Acknowledgement: The course slides are adapted from the slides prepared by R. Sedgewick and K. Wayne of Princeton University.

## Hashing: basic plan

Save items in a **key-indexed table** (index is a function of the key).

### Hash function

Method for computing array index from key.

- Computing the hash function.
- Equality test: Method for checking whether two keys are equal.
- Collision resolution: Algorithm and data structure to handle two keys that hash to the same array index.

### Classic space-time tradeoff

- No space limitation: trivial hash function with key as index.
- No time limitation: trivial collision resolution with sequential search.
- Space and time limitations: hashing (the real world).

### Q. Can we do better?

**A.** Yes, but with different access to the data (if we don’t need ordered ops).
Computing the hash function

**Idealistic goal.** Scramble the keys uniformly to produce a table index.
- Efficiently computable.
- Each table index equally likely for each key.

**Ex 1. Phone numbers.**
- Bad: first three digits.
- Better: last three digits.

**Ex 2. Social Security numbers.**
- Bad: first three digits.
- Better: last three digits.

**Practical challenge.** Need different approach for each key type.

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Java’s hash code conventions

All Java classes inherit a method `hashCode()`, which returns a 32-bit int.

**Requirement.** If `x.equals(y)`, then `(x.hashCode() == y.hashCode())`.

**Highly desirable.** If `!x.equals(y)`, then `(x.hashCode() != y.hashCode())`.

**Default implementation.** Memory address of `x`.

**Legal (but poor) implementation.** Always return 17.

**Customized implementations.** Integer, Double, String, File, URL, Date, ...

**User-defined types.** Users are on their own.

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Implementing hash code: integers, booleans, and doubles

**Java library implementations**

```java
public final class Integer {
    private final int value;

    public int hashCode() {
        return value;
    }
}
```

```java
public final class Double {
    private final double value;

    public int hashCode() {
        long bits = doubleToLongBits(value);
        return (int) (bits ^ (bits >>> 32));
    }
}
```

```java
public final class Boolean {
    private final boolean value;

    public int hashCode() {
        if (value) return 1231;
        else       return 1237;
    }
}
```

**convert to IEEE 64-bit representation; xor most significant 32-bits with least significant 32-bits**
Implementing hash code: strings

Horner’s method to hash string of length $L$: $L$ multiplies/adds.

Equivalent to $h = s[0] \cdot 31^{L-1} + \ldots + s[L-1] \cdot 31^1 + s[L-2] \cdot 31^1 + s[L-1] \cdot 31^0$.

Ex.

```
String s = "call";
int code = s.hashCode();
```

Implementing hash code: user-defined types

```
public final class Transaction implements Comparable<Transaction> {
    private final String who;
    private final Date when;
    private final double amount;

    public Transaction(String who, Date when, double amount) { /* as before */ }

    public boolean equals(Object y) { /* as before */ }

    public int hashCode() {
        int hash = 17;
        hash = 31*hash + who.hashCode();
        hash = 31*hash + when.hashCode();
        hash = 31*hash + ((Double) amount).hashCode();
        return hash;
    }
}
```

Hash code design

"Standard" recipe for user-defined types.

- Combine each significant field using the $31x + y$ rule.
- If field is a primitive type, use wrapper type `hashCode()`.
- If field is null, return 0.
- If field is a reference type, use `hashCode()`.
- If field is an array, apply to each entry.

In practice. Recipe works reasonably well; used in Java libraries.

In theory. Keys are bitstring; "universal" hash functions exist.

Basic rule. Need to use the whole key to compute hash code; consult an expert for state-of-the-art hash codes.
Modular hashing

Hash code. An int between \(-2^{31} \text{ and } 2^{31}-1\).

Hash function. An int between \(0\) and \(M-1\) (for use as array index).

Typically a prime or power of 2

```java
private int hash(Key key)
{  return key.hashCode() % M;  }
```

Bug

```java
private int hash(Key key)
{  return Math.abs(key.hashCode()) % M;  }
```

1-in-a-billion bug

```java
private int hash(Key key)
{  return (key.hashCode() & 0x7fffffff) % M;  }
```

Correct

```
hashCode() of "polygenelubricants" is \(-2^{31}\)
```

Uniform hashing assumption

Uniform hashing assumption. Each key is equally likely to hash to an integer between \(0\) and \(M-1\).

Bins and balls. Throw balls uniformly at random into \(M\) bins.

Birthday problem. Expect two balls in the same bin after \(\sim \sqrt{M / 2}\) tosses.

Coupon collector. Expect every bin has \(\geq 1\) ball after \(\sim M \ln M\) tosses.

Load balancing. After \(M\) tosses, expect most loaded bin has \(\Theta(\log M / \log \log M)\) balls.

Hashing

- Hash functions
- Separate chaining
- Linear probing
Collisions

**Collision.** Two distinct keys hashing to same index.

- Birthday problem ⇒ can’t avoid collisions unless you have a ridiculous (quadratic) amount of memory.
- Coupon collector + load balancing ⇒ collisions will be evenly distributed.

**Challenge.** Deal with collisions efficiently.

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<tr>
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<th>1</th>
<th>2</th>
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</thead>
<tbody>
<tr>
<td>&quot;at&quot;</td>
<td>&quot;it&quot;</td>
<td>&quot;time&quot;</td>
<td>-hash(&quot;at&quot;) = 3</td>
<td>3</td>
</tr>
<tr>
<td>hash(&quot;it&quot;) = 3</td>
<td>3</td>
<td>&quot;it&quot;</td>
<td></td>
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</tr>
</tbody>
</table>

Separate chaining ST: Java implementation

```java
public class SeparateChainingHashST<Key, Value> {
    private int M = 97; // number of chains
    private Node[] st = new Node[M]; // array of chains

    private static class Node {
        private Object key;
        private Object val;
        private Node next;
    }

    private int hash(Key key) {
        return (key.hashCode() & 0x7fffffff) % M;
    }

    public Value get(Key key) {
        int i = hash(key);
        for (Node x = st[i]; x != null; x = x.next)
            if (key.equals(x.key)) return (Value) x.val;
        return null;
    }
}
```

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    private Node[] st = new Node[M]; // array of chains

    private static class Node {
        private Object key;
        private Object val;
        private Node next;
    }

    private int hash(Key key) {
        return (key.hashCode() & 0x7fffffff) % M;
    }

    public void put(Key key, Value val) {
        int i = hash(key);
        for (Node x = st[i]; x != null; x = x.next)
            if (key.equals(x.key)) { x.val = val; return; }
        st[i] = new Node(key, val, st[i]);
    }
}
```
Analysis of separate chaining

**Proposition.** Under uniform hashing assumption, probability that the number of keys in a list is within a constant factor of $N / M$ is extremely close to 1.

**Pf sketch.** Distribution of list size obeys a binomial distribution.

**Consequence.** Number of probes for search/insert is proportional to $N / M$.
- $M$ too large ⇒ too many empty chains.
- $M$ too small ⇒ chains too long.
- Typical choice: $M \sim N / 5$ ⇒ constant-time ops.

ST implementations: summary

<table>
<thead>
<tr>
<th>implementation</th>
<th>worst-case cost</th>
<th>average case</th>
<th>ordered iteration?</th>
<th>key interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>search</td>
<td>insert</td>
<td>delete</td>
<td>search</td>
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<tr>
<td>sequential search</td>
<td>N</td>
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<td>binary search (ordered array)</td>
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<td>1.38 lg N</td>
<td>?</td>
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<td>red-black tree</td>
<td>2 lg N</td>
<td>2 lg N</td>
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<td>separate chaining</td>
<td>lg N *</td>
<td>lg N *</td>
<td>lg N *</td>
<td>3-5 *</td>
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</tbody>
</table>

* under uniform hashing assumption

Collision resolution: open addressing

**Open addressing.** [Amdahl-Boehme-Rocherster-Samuel, IBM 1953]
When a new key collides, find next empty slot, and put it there.
Hash. Map key to integer $i$ between 0 and $M - 1$.
Insert. Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.

Linear probing hash table

$M = 16$

$\text{hash(S)} = 6$

$\text{insert S}$

Linear probing hash table

$M = 16$

$\text{hash(S)} = 6$

$\text{insert S}$
Hash. Map key to integer $i$ between 0 and $M - 1$.
Insert. Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.

Linear probing hash table

M = 16

insert $E$
hash($E$) = 10

M = 16

Linear probing hash table

M = 16

insert $E$
hash($E$) = 10

M = 16
Linear probing hash table

Hash. Map key to integer $i$ between 0 and $M - 1$.
Insert. Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.

linear probing hash table

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$M = 16$

Linear probing hash table

Hash. Map key to integer $i$ between 0 and $M - 1$.
Insert. Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.

insert A
hash(A) = 4

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$M = 16$
**Linear probing hash table**

**Hash.** Map key to integer $i$ between 0 and $M - 1$.

**Insert.** Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.

---

**Insert R**

hash(R) = 14

---

**Linear probing hash table**

---

**Hash.** Map key to integer $i$ between 0 and $M - 1$.

**Insert.** Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.

---

**Insert R**

hash(R) = 14
**Linear probing hash table**

**Hash.** Map key to integer \( i \) between 0 and \( M - 1 \).

**Insert.** Put at table index \( i \) if free; if not try \( i + 1, i + 2 \), etc.

Linear probing hash table

\[
\begin{array}{cccccccccccccccc}
0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \\
[\text{A S E R}] & & & & & & & & & & & & & & & \\
\end{array}
\]

\( M = 16 \)

**Insert C**

\[
\begin{array}{cccccccccccccccc}
0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \\
[\text{A S E R C}] & & & & & & & & & & & & & & & \\
\end{array}
\]

\( M = 16 \)
Hash. Map key to integer $i$ between 0 and $M - 1$.

Insert. Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.

Linear probing hash table

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Linear probing hash table

**Hash.** Map key to integer $i$ between 0 and $M - 1$.

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```
insert H
hash(H) = 4
```

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M = 16

H

Linear probing hash table

**Hash.** Map key to integer $i$ between 0 and $M - 1$.

**Insert.** Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.

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Linear probing hash table

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H
**Linear probing hash table**

**Hash.** Map key to integer $i$ between 0 and $M - 1$.

**Insert.** Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.

```
insert X
hash(X) = 15
```

```
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
```

```
M = 16
```

A C S H E R

---

```
insert X
hash(X) = 15
```

```
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
```

```
M = 16
```

A C S H E R X

---

```
insert X
hash(X) = 15
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```
M = 16
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A C S H E R X

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```
M = 16
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A C S H E R X

---

```
insert X
hash(X) = 15
```

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0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
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```
M = 16
```

A C S H E R X

---
**Linear probing hash table**

*Hash.* Map key to integer $i$ between 0 and $M - 1$.

*Insert.* Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.

```plaintext
insert M
hash(M) = 1
```

<table>
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$M = 16$

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**Linear probing hash table**

*Hash.* Map key to integer $i$ between 0 and $M - 1$.

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**Linear probing hash table**

*Hash.* Map key to integer $i$ between 0 and $M - 1$.

*Insert.* Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.

```plaintext
linear probing hash table
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Linear probing hash table

Hash. Map key to integer $i$ between 0 and $M - 1$.
Insert. Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.

```
insert P
hash(P) = 14
```

```
w[] M A C S H E R X
M = 16
```

```
P M A C S H E R X
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| L |

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**Linear probing hash table**

**Hash.** Map key to integer \( i \) between 0 and \( M - 1 \).

**Insert.** Put at table index \( i \) if free; if not try \( i + 1 \), \( i + 2 \), etc.

\[
\begin{array}{cccccccccccccccc}
0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \\
\hline
\end{array}
\]

\( M = 16 \)

**Search.** Search table index \( i \); if occupied but no match, try \( i + 1 \), \( i + 2 \), etc.

\[
\begin{array}{cccccccccccccccc}
0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \\
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\( M = 16 \)
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**Search.** Search table index $i$; if occupied but no match, try $i + 1$, $i + 2$, etc.

search $E$
hash($E$) = 10

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<tr>
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<tbody>
<tr>
<td>$w[]$</td>
</tr>
<tr>
<td>P M A C S H L E _ _ _ R X</td>
</tr>
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**Search hit** (return corresponding value)

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**Search.** Search table index $i$; if occupied but no match, try $i + 1$, $i + 2$, etc.

search $L$
hash($L$) = 6

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search $K$
hash($K$) = 5

$M = 16$

Linear probing hash table

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Linear probing hash table

Hash. Map key to integer $i$ between 0 and $M - 1$.
Insert. Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index $i$; if occupied but no match, try $i + 1$, $i + 2$, etc.

```java
public class LinearProbingHashST<Key, Value> {
    private int M = 30001;
    private Value[] vals = (Value[]) new Object[M];
    private Key[] keys = (Key[]) new Object[M];

    private int hash(Key key) {
        /* as before */
    }

    public void put(Key key, Value val) {
        int i;
        for (i = hash(key); keys[i] != null; i = (i+1) % M)
            if (keys[i].equals(key))
                break;
        keys[i] = key;
        vals[i] = val;
    }

    public Value get(Key key) {
        for (int i = hash(key); keys[i] != null; i = (i+1) % M)
            if (key.equals(keys[i]))
                return vals[i];
        return null;
    }
}
```

Linear probing - Summary

Hash. Map key to integer $i$ between 0 and $M - 1$.
Insert. Put at table index $i$ if free; if not try $i + 1$, $i + 2$, etc.
Search. Search table index $i$; if occupied but no match, try $i + 1$, $i + 2$, etc.

Note. Array size $M$ must be greater than number of key-value pairs $N$. 
### Clustering

**Cluster.** A contiguous block of items.

**Observation.** New keys likely to hash into middle of big clusters.

---

### Knuth’s parking problem

**Model.** Cars arrive at one-way street with $M$ parking spaces.

Each desires a random space $i$: if space $i$ is taken, try $i+1$, $i+2$, etc.

**Q.** What is mean displacement of a car?

**Figure.**

- **Half-full.** With $M/2$ cars, mean displacement is $\sim 3/2$.
- **Full.** With $M$ cars, mean displacement is $\sim \sqrt{\pi M}/8$.

---

### Analysis of linear probing

**Proposition.** Under uniform hashing assumption, the average number of probes in a linear probing hash table of size $M$ that contains $N = \alpha M$ keys is:

$$\sim \frac{1}{2} \left( 1 + \frac{1}{1 - \alpha} \right)$$

- **search hit**
- **search miss / insert**

**Parameters.**

- $M$ too large $\Rightarrow$ too many empty array entries.
- $M$ too small $\Rightarrow$ search time blows up.
- Typical choice: $\alpha = N/M \sim \frac{1}{2}$.

- # probes for search hit is about $3/2$
- # probes for search miss is about $5/2$

---

### ST implementations: summary

<table>
<thead>
<tr>
<th>Implementation</th>
<th>worst-case cost (after $N$ inserts)</th>
<th>average case (after $N$ random inserts)</th>
<th>ordered deletion?</th>
<th>key interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>sequential</td>
<td>search: $N$ insert: $N$ delete: $N$</td>
<td>search hit: $N/2$ insert: $N/2$ delete: $N/2$</td>
<td>no equals()</td>
<td>equals()</td>
</tr>
<tr>
<td>binary search</td>
<td>search (unordered list): $\lg N$ insert: $N$ delete: $N$</td>
<td>search hit: $N/2$ insert: $N/2$ delete: $N/2$</td>
<td>yes compareTo()</td>
<td>compareTo()</td>
</tr>
<tr>
<td>BST</td>
<td>search: $N$ insert: $N$ delete: $N$</td>
<td>search hit: $1.38 \lg N$ insert: $1.38 \lg N$ delete: $1$</td>
<td>yes compareTo()</td>
<td>compareTo()</td>
</tr>
<tr>
<td>red-black tree</td>
<td>search: $2 \lg N$ insert: $2 \lg N$ delete: $2 \lg N$</td>
<td>search hit: $1.00 \lg N$ insert: $1.00 \lg N$ delete: $1.00 \lg N$</td>
<td>yes compareTo()</td>
<td>compareTo()</td>
</tr>
<tr>
<td>separate chaining</td>
<td>search: $3-5^<em>$ insert: $3-5^</em>$ delete: $3-5^*$</td>
<td>search hit: $3-5^<em>$ insert: $3-5^</em>$ delete: $3-5^*$</td>
<td>no equals()</td>
<td>equals()</td>
</tr>
<tr>
<td>linear probing</td>
<td>search: $3-5^<em>$ insert: $3-5^</em>$ delete: $3-5^*$</td>
<td>search hit: $3-5^<em>$ insert: $3-5^</em>$ delete: $3-5^*$</td>
<td>no equals()</td>
<td>equals()</td>
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</tbody>
</table>

* under uniform hashing assumption
War story: String hashing in Java

String `hashCode()` in Java 1.1.

- For long strings: only examine 8-9 evenly spaced characters.
- Benefit: saves time in performing arithmetic.

```java
public int hashCode()
{
    int hash = 0;
    int skip = Math.max(1, length() / 8);
    for (int i = 0; i < length(); i += skip)
        hash = s[i] + (37 * hash);
    return hash;
}
```

- Downside: great potential for bad collision patterns.

http://www.cs.princeton.edu/introcs/13loop/Hello.java
http://www.cs.princeton.edu/introcs/13loop/Hello.class
http://www.cs.princeton.edu/introcs/12type/index.html

War story: algorithmic complexity attacks

Q. Is the uniform hashing assumption important in practice?
A. Obvious situations: aircraft control, nuclear reactor, pacemaker.
A. Surprising situations: denial-of-service attacks.

Real-world exploits. [Crosby-Wallach 2003]
- Bro server: send carefully chosen packets to DOS the server, using less bandwidth than a dial-up modem.
- Perl 5.8.0: insert carefully chosen strings into associative array.
- Linux 2.4.20 kernel: save files with carefully chosen names.

Algorithmic complexity attack on Java

Goal. Find family of strings with the same hash code.
Solution. The base 31 hash code is part of Java's string API.

```
key   hashCode()
---   --------
"Aa"  2112
"BB"  2112
```

```
key   hashCode()
---   --------
"AaAaAaAa"  -540425984
"AaAaAaBB"  -540425984
"AaAaBBBb"  -540425984
"AaBBBbaa"  -540425984
"AaBBBbaa"  -540425984
"AaBBBBba"  -540425984
"AaBBBBbB"  -540425984
"AaBBBBBB"  -540425984

key   hashCode()
---   --------
"Bb"  2112
"BB"  2112
```

```
key   hashCode()
---   --------
"BbBbBbBb"  -540425984
"BbBbBbBb"  -540425984
"BbBbBbBb"  -540425984
"BbBbBbBb"  -540425984
"BbBbBbBb"  -540425984
"BbBbBbBb"  -540425984
"BbBbBbBb"  -540425984
```

Diversion: one-way hash functions

One-way hash function. "Hard" to find a key that will hash to a desired value (or two keys that hash to same value).

Ex. MD4, MD5, SHA-0, SHA-1, SHA-2, WHIRLPOOL, RIPEMD-160, ...

Applications. Digital fingerprint, message digest, storing passwords.

Caveat. Too expensive for use in ST implementations.

String password = args[0];
MessageDigest sha1 =
MessageDigest.getInstance("SHA1");
byte[] bytes = sha1.digest(password);
/* prints bytes as hex string */
### Separate chaining vs. linear probing

**Separate chaining.**
- Easier to implement delete.
- Performance degrades gracefully.
- Clustering less sensitive to poorly-designed hash function.

**Linear probing.**
- Less wasted space.
- Better cache performance.

Q. How to delete?
Q. How to resize?

### Hashing: variations on the theme

Many improved versions have been studied.

**Two-probe hashing.** (separate-chaining variant)
- Hash to two positions, insert key in shorter of the two chains.
- Reduces expected length of the longest chain to $\log \log N$.

**Double hashing.** (linear-probing variant)
- Use linear probing, but skip a variable amount, not just 1 each time.
- Effectively eliminates clustering.
- Can allow table to become nearly full.
- More difficult to implement delete.

**Cuckoo hashing.** (linear-probing variant)
- Hash key to two positions; insert key into either position; if occupied, reinser displaced key into its alternative position (and recur).
- Constant worst case time for search.

### Hash tables vs. balanced search trees

**Hash tables.**
- Simpler to code.
- No effective alternative for unordered keys.
- Faster for simple keys (a few arithmetic ops versus $\log N$ compares).
- Better system support in Java for strings (e.g., cached hash code).

**Balanced search trees.**
- Stronger performance guarantee.
- Support for ordered ST operations.
- Easier to implement `compareTo()` correctly than `equals()` and `hashCode()`.

**Java system includes both.**
- Red-black BSTs: `java.util.TreeMap`, `java.util.TreeSet`
- Hash tables: `java.util.HashMap`, `java.util.IdentityHashMap`