CSc 120
Introduction to Computer Programming II

15: Hashing
Hashing
Searching

We have seen two search algorithms:

- linear (sequential) search \( O(n) \)
  - the items are not sorted

- binary search \( O(\log n) \)
  - the items are sorted
  - must consider the cost of sorting

• Can we do better?

• Have you considered how a Python dictionary might be implemented?
ADT - Dictionary

• A dictionary is an ADT that holds key/value pairs and provides the following operations:
  – put(key, value)
    o makes an entry for a key/value pair
    o assumes key is not already in the dictionary
  – get(key) looks up key in the dictionary
    o returns the value associated with key (and None if not found)
Exercise

Implement the Dictionary ADT.

Usage:

```python
>>> d = Dictionary(7)
>>> d.put('five', 5)
>>> d.put('three', 3)
```

Hint:

```python
>>> d._pairs
[['five', 5], ['three', 3], None, None, None, None, None, None, None, None]
```

(See solution on slide 27.)
Performance

• What is big-O of the Dictionary's methods?
  – put()
  – get()

• Can we do better than O(n) for get()?

• Consider this:
  alist[3] # this "get" or "lookup" is O(1)

• Why is this O(1)?
  elements of lists are contiguous
  easy to compute starting point plus offset

• Can we 'transform' keys into integers that fall into a small, contiguous range?
Beating $O(n)$

Can we 'transform' keys into integers that fall into a small range?

"hello" -> 147
"a"     -> 422

How could we turn a key (string) into an integer?
- simple method: use the length

“Hash” the key (colloquial meaning)
  Chop up the key
  Scramble the key to get a value
Hashing

• A hash function is a function that can be used to map data of arbitrary size to a value in a fixed range

• Is the following a hash function?

    ```python
def hash(key):
    return len(key)
```

• Strings are arbitrary length
  – modify `hash(key)` to return a value in a fixed range
  – an integer between 0 and 7
Exercise

Problem:

Modify the Dictionary ATD to use a hash function to compute the index for a new key/value pair.

(See solution on slide 28.)
Hashing

Given this hash function:

```python
def hash(key):
    return len(key) % 7
```

What happens in this situation?

```python
>>> d.put('hello', 14)
>>> d.put('e', 351)
>>> d.put('hat', 8)
>>> d.put('consciousness', 1)
```
Hashing

• Hash results:

<table>
<thead>
<tr>
<th>key</th>
<th>hash value</th>
</tr>
</thead>
<tbody>
<tr>
<td>'hello'</td>
<td>5</td>
</tr>
<tr>
<td>'e'</td>
<td>1</td>
</tr>
<tr>
<td>'hat'</td>
<td>3</td>
</tr>
<tr>
<td>'consciousness'</td>
<td>5</td>
</tr>
</tbody>
</table>

• *Collision*: two or more keys have the same hash value
Hashing

• Hash results:

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</tr>
<tr>
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</tr>
</tbody>
</table>

Collision

• Dictionary implementation view:

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</table>

Need a place to put ['consciousness', 1]

Need a place to put ['consciousness', 1]
Hashing and collisions

• *perfect hash function*: every key hashes to a unique value
  – most hash functions are not perfect

• Need a systematic method for placing keys in a Dictionary (hash table) when collisions occur.

<table>
<thead>
<tr>
<th>0</th>
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</tr>
</tbody>
</table>

  \[\text{[e', 351]} \quad \text{[hat', 8]} \quad \text{[hello', 14]}\]

Need a place to put ["consciousness", 1]
Collision Resolution

• Methods for resolving collisions:
  – increase the table size (the list in our example)
    consider social security numbers: 333-55-8888
    9 digits / $10^9$ entries

  – open addressing: a method of collision resolution characterized by "probing"
  – linear probing
    o compute the hash value
    o on collision, sequentially visit each slot in the hash table to find
      an available spot
    o visit each slot by going 'lower' in the table (decrement by 1)
    o wrap if necessary
Collision Resolution

• Simplify the example by using integers for keys
• Hash function
  
h(key) = key % 7
• Hash values for the keys: 14, 2, 10, 19

<table>
<thead>
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• Hash table

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Collision Resolution

• keys: 14, 2, 10, 19

• Now add 24
  – h(key) = key % 7
    = 24 % 7
    = 3  ← collision, use open addressing

• Hash table

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h(24) = 3  ← collision
Collision Resolution

• keys: 14, 2, 10, 19

• Now add 24
  – $h(key) = key \% 7$
  – $= 24 \% 7$
  – $= 3$  $\leftarrow$ collision, use open addressing

• Hash table

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$h(24) = 3$  $\leftarrow$ collision

look lower  $\rightarrow$ occupied
Collision Resolution

- keys: 14, 2, 10, 19
- Now add 24
  - \( h(key) = key \% 7 \)
    - \( = 24 \% 7 \)
    - \( = 3 \) → collision, use open addressing
- Hash table

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h(24) = 3 → collision

look lower → occupied

look lower → empty
Collision Resolution

• *Probe sequence*: the locations examined when inserting a new key

  \[ h(24) = 3 \]

• The hash computation is the first "probe"

• Hash table

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Collision Resolution

• *Probe sequence*: the locations examined when inserting a new key
  
  \( h(24) = 3 \)

• The hash computation is the first "probe"

• Hash table

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first probe – collision 3
Collision Resolution

• *Probe sequence*: the locations examined when inserting a new key
  
  \[ h(24) = 3 \]

• The hash computation is the first "probe"

• Hash table

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  first probe – collision 3

  second probe – occupied 2
Collision Resolution

- **Probe sequence**: the locations examined when inserting a new key
  
  \[ h(24) = 3 \]

- The hash computation is the first "probe"

- Hash table

```
<table>
<thead>
<tr>
<th>0</th>
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</table>
```

- First probe – collision 3
- Second probe – occupied 2
- Third probe – empty 1
Collision Resolution

- **Probe sequence**: the locations examined when inserting a new key
  
  \[ h(24) = 3 \]

- The hash computation is the first "probe"

- Hash table

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- first probe – collision 3
- second probe – occupied 2
- third probe – empty 1
Exercise

Use open addressing to insert the key 23 into the hash table below. Give the probe sequence.

*The hash function is the key % 7*

hash table

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</tbody>
</table>
Collision Resolution

open addressing:

- the probe sequence is linear
- the probe decrement is 1

*open addressing with linear probing* has serious performance problems (!!)

When two keys collide at the same hash value, they will follow the same initial probe sequence

Can we do better?  
*Hint: change the probe decrement.*
Hashing

• SHA-1 (Secure Hash Algorithm 1)
  • cryptographic hash function designed by the NSA
  • 120 bits
  • shown as hexadecimal number, 40 digits long

• MD5 (Message Digest 5)
  – widely used hash function to verify data integrity
  – now compromised
  – 128 bits
ADT – Dictionary solution 1

class Dictionary:
    def __init__(self, capacity):
        # each element will be a key/value pair
        self._pairs = [None] * capacity
        self._nextempty = 0

    def put(self, k, v):
        self._pairs[self._nextempty] = [k, v]
        self._nextempty += 1

    def get(self, k):
        for pair in self._pairs[0:self._nextempty]:
            if pair[0] == k:
                return pair[1]
        return None
class Dictionary:
    def __init__(self, capacity):
        # each element will be a key/value pair
        self._pairs = [None] * capacity

    def _hash(self, k):
        return len(k) % len(self._pairs)

    def put(self, k, v):
        self._pairs[self._hash(k)] = [k, v]  # use the hash function

    def get(self, k):
        return self._pairs[self._hash(k)][1]  # use the hash function
Questions

What is a hash function?

What is a collision?

In open addressing with linear probing, how are collisions resolved?
Collision Resolution (revisited)

open addressing
  – *open addressing with linear probing*
    o compute the hash value
    o on collision, sequentially visit each slot in the hash table to find an available spot
    o visit each slot by going 'lower' in the table (decrement by 1)
    o wrap if necessary

terminology
  – the probe sequence is linear
  – the probe decrement is 1
Collision Resolution (revisited)

• keys: 14, 2, 10, 19

• Now add 24
  – \( h(\text{key}) = \text{key} \mod 7 \)
  \[ = 24 \mod 7 \]
  \[ = 3 \quad \rightarrow \text{collision, use open addressing} \]

• Hash table

<table>
<thead>
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\[ h(24) = 3 \quad \rightarrow \text{collision} \]

look lower – occupied

look lower – empty
Exercise

Modify the put() method of the ADT below to implement open addressing with linear probing.

class Dictionary:
    def __init__(self, capacity):
        # each element will be a key/value pair
        self._pairs = [None] * capacity

    def _hash(self, k):
        return len(k) % len(self._pairs)

    def put(self, k, v):
        self._pairs[self._hash(k)] = [k,v]  #use the hash function

    ....
Clusters

• *Cluster*: a sequence of adjacent, occupied entries in a hash table

• problems with open addressing with linear probing
  – colliding keys are inserted into empty locations below the collision location
  – on each collision, a key is added at the edge of a cluster
  – the edge of the cluster keeps growing
  – the edges begin to meet with other clusters
  – these combine to make *primary clusters*
Collision Resolution

open addressing
  – idea: need a probe decrement that is different for keys that hash to the same value

simple example
  – the use mod for the hash
  – use quotient for the probe
    o note: cannot use 0

  – probe decrement function \( p(key) \)
    the quotient of key after division by 7 (if the quotient is 0, then 1)
    or
    \[ \text{max}(1, \frac{\text{key}}{7}) \]

called open addressing with double hashing
Collision Resolution – double hashing

• functions
  
  \[ h(\text{key}) = \text{key} \mod 7 \]
  
  \[ p(\text{key}) = \max(1, \text{key} \div 7) \]

• values for the keys: 10, 2, 19, 14, 24, 23

<table>
<thead>
<tr>
<th>key</th>
<th>hash value</th>
<th>probe decrement</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3</td>
<td>1</td>
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Collision Resolution – double hashing

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</table>

hash table after inserting keys: 10, 2, 19, 14

<table>
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Now insert key 24:

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h(24) = 3 collision

What is the decrement?
What is the probe sequence?
Collision Resolution – double hashing

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$h(24) = 3$ collision

What is the decrement? 3
What is the probe sequence? 3, 0, 4
Exercise

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</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>19</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>24</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>23</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Use double hashing to insert key 23:

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>2</td>
<td>10</td>
<td>24</td>
<td>19</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Collision Resolution

open addressing with double hashing
  – compute the hash value
  – on collision, use the probe decrement function to determine what slot to visit next
  – wrap if necessary

improvement over linear probing
  – when two keys collide, they usually follow different probe sequences when a search is made for an empty location
    o hash(10) = 3    hash(24) = 3
    o probe(10) = 1   probe(24) = 3
  – prevents primary clustering
Hash functions and collisions

• Consider an *ideal hash* function $h(k)$
  – it maps keys to hash values (slots) uniformly and randomly

• Suppose $T$ is a hash table having $M$ table entries from 0 to $M-1$

• An ideal hash function would imply that any slot from 0 to $M-1$ is equally likely

• All slots equally likely, implies collisions would be infrequent.

• Is that true?
collision phenomenon

• von Mises Birthday Paradox
  – if there are 23 or more people in a room, there is a > 50% chance that two or more will have the same birthday
Ball tossing model

Given

- a table T with 365 slots  
  (each is a different day of the year)
- toss 23 balls at random into these 365 slots

then

- there is a > 50% chance we will toss 2 or more balls into the same slot

What?

- 23 balls in the table
- the table is only 6.3% full
  \[ 23/365 = 0.063 \]
- and we have a 50% chance of a collision!
collision phenomenon

Ball tossing model

\[ P(n) = \text{probability that tossing } n \text{ balls into 365 slots has at least one collision} \]

\[ P(n) = 1 - \frac{365!}{365^n (365 - n)!} . \]
collision phenomenon

\[ P(n) = \text{probability that tossing } n \text{ balls into } 365 \text{ slots has at least one collision} \]

<table>
<thead>
<tr>
<th>( n )</th>
<th>( P(n) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.027</td>
</tr>
<tr>
<td>10</td>
<td>0.117</td>
</tr>
<tr>
<td>20</td>
<td>0.411</td>
</tr>
<tr>
<td>23</td>
<td>0.572</td>
</tr>
<tr>
<td>30</td>
<td>0.706</td>
</tr>
<tr>
<td>40</td>
<td>0.891</td>
</tr>
<tr>
<td>50</td>
<td>0.970</td>
</tr>
<tr>
<td>60</td>
<td>0.994</td>
</tr>
<tr>
<td>70</td>
<td>0.99915958</td>
</tr>
<tr>
<td>80</td>
<td>0.99991433</td>
</tr>
<tr>
<td>100</td>
<td>0.99999969</td>
</tr>
</tbody>
</table>

At 23, greater than 50% chance
collision phenomenon

P(n) = probability that tossing n balls into 365 slots has at least one collision

<table>
<thead>
<tr>
<th>n</th>
<th>P(n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.027</td>
</tr>
<tr>
<td>10</td>
<td>0.117</td>
</tr>
<tr>
<td>20</td>
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<td>80</td>
<td>0.99991433</td>
</tr>
<tr>
<td>100</td>
<td>0.99999969</td>
</tr>
</tbody>
</table>

at 23, greater than 50% chance

Our results:
58 people/ 365 possible birthdays
3 collisions:
July 14
Aug 1
Aug 18
Collision resolution

A collision resolution algorithm must be guaranteed to check every slot.

  linear probing  - yes (it sequentially walks through the slots)
  double hashing - ?

Does the probe sequence used for double hashing cover the entire table? (I.e., is any slot ever missed?)
**Collision resolution – double hashing**

<table>
<thead>
<tr>
<th>key</th>
<th>hash value</th>
<th>probe decrement</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>19</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>2</td>
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<td>24</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>23</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

**Question:** Does the probe sequence cover the entire table?

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Use key 24. Show that the probe sequence visits each slot. (Keep wrapping.)
Collision resolution

The probe sequence covers every slot.  
This is true for every key in the table
  ○ try it for other keys

Why?

The table size $M$ and probe decrement are relatively prime. Guarantees that the probe sequence covers the table.

relatively prime
  – have no common divisors other than 1
  – think of reducing the fraction $36/45$ to $4/5$
Collision resolution

Two policies
  - open addressing
    o with linear probing
    o with double hashing

A third policy
  - separate chaining
Collision Resolution

separate chaining
  – each table location references a linked list
  – on collision, add to the linked list, starting at the collision slot

table with keys 24 and 10 (using %7 for the hash):

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>

- 10
- 20 None
- 24 None

52
Complexity

Analysis of separate chaining

If we have N keys, what is

- best case complexity for search:
  (the key is the first item in the linked-list) $O(1)$
- worst case complexity for search:
  (must exhaustively search one linked-list) $O(n)$

We have not been analyzing the average case.

We will use known results for average case of the collision resolution policies.
Load factor

The load factor of a hash table with $N$ keys and table size $M$ is given by the following:

$$\lambda = \frac{N}{M}$$

load factor is a measure of how full the table is

Complexity is expressed in terms of the load factor.
EXERCISE

We have 60,000 items to store in a hash table using open addressing with linear probing and we want a load factor of .75.

How big should the hash table be?
Complexity

As load factor increases, efficiency of inserting new keys decreases

Collisions
- must enumerate through the table to get an empty slot

Searching
- find it on the first try
- search by using the probe sequence
- or search the linked list

We will use known results for the average cases of successful and unsuccessful search for the collision resolution policies
Assume a table with load factor: \[ \lambda = \frac{N}{M} \]

Linear probing:
- clusters form
- leads to long probe sequences

It can be shown that the average number of probes is

\[ \frac{1}{2} \left( 1 + \frac{1}{1 - \lambda} \right) \]  
for successful search

\[ \frac{1}{2} \left( 1 + \frac{1}{(1 - \lambda)^2} \right) \]  
for unsuccessful search

Bad when load factor is close to 1
Not too bad when load factor is .75 or less
Results

```python
>>> # load factor is .75
>>> 
>>> # linear probing - successful
>>> 
>>> .5 * (1 + 1/.25)
2.5

>>> # linear probing - unsuccessful
>>> 
>>> .5 * (1 + 1/(.25 *.25))
8.5
```
Assume a table with load factor:

\[ \lambda = \frac{N}{M} \]

Double hashing:
clustering less common

It can be shown that the average number of probes is

\[ \frac{1}{\lambda} \ln \left( \frac{1}{1 - \lambda} \right) \]

for successful search

\[ \left( \frac{1}{1 - \lambda} \right) \]

for unsuccessful search

Very good when load factor is .75 or less
### Results

```python
>>> # load factor is .75
>>>
>>> # double hashing - successful
>>> import math
>>> 1/.75 * math.log(4)
1.8483924814931874
>>> # double hashing – unsuccessful
>>> 1/.25
4.0
```
Assume a table with load factor: \[ \lambda = \frac{N}{M} \]

Separate chaining:
- all keys that collide at a given has location are on the same linked list

It can be shown that the average number of probes is

\[ 1 + \frac{1}{2} \lambda \]
for successful search

\[ \lambda \]
for unsuccessful search

*Compare the three methods*
### Theoretical Results (number of probes)

#### Successful search

<table>
<thead>
<tr>
<th>Load Factor</th>
<th>0.50</th>
<th>0.75</th>
<th>0.90</th>
<th>0.99</th>
</tr>
</thead>
<tbody>
<tr>
<td>separate chaining</td>
<td>1.25</td>
<td>1.37</td>
<td>1.45</td>
<td>1.49</td>
</tr>
<tr>
<td>linear probing</td>
<td>1.50</td>
<td>2.50</td>
<td>5.50</td>
<td>50.5</td>
</tr>
<tr>
<td>double hashing</td>
<td>1.39</td>
<td>1.85</td>
<td>2.56</td>
<td>4.65</td>
</tr>
</tbody>
</table>

#### Unsuccessful search

<table>
<thead>
<tr>
<th>Load Factor</th>
<th>0.50</th>
<th>0.75</th>
<th>0.90</th>
<th>0.99</th>
</tr>
</thead>
<tbody>
<tr>
<td>separate chaining</td>
<td>0.50</td>
<td>0.75</td>
<td>0.90</td>
<td>0.99</td>
</tr>
<tr>
<td>linear probing</td>
<td>2.50</td>
<td>8.50</td>
<td>50.50</td>
<td>5000.00</td>
</tr>
<tr>
<td>double hashing</td>
<td>2.00</td>
<td>4.00</td>
<td>10.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>
Hashing Functions

Good performance requires a good hashing function.
  – the hash function should not cause clustering

Most hash functions
  – map keys to numbers (if not already numbers)
  – then reduce that using mod

Example:
  'hello' → len('hello') % 7

Must be aware of properties of the hashing function.
Hashing Functions

Example: hashing function $hash$

- add the ord values of a string
- mod by the table size $M$

For the key 'bat':

- $hash('bat', M) = (ord('b') + ord('a') + ord('t')) \mod M$

```python
def hash(key, M):
    sum = 0
    for c in key:
        sum += ord(c)
    return sum \mod M
```

What are the properties of this hash function?
Does it cause clustering?
def hash(key, M):
    sum = 0
    for c in key:
        sum += ord(c)
    return sum % M

Use:
>>> hash("bat", 7)
3
>>> hash("tab", 7)
3
>>> hash("atb", 7)
3
>>> hash("tide", 7)
2
>>> hash("tied", 7)
2
Hashing Functions

Example: hashing function $h$
- add the ord values of a string
- mod by the table size $M$

$$hash('bat', M) = (\text{ord('b')} + \text{ord('a')} + \text{ord('t')}) \mod M$$

$$hash('tab', M) = (\text{ord('t')} + \text{ord('a')} + \text{ord('b')}) \mod M$$

What are the properties of this hash function?
- anagrams hash to the same value

Will that matter?
If it does, how would we fix that?
Hashing Functions

Example: hashing function $h$
- add the ord values of a string
- mod by the table size $M$

Modify to multiply by character position, i.e.,

$$\text{hash('bat', M)} = (\text{ord('b')}*1 + \text{ord('a')}*2 + \text{ord('t')}*3) \mod M$$

$$\text{hash('tab', M)} = (\text{ord('t')}*1 + \text{ord('a')}*2 + \text{ord('b')}*3) \mod M$$
Hashing Functions

Pitfalls with mod
\[ h(k) = k \mod M \]

Avoid powers of 2 for M
\[ \text{for } M = 2^b, \quad h(k) = k \mod 2^b \]

This elects the \( b \) low order bits of \( k \)

In general, when using mod
avoid powers of 2
use prime numbers for \( M \)