

Data Structures & Algorithms 1

Topic 8 – Hash Tables

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Hash Tables

- A hash table is a data structure that offers very fast insertion and searching
- No matter how many data items there are, insertion and searching take close to constant time, nearly instantaneous or $O(1)$
- Disadvantage is that because they are based on arrays, they are difficult to expand
- Performance may degrade when a table becomes too full
- Items cannot be visited in any order
- However, if you know the size of your database and don't need to access items in order hash tables are excellent

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Hashing

- Hashing is used when the items to be stored do not have any obvious array index where you would look them up (what page is "cat" on in the dictionary?)
- The basic idea is that a range of key values is transformed into a range of array index values
- The trick is that you can figure out what the appropriate array index is without having to do a binary search $O(\log n)$
- The array index can be calculated by simply analyzing the item to be stored

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Example



- Lets say we want to store a 50,000-word English language dictionary in memory
- Ideally, every word should occupy its own slot in the 50,000 size array, making access very fast
- But what's the relationship of index numbers to words?
- For example, what slot do we access to find the definition for a word like *cats*?
- It's not immediately obvious – we need some system

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Conversion

- One possible system for converting words into a index number might be to add up the alphabetic-number of each letter
 - For example, to convert *cats* into an index we could add up
 - C = 3
 - A = 1
 - T = 20
 - S = 19
- 
- This gives us a total of 43, indicating that according to this system, *cats* will be stored in slot number 43 of the array
 - Now we can look up slot 43 instantly, without having to do a linear search or even a binary search of the array

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Example

- How good is this system?
- One problem is that the range of possible values is low
 - Assuming a limit of 10 letters, then the biggest possible index is 26×10 (zzzzzzzzzz)
- That means that we have to squash ~50,000 words into just 260 slots in an array
- With an average of 192 words per slot, we would have to perform a linear search through them, degrading the performance
- Another problem is that the words would not be evenly distributed – some slots might have thousands of words
 - Hundreds of words sum to the same total as *cats*
 - Was, tin, give, tend etc.

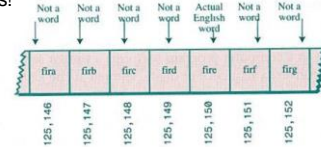
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Better Idea

- In order to increase the range we could try multiplying each letter instead of adding them
- If we multiply each letter by successive powers of 27 then each letter is guaranteed to map to a separate index
 - Cats** would be $3 \cdot 27^0 + 1 \cdot 27^1 + 20 \cdot 27^2 + 19 \cdot 27^3 = 388,587$
 - Zzzzzzzzzz** would be $26 \cdot 27^0 + 26 \cdot 27^1 + 26 \cdot 27^2 + 26 \cdot 27^3 + 26 \cdot 27^4 + 26 \cdot 27^5 + 26 \cdot 27^6 + 26 \cdot 27^7 + 26 \cdot 27^8 + 26 \cdot 27^9 = 7 \text{ trillion}$
- Problem – the array is ridiculously big and most slots will be empty!

Waste of Space

- Every single letter permutation is assigned a slot in the array
- But most random permutations of letters do not form words!



Hashing

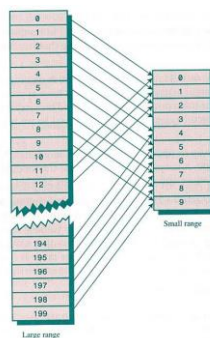
- What we need is a system to compress a huge range of numbers we obtain from the numbers-multiplied-by-powers system into a range that matches a reasonably sized array
- If our dictionary has 50,000 words then its best to pick a storage array twice this size in order to maximize the probability that every word gets its own slot
- A modulo operator (%) can be used to map a range of 0 to 7 trillion into a range of 0 to 100,000
- If we apply a modulo of 100,000 then this means that every time the bigger number goes over this, it wraps back to 0, guaranteeing that it will be in the correct range

Modulo

- Modulo just divides the number by the modulus and gives us the remainder
 - $1,234,843,632 \% 100,000 = 43,632$
 - $255,243,764,325 \% 100,000 = 64,325$
 - $285 \% 100,000 = 285$
- No matter what number we use, the result will always be in the range of 0 to 100,000
- This is an example of a **hash function** – we hash (convert) a value in a large range to a number in a smaller range
- The smaller range corresponds to the index numbers in the array
- An array into which data is inserted using a hash function is called a **hash table**

Hashing

- Use the modulo operator to squeeze a huge range of numbers into a range about twice as big as the number we want to store
 - $\text{arraySize} = \text{numberWords} \cdot 2$
 - $\text{arrayIndex} = \text{hugeNumber} \% \text{arraySize}$



Hash Functions

- Hash functions involve a two-step process
- The **first step** is to turn the item into a unique number
- The **second step** is to generate a **hash index** by hashing the unique number into the range of the hash table using the modulo function
- The item is then inserted into the slot in the hash table which has the same number as the **hash index**

First step

- If the item to be put into the hash table is already a unique number then you can skip this step
- If not then the features of the object must be used to create a **unique number**
- Number the features and combine them in such a way that each feature makes a unique contribution to the number

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First step

- A good system for hashing strings is to raise each letter to successive powers so each letter makes a unique contribution
 - **Cats** would be $3 \cdot 27^0 + 1 \cdot 27^1 + 20 \cdot 27^2 + 19 \cdot 27^3 = 373,977$
- Why?
 - There are 26 letters in the alphabet
 - The contribution of the first letter can be between 1 → 26
 - The contribution of the second letter can be between 27 → 702
 - The contribution of the third letter can be between 729 → 18,954
 - Every letter contributes different multiples which do not overlap
 - Therefore every word will generate a unique number
 - Given the number we can always recover the word with certainty by working backwards

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First step

- If you used a smaller power than the size of the alphabet then the same words could generate the same number
- Let's use powers of 3 as an example
 - **Cats** would be $3 \cdot 3^0 + 1 \cdot 3^1 + 20 \cdot 3^2 + 19 \cdot 3^3 = 699$
 - **Lass** would be $12 \cdot 3^0 + 1 \cdot 3^1 + 19 \cdot 3^2 + 19 \cdot 3^3 = 699$
- If you use a bigger power than the size of the alphabet then that's fine but you're doing more calculation than you need to
- ASCII has 127 possible values so to generate unique numbers for ASCII strings it is sufficient to raise to powers of 128
- It doesn't matter whether the powers count up or down or are in a random order **so long as they are all different!**

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Second step

- The second step is to modulo the unique number (which could be huge) by the size of the hash table
- This gives a number which corresponds to a slot in the hash table
- It is important to use a prime number as the size of the hash table
 - $9,672,566,767 \% 100,000 = 66,767$
 - $473,944,666,767 \% 100,000 = 66,767$
 - $66,767 \% 100,000 = 66,767$
 - $7,395,838,578,258,696,795,683,856,866,767 \% 100,000 = 66,767$
- If you don't use a prime number then only part of the unique number will contribute to the **hash index**
- Many different objects with a few features in common will end up generating the same **hash index**

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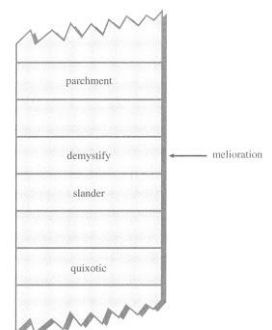
Prime Sized

- **Prime** sized hash tables are better because regular patterns in the data will be eliminated by a prime modulus
- Imagine we're hashing ten exam marks which have all been rounded up to the nearest 10%
- If we pick an array size of 20 then every mark will either be hashed into slot 10 (10%, 30%, 50%, 90%) or slot 0 (20%, 40%, 60%, 80%)
- If we use a prime number size, say **19**, then all of these marks will hash into different slots
- Any regular patterns in the data are eliminated by using a prime modulus

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Collisions

- On average, there should be one word in every second slot
- However, there's no guarantee that two words won't hash to the same array index
- Imagine you go to insert the word **melioration** and you find that the appropriate slot already contains the word **demystify**
- This is called a collision



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Open Addressing

- There are two main approaches for resolving collisions
- One approach called **open addressing** is to search the array in some systematic way, looking for the next empty cell
 - if **cats** hashes to 5,421 but this location is already occupied by **parsnip** then we could try to insert **cats** in slot 5,422
- A second approach is called **separate chaining** where linked lists are stored in each slot of the array
 - add **cats** as a new node of the linked list stored in slot 5,421



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Open Addressing

- There are several different methods for open addressing
 - Linear probing** – move along linearly looking for the next available space
 - Quadratic probing** – makes systematic jumps to look for free spaces
 - Double hashing** – hash the key again to find how big the jumps should be

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Linear Probing

- Here we search sequentially for vacant slots
- If slot 5,421 is occupied then we next try 5,422 then 5,423 etc. until we find an empty cell
- The problem is that approach is that in areas where there are few empty slots, even more items tend to build up in the vicinity
- This effect is called **clustering**
- If the data is not randomly distributed then you can get major bottlenecks where there are big groupings of items with no free slots
- Performance degrades because nearly every item is displaced and you have to go through big long linear searches to find them



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Quadratic Probing

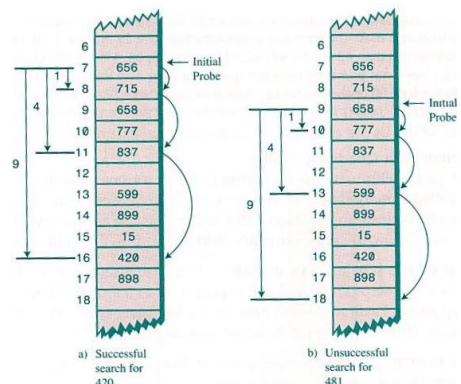
- Once a cluster forms it gets bigger and bigger because new items have nowhere to go so they are pushed out to the edges of the cluster
- Quadratic probing** is an attempt to keep clusters from forming
- The idea is to probe widely separated slots rather than those adjacent to the primary hash site
- Every time there is a collision, the algorithm jumps further and further away from the original slot

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Quadratic Probing

- In a linear probe, if the primary hash index is x , subsequent probes are $x+1$, $x+2$, $x+3$ etc.
- In quadratic probing, probes go to $x+1$, $x+4$, $x+9$, $x+16$, $x+25$ etc.
- The distance from the initial problem is the square of the step number: e.g. $x+5^2$ is step 5
- The probe becomes increasingly desperate and keeps searching further and further away with each step
- Clusters won't form as easily because if items are already bunched up the new item will be placed far away

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Quadratic Probes

- Quadratic probes can eliminate primary clustering but they lead to a more subtle clustering problem
- The problem is that all the keys that hash to a particular slot will follow the same jumps in trying to find a vacant slot
- Secondary clustering** is caused when many items hash to the same slot
- To avoid primary and secondary clustering, double hashing is often used

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Double Hashing

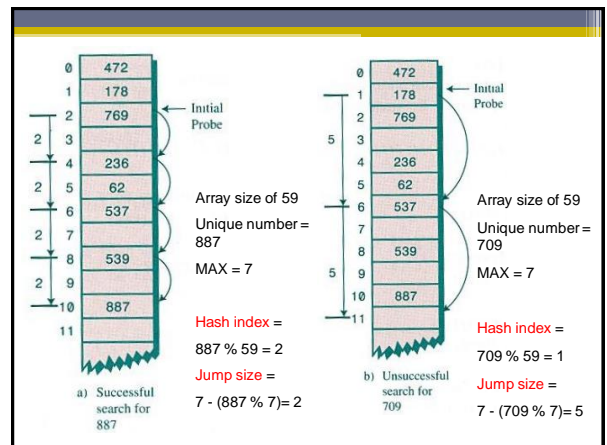
- Secondary clustering results because two items that hash to the same slot will always follow the same sequence of jumps
 - 1, 4, 9, 16, 25...
- If a particular slot is very popular then secondary clustering develops around those jump sizes
- We want items that generate the same hash index to follow different jump sizes
- The trick is to use a **different hash function** to generate a unique **jump size** for items that generated the same **hash index**
 - The primary hash function generates the **hash index** for the item
 - The secondary hash function generates the **jump size** for the item

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Double Hashing

- The secondary hash function takes in the unique number for the item and outputs a jump size in a given range
 - The jump size is obviously smaller than the size of the hash table
- The secondary hash function must have certain characteristics
 - It must not be the same as the primary hash function
 - It must never output a 0 (or else there would be no step, the algorithm would go into an infinite loop and the program would seize up)
- The following formula outputs a value between 1 and MAX
 - $\text{jumpSize} = \text{MAX} - (\text{unique number} \% \text{MAX})$
 - Let MAX be 7 and unique number be 258
 - $\text{jumpSize} = 7 - (258 \% 7) = 1$

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Prime Sized

- Double hashing also requires the size of the hash table to be prime
- If the array size was 15 and a particular key hashes to 0 with a **jump size of 5** then the probe sequence will be
 - 0, 5, 10, 0, 5, 10, 0 etc.
- If these cells are all full the algorithm will loop forever
- Prime numbers make sure every cell is considered
- Imagine an array size of 13 with a jump size of 5
 - 0, 5, 10, 2, 7, 12, 4, 9, 1, 6, 11, 3 etc.
- If there is any empty cell, the algorithm will find it with a prime jump size

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Open Addressing

- Open addressing leads to a problem with deletion
- A probe gives up its search once it comes across an empty slot
- But what if the item you're searching for is there but one of the items it collided with before it has been since deleted?
- We solve this problem by filling a slot with a deleted value (e.g. -1) when an item has been deleted, rather than making it empty
- This way the probe will know to keep going instead of stopping
- This is called a **tombstone**
- When tombstones build up you should periodically rehash your table to get rid of them



Index	Contents
5016	parsnip
5017	-1
5018	house
5019	cats

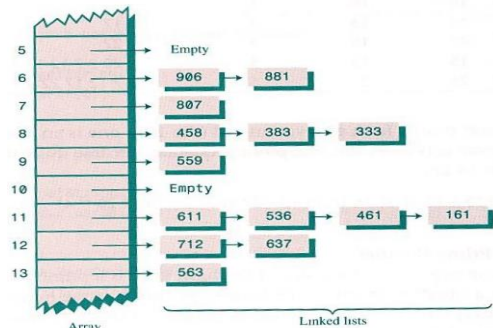
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Separate Chaining



- Rather than trying to put each item in a separate slot, another approach is to install a **linked list** in each slot
- If collisions occur and several items end up in the same slot, then they are simply added to the linked list
- When looking for an item at a particular slot, simply search through the linked list containing all of the items hashing to that slot
- So long as the linked lists don't become too long then the performance shouldn't be too badly affected

Separate Chaining



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Load Factor



- The **load factor** is the ratio between the size of the hash table and the number of items in it
 - Load factor of 1 = as many items as there are slots
 - Load factor of 0 = hash table is empty
- With **open addressing** the maximum load factor is obviously 1 because each slot can only hold one item
- With **separate chaining** it is normal for the load factor to be higher than 1 because each slot holds a linked list
 - Finding the initial slot is $O(1)$ time but searching through the linked list is $O(M)$ where M is the average number of items in each linked list
 - Therefore, we'd like to keep M around 1
 - With a load factor of 1, about a third of slots will be empty, about a third will hold one item and about a third will hold two or more items

Efficiency



- Insertion and searching in hash tables should approach $O(1)$ time
 - The number of items in the hash table should have no impact on the amount of time taken to find an item
- If no collision occurs all we need to do is call the hash function and access one slot in the array
- If collisions occur, access times become dependent on the resulting probe lengths
 - A slot must be checked to see if it is empty or if it contains the item we're looking for
- Search or insertion time is therefore proportional to the length of the probe
- Average probe length is in turn dependent on the **load factor**

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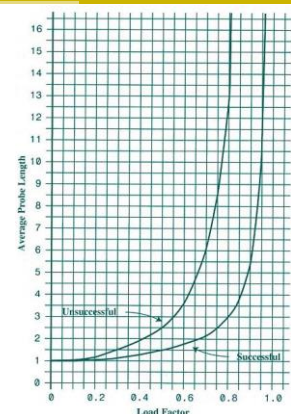
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Open Addressing

- As load factor increases, probe lengths grow longer and efficiency drops
- Loss of efficiency with high load factors is more serious for open addressing than for separate chaining
- Unsuccessful searches take longest because the probe must go all the way through the probe sequence before it is sure it can't find the item
- When nearly every slot is full you might end up looking through half the hash table before finding an empty slot!

Linear Probing

Load factor needs to be kept below $2/3$ for decent performance and preferably below $1/2$

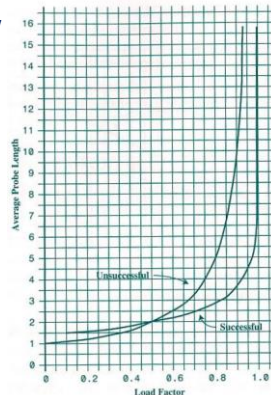


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Quadratic probing / Double Hashing

Slightly higher load factor can be tolerated



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Separate Chaining

- The most time-consuming part is comparing the search key of the item with the keys of other items in the linked list
- If N data items have been inserted into a hash table then
 - $\text{AverageLinkedListLength} = N / \text{HashTableSize}$
- In other words, **average list length = load factor**

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Separate Chaining

- In a successful search, on average half of the items in a linked list will have to be checked
 - 1 step needed for the hashing operation
 - Search time = $1 + \text{loadFactor} / 2$
- In an unsuccessful search, all of the items must be checked
 - Search time = $1 + \text{loadFactor}$
- If the linked list is ordered then on average only half of the items must be examined in an unsuccessful search
- In this case the search times for successful and unsuccessful searches converge

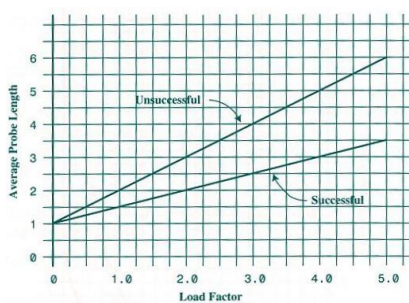
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Insertion

- If the linked lists are not ordered then insertion is always immediate so the insertion time is **1**
- If the lists are ordered then on average half of the items in each list must be examined so the insertion time is **$1 + \text{loadFactor} / 2$**

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Separate Chaining



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Summary

- In **open addressing** performance degrades badly as the load factor increase above $\frac{1}{2}$
- In **separate chaining** it can rise above 1 without hurting performance too much
- As load factor increases, performance only degrades linearly using **separate chaining**
- Deletion is also easier with **separate chaining** because we don't need to worry about probes being misled by encountering empty slots where an item has been deleted
- Using **open addressing** every deletion leaves behind a tombstone which adds to the load factor

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Summary

- If using open addressing, **double hashing** is slightly better than **quadratic probing**
- However, if there's plenty of memory and the data won't expand after the table is created then **linear probing** can be handier to implement and will cause little performance penalty with a load factor under $\frac{1}{2}$
- If the number of items to be inserted into the hash table is unknown then **separate chaining** is a safer bet
- If there are going to be many deletions then **separate chaining** is the way to go because an **open addressing** hash table will fill up with tombstones

