

Lecture 10: Hashing III: Open Addressing

Lecture Overview

- Open Addressing, Probing Strategies
- Uniform Hashing, Analysis
- Cryptographic Hashing

Readings

CLRS Chapter 11.4 (and 11.3.3 and 11.5 if interested)

Open Addressing

Another approach to collisions:

- **no chaining**; instead all items stored in table (see Fig. 1)

item ₂
item ₁
item ₃

이 가정 만족하기 위해서.
 $\#slots \geq \#elements$

Figure 1: Open Addressing Table

- **one item per slot** $\Rightarrow m \geq n$ $\rightarrow \#slots \rightarrow \#elements$.
- hash function specifies *order* of slots to probe (try) for a key (for insert/search/delete), not just one slot; **in math. notation**:

We want to design a function h , with the property that for all $k \in \mathcal{U}$:

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

↙
↘
↘

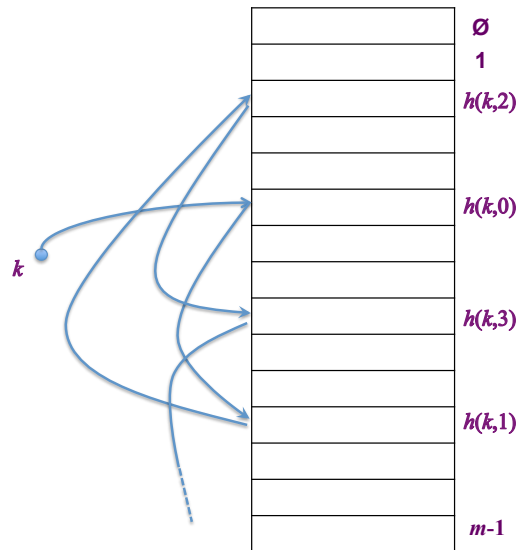
universe of keys trial count slot in table

$$h(k, i) = \varepsilon$$

↑ ↑
 trial slot

$$\langle h(k, 0), h(k, 1), \dots, h(k, m-1) \rangle$$

is a permutation of $0, 1, \dots, m-1$. i.e. if I keep trying $h(k, i)$ for increasing i , I will eventually hit all slots of the table.



↑
trial 2/3/4/...

Figure 2: Order of Probes

Insert(k,v) : Keep probing until an empty slot is found. Insert item into that slot.

```
for i in xrange(m):
    if T[h(k, i)] is None:           # empty slot
        T[h(k, i)] = (k, v)         # store item
    return
raise 'full'
```

Example: Insert $k = 496$

Search(k): As long as the slots you encounter by probing are occupied by keys $\neq k$, keep probing until you either encounter k or find an empty slot—return *success* or *failure* respectively.

```
for i in xrange(m):
    if T[h(k, i)] is None:           # empty slot?
        return None                 # end of "chain"
    elif T[h(k, i)][0] == k:         # matching key
        return T[h(k, i)]           # return item
    return None                      # exhausted table
```

empty → none

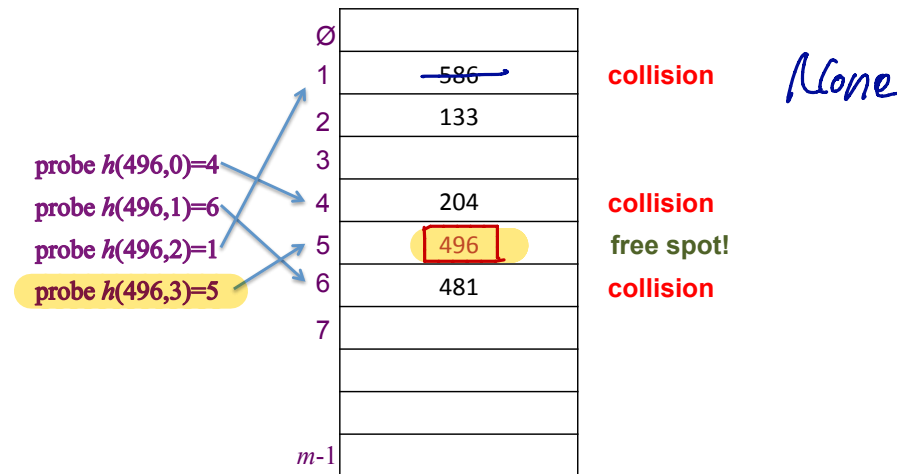


Figure 3: Insert Example

Deleting Items?

- can't just find item and remove it from its slot (i.e. set $T[h(k, i)] = \text{None}$)
- example: delete(586) \Rightarrow search(496) fails \Rightarrow Search(496) \rightarrow return None.
incorrectly deleted.
- replace item with special flag: "DeleteMe", which Insert treats as None but Search doesn't
keeps going with "DeleteMe"

Probing Strategies

Linear Probing

\leftarrow 충돌 발생시 옆자리!

가장: $(k, i) \rightarrow$ permutation.

$h(k, i) = (h'(k) + i) \bmod m$ where $h'(k)$ is ordinary hash function
table size.

- like street parking
- problem? clustering—cluster: consecutive group of occupied slots
 as clusters become longer, it gets more likely to grow further (see Fig. 4)
- can be shown that for $0.01 < \alpha < 0.99$ say, clusters of size $\Theta(\log n)$.

Double Hashing

$h(k, i) = (h_1(k) + i \cdot h_2(k)) \bmod m$ where $h_1(k)$ and $h_2(k)$ are two ordinary hash functions.

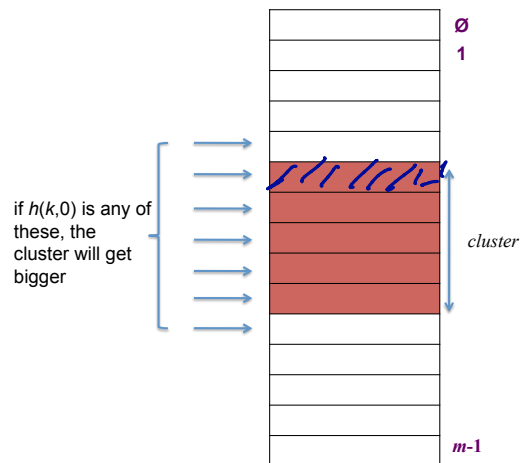


Figure 4: Primary Clustering

- actually hit all slots (permutation) if $h_2(k)$ is relatively prime to m for all k
why?

$$h_1(k) + i \cdot h_2(k) \bmod m = h_1(k) + j \cdot h_2(k) \bmod m \Rightarrow m \text{ divides } (i - j)$$

- e.g. $m = 2^r$, make $h_2(k)$ always odd

Uniform Hashing Assumption (cf. Simple Uniform Hashing Assumption)

Each key is equally likely to have any one of the $m!$ permutations as its probe sequence

- not really true
- but double hashing can come close

Analysis

Suppose we have used open addressing to insert n items into table of size m . Under the uniform hashing assumption the next operation has expected cost of $\leq \frac{1}{1 - \alpha}$, where $\alpha = n/m (< 1)$.

Example: $\alpha = 90\% \Rightarrow 10$ expected probes

$$\frac{1}{1 - \frac{n}{m}}$$

$$\text{cost} \leq \frac{m}{m - n}$$

$$\alpha \approx 0.5$$



re-size

3/4 full.

Strategy

2/3 full

3/4 full.

Proof:

Suppose we want to insert an item with key k . Suppose that the item is not in the table.

- probability first probe successful: $\frac{m-n}{m} =: p = 1-\alpha$.
(n bad slots, m total slots, and first probe is uniformly random)
- if first probe fails, probability second probe successful: $\frac{m-n}{m-1} \geq \frac{m-n}{m} = p$
(one bad slot already found, $m-n$ good slots remain and the second probe is uniformly random over the $m-1$ total slots left)
- if 1st & 2nd probe fail, probability 3rd probe successful: $\frac{m-n}{m-2} \geq \frac{m-n}{m} = p$
(since two bad slots already found, $m-n$ good slots remain and the third probe is uniformly random over the $m-2$ total slots left)
- ...

\Rightarrow Every trial, success with probability at least p .

Expected Number of trials for success?

$$\frac{1}{p} = \frac{1}{1-\alpha}.$$

With a little thought it follows that search, delete take time $O(1/(1-\alpha))$. Ditto if we attempt to insert an item that is already there. ■

Open Addressing vs. Chaining

Open Addressing: better cache performance (better memory usage, no pointers needed)

Chaining: less sensitive to hash functions (OA requires extra care to avoid clustering) and the load factor α (OA degrades past 70% or so and in any event cannot support values larger than 1)

Cryptographic Hashing

A cryptographic hash function is a deterministic procedure that takes an arbitrary block of data and returns a fixed-size bit string, the (cryptographic) hash value, such that an accidental or intentional change to the data will change the hash value. The data to be encoded is often called the *message*, and the hash value is sometimes called the *message digest* or simply digest.

The ideal cryptographic hash function has the properties listed below. d is the number of bits in the output of the hash function. You can think of m as being 2^d . d is typically 160 or more. These hash functions can be used to index hash tables, but they are typically used in computer security applications.

Desirable Properties

1. **One-Way (OW)**: Infeasible, given $y \in_R \{0, 1\}^d$ to find any x s.t. $h(x) = y$. This means that if you choose a random d -bit vector, it is hard to find an input to the hash that produces that vector. This involves “inverting” the hash function.
2. **Collision-resistance (CR)**: Infeasible to find x, x' , s.t. $x \neq x'$ and $h(x) = h(x')$. This is a collision, two input values have the same hash.
3. **Target collision-resistance (TCR)**: Infeasible given x to find $x' \neq x$ s.t. $h(x) = h(x')$.

TCR is weaker than CR. If a hash function satisfies CR, it automatically satisfies TCR. There is no implication relationship between OW and CR/TCR.

Applications

1. **Password storage**: Store $h(PW)$, not PW on computer. When user inputs PW' , compute $h(PW')$ and compare against $h(PW)$. The property required of the hash function is OW. The adversary does not know PW or PW' so TCR or CR is not really required. Of course, if many, many passwords have the same hash, it is a problem, but a small number of collisions doesn't really affect security.
2. **File modification detector**: For each file F , store $h(F)$ securely. Check if F is modified by recomputing $h(F)$. The property that is required is TCR, since the adversary wins if he/she is able to modify F without changing $h(F)$.
3. **Digital signatures**: In public-key cryptography, Alice has a public key PK_A and a private key SK_A . Alice can sign a message M using her private key to produce $\sigma = \text{sign}(SK_A, M)$. Anyone who knows Alice's public key PK_A can verify Alice's signature by checking that $\text{verify}(M, \sigma, PK_A)$ is true. The adversary wants to forge a signature that verifies. For large M it is easier to sign $h(M)$ rather than M , i.e., $\sigma = \text{sign}(SK_A, h(M))$. The property that we

require is CR. We don't want an adversary to ask Alice to sign x and then claim that she signed x' , where $h(x) = h(x')$.

Implementations

There have been many proposals for hash functions which are OW, CR and TCR. Some of these have been broken. MD-5, for example, has been shown to not be CR. There is a competition underway to determine SHA-3, which would be a Secure Hash Algorithm certified by NIST. Cryptographic hash functions are significantly more complex than those used in hash tables. You can think of a cryptographic hash as running a regular hash function many, many times with pseudo-random permutations interspersed.

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