



COMP 2012H Honors Object-Oriented Programming and Data Structures

Topic 17: Hashing

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Motivation

- How would you **find** a student record given just the student's name?
- How does an electronic dictionary **look up** for a word, say, "computer"?
- Each machine has an IP address in the Internet. How will an internet service **look up** an IPv6 address?



Part I

Hashing



=

79054025
255fb1a2
6e4bc422
aef54eb4

General Idea

| | |
|---|------------|
| 0 | |
| 1 | |
| 2 | data item |
| 3 | john 25000 |
| 4 | phil 31250 |
| 5 | |
| 6 | dave 27500 |
| 7 | mary 28200 |
| 8 | |
| 9 | |

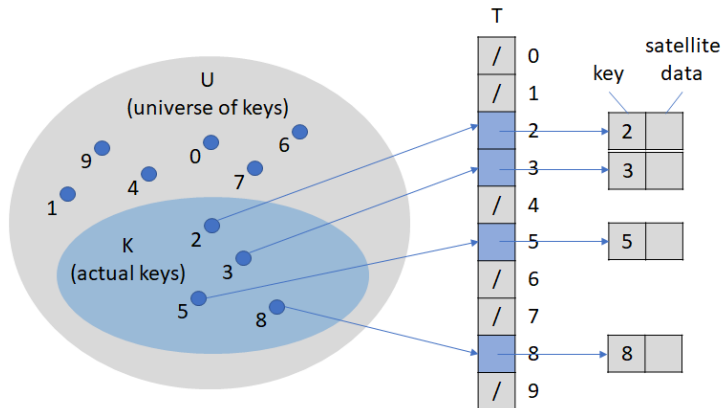
- A **hash table** is an **array** of some **fixed size**, containing all the data items.
- Each item has a **key**; **search** is performed based on the keys.
- Each key is mapped into some position in the array in the range **0** to **$m - 1$** , where **m** is the array size.
- The mapping is called **hash function**.
- Example applications:

- Compilers use hash tables, called **symbol tables**, to keep track of declared identifiers in a program.
- On-line spell checkers: After **hashing** the entire dictionary, one can check each word in **constant time** and print out the mis-spelled words in order of their appearance in the document.

Hash Table

- **Hash table** is a data structure that supports: **search**, **insertion**, and **deletion** (deletion may be unnecessary in some applications).
- The implementation of **hash tables** is called **hashing**.
- **Hashing** is a technique which allows the executions of above operations in **constant time** on average.
- Unlike other data structures such as linked lists or binary trees, data items are generally **not** ordered in **hash tables**.
- As a consequence, **hash tables** don't support the following operations
 - ▶ **find_min** and **find_max**
 - ▶ finding successor and predecessor
 - ▶ reporting data within a given range
 - ▶ listing out the data in order

Unrealistic Solution



- Universe of **keys** U is the set of **all possible values** of the keys.
- Each position, also called a **slot**, in the **hash table** T corresponds to a key in U .
 - ▶ $T[k]$ corresponds to a data item with key k .
 - ▶ If the table contains no data with key k , then $T[k] = \text{nil}$.

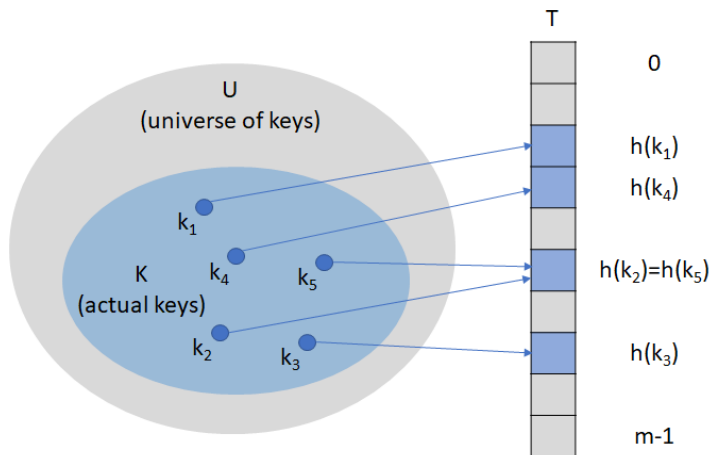
Unrealistic Solution ..

- Insertion, deletion and search all take constant time.
- Problem: it wastes too much space if the universe of keys is large compared with the actual number of data to be stored.

E.g., in HKUST, student IDs are 8-digit integers. So the key universe has a size of 10^8 , but we only have ~ 7000 students (not counting the alumni)!

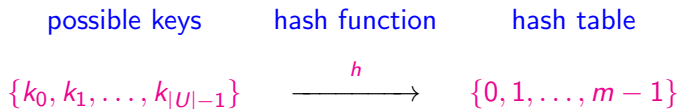


Hash Function



- Hash function, h maps the universe of keys U into the slots of a hash table $T[0, 1, \dots, m-1]$.
- Several keys may be mapped to the same slot.

Hash Function ..



- Usually, $m \ll |U|$.
- The keys k_i are assumed to be **natural numbers**.
- If they are not, they can always be converted or interpreted in natural numbers.
- $h(k_i)$ = an integer in $[0, \dots, m-1]$ is called the **hash value** of k_i .
- With **hashing**, an item of key k is stored in $T[h(k)]$.

Collision Problem



- Two keys may be **hashed** to the same **slot**.
- **Question**: Can we ensure that any two **distinct keys** are **hashed** to **different slots**?
- **No!** If $N > m$, where
 - ▶ m = size of the **hash table**, and
 - ▶ N = number of data

Solution:

1. Design a good **hash function** that is
 - ▶ **fast** to compute, and
 - ▶ can **minimize** the number of **collisions**
2. Design a method to resolve the **collisions** when they occur.

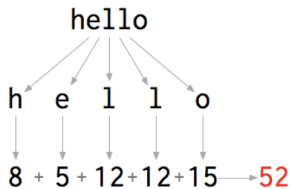
Hash Function Design

- A simple and reasonable strategy: $h(k) = k \bmod m$.
- e.g. $m = 12, k = 100, h(k) = 4$
- It requires only a single division operation (quite fast).
- Certain values of m should be avoided: e.g., if $m = 2^p$, then $h(k)$ is just the p lowest-order bits of k ; thus, the hash function does not depend on all the bits.
- Similarly, if the keys are decimal numbers, m should not be set to be a power of 10.
- It's a good practice to set the table size m to a prime number.
- Good values for m : primes not too close to exact powers of 2
 - ▶ e.g., for a hash table to hold 2,000 numbers, if we don't mind an average of 3 numbers being hashed to the same slot, choose $m = 701$.

How to Deal with String Keys: Method 1

Add up the ASCII values of the characters in the string.

(For simplicity, we only use their positions in the alphabets here.)



- Most hash functions assume that keys are natural numbers. If keys are not natural numbers, a way must be found to interpret them as natural numbers.
- Problems:
 - ▶ Different permutations of the same set of characters would have the same hash value.
 - ▶ If the table size is large, the keys do not distribute well.
 - ▶ e.g., $m = 10,007$ (a prime number) and all string keys have ≤ 8 characters. Since ASCII values ≤ 127 , their numeric keys are in the range between 0 and $127 \times 8 = 1,016$.

How to Deal with String Keys: Method 2

$$h(\text{key}) = (\text{key}[0] + 27 \cdot \text{key}[1] + 27^2 \cdot \text{key}[2]) \bmod m$$

where m is hash table size.

- If the first 3 characters are random and the table size m is 10,007, then it is a reasonably equitable distribution.
- Problems:
 - ▶ letters in an English word are not random;
 - ▶ according to some dictionary, there are only 2,851 different combinations for the first 3 letters of English words;
 - ▶ therefore, only at most 28% of the table can actually be hashed to (if $m = 10,007$).

How to Deal with String Keys: Method 3

$$\begin{aligned}h(\text{key}) &= \left(\sum_{i=0}^{L-1} 37^{(L-1-i)} \cdot \text{key}[i] \right) \bmod m \\&= \left(37^{(L-1)} \cdot \text{key}[0] + 37^{(L-2)} \cdot \text{key}[1] + \dots + \text{key}[L-1] \right) \bmod m\end{aligned}$$

where L is the length of a **key**.

- This **hash function** involves **all** characters in the key and the **hash values** are expected to **distribute well**.

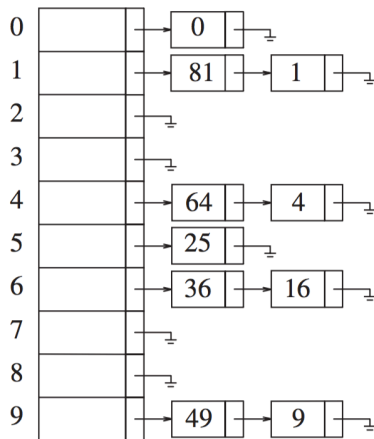
Part II

Collision Handling



Separate Chaining

- **Keys**: the set of squared numbers $\{1, 4, 9, 16, \dots\}$.
- **Hash function**: $h(k) = k \bmod 10$.
- Using the idea of **equivalence classes**.



- The **hash table** is more than a simple array, but a table of **linked lists**.
- **Keys** having the **same** hash values are **chained** on a **separate linked list**.

Separate Chaining Operations

To insert a key k :

- Compute $h(k)$.
- If $T[h(k)]$ contains a **null pointer**, the list (or chain) is **empty**. Initialize this table entry to point to a linked list with a single node containing k alone.
- If $T[h(k)]$ points to a non-empty list, add k to the **beginning** of the list.

To **delete** a key k

- Compute $h(k)$ to determine which list to traverse.
- Search for the key k in the list that $T[h(k)]$ points to.
- **Delete** the item with key k if it is found.

Separate Chaining Features

- If the **hash function** works well, the number of keys in each linked list will be a **small constant**.
- Therefore, we expect that each **search**, **insertion**, and **deletion** can be done in **constant time**.
- **Disadvantage**: Memory allocations and de-allocations in linked list manipulations slow down the operations.
- **Advantage**: deletion is easy.

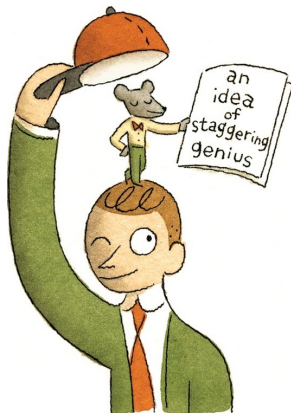


Open Addressing

- Instead of putting **keys** of the same **hash value** into a **chain**, **open addressing** will **relocate** the key **k** to be inserted if it **collides** with an existing key.
- **Open addressing** needs to determine the **sequence** of **slots** to be examined for **key relocation**.
- Key **k** may be stored at an entry different from $T[h(k)]$.
- Two issues arise:
 - ▶ what is the relocation scheme?
 - ▶ how to search for **k** later?
- Three common methods for **resolving collisions** in **open addressing**
 1. **linear probing**
 2. **quadratic probing**
 3. **double hashing**

Basic Strategy of Open Addressing

- To insert a key k , compute $h_0(k)$.
- If $T[h_0(k)]$ is **empty**, insert it there.
- If **collision** occurs, probe **alternative cell** in the following order: $h_1(k), h_2(k), \dots$, until an **empty cell** is found.
- $h_i(k) = (\text{hash}(k) + f(i)) \bmod m$, where the function f determines the **collision resolution** strategy and $f(0) = 0$.
- Different **open addressing** methods differ in the definition of $f()$.



Linear Probing: Insertion

$$\begin{aligned}f(i) &= i \\h_i(k) &= (\text{hash}(k) + i) \bmod m\end{aligned}$$

- Basic strategy: Table cells are probed **sequentially** (with wrap-around) until an **empty slot** is found.
- Again let m be the table size and N be the number of items.
- Let k be the new key to be inserted; compute $\text{hash}(k)$.
- For $i = 0$ to $m - 1$, compute $j = (\text{hash}(k) + i) \bmod m$.
- If $T[j]$ is **empty**, then we put k there and stop.
- If **no** empty slot can be found to put k , the table is full; report an error.

Linear Probing: Example

- $\text{hash}(k) = k \bmod 10$
- Insert the following keys: 89, 18, 49, 58, 69
- To insert 58, probe $T[8]$, $T[9]$, $T[0]$, $T[1]$
- To insert 69, probe $T[9]$, $T[0]$, $T[1]$, $T[2]$

| Table Index | Insert 89 | Insert 18 | Insert 49 | Insert 58 | Insert 69 |
|-------------|-----------|-----------|-----------|-----------|-----------|
| 0 | | | | | |
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | |
| 6 | | | | | |
| 7 | | | | | |
| 8 | | | | | |
| 9 | | | | | |

Primary Clustering

- We call a block of **contiguously** occupied table entries a **cluster**.
- On average, when we insert a new key k , we may hit the **middle** of a cluster. Therefore, the time to insert k would be proportional to **half** the size of a cluster.
⇒ the larger the cluster, the slower the performance.
- **Linear probing** has the following **disadvantages**:
 - ▶ Once $h(k)$ falls into a cluster, this cluster will definitely **grow** in size by one. Thus, this may worsen the performance of insertions in the future.
 - ▶ If two clusters are only separated by one entry, they may be **merged** together by an insertion to that entry.
⇒ cluster size can increase drastically by **1** insertion.
 - ▶ This means that the performance of insertion can deteriorate drastically after a single insertion.
 - ▶ Large clusters are easy targets for **collisions**.

Quadratic Probing

$$f(i) = i^2$$

$$h_i(k) = (\text{hash}(k) + i^2) \bmod m$$

| Table Index | Insert 89 | Insert 18 | Insert 49 | Insert 58 | Insert 69 |
|-------------|-----------|-----------|-----------|-----------|-----------|
| 0 | | | | | |
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | |
| 6 | | | | | |
| 7 | | | | | |
| 8 | | | | | |
| 9 | | | | | |

Quadratic Probing: Example

- Example:

- ▶ $\text{hash}(k) = k \bmod 10$
- ▶ Insert the following keys: 89, 18, 49, 58, 69
- ▶ To insert 58, probe $T[8]$, $T[9]$, $T[(8 + 4) \bmod 10]$
- ▶ To insert 69, probe $T[9]$, $T[(9 + 1) \bmod 10]$,
 $T[(9 + 4) \bmod 10]$

- Two keys with different home positions will have different probe sequences. E.g.,

- ▶ $m = 101$, $h(k_1) = 30$, $h(k_2) = 29$
- ▶ probe sequence for k_1 : $30, 30 + 1, 30 + 4, 30 + 9$
- ▶ probe sequence for k_2 : $29, 29 + 1, 29 + 4, 29 + 9$

- If the table size is prime, then a new key can always be inserted if the table is at least half empty (see proof in reference book by Weiss).

Secondary Clustering

- Keys that hashed to the **same** home position will probe the **same alternative cells**.
- Simulation results suggest that it generally causes **less than an extra half** probe per search.
- To avoid **secondary clustering**, the **probe sequence** need to be a function of the original key value, **not** the home position.



Double Hashing

- To alleviate the problem of **clustering**, the sequence of probes for a key should be **independent** of its primary home position.
- Thus, use **two hash functions**: $\text{hash}()$ and $\text{hash}_2()$.

$$\begin{aligned}f(i) &= i \times \text{hash}_2(k) \\h_i(k) &= (\text{hash}(k) + i \times \text{hash}_2(k)) \bmod m\end{aligned}$$

- e.g., $\text{hash}_2(k) = R - (k \bmod R)$, where $R < m$ and R is **prime**.



Double Hashing: Example

- $h_i(k) = (\text{hash}(k) + i \times \text{hash}_2(k)) \bmod m$
- $m = 10, R = 7, \text{hash}(k) = k \bmod 10, \text{hash}_2(k) = 7 - (k \bmod 7)$
- Insert the following keys: 89, 18, 49, 58, 69
- 2nd probe for 49: $T[(9 + 7) \bmod 10]$; 58: $T[(8 + 5) \bmod 10]$;
- 2nd probe for 69: $T[(9 + 1) \bmod 10]$

| Table Index | Insert 89 | Insert 18 | Insert 49 | Insert 58 | Insert 69 |
|-------------|-----------|-----------|-----------|-----------|-----------|
| 0 | | | | | |
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | |
| 6 | | | | | |
| 7 | | | | | |
| 8 | | | | | |
| 9 | | | | | |

Double Hashing: Choice of hash_2

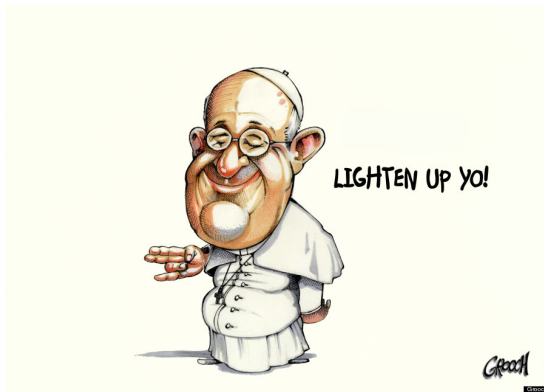
- $\text{hash}_2()$ must **never** evaluate to **zero**.
- For any key k , $\text{hash}_2(k)$ must be **relatively prime** to the table size m . Otherwise, we will only be able to examine a **fraction** of the table entries.
- E.g., if $\text{hash}(k) = 0$ and $\text{hash}_2(k) = m/2$, then we can only examine the entries $T[0]$, $T[m/2]$, and nothing else!
- One solution is to make m **prime**, and choose R to be a **prime number** smaller than m , and set

$$\text{hash}_2(k) = R - (k \bmod R)$$

- **Quadratic probing**, however, does not require the use of a second hash function, and thus is likely to be **simpler** and **faster** in practice.

Part III

Final Remarks



Deletion in Open Addressing

- Actual **deletion** **cannot** be performed in **open addressing** hash tables, otherwise the probing sequence will be broken.
- **Solution**: Add an extra field to each table entry, and mark it as
 - ▶ **EMPTY**
 - ▶ **ACTIVE**
 - ▶ **DELETED**
- It is also called **lazy deletion**.



Re-hashing

- Load factor $\alpha = N/m$, where N is the number of actually hashed items in the hash table.
- The operations in a hash table will become slower drastically when α becomes large.
- When α becomes large, (roughly) double the table size and re-hash all data items with a new hash function.
- Obviously, re-hashing is a very expensive operation. Fortunately, it usually happens infrequently in a well-designed hash table.



That's all!

Any questions?

