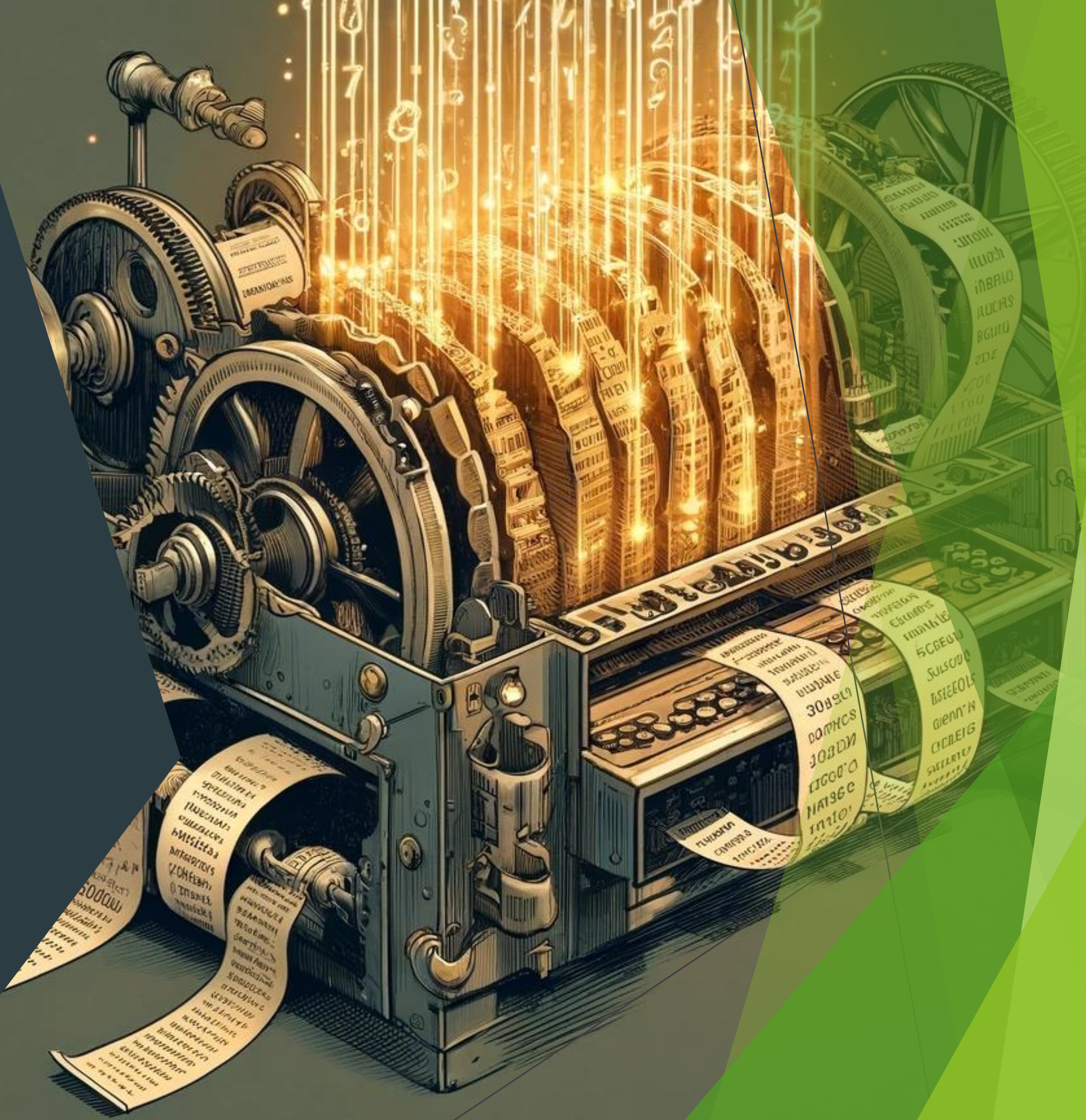
ECE2810J
Data Structures and Algorithms

- **Hashing: Basics and Hash Function**
- **Learning Objectives:**
  - Know the purpose of hashing
  - Understand the collision problem
  - Know how to design a good hash function



Outline

REVIEW OF DICTIONARY

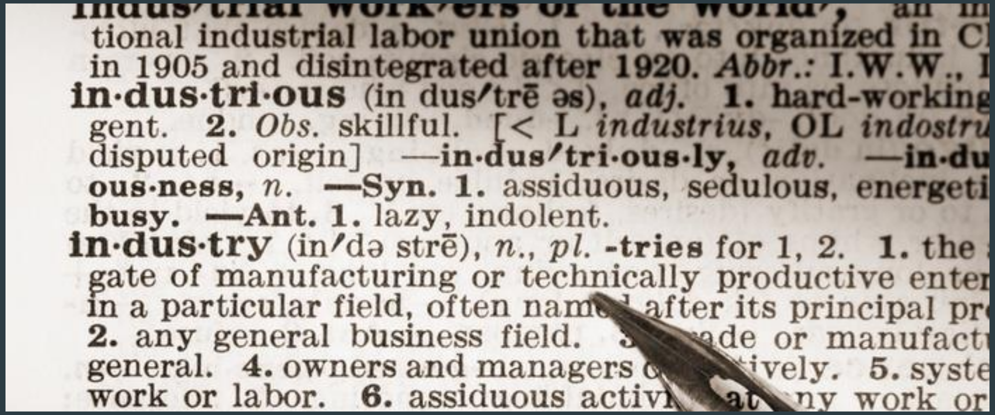
HASHING BASICS

HASH FUNCTION

Dictionary

- How do you use a dictionary?
  - Look up a “word” and find its meaning.
- We also have an abstract data type called dictionary.
  - It is a collection of pairs, each containing a key and an value

    `(key, value)`
  - Important: Different pairs have different keys.


tional industrial labor union that was organized in C
in 1905 and disintegrated after 1920. *Abbr.:* I.W.W., I
in·dus·tri·ous (in dus′trē əs), *adj.* **1.** hard-working
gent. **2.** *Obs.* skillful. [< L *industrius*, OL *indostru*
disputed origin] **—in·dus′tri·ous·ly,** *adv.* **—in·du**
ous·ness, *n.* **—Syn. 1.** assiduous, sedulous, energeti
busy. **—Ant. 1.** lazy, indolent.
in·dus·try (in′də strē), *n., pl.* **-tries** for 1, 2. **1.** the
gate of manufacturing or technically productive enter
in a particular field, often nam after its principal pr
2. any general business field. ade or manufactu
general. **4.** owners and managers ively. **5.** syste
work or labor. **6.** assiduous activi ny work or

Dictionary

- Key space is usually more regular/structured than value space, so easier to search.

- Dictionary is optimized to quickly add `(key, value)` pair and retrieve value by key.

Methods

- **`Value find(Key k)`**: Return the value whose key is **`k`**. Return **`Null`** if none.
- **`void insert(Key k, Value v)`**: Insert a pair **`(k, v)`** into the dictionary. If the pair with key as **`k`** already exists, update its value.
- **`Value remove(Key k)`**: Remove the pair with key as **`k`** from the dictionary and return its value. Return **`Null`** if none.

Runtime for Array Implementation

`Pair Array[MAXSIZE]:`

a	b	c	d			

- Unsorted array
  - find() $O(n)$
  - insert() $O(n)$: $O(n)$ to verify duplicate, $O(1)$ to put at the end
  - remove() $O(n)$: $O(n)$ to verify existence, $O(1)$ to exchange the "hole" with the last element
- Sorted array
  - find() $O(\log n)$: binary search
  - insert() $O(n)$: $O(\log n)$ to verify duplicate, $O(n)$ to insert
  - remove() $O(n)$: $O(\log n)$ to verify existence, $O(n)$ to remove

Can we do **`find`**, **`insert`**, and **`remove`** in $O(1)$ time?

Outline

- Review of Dictionary
- Hashing Basics
- Hash Function

Hashing: High-Level Idea

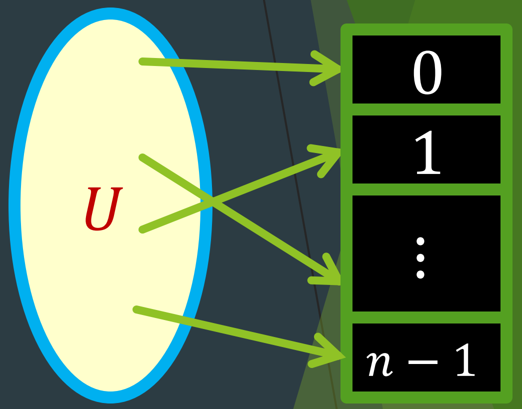
- Setup: A universe U of objects
  - E.g., All names, all IP addresses, etc.
  - Generally, very BIG!
- Goal: Want to maintain an evolving set $S \subseteq U$
  - E.g., 200 students, 500 IP addresses
  - Generally, of reasonable size.
- Naïve solutions

1. Array-based solution (index by $u \in U$)
   - $\Theta(1)$ operation time, BUT $\Theta(|U|)$ space.
2. Linked list-based solution:
   - $\Theta(|S|)$ space, BUT $\Theta(|S|)$ operation time.

Can we get the best of both solutions?

Hashing: High-Level Idea

- Solution:
  - Pick an array A of n buckets.
    - $n = c|S|$: a small multiple of $|S|$.
  - Choose a hash function $h: U \rightarrow \{0,1,\ldots,n-1\}$
    - h is fast to compute.
    - The same key is always mapped to the same location.
  - Store item k in A[h(k)]



- The array is called hash table
  - An array of buckets, where each bucket contains items as assigned by a hash function.
  - h[k] is called the home bucket of key k.

Hashing Example

- Pairs are: (22,a), (33,b), (3,c), (73,d), (85,e)
- Hash table is `A[0:7]` and table size is `M = 8`
- Hash function is `h[key] = key/11`
- Every item with `key` is stored in the bucket `A[h(key)]`

(3,c)		(22,a)	(33,b)			(73,d)	(85,e)
[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]

Question: What is the time complexity for `find()`, `insert()`, and `remove()`?

O(1)

Achieves both fast runtime and efficient memory usage

What Can Go Wrong?

[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]
(3,c)		(22,a)	(33,b)			(73,d)	(85,e)

- Where does (35, g) go?
- Problem: The home bucket for (35, g) is already occupied!
  - This is a "collision".

Collision and Collision Resolution

- Collision occurs when the hash function maps two or more items—all having different search keys—into the same bucket.

- What to do when there is a collision?
  - Collision-resolution scheme: assigns distinct locations in the hash table to items involved in a collision.

- Two major schemes:
  - Separate chaining
  - Open addressing

Insight of Collision: Birthday Problem

- Consider n people with random birthdays (i.e., with each day of the year equally likely). What is the smallest n so that there is at least a 50% chance that two people have the same birthday?

  A. 23

  B. 57

  C. 184

  D. 367

Collision is inevitable!

Insight of Collision: Birthday Problem

- Consider n people with random birthdays (i.e., with each day of the year equally likely). What is the smallest n so that there is at least a 50% chance that two people have the same birthday?

A. 23

B. 57

C. 184

D. 367

We want to find the smallest n for which

$$1 - \prod_{i=0}^{n-1} \frac{365-i}{365} > 0.5$$

Collision is inevitable!

Hash Table Issues

- Choice of the hash function.
- Collision resolution scheme.
- Size of the hash table and rehashing.

Outline

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Hash Function Design Criteria

- Must compute a bucket for every key in the universe.
- Must compute the same bucket for the same key.
- Should be easy and quick to compute.
- Minimizes collision
  - Spread keys out evenly in hash table
  - Gold standard: completely random hashing
    - The probability that a randomly selected key has bucket i as its home bucket is $1/n$, $0 \leq i < n$.
    - Completely random hashing minimizes the likelihood of a collision when keys are selected at random.
    - However, completely random hashing is **infeasible** due to the need to remember the random bucket.

The hardest criterion

Bad Hash Functions

- Example: keys = phone number in China (11 digits)
  - $|U| = 10^{11}$
  - Terrible hash function: $h(key)$ = first 3 digits of key, i.e., area code
    - The keys are not spread out evenly. Buckets 010, 021 may have a lot of keys mapped to them, while some buckets have no keys.
  - Mediocre hash function: $h(key)$ = last 3 digits of key.
    - Still vulnerable to patterns in last 3 digits.

Hash Functions

- Hash function ($h(key)$) maps key to buckets in two steps:

1. Convert key into an integer in case the key is not an integer.
    - A function $t(key)$ which returns an integer value, known as hash code.
2. Compression map: Map an integer (hash code) into a home bucket.
    - A function $c(hashcode)$ which gives an integer in the range $[0, n-1]$, where n is the number of buckets in the table.

- In summary, $h(key) = c(t(key))$, which gives an index in the table.

Map Non-integers into Hash Code

- String: use the ASCII (or UTF-8) encoding of each char and then perform arithmetic on them.
- Floating-point number: treat it as a string of bits.
- Images, (viral) code snippets, (malicious) Web site URLs: in general, treat the representation as a bit-string, using all of it or extracting parts of it (i.e., www.sjtu.edu.cn).

Strings to Integers

- Simple scheme: adds up all the ASCII codes for all the chars in the string.
  - Example: t("He") = 72 + 101 = 173.
- Not good. Why?
  - Consider English words "post", "pots", "spot", "stop", "tops".

Strings to Integers

- A better strategy: Polynomial hash code taking positional info into account.

$$t(s[]) = s[0]a^{k-1} + s[1]a^{k-2} + \cdots + s[k-2]a + s[k-1]$$

where a is a constant.

- If $a = 33$, the hash codes for “post” and “stop” are

$$t(\text{post}) = 112 \cdot 33^3 + 111 \cdot 33^2 + 115 \cdot 33 + 116 = 4149734$$
$$t(\text{stop}) = 115 \cdot 33^3 + 116 \cdot 33^2 + 111 \cdot 33 + 112 = 4262854$$

Strings to Integers

$$t(s[]) = s[0]a^{k-1} + s[1]a^{k-2} + \cdots + s[k-2]a + s[k-1]$$

- Good choice of a for English words: 31, 33, 37, 39, 41
  - What does it mean for a to be a good choice? Why are these particular values good?
  - Answer: according to statistics on 50,000 English words, each of these constants will produce less than 7 collisions.

- In Java, its **`string`** class has a built-in **`hashCode()`** function. It takes $a = 31$. Why?
  - Multiplication by 31 can be replaced by a shift and a subtraction for better performance:

```
31*i == (i << 5) - i
```

Hash function criteria: Should be easy and quick to compute.

Compression Map

- Map an integer (hash code) into a home bucket.
- The most common method is by modulo arithmetic.

  `homeBucket = c(hashcode) = hashcode % n`
  where n is the number of buckets in the hash table.

- Example: Pairs are (22,a), (33,b), (3,c), (55,d), (79,e). Hash table size is 7.

[0]	[1]	[2]	[3]	[4]	[5]	[6]
	(22,a)	(79,e)	(3,c)		(33,b)	(55,d)

Hashing by Modulo

- In practice, keys of an application tend to have a specific pattern.
  - For example, memory address in computer is multiple of 4.

- The choice of the hash table size n will affect the distribution of home buckets.

Hashing by Modulo

- Suppose the keys of an application are more likely to be mapped into even integers.
  - E.g., memory address is always a multiple of 4.

- When the hash table size n is an even number, even integers are hashed into even home buckets.
  - E.g., n = 14: 20%14 = 6, 32%14 = 4, 8%14 = 8

- The bias in the keys results in a bias toward the even home buckets.
  - All odd buckets are **<u>guaranteed</u>** to be empty.
  - The distribution of home buckets is not uniform!

Hashing by Modulo

- However, when the hash table size n is odd, even (or odd) integers may be hashed into both odd and even home buckets.
  - E.g., n = 15: 20%15 = 5, 32%15 =2, 8%15 = 8

    15%15 = 0, 3%15 = 3, 23%15 = 8

- The bias in the keys does not result in a bias toward either the odd or even home buckets.
  - Better chance of uniform distribution of home buckets.
- So <u>**do not**</u> use an even hash table size n.

Hashing by Modulo

- Similar **biased** distribution of home buckets happens in practice when the hash table size n is a multiple of small prime numbers.
- The effect of each prime divisor p of n **decreases** as p gets **larger**.
- Ideally, choose the hash table size n as a **large prime number**.

Code Exercise: Hashing by Modulo (~15 mins)

- Code can be found in :
  - Canvas -> Code Exercise -> Hashing