Wouldn’t it be wonderful if...

- Search through a collection could be accomplished in $\Theta(1)$ with relatively small memory needs?
- Let’s try this:
  - Assume we have an array of length $m$ (call it HT)
  - Assume we have a function $h(x)$ that maps from our key space to $\{0, 1, 2, \ldots, m-1\}$
    - e.g., $h: \mathbb{Z} \rightarrow \{0, 1, 2, \ldots, m-1\}$ for integer keys
    - Let’s also assume $h(x)$ is efficient to compute
- This is the basic premise of hash tables
How do we search/insert with a hash map?

- **Insert:**
  
  \[ i = h(x) \]
  
  \[ HT[i] = x \]

- **Search:**
  
  \[ i = h(x) \]
  
  \[ \text{if (HT}[i] == x) \text{ return true; else return false;} \]

- **This is a very general, simple approach to a hash table implementation**
  
  - Where will it run into problems?
What do we do if $h(x) == h(y)$ where $x != y$?

- Called a *collision*
Consider an example

- Company has 500 employees
- Stores records using a hashmap with 1000 entries
- Employee SSNs are hashed to store records in the hashmap
  - Keys are SSNs, so |keyspace| == 10^9
- Specifically what keys are needed can’t be known in advance
  - Due to employee turnover
- What if one employee (with SSN x) is fired and replacement has an SSN of y?
  - Can we design a hash function that guarantees h(y) does not collide with the 499 other employees’ hashed SSNs?
Can we ever guarantee collisions will not occur?

- Yes, if the our keyspace is smaller than our hashmap
  - If $|\text{keyspace}| \leq m$, *perfect hashing* can be used
    - i.e., a hash function that maps every key to a distinct integer $< m$
    - Note it can also be used if $n < m$ and the keys to be inserted are known in advance
      - e.g., hashing the keywords of a programming language during compilation
  - If $|\text{keyspace}| > m$, collisions cannot be avoided
Can we reduce the number of collisions?

- Using a good hash function is a start
  - What makes a good hash function?
    1. Utilize the entire key
    2. Exploit differences between keys
    3. Uniform distribution of hash values should be produced
Examples

- Hash list of classmates by phone number
  - Bad?
    - Use first 3 digits
  - Better?
    - Consider it a single int
    - Take that value modulo $m$

- Hash words
  - Bad?
    - Add up the ASCII values
  - Better?
    - Use Horner’s method to do modular hashing again
      - See Section 3.4 of the text
The madness behind Horner’s method

- **Base 10**
  - 12345
  - \[1 \times 10^4 + 2 \times 10^3 + 3 \times 10^2 + 4 \times 10^1 + 5 \times 10^0\]

- **Base 2**
  - 10100
  - \[1 \times 2^4 + 0 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 0 \times 2^0\]

- **Base 16**
  - BEEF3
  - \[11 \times 16^4 + 14 \times 16^3 + 14 \times 16^2 + 15 \times 16^1 + 3 \times 16^0\]

- **ASCII Strings**
  - HELLO
  - \[72 \times 256^4 + 69 \times 256^3 + 76 \times 256^2 + 76 \times 256^1 + 79 \times 256^0\]
Overall a good simple, general approach to implement a hash map

Basic formula:
- \( h(x) = c(x) \mod m \)
  - Where \( c(x) \) converts \( x \) into a (possibly) large integer

Generally want \( m \) to be a prime number
- Consider \( m = 100 \)
- Only the least significant digits matter
  - \( h(1) = h(401) = h(4372901) \)
We’ve done what we can to cut down the number of collisions, but we still need to deal with them.

Collision resolution: two main approaches

- Open Addressing
- Closed Addressing
Open Addressing

- i.e., if a pigeon’s hole is taken, it has to find another
- If $h(x) == h(y) == i$
  - And $x$ is stored at index $i$ in an example hash table
  - If we want to insert $y$, we must try alternative indices
    - This means $y$ will not be stored at HT[$h(y)$]
      - We must select alternatives in a consistent and predictable way so that they can be located later
Linear probing

● **Insert:**
  ○ If we cannot store a key at index i due to collision
    ■ Attempt to insert the key at index i+1
    ■ Then i+2 …
    ■ And so on …
    ■ mod m
    ■ Until an open space is found

● **Search:**
  ○ If another key is stored at index i
    ■ Check i+1, i+2, i+3 … until
      ● Key is found
      ● Empty location is found
      ● We circle through the buffer back to i
Linear probing example

- $h(x) = x \mod 11$
- Insert 14, 17, 25, 37, 34, 16, 26

- How would deletes be handled?
  - What happens if key 17 is removed?
Alright! We solved collisions!

- Well, not quite…
- Consider the load factor $\alpha = \frac{n}{m}$
- As $\alpha$ increases, what happens to hash table performance?

- Consider an empty table using a good hash function
  - What is the probability that a key $x$ will be inserted into any one of the indices in the hash table?

- Consider a table that has a cluster of $c$ consecutive indices occupied
  - What is the probability that a key $x$ will be inserted into the index directly after the cluster?
Avoiding clustering

- We must make sure that even after a collision, all of the indices of the hash table are possible for a key
  - Probability of filled locations need to be distributed throughout the table
Double hashing

- After a collision, instead of attempting to place the key $x$ in $i+1 \mod m$, look at $i+h_2(x) \mod m$
  - $h_2()$ is a second, different hash function
    - Should still follow the same general rules as $h()$ to be considered good, but needs to be different from $h()$
      - $h(x) == h(y) \text{ AND } h_2(x) == h_2(y)$ should be very unlikely
        - Hence, it should be unlikely for two keys to use the same increment
Double hashing

- $h(x) = x \mod 11$
- $h_2(x) = (x \mod 7) + 1$
- Insert 14, 17, 25, 37, 34, 16, 26

Why could we not use $h_2(x) = x \mod 7$?
  - Try to insert 2401
A few extra rules for h2()

- Second hash function cannot map a value to 0
- You should try all indices once before trying one twice

- Were either of these issues for linear probing?
As $\alpha \to 1$...

- Meaning $n$ approaches $m$...
- Both linear probing and double hashing degrade to $\Theta(n)$
  - How?
    - Multiple collisions will occur in both schemes
    - Consider inserts and misses...
      - Both continue until an empty index is found
        - With few indices available, close to $m$ probes will need to be performed
          - $\Theta(m)$
        - $n$ is approaching $m$, so this turns out to be $\Theta(n)$
Open addressing issues

- Must keep a portion of the table empty to maintain respectable performance
  - For linear hashing $\frac{1}{2}$ is a good rule of thumb
    - Can go higher with double hashing
Closed addressing

- i.e., if a pigeon’s hole is taken, it lives with a roommate
- Most commonly done with separate chaining
  - Create a linked-list of keys at each index in the table
    - As with DLBs, performance depends on chain length
      - Which is determined by $\alpha$ and the quality of the hash function
In general...

- Closed-addressing hash tables are fast and efficient for a large number of applications