

# DSC 40B

## *Theoretical Foundations II*

Lecture 9 | Part 1

**Warmup**

## Exercise

- ▶ How fast can we query/insert with these data structures?

	Query	Insert
Unsorted linked list		
Unsorted array		
Sorted array		
BST		

# DSC 40B

## *Theoretical Foundations II*

Lecture 9 | Part 2

### **Direct Address Tables**

# Counting Frequencies

- How many times does each age appear?

PID	Name	Age
A1843	Wan	24
A8293	Deveron	22
A9821	Vinod	41
A8172	Aleix	17
A2882	Kayden	4
A1829	Raghu	51
A9772	Cui	48
⋮	⋮	⋮

## Exercise

What data structure would you use to store the age counts?

# Direct Address Tables

- ▶ Idea: keep an **array** `arr` of length, say, 125.
- ▶ Initialize to zero.
- ▶ If we see age  $x$ , increment `arr[x]` by one.

# Building the Table

```
# loading the table  
table = np.zeros(125)  
  
for age in ages:  
    table[age] += 1
```

- Time complexity if there are  $n$  people?

# Query

```
# query: how many people are 55?  
print(table[55])
```

- ▶ Time complexity if there are  $n$  people?



# Counting Names

- How many times does each name appear?

PID	Name	Age
A1843	Wan	24
A8293	Deveron	22
A9821	Vinod	41
A8172	Aleix	17
A2882	Kayden	4
A1829	Raghu	51
A9772	Cui	48
⋮	⋮	⋮

# Downsides

- ▶ DATs are **fast**.
- ▶ What are the downsides of DATs?
- ▶ Could we use a DAT to store:
  - ▶ zip codes?
  - ▶ phone numbers?
  - ▶ credit card numbers?
  - ▶ names?

# Downsides

- ▶ Things being stored must be integers, or convertible to integers
  - ▶ why? valid array indices
- ▶ Must come from a small range of possibilities
  - ▶ why? memory usage. example: phone numbers

# Hash Tables

- ▶ Insight: anything can be “converted” to an integer through **hashing**.
- ▶ But not uniquely!
- ▶ Hash tables have many of the same advantages as DATs, but work more generally.

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## *Theoretical Foundations II*

Lecture 9 | Part 3

Hashing

# Hashing

- ▶ One of the most important ideas in CS.
- ▶ Tons of uses:
  - ▶ Verifying message integrity.
  - ▶ Fast queries on a large data set.
  - ▶ Identify if file has changed in version control.

# Hash Function

- ▶ A **hash function** takes a (large) object and returns a (smaller) “fingerprint” of that object.
- ▶ Usually the fingerprint is a number, guaranteed to be in some range.

## How?

- ▶ Looking at certain bits, combining them in ways that *look* random (but aren't!)



# Hash Function Properties

- ▶ Hashing same thing twice returns the same hash.
- ▶ Unlikely that different things have same fingerprint.
  - ▶ But not impossible!

# Collisions

- ▶ Hash functions map objects to numbers in a defined range.
  - ▶ Example: given image, return number in  $[0, 1, 2, \dots, 1024]$
- ▶ There will be two images with the same hash.
  - ▶ **Pigeonhole principle**: if there are  $n$  pigeons,  $< n$  holes, there will a hole with  $\geq 2$  pigeons.
- ▶ **Collision**: two objects have the same hash

# **“Good” Hash Functions**

- ▶ A good hash function tries to minimize collisions.

# Hashing in Python

- The `hash` function computes a hash.

```
»> hash("This is a test")  
-670458579957477203  
»> hash("This is a test")  
-670458579957477203  
»> hash("This is a test!")  
1860306055874153109
```

# MD5

- ▶ MD5 is a **cryptographic** hash function.
  - ▶ Hard to “reverse engineer” input from hash.

- ▶ Returns a *really large* number in hex.

a741d8524a853cf83ca21eabf8cea190

- ▶ Used to “fingerprint” whole files.

# Example

```
> echo "My name is Justin" | md5  
a741d8524a853cf83ca21eabf8cea190
```

```
> echo "My name is Justin" | md5  
a741d8524a853cf83ca21eabf8cea190
```

```
> echo "My name is Justin!" | md5  
f11eed2391bbd0a5a2355397c089fafd
```

# Example

```
> md5 slides.pdf  
e3fd4370fda30ceb978390004e07b9df
```

# Why?

- ▶ I release a piece of software.
- ▶ I host it on Google Drive.
- ▶ Someone (Google, US Gov., etc.) decides to insert extra code into software to spy on users.
- ▶ You have no way of knowing.



# Why?

- ▶ I release a piece of software & **publish the hash**.
- ▶ I host it on Google Drive.
- ▶ Someone inserts extra code.
- ▶ You download the software and hash it. If hash is different, you know the file has been changed!

## Another Use: De-duplication

- ▶ Building a massive training set of images.
- ▶ Given a new image, is it already in my collection?
- ▶ Don't need to compare images pixel-by-pixel!
- ▶ Instead, compare **hashes**.

# Hashing for Data Scientists

- ▶ Don't need to know much about *how* the hash function works.
- ▶ But should know how they are used.

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## *Theoretical Foundations II*

Lecture 9 | Part 4

### Hash Tables

# Membership Queries

- ▶ **Given:** a collection of  $n$  numbers and a target  $t$ .
- ▶ **Find:** determine if  $t$  is in the collection.

# Goal

- ▶ DATs are fast, but won't work for things that aren't numbers in a small range.
- ▶ Idea: hash objects to numbers in a small range, use a DAT.
- ▶ But must deal with collisions.

# Hash Tables

- ▶ Pick a table size  $m$ .
  - ▶ Usually  $m \approx$  number of things you'll be storing.
- ▶ Create hash function to turn input into a number in  $\{0, 1, \dots, m - 1\}$ .
- ▶ Create DAT with  $m$  bins.

# Example

```
hash('hello') == 3  
hash('data') == 0  
hash('science') == 4
```

0   1   2   3   4   ...    $m - 1$



# Collisions

- ▶ The **universe** is the set of all possible inputs.
- ▶ This is usually much larger than  $m$  (even infinite).
- ▶ Not possible to assign each input to a unique bin.
- ▶ If  $\text{hash}(a) == \text{hash}(b)$ , there is a **collision**.

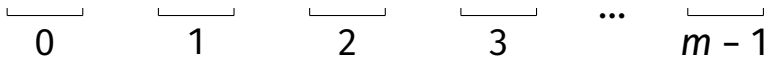
# Example

```
hash('hello') == 3  
hash('data') == 0  
hash('san diego') == 3
```

0    1    2    3    4    ...     $m - 1$

# Chaining

- ▶ Collisions stored in same bin, in linked list.
- ▶ **Query:** Hash to find bin, then linear search.



# The Idea

- ▶ A good hash function will utilize all bins evenly.
  - ▶ Looks like uniform random distribution.
- ▶ If  $m \approx n$ , then only a few elements in each bin.
- ▶ As we add more elements, we need to add bins.

# Average Case

- ▶  $n$  elements in bin.
- ▶  $m$  bins.
- ▶ Assume elements placed randomly in bins<sup>1</sup>.
- ▶ Expected bin size:

---

<sup>1</sup>Of course, they are placed deterministically.

# Average Case

- ▶  $n$  elements in bin.
- ▶  $m$  bins.
- ▶ Assume elements placed randomly in bins<sup>1</sup>.
- ▶ Expected bin size:  $n/m$

---

<sup>1</sup>Of course, they are placed deterministically.

# Analysis

- ▶ Query:
  - ▶ Time to find correct bin:
  - ▶ Expected number of elements in the bin:
  - ▶ Time to perform linear search:
  - ▶ Total:

# Analysis

- ▶ Query:
  - ▶ Time to find correct bin:  $\Theta(1)$
  - ▶ Expected number of elements in the bin:
  - ▶ Time to perform linear search:
  - ▶ Total:



# Analysis

- ▶ Query:
  - ▶ Time to find correct bin:  $\Theta(1)$
  - ▶ Expected number of elements in the bin:  $n/m$
  - ▶ Time to perform linear search:
  - ▶ Total:

# Analysis

- ▶ Query:
  - ▶ Time to find correct bin:  $\Theta(1)$
  - ▶ Expected number of elements in the bin:  $n/m$
  - ▶ Time to perform linear search:  $\Theta(n/m)$
  - ▶ Total:

# Analysis

- ▶ Query:
  - ▶ Time to find correct bin:  $\Theta(1)$
  - ▶ Expected number of elements in the bin:  $n/m$
  - ▶ Time to perform linear search:  $\Theta(n/m)$
  - ▶ Total:  $\Theta(1 + n/m)$

# Analysis

- ▶ Query:
  - ▶ Time to find correct bin:  $\Theta(1)$
  - ▶ Expected number of elements in the bin:  $n/m$
  - ▶ Time to perform linear search:  $\Theta(n/m)$
  - ▶ Total:  $\Theta(1 + n/m)$
  - ▶ We usually guarantee  $m = O(n)$

# Analysis

- ▶ Query:
  - ▶ Time to find correct bin:  $\Theta(1)$
  - ▶ Expected number of elements in the bin:  $n/m$
  - ▶ Time to perform linear search:  $\Theta(n/m)$
  - ▶ Total:  $\Theta(1 + n/m)$
  - ▶ We usually guarantee  $m = O(n)$
  - ▶ Expected time:  $\Theta(1)$ .

# Worst Case

- ▶ Everything hashed to same bin.
  - ▶ Really unlikely!
  - ▶ Adversarial attack?
- ▶ Query:
  - ▶  $\Theta(1)$  to find bin
  - ▶  $\Theta(n)$  for linear search.
  - ▶ Total:  $\Theta(n)$ .

## Exercise

What is the worst case time complexity of inserting an element into a hash table that uses chaining with linked lists?

# Growing the Hash Table

- ▶ Insertions take  $\Theta(1)$  **unless** the hash table needs to grow.
- ▶ We need to ensure that  $m \leq c \cdot n$ .
  - ▶ Otherwise, too many collisions.
- ▶ If we add a bunch of elements, we'll need to increase  $m$ .
- ▶ Increasing  $m$  means allocating a new array,  $\Theta(m) = \Theta(n)$  time.



## Main Idea

Hash tables support constant (expected) time insertion and membership queries.

# Dictionaries

- ▶ Hash tables can also be used to store (key, value) pairs.
- ▶ Often called **dictionaries** or **associative arrays**.

# Hashing in Python

- ▶ `dict` and `set` implement hash tables.
- ▶ Querying is done using `in`:

```
»> # make a set
»> L = {3, 6, -2, 1, 7, 12}
»> 1 in L # Theta(1)
False
»> 7 in L # Theta(1)
True
```

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## *Theoretical Foundations II*

Lecture 9 | Part 5

### Fast Algorithms with Hash Tables

# Faster Algorithms

- ▶ Hashing is a super common trick.
- ▶ The “best” solution to interview problems often involves hashing.

## Example 1: The Movie Problem

- ▶ You're on a flight that will last  $D$  minutes.
- ▶ You want to pick two movies to watch.
- ▶ Find two whose durations sum to **exactly**  $D$ .

## Recall: Previous Solutions

- ▶ Brute force:  $\Theta(n^2)$ .
- ▶ Sort, use sorted structure:  $\Theta(n \log n) + \Theta(n)$ .
- ▶ Theoretical lower bound:  $\Omega(n)$ ?
- ▶ Can we speed this up with hash tables?

# Idea

- ▶ To use hash tables, we want to frame problem as a **membership query**.



# Example

- ▶ Suppose flight is 360 minutes long.
- ▶ Suppose first movie is fixed: 120 minutes.
- ▶ Is there a movie lasting  $(360 - 120) = 140$  minutes?

```
def optimize_entertainment_hash(times, D):  
    hash_table = dict()  
    for i, time in enumerate(times):  
        hash_table[time] = i  
  
    for i, time in enumerate(times):  
        target = D - time  
        if target in hash_table:  
            return i, hash_table[target]
```

## Example 2: Anagrams

### Definition

Two strings  $w_1$  and  $w_2$  are **anagrams** if the letters of  $w_1$  can be permuted to make  $w_2$ .

# Examples

- ▶ abcd / dbca
- ▶ listen / silent
- ▶ sandiego / doginsea

# Problem

- ▶ Given a collection of  $n$  strings, determine if any two of them are anagrams.

## Exercise

Design an efficient algorithm for solving this problem. What is its time complexity?

# Solution

- ▶ We need to turn this into a **membership query**.
- ▶ **Trick:** two strings are anagrams iff

`sorted(w_1) == sorted(w_2)`

```
def any_anagrams(words):  
    seen = set()  
    for word in words:  
        w = sorted(word)  
        if w in seen:  
            return True  
        else:  
            seen.add(w)
```



## Hashing **Downsides**

- ▶ Problem must involve **membership query**.

## Example: The Movie Problem

- ▶ You're on a flight that will last  $D$  minutes.
- ▶ You want to pick two movies to watch.
- ▶ Find two whose added durations is **closest** to  $D$ .

## Hashing **Downsides**

- ▶ No locality: similar items map to different bins.
- ▶ There is no way to quickly query entry closest to given input.

## Example: Number of Elements

- ▶ Given a collection of  $n$  numbers and two endpoints,  $a$  and  $b$ , determine how many of the numbers are contained in  $[a, b]$ .
- ▶ Not a membership query.
- ▶ Idea: **sort** and use modified binary search.

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## *Theoretical Foundations II*

Lecture 9 | Part 6

### Hash Table Drawbacks

# Hashing **Downsides**

- ▶ No locality: similar items map to different bins.
- ▶ But we often want similar items at the same time.
- ▶ Results in many **cache misses**, **slow**.

# Hashing **Downsides**

- ▶ Memory overhead.

# Hash Tables vs. BSTs

- ▶ Hash Table:  $\Theta(1)$  insertion, query (expected time).
- ▶ BST:  $\Theta(\log n)$  insertion, query (if balanced).
- ▶ Why ever use a BST?



# Hash Tables vs. BSTs

- ▶ Hash tables keep items in arbitrary order.
- ▶ Example: how many elements are in the interval  $[3, 23]$ ?
- ▶ Example: what is the min/max/median?
- ▶ BSTs win when order is important.