

## Maps and hash tables

Data Structures and Algorithms for Computational Linguistics III  
(ISCL-BA-07)

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## Hashing and hash-based data structure

- A *hash function* is a one-way function that takes a variable-length object, and turns it into a fixed-length bit string
- Most common applications of hash functions is the *map* (or *associative array*, or *dictionary*, or *symbol table*) data structure
- Maps are array-like data structures ( $O(1)$  access/update) but can be indexed using arbitrary objects (e.g., strings)
- Hashing has many other applications
  - Database indexing
  - Cache management
  - Efficient duplicate detection
  - File signatures: verification against corrupt/tampered files
  - Password storage
  - Electronic signatures
  - Other cryptographic algorithms/applications

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Winter Semester 2023/24 1 / 23

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## Maps and sets

- Two common data structures that use hashing is sets and maps (Python `dict`)
- set* abstract data type is based on the sets in mathematics: unordered collection without duplicates
- map* abstract data type is a collection that allows indexing with almost any data type (Python `dicts` require immutable data types)
- Basic operations include

Sets:

- Check whether an object is in the set (`x in a`)
- Add an element to a set (`a.add(x)`)
- Remove an element from a set (`a.remove(x)`)

Maps:

- Retrieve the value of a key (`d[key]`)
- Associate a key with a value (`d[key] = val`)
- Remove a key-value pair (`del d[key]`)

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## Implementing sets and maps

	Check/retrieve	Add	Remove
Sorted array:	$O(\log n)$	$O(n)$	$O(n)$
Unsorted array:	$O(n)$	$O(1)$	$O(n)$
Skip list:	$O(\log n)$	$O(\log n)$	$O(\log n)$
Balanced search tree:	$O(\log n)$	$O(\log n)$	$O(\log n)$
Hash tables:	$O(1)$	$O(1)$	$O(1)$

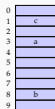
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## An trivial array implementation

store each element  $i$  at index  $i$  (assuming non-negative integer keys for now)



- All operations are  $O(1)$
- Cannot handle non-integer, negative keys
- Wastes a lot of memory if key values are spread across a wide range

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## Hash functions

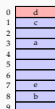
- A hash function  $h()$  maps a key to an integer index between 0 and  $m$  (size of the array)
- We use  $h(k)$  as an index to an array (of size  $m$ )
- If we map two different key values to the same integer, a *collision* occurs
- The main challenge with implementing hash maps is to avoid and handle the collisions
- We can think of a hash function in two parts:
  - map any object (variable bit string) to an integer (e.g., 32 or 64 bit)
  - compress the range of integers to map size ( $m$ )

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## Compressing the hash codes



- An easy way to map any integer to range  $[0, m]$  is to use modulo  $m + 1$
- Good hash functions minimize collisions, but collisions occur
- Collisions has to be handled by a map data structure. Two common approaches:
  - Separate chaining
  - Open addressing

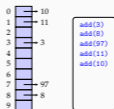
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## Separate chaining

or closed addressing



- Each array element keeps a pointer to a secondary container (typically a list)
- When a collision occurs, add the item to the list,

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## Separate chaining

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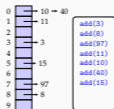
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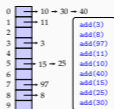
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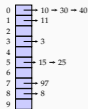


- Each array element keeps a pointer to a secondary container (typically a list)
- When a collision occurs, add the item to the list,
- Why not just add to the head of the list?

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## Complexity of separate chaining

is it really  $O(1)$ ?

- All operations require locating the element first
- Cost of locating an element include hashing (constant) + search in secondary data structure
- This means worst-case complexity is  $O(n)$
- With a good hash function, the probability of a collisions is  $n/m$ : average bucket size is  $O(n/m) = O(1)$  (if  $m > n$ )
- Expected complexity for all operations is  $O(1)$

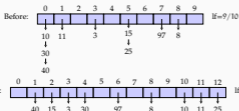
## Load factor for separate chaining

- Load factor of a hash map is

$$\text{load factor} = \frac{\text{number of entries}}{\text{number of indices}}$$

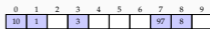
- Low load factor means
  - better run time (fewer collisions)
  - more memory usage
- When load factor is over a threshold, the map is extended (needs rehash)
- Recommendation vary, but a load factor around 0.75 is considered optimal

## Rehashing



## Open addressing (linear probing)

adding/accessing items

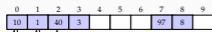


add(3)  
add(8)  
add(97)  
add(11)  
add(10)

- During insertion, if there is a collision, look for the next empty slot, and insert
- During lookup, probe until there is an empty slot

## Open addressing (linear probing)

adding/accessing items



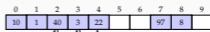
h(40)

- During insertion, if there is a collision, look for the next empty slot, and insert
- During lookup, probe until there is an empty slot

add(3)  
add(8)  
add(97)  
add(11)  
add(10)  
add(40)

## Open addressing (linear probing)

adding/accessing items



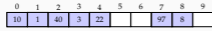
h(22)

- During insertion, if there is a collision, look for the next empty slot, and insert
- During lookup, probe until there is an empty slot

add(3)  
add(8)  
add(97)  
add(11)  
add(10)  
add(40)  
add(22)

## Open addressing (linear probing)

deleting items

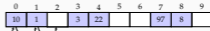


remove(40)

- We can locate an element as usual, and delete it

## Open addressing (linear probing)

deleting items



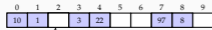
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remove(40)

## Open addressing (linear probing)

deleting items



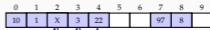
h(22)

- We can locate an element as usual, and delete it
- However, this breaks probing: now h(22) will point to an empty slot
- Rearranging the remaining items is complex & costly

remove(40)  
contains(22)

## Open addressing (linear probing)

deleting items



h(22)

- We can locate an element as usual, and delete it
- However, this breaks probing: now h(22) will point to an empty slot
- Rearranging the remaining items is complex & costly
- We insert a special value,
  - During lookup, treat it as full
  - During insertion, treat it as empty

remove(40)  
contains(22)

## Quadratic probing

- Linear probing tends to create clusters of items, especially if load factor is high ( $> 0.5$ )
- Quadratic probing provides some improvements
- Probe  $(h(k) + i^2) \bmod m$  for  $i = 0, 1, \dots$  until an empty slot is found
- If  $m$  is prime, and load factor is less than 0.5, quadratic probing is guaranteed to find an empty slot
- Although better than linear probing, quadratic probing creates its own kind of clustering

## Double hashing

- Similar to quadratic probing, probe non-linearly
- Instead of probing the next item, probe  $(h(k) + i \times h'(k)) \bmod m$  for  $i = 0, 1, \dots$  where  $h'(k)$  another hash function
- A common choice is  $h'(k) = q - (k \bmod q)$  for a prime number  $q < m$

## Using a pseudo random number generator

- This method probes  $(h(k) + i \times r_i) \bmod m$  for  $i = 0, 1, \dots$  where  $r_i$  is the  $i^{\text{th}}$  number generated by a pseudo random number generator
- Pseudo random number generators generate numbers that are close to uniform. However given the same seed, the sequence is deterministic
- This approach is the most common choice for modern programming languages/environments
- This also avoids problems with inputs that intentionally generate hash collisions

## Aside: hash DoS attacks

- A denial-of-service (DoS) attack aims to break or slow down an Internet site/service
- A particular attack (in 2003, but also 2011) made use of hash table implementation of popular programming languages
- Input to a web-based program is passed as key-value pairs, which are typically stored in a dictionary
- If one intentionally posts an input with a large number of colliding keys,
  - the hash table implementation needs to chain long sequences (separate chaining) or probe a large number of times (open addressing)
  - and eventually re-hash
- This increases expected to  $O(1)$  time to worst-case complexity

## Hash functions

and their properties

- A hash function must be consistent: if  $a == b$ ,  $h(a) == h(b)$
- A hash function should minimize collisions: values for  $h$  should be uniformly distributed
- A hash function should be fast to compute (...or maybe not – if you are using it for passwords)

## Hash codes

- Earlier we suggested dividing the hash function into two
  - A hash code that maps a variable-size object to an integer
  - A compression method that squeezes the integer value to hash table size
- A hash code avoid collisions: colliding hash codes are unavoidably mapped the same table address
- A naive approach is to truncate (e.g., take the most or least significant bits), or pad with an arbitrary pattern (if object is shorter than the hash code)
- This approach creates many collisions in real-world usage

## Hash codes

xor or add

- A simple approach is based on
  - Bitwise add each  $k$ -bit segment of the memory representation of the object, ignoring the overflow:  $h(x) = \sum_i x_i$
  - Similarly, one can use XOR instead of addition
- These methods meet the hash code requirement: if  $a == b$ , then  $h(a) == h(b)$
- However, in practice, they create many collisions because of their associativity
  - $abc$ ,  $bca$  and  $cba$  all get the same hash code

## Polynomial hash codes

- Polynomial hash codes are calculated using

$$h(x) = \sum_{i=0}^n x_i a^{n-i-1} = x_0 a^{n-1} + x_1 a^{n-2} + \dots + x_{n-1}$$

- The important aspect is that now the function will produce different values with sequences with the same items in a different order
- The exact form is motivated by quick computation if rewritten as

$$x_{n-1} + a(x_{n-2} + a(x_{n-3} + \dots))$$

## Cyclic-shift hash codes

- Instead of multiplying with powers of a constant, cyclic-shift hashing shifts some bits from one end to the other at each step in running sum
- Since bitwise operations are simple, this is a fast way of obtaining a non-associative valid hash code

```

101001100110100
1100111010010100

def cyclic_shift(a):
    mask = 0xffff
    b = 0
    for ch in a:
        h = (h << 5 & mask) | (h >> 11)
        h ^= ord(ch)
    return h

```

## A short divergence: cryptographic hash functions

- Hash functions has an important role in cryptography
- In cryptography, it is important to have hash functions for which it is difficult to find two keys with the same hash value
- There are a wide range of well-known hash functions (which are also available in most programming environments)
  - MD5
  - SHA-1
  - RIPMD-160
  - Whirlpool
  - SHA-2
  - SHA-3
  - BLAKE2
  - BLAKE3
- These functions are designed for applications like digital fingerprinting, password storage
- Computationally inefficient for use in data structures

## Summary

- Hash functions are useful for implementing map ADT efficiently
- Hash functions have a wide range of other applications
- The main issue in implementing a hash function is avoiding collisions, and handling them efficiently when they occur
- Reading: Goodrich, Tamassia, and Goldwasser (2013, chapter 10)

Next:

- Algorithms on strings: pattern matching, edit distance, tries
- Reading: Goodrich, Tamassia, and Goldwasser (2013, chapter 13), Jurařský and Martin (2009, section 3.11, or 2.5 in online draft)

## Acknowledgments, credits, references

- Goodrich, Michael T., Roberto Tamassia, and Michael H. Goldwasser (2013). *Data Structures and Algorithms in Python*. John Wiley & Sons, Incorporated. <https://doi.org/10.1118/476734>.
- Jurařský, Daniel and James H. Martin (2009). *Speech and Language Processing: An Introduction to Natural Language Processing, Computational Linguistics, and Speech Recognition*, second edition. Pearson Prentice Hall. <https://doi.org/10.1118/476734>.

