.037551
2.0	2	4331.934797	3.872915	0.037947
2.2	2	4335.932864	3.869344	0.038864
2.4	2	4336.851103	3.868525	0.040728
3.6	2	4328.079694	3.876365	0.038323
4.8	2	4336.937169	3.868448	0.042185
7.2	2	4331.211905	3.873562	0.038510
9.6	2	4336.786582	3.868582	0.043544
14.4	2	4333.388402	3.871616	0.038374
19.2	2	4329.037487	3.875507	0.046952

Table 11: Bound test on NVIDIA TESLA A100 using 2 hash functions

From the Table 11, 12, 13, 14 and Figure 4, we can see that when choosing 2 hash functions, the performance remains almost the same after $l \geq 1.4$ (bound length $\geq 1.4 \log n$). The peak performances are 4336.965930 and 4516.142393 millions of operations per second, respectively.

When choosing 3 hash functions, we only need $l \geq 0.4$ to get a good performance. This may because we choose a relative good hash function, xxHash, whose quality is excellent to easily pass Google hash test. And using 3 hash function itself makes the number of evictions much fewer than using 2 hash functions.

The best bound in our experiment is bolded in the table below, see Table 11, 12, 13, 14 and Figure 4 for more details.

l	t	MOPS	Time (ms)	StdDev
0.2	3	N/A	N/A	N/A
0.4	3	**4516.142393**	3.714944	0.047456
0.6	3	4516.943821	3.714285	0.042790
0.8	3	4511.129706	3.719072	0.048300
1.0	3	4511.479023	3.718784	0.050594
1.2	3	4514.874533	3.715987	0.046709
1.4	3	4511.129590	3.719072	0.050060
1.6	3	4511.533343	3.718739	0.048303
1.8	3	4511.595532	3.718688	0.049938
2.0	3	4509.577610	3.720352	0.051675
2.2	3	4509.236274	3.720634	0.050588
2.4	3	4513.382040	3.717216	0.050051
3.6	3	4510.206033	3.719834	0.051105
4.8	3	4512.162369	3.718221	0.051948
7.2	3	4511.051972	3.719136	0.047064
9.6	3	4512.240083	3.718157	0.048978
14.4	3	4506.902747	3.722560	0.047575
19.2	3	4513.622961	3.717018	0.050403

Table 12: Bound test on NVIDIA TESLA A100 using 3 hash functions

l	t	MOPS	Time (ms)	StdDev
0.2	2	N/A	N/A	N/A
0.4	2	N/A	N/A	N/A
0.6	2	N/A	N/A	N/A
0.8	2	N/A	N/A	N/A
1.0	2	N/A	N/A	N/A
1.2	2	N/A	N/A	N/A
1.4	2	657.483519	25.517318	0.312952
1.6	2	646.936886	25.933312	0.659120
1.8	2	641.007204	26.173210	0.573636
2.0	2	620.847396	27.023092	0.606418
2.2	2	658.149056	25.491514	0.317434
2.4	2	659.814903	25.427155	0.147894
3.6	2	**661.132839**	25.376468	0.109419
4.8	2	658.687197	25.470688	0.214283
7.2	2	644.927489	26.014112	0.493037
9.6	2	641.568838	26.150298	0.707538
14.4	2	634.861433	26.426579	0.982739
19.2	2	643.584807	26.068384	0.742324

Table 13: Bound test on NVIDIA 2060 SUPER using 2 hash functions

3.5 Comparison with Others

I compare my program's performance with some open source code found in github. From Figure at the top of result section, we can find that our program obtain a much higher performance both in insertion and lookup than all the open source codes I compared.

All the codes are tested in the same environment with GPU of NVIDIA RTX 2060 SUPER except for the first column (the result of my code on

l	t	MOPS	Time (ms)	StdDev
0.2	3	N/A	N/A	N/A
0.4	3	693.425597	24.194688	0.115743
0.6	3	693.467047	24.193242	0.116118
0.8	3	690.305337	24.304051	0.234168
1.0	3	693.034023	24.208358	0.143322
1.2	3	693.265324	24.200282	0.120261
1.4	3	681.274671	24.626214	0.550600
1.6	3	693.066273	24.207232	0.109783
1.8	3	**693.658439**	24.186567	0.115933
2.0	3	691.121569	24.275347	0.161366
2.2	3	685.183113	24.485741	0.552498
2.4	3	665.937249	25.193389	0.589150
3.6	3	684.540419	24.508730	0.585207
4.8	3	693.442664	24.194093	0.113214
7.2	3	692.317996	24.233396	0.213677
9.6	3	691.614976	24.258029	0.131916
14.4	3	692.744288	24.218483	0.133526
19.2	3	693.520618	24.191373	0.115917

Table 14: Bound test on NVIDIA 2060 SUPER using 3 hash functions

NVIDIA TESLA A100).

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