

Fundamental Algorithms

Chapter 7: Hash Tables

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Generalised Search Problem

Definition (Search Problem)

Input: a sequence or set A of n elements $\in \mathcal{A}$, and an $x \in \mathcal{A}$.

Output: Index $i \in \{1, \dots, n\}$ with $x = A[i]$, or NIL, if $x \notin A$.

- complexity depends on data structure
- complexity of operations to set up data structure? (insert/delete)

Definition (Generalised Search Problem)

- Store a set of objects consisting of a key and additional data:

Object := (
 key: **Integer**, .
 record: **Data**);

- search/insert/delete objects in this set

Direct-Address Tables

Definition (table as data structure)

- similar to array: access element via index
- usually contains elements only for some of the indices

Direct-Address Table:

- assume: limited number of values for the keys:
 $U = \{0, 1, \dots, m - 1\}$
- allocate table of size m
- use keys directly as index

Direct-Address Tables (2)

```
DirAddrInsert(T:Table , x:Object) {  
    T[x.key] := x;  
}
```

```
DirAddrDelete(T:Table , x:Object){  
    T[x.key] := NIL;  
}
```

```
DirAddrSearch(T:Table , key:Integer){  
    return T[key];  
}
```

Direct-Address Tables (3)

Advantage:

- very fast: search/delete/insert is $\Theta(1)$

Disadvantages:

- m has to be small, or otherwise, the table has to be very large!
- if only few elements are stored, lots of table elements are unused (waste of memory)
- all keys need to be distinct (they should be, anyway)

Hash Tables

Idea: compute index from key

Wanted: function h that

- maps a given key to an index,
- has a relatively small range of values, and
- can be computed efficiently,

Definition (hash function, hash table)

Such a function h is called a **hash function**.

The respective table is called a **hash table**.

Hash Tables – Insert, Delete, Search

```
HashInsert(T:Table , x:Object) {  
    T[h(x.key)] := x;  
}
```

```
HashDelete(T:Table , x:Object) {  
    T[h(x.key)]:= NIL;  
}
```

```
HashSearch(T:Table , x:Object) {  
    return T[h(x.key)];  
}
```

So Far: Naive Hashing

Advantages:

- still very fast: search/delete/insert is $\Theta(1)$, if h is $\Theta(1)$
- size of the table can be chosen freely, provided there is an appropriate hash function h

Disadvantages:

- values of h have to be distinct for all keys
- however: impossible to find a hash function that produces distinct values for any set of stored data

ToDo: deal with **collisions**:

objects with different keys that share a common hash value have to be stored in the same table element

Resolve Collisions by Chaining

Idea:

- use a table of **containers**
- containers can hold an arbitrarily large amount of data
- using (linked) lists as containers: **chaining**

```
ChainHashInsert(T:Table, x:Object) {  
    insert x into T[h(x.key)];  
}
```

```
ChainHashDelete(T:Table, x:Object) {  
    delete x from T[h(x.key)];  
}
```

Resolve Collisions by Chaining

```
ChainHashSearch(T:Table , x:Object) {  
    return ListSearch(x, T[h(x.key)] );  
    ! result: reference to x or NIL, if x not found;  
}
```

Advantages:

- hash function no longer has to return distinct values
- still very fast, if the lists are short

Disadvantages:

- delete/search is $\Theta(k)$, if k elements are in the accessed list
- worst case: all elements stored in one single list (very unlikely).

Chaining – Average Search Complexity

Assumptions:

- hash table has m slots (table of m lists)
- contains n elements \Rightarrow **load factor**: $\alpha = \frac{n}{m}$
- $h(k)$ can be computed in $O(1)$ for all k
- all values of h are equally likely to occur

Search complexity:

- on average, the list corresponding to the requested key will have α elements
- unsuccessful search: compare the requested key with all objects in the list, i.e. $O(\alpha)$ operations
- successful search: requested key last in the list;
 \Rightarrow also $O(\alpha)$ operations

Expected: Average complexity: $O(1 + \alpha)$ operations

Hash Functions

A good hash function should:

- satisfy the assumption of even distribution:
each key is equally likely to be hashed to any of the slots:

$$\sum_{k: h(k)=j} (P(\text{key} = k)) = \frac{1}{m} \quad \text{for all } j = 0, \dots, m - 1$$

- be easy to compute
- be “non-smooth”: keys that are close together should not produce hash values that are close together (to avoid clustering)

Simplest choice: $h = k \bmod m$ (m a prime number)

- easy to compute; even distribution if keys evenly distributed
- however: **not** “non-smooth”

The Multiplication Method for Integer Keys

Two-step method

1. multiply k by constant $0 < \gamma < 1$, and extract fractional part of $k\gamma$
2. multiply by m , and use integer part as hash value:

$$h(k) := \lfloor m(\gamma k \bmod 1) \rfloor = \lfloor m(\gamma k - \lfloor \gamma k \rfloor) \rfloor$$

Remarks:

- value of m uncritical; e.g. $m = 2^p$
- value of γ needs to be chosen well
- in practice: use fix-point arithmetics
- non-integer keys: use encoding to integers (ASCII, byte encoding, ...)

Open Addressing

Definition

- no containers: table contains objects
- each slot of the hash table either contains an object or NIL
- to resolve collisions, more than one position is allowed for a specific key

Hash function: generates **sequence** of hash table indices:

$$h: U \times \{0, \dots, m-1\} \rightarrow \{0, \dots, m-1\}$$

General approach:

- store object in the first empty slot specified by the probe sequence
- empty slot in the hash table guaranteed, if the probe sequence $h(k, 0), h(k, 1), \dots, h(k, m-1)$ is a permutation of $0, 1, \dots, m-1$

Open Addressing – Algorithms

```
OpenHashInsert(T:Table, x:Object) : Integer {  
    for i from 0 to m-1 do {  
        j := h(x.key, i);  
        if T[j]=NIL then { T[j] := x; return j; }  
    }  
    cast error "hash_table_overflow"  
}
```

```
OpenHashSearch(T:Table, k:Integer) : Object {  
    i := 0;  
    while T[h(k,i)]  $\diamond$  NIL and i < m {  
        if k = T[h(k,i)].key then return T[h(k,i)];  
        i := i+1;  
    }  
    return NIL;  
}
```

Open Addressing – Linear Probing

Hash function: $h(k, i) := (h_0(k) + i) \bmod m$

- first slot to be checked is $T[h_0(k)]$
- second probe slot is $T[h_0(k) + 1]$, then $T[h_0(k) + 2]$, etc.
- wrap around to $T[0]$ after $T[m - 1]$ has been checked

Main problem: clustering

- continuous sequences of occupied slots (“clusters”) cause lots of checks during searching and inserting
- clusters tend to grow, because all objects that are hashed to a slot inside the cluster will increase it
- slight (but minor) improvement: $h(k, i) := (h_0(k) + ci) \bmod m$

Main advantage: simple and fast

- easy to implement
- cache efficient!

Open Addressing – Quadratic Probing

Hash function: $h(k, i) := (h_0(k) + c_1 i + c_2 i^2) \bmod m$

- how to choose constants c_1 and c_2 ?
- objects with identical $h_0(k)$ still have the same sequence of hash values
("secondary clustering")

Idea: double hashing $h(k, i) := (h_0(k) + i \cdot h_1(k)) \bmod m$

- if h_0 is identical for two keys, h_1 will generate different probe sequences

Open Addressing – Double Hashing

$$h(k, i) := (h_0(k) + i \cdot h_1(k)) \pmod{m}$$

How to choose h_0 and h_1 :

- range of h_0 : $U \rightarrow \{0, \dots, m - 1\}$ (cover entire table)
- $h_1(k)$ must never be 0 (no probe sequence generated)
- $h_1(k)$ should be prime to m for all k
→ probe sequence will try all slots
- if d is the greatest common divisor of $h_1(k)$ and m , only $\frac{1}{d}$ of the hash slots will be probed

Possible choices:

- $m = 2^M$ and let h_1 generate odd numbers, only
- m a prime number, and $h_1: U \rightarrow \{1, \dots, m_1\}$ with $m_1 < m$

Collisions and Clustering

Scenarios for Collisions:

- keys share the same primary hash value: $h(k_1, 0) = h(k_2, 0)$
→ same sequence of hash values for linear and quadratic probing
- keys share a value of the hash sequence: $h(k_1, i) = h(k_2, j)$
→ same sequence of hash values for linear probing
→ different hash values for next try: $h(k_1, i + 1) \neq h(k_2, j + 1)$

Example:

- multiple keys that share the same has values
- linear hashing will cause primary cluster
- cluster will also grow by all keys mapped to a hash value within this cluster

Open Addressing – Deletion

Problem remaining: how to delete?

- search entry, remove it
- does not work:
 - insert 3, 7, 8 having same hash-value, then delete 7
 - how to find 8?

⇒ do not delete, just mark as deleted

Next problem:

- searching stops if first empty entry found
- after many deletions: lots of unnecessary comparisons!

Open Addressing – Deletion (2)

Deletion general problem for open hashing

- only “solution”: new construction of table after some deletions
- hash tables therefore commonly don't support deletion

Inserting

- inserting efficient, but too many inserts \Rightarrow not enough space
- \Rightarrow if ratio α too big, new construction of table with larger size

Still...

- searching faster than $O(\log n)$ possible