CSE 332: Data Structures & Parallelism
Lecture 11: More Hashing

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Today

• Dictionaries
  – Hashing
Hash Tables: Review

• Aim for constant-time (i.e., $O(1)$) find, insert, and delete
  – “On average” under some reasonable assumptions

• A hash table is an array of some fixed size
  – But growable as we’ll see

![Diagram of hash table and operations]
Hashing Choices

1. Choose a Hash function
2. Choose TableSize
3. Choose a Collision Resolution Strategy from these:
   - Separate Chaining
   - Open Addressing
     - Linear Probing
     - Quadratic Probing
     - Double Hashing

• Other issues to consider:
  - Deletion?
  - What to do when the hash table gets “too full”?
Open Addressing: Linear Probing

- Why not use up the empty space in the table?
- Store directly in the array cell (no linked list)
- How to deal with collisions?
- If $h(\text{key})$ is already full,
  - try $(h(\text{key}) + 1) \% \text{TableSize}$. If full,
  - try $(h(\text{key}) + 2) \% \text{TableSize}$. If full,
  - try $(h(\text{key}) + 3) \% \text{TableSize}$. If full...

- Example: insert 38, 19, 8, 109, 10
Open Addressing: Linear Probing

- Another simple idea: If \( h(\text{key}) \) is already full,
  - try \( (h(\text{key}) + 1) \mod \text{TableSize} \). If full,
  - try \( (h(\text{key}) + 2) \mod \text{TableSize} \). If full,
  - try \( (h(\text{key}) + 3) \mod \text{TableSize} \). If full...

- Example: insert 38, 19, 8, 109, 10

<table>
<thead>
<tr>
<th>0</th>
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<tbody>
<tr>
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</table>
Open Addressing: Linear Probing

• Another simple idea: If \( h(key) \) is already full,
  – try \( (h(key) + 1) \mod \text{TableSize} \). If full,
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• Example: insert 38, 19, 8, 109, 10

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Open Addressing: Linear Probing

- Another simple idea: If \( h(\text{key}) \) is already full,
  - try \((h(\text{key}) + 1) \mod \text{TableSize}\). If full,
  - try \((h(\text{key}) + 2) \mod \text{TableSize}\). If full,
  - try \((h(\text{key}) + 3) \mod \text{TableSize}\). If full...

- Example: insert 38, 19, 8, 109, 10
Open Addressing: Linear Probing

• Another simple idea: If $h(\text{key})$ is already full,
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• Example: insert 38, 19, 8, 109, 10

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<tbody>
<tr>
<td>0</td>
<td>8</td>
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<td>1</td>
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</tr>
</tbody>
</table>
**Open addressing**

Linear probing is *one example* of open addressing

In general, *open addressing* means resolving collisions by trying a sequence of other positions in the table.

Trying the *next* spot is called *probing*

- We just did *linear probing*:
  - \( i^{th} \) probe: \( (h(key) + i) \mod TableSize \)
- In general have some *probe function* \( f \) and:
  - \( i^{th} \) probe: \( (h(key) + f(i)) \mod TableSize \)

Open addressing does poorly with high load factor \( \lambda \)

- So want larger tables
- Too many probes means no more \( O(1) \)
**Terminology**

We and the book use the terms
- “chaining” or “separate chaining”
- “open addressing”

Very confusingly,
- “open hashing” is a synonym for “chaining”
- “closed hashing” is a synonym for “open addressing”
Open Addressing: Linear Probing

What about find? If value is in table? If not there? Worst case?

What about delete?

How does open addressing with linear probing compare to separate chaining?
Open Addressing: Other Operations

**insert** finds an open table position using a probe function.

What about **find**?
- Must use same probe function to “retrace the trail” for the data
- Unsuccessful search when reach empty position

What about **delete**?
- **Must** use “lazy” deletion. Why?
  - Marker indicates “no data here, but don’t stop probing”

```
  10  ×  /  23  /  /  16  ×  26
```
- Note: **delete** with chaining is plain-old list-remove
Primary Clustering

It turns out linear probing is a bad idea, even though the probe function is quick to compute (a good thing)

- Tends to produce clusters, which lead to long probe sequences
- Called primary clustering
- Saw the start of a cluster in our linear probing example
Analysis of Linear Probing

• **Trivial fact:** For any $\lambda < 1$, linear probing will find an empty slot
  – It is “safe” in this sense: no infinite loop unless table is full

• **Non-trivial facts** we won’t prove:
  Average # of probes given $\lambda$ (in the limit as TableSize $\rightarrow \infty$)
  – Unsuccessful search:
    $$\frac{1}{2} \left( 1 + \frac{1}{(1 - \lambda)^2} \right)$$
  – Successful search:
    $$\frac{1}{2} \left( 1 + \frac{1}{1 - \lambda} \right)$$

• This is pretty bad: need to leave sufficient empty space in the table to get decent performance (see chart)
Analysis in chart form

- Linear-probing performance degrades rapidly as table gets full
  - (Formula assumes “large table” but point remains)

- By comparison, separate chaining performance is linear in $\lambda$ and has no trouble with $\lambda > 1$
Open Addressing: Linear probing

\[(h(key) + f(i)) \% \text{TableSize}\]

- For linear probing:
  \[f(i) = i\]

- So probe sequence is:
  0\(^{th}\) probe: \[h(key) \% \text{TableSize}\]
  1\(^{st}\) probe: \[(h(key) + 1) \% \text{TableSize}\]
  2\(^{nd}\) probe: \[(h(key) + 2) \% \text{TableSize}\]
  3\(^{rd}\) probe: \[(h(key) + 3) \% \text{TableSize}\]
  ...
  \[i^{th}\) probe: \[(h(key) + i) \% \text{TableSize}\]
Open Addressing: Quadratic probing

• We can avoid primary clustering by changing the probe function…

\[(h(key) + f(i)) \mod \text{TableSize}\]

– For quadratic probing:

\[f(i) = i^2\]

– So probe sequence is:

• 0\(^{th}\) probe: \(h(key) \mod \text{TableSize}\)
• 1\(^{st}\) probe: \((h(key) + 1) \mod \text{TableSize}\)
• 2\(^{nd}\) probe: \((h(key) + 4) \mod \text{TableSize}\)
• 3\(^{rd}\) probe: \((h(key) + 9) \mod \text{TableSize}\)
• ...
• \(i^{th}\) probe: \((h(key) + i^2) \mod \text{TableSize}\)

• Intuition: Probes quickly “leave the neighborhood”
**Quadratic Probing Example**

The formula for the \( i \text{th} \) probe is:

\[
\text{ith probe: } (h(\text{key}) + i^2) \mod \text{TableSize}
\]

<table>
<thead>
<tr>
<th>Index</th>
<th>Value</th>
<th>TableSize=10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>89</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>49</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>5</td>
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<td>79</td>
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<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Quadratic Probing Example

TableSize = 10

insert(89)
Quadratic Probing Example

TableSize = 10

insert(89)

insert(18)
Quadratic Probing Example

TableSize = 10

insert(89)
insert(18)
insert(49)
Quadratic Probing Example

TableSize = 10

insert(89)
insert(18)
insert(49)

49 \% 10 = 9 \text{ collision!}

(49 + 1) \% 10 = 0

insert(58)
Quadratic Probing Example

TableSize = 10

insert(89)

insert(18)

insert(49)

insert(58)

58 % 10 = 8 collision!

(58 + 1) % 10 = 9 collision!

(58 + 4) % 10 = 2

insert(79)
### Quadratic Probing Example

TableSize = 10

<table>
<thead>
<tr>
<th>Index</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>49</td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>58</td>
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<tr>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td>9</td>
<td>89</td>
</tr>
</tbody>
</table>

- **insert(89)**
- **insert(18)**
- **insert(49)**
- **insert(58)**
- **insert(79)**
  - 79 % 10 = 9 **collision!**
  - (79 + 1) % 10 = 0 **collision!**
  - (79 + 4) % 10 = 3
Another Quadratic Probing Example

ith probe: \( h(key) + i^2 \) \% TableSize

TableSize = 7

Insert:

| 76 | (76 \% 7 = 6) |
| 40 | (40 \% 7 = 5) |
| 48 | (48 \% 7 = 6) |
| 5  | (5 \% 7 = 5)  |
| 55 | (55 \% 7 = 6) |
| 47 | (47 \% 7 = 5) |
Another Quadratic Probing Example

TableSize = 7

Insert:

- 76 (76 % 7 = 6)
- 40 (40 % 7 = 5)
- 48 (48 % 7 = 6)
- 5 (5 % 7 = 5)
- 55 (55 % 7 = 6)
- 47 (47 % 7 = 5)

ith probe: \((h(key) + i^2) \mod \text{TableSize}\)
Another Quadratic Probing Example

TableSize = 7

Insert:

| ith probe: \( h(key) + i^2 \) % TableSize |
|---|---|
| 0 | |
| 1 | |
| 2 | |
| 3 | |
| 4 | |
| 5 | 40 |
| 6 | 76 |

- 76 \((76 \% 7 = 6)\)
- 40 \((40 \% 7 = 5)\)
- 48 \((48 \% 7 = 6)\)
- 5 \((5 \% 7 = 5)\)
- 55 \((55 \% 7 = 6)\)
- 47 \((47 \% 7 = 5)\)
Another Quadratic Probing Example

TableSize = 7

Insert:

- 76 (76 % 7 = 6)
- 40 (40 % 7 = 5)
- 48 (48 % 7 = 6)
- 5 (5 % 7 = 5)
- 55 (55 % 7 = 6)
- 47 (47 % 7 = 5)
Another Quadratic Probing Example

TableSize = 7

Insert:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>48</td>
<td></td>
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<tr>
<td>1</td>
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<td>6</td>
<td>76</td>
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</tr>
</tbody>
</table>

Insert:

- 76 \( (76 \% 7 = 6) \)
- 40 \( (40 \% 7 = 5) \)
- 48 \( (48 \% 7 = 6) \)
- 5 \( (5 \% 7 = 5) \)
- 55 \( (55 \% 7 = 6) \)
- 47 \( (47 \% 7 = 5) \)

ith probe: \( h(key) + i^2 \) \% TableSize
Another Quadratic Probing Example

TableSize = 7

Insert:

76 \quad (76 \% 7 = 6)
40 \quad (40 \% 7 = 5)
48 \quad (48 \% 7 = 6)
5 \quad (5 \% 7 = 5)
55 \quad (55 \% 7 = 6)
47 \quad (47 \% 7 = 5)
Another Quadratic Probing Example

TableSize = 7

Insert:

76  (76 % 7 = 6)
40  (40 % 7 = 5)
48  (48 % 7 = 6)
5   (5 % 7 = 5)
55  (55 % 7 = 6)
47  (47 % 7 = 5)

(47 + 1) % 7 = 6 collision!
(47 + 4) % 7 = 2 collision!
(47 + 9) % 7 = 0 collision!
(47 + 16) % 7 = 0 collision!
(47 + 25) % 7 = 2 collision!

Will we ever get a 1 or 4?!?
Another Quadratic Probing Example

insert(47) will always fail here. Why?

For all \( i \), \( (5 + i^2) \) \( \% \) 7 is 0, 2, 5, or 6

Proof uses induction and

\[
(5 + i^2) \% 7 = (5 + (i - 7)^2) \% 7
\]

In fact, for all \( c \) and \( k \),

\[
(c + i^2) \% k = (c + (i - k)^2) \% k
\]
From bad news to good news

Bad News:
- After `TableSize` quadratic probes, we cycle through the same indices

Good News:
- If `TableSize` is prime and $\lambda < \frac{1}{2}$, then quadratic probing will find an empty slot in at most $\frac{\text{TableSize}}{2}$ probes
- So: If you keep $\lambda < \frac{1}{2}$ and `TableSize` is prime, no need to detect cycles
- Proof posted in `lecture11.txt` (slightly less detailed proof in textbook)
  - For prime $T$ and $0 \leq i, j \leq T/2$ where $i \neq j$,
    \[(h(\text{key}) + i^2) \mod T \neq (h(\text{key}) + j^2) \mod T\]
    That is, if $T$ is prime, the first $T/2$ quadratic probes map to different locations
Quadratic Probing: Success guarantee for $\lambda < \frac{1}{2}$

- If size is prime and $\lambda < \frac{1}{2}$, then quadratic probing will find an empty slot in size/2 probes or fewer.
  - show for all $0 \leq i, j \leq \text{size}/2$ and $i \neq j$
    
    
    $$(h(x) + i^2) \mod \text{size} \neq (h(x) + j^2) \mod \text{size}$$
  
  - by contradiction: suppose that for some $i \neq j$:
    
    $$(h(x) + i^2) \mod \text{size} = (h(x) + j^2) \mod \text{size}$$
    
    $$(i^2 \mod \text{size} = j^2 \mod \text{size})$$
    
    $$(i^2 - j^2) \mod \text{size} = 0$$
    
    $$/ [(i + j)(i - j)] \mod \text{size} = 0$$
  
  BUT size does not divide $(i-j)$ or $(i+j)$

How can $i+j = 0$ or $i+j = \text{size}$ when:

$$i \neq j \text{ and } 0 \leq i, j \leq \text{size}/2?$$

Similarly how can $i-j = 0$ or $i-j = \text{size}$?

First size/2 probes distinct. If < half full, one is empty.

First size/2 probes will be distinct, and if less than half of table is full then after size/2 probes you will find one of those empty spots

Size would need to divide one of these
Clustering reconsidered

• Quadratic probing does not suffer from primary clustering: As we resolve collisions we are not merely growing “big blobs” by adding one more item to the end of a cluster, we are looking $i^2$ locations away, for the next possible spot.

• But quadratic probing does not help resolve collisions between keys that initially hash to the same index
  – Any 2 keys that initially hash to the same index will have the same series of moves after that looking for any empty spot
  – Called secondary clustering

• Can avoid secondary clustering with a probe function that depends on the key: double hashing…
Open Addressing: Double hashing

Idea: Given two good hash functions $h$ and $g$, it is very unlikely that for some key, $h(key) == g(key)$

$(h(key) + f(i)) \mod \text{TableSize}$

- For double hashing:
  \[ f(i) = i \times g(key) \]

- So probe sequence is:
  - $0^{th}$ probe: $h(key) \mod \text{TableSize}$
  - $1^{st}$ probe: $(h(key) + g(key)) \mod \text{TableSize}$
  - $2^{nd}$ probe: $(h(key) + 2 \times g(key)) \mod \text{TableSize}$
  - $3^{rd}$ probe: $(h(key) + 3 \times g(key)) \mod \text{TableSize}$
  - ...
  - $i^{th}$ probe: $(h(key) + i \times g(key)) \mod \text{TableSize}$

- Detail: Make sure $g(key)$ can’t be 0
Open Addressing: Double Hashing

- Insert these values into the hash table in this order. Resolve any collisions with double hashing:
  - 13
  - 28
  - 33
  - 147
  - 43

Hash Functions:
- \( h(key) = key \mod T \)
- \( g(key) = 1 + ((key/T) \mod (T-1)) \)

\[
\text{ith probe: } (h(key) + i \times g(key)) \mod \text{TableSize}
\]
**Double Hashing**

Insert these values into the hash table in this order. Resolve any collisions with double hashing:

- 13
- 28
- 33
- 147
- 43

**Hash Functions:**

\[
\begin{align*}
\text{h(key)} &= \text{key mod } T \\
\text{g(key)} &= 1 + ((\text{key}/T) \mod (T-1))
\end{align*}
\]

**ith probe:** \( (\text{h(key)} + i \times \text{g(key)}) \mod \text{TableSize} \)

T = 10 (TableSize)
Double Hashing

Insert these values into the hash table in this order. Resolve any collisions with double hashing:

13 28 33 147 43

T = 10 (TableSize)

Hash Functions:

\[ h(key) = key \mod T \]
\[ g(key) = 1 + ((key/T) \mod (T-1)) \]

\[ \text{ith probe: (}h(key) + i\times g(key)\text{)} \mod \text{TableSize} \]
## Double Hashing

Insert these values into the hash table in this order. Resolve any collisions with double hashing:

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
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**Hash Functions:**

\[
\begin{align*}
  h(key) &= key \mod T \\
  g(key) &= 1 + ((key/T) \mod (T-1))
\end{align*}
\]

**T = 10** (TableSize)

\[\text{ith probe: } (h(key) + i \times g(key)) \mod \text{TableSize}\]

- 13
- 28
- 33 → \(g(33) = 1 + 3 \mod 9 = 4\)
- 147
- 43

1/31/2018
Double Hashing

Insert these values into the hash table in this order. Resolve any collisions with double hashing:

13
28
33
147
43

T = 10 (TableSize)

Hash Functions:

\[ h(key) = key \mod T \]
\[ g(key) = 1 + ((key/T) \mod (T-1)) \]

\[ \text{ith probe: } (h(key) + i \times g(key)) \mod \text{TableSize} \]
**Double Hashing**

Insert these values into the hash table in this order. Resolve any collisions with double hashing:

13
28
33
147

\[ g(147) = 1 + 14 \text{ mod } 9 = 6 \]

43
\[ g(43) = 1 + 4 \text{ mod } 9 = 5 \]

We have a problem:

\[
\begin{align*}
3 + 0 &= 3 & 3 + 5 &= 8 & 3 + 10 &= 13 \\
3 + 15 &= 18 & 3 + 20 &= 23
\end{align*}
\]
Double-hashing analysis

- **Intuition**: Since each probe is “jumping” by $g(\text{key})$ each time, we “leave the neighborhood” and “go different places from other initial collisions”

But, as in quadratic probing, we could still have a problem where we are not "safe" due to an infinite loop despite room in table

  - It is known that this cannot happen in at least one case:
    - For primes $p$ and $q$ such that $2 < q < p$
      - $h(\text{key}) = \text{key} \% p$
      - $g(\text{key}) = q - (\text{key} \% q)$
Yet another reason to use a prime TableSize

- So, for double hashing
  
  \[i^{th} \text{ probe: } (h(key) + i \times g(key)) \mod \text{ TableSize}\]

- Say \(g(key)\) divides Tablesize
  
  - That is, there is some integer \(x\) such that \(x \times g(key) = \text{Tablesize}\)
  
  - After \(x\) probes, we’ll be back to trying the same indices as before

- Ex:
  
  - Tablesize=50
  
  - \(g(key)\)=25
  
  - Probing sequence:
    
    - \(h(key)\)
    
    - \(h(key)+25\)
    
    - \(h(key)+50=h(key)\)
    
    - \(h(key)+75=h(key)+25\)

- Only 1 & itself divide a prime
More double-hashing facts

• Assume “uniform hashing”
  – Means probability of \( g(\text{key1}) \mod p = g(\text{key2}) \mod p \) is \( 1/p \)

• Non-trivial facts we won’t prove:
  Average # of probes given \( \lambda \) (in the limit as TableSize → \( \infty \))
  – Unsuccessful search (intuitive):
    \[
    \frac{1}{1 - \lambda}
    \]
  – Successful search (less intuitive):
    \[
    \frac{1}{\lambda \log_e \left( \frac{1}{1 - \lambda} \right)}
    \]

• Bottom line: unsuccessful bad (but not as bad as linear probing),
  but successful is not nearly as bad
Charts

Uniform Hashing

<table>
<thead>
<tr>
<th>Load Factor</th>
<th>Average # of Probes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>0.08</td>
<td>1.00</td>
</tr>
<tr>
<td>0.15</td>
<td>2.00</td>
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<tr>
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<tr>
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<td>4.00</td>
</tr>
<tr>
<td>0.36</td>
<td>5.00</td>
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<tr>
<td>0.43</td>
<td>6.00</td>
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<tr>
<td>0.50</td>
<td>7.00</td>
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<tr>
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<tr>
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Load Factor

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- uniform hashing found

Linear Probing

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Where are we?

• **Separate Chaining** is easy  
  – *find*, *delete* proportional to load factor on average  
  – *insert* can be constant if just push on front of list  

• **Open addressing** uses probing, has clustering issues as table fills  

Why use it:  
  – Less memory allocation?  
    • Some run-time overhead for allocating linked list (or whatever) nodes; open addressing could be faster  
  – Easier data representation?  

• Now:  
  – Growing the table when it gets too full (aka “rehashing”)  
  – Relation between hashing/comparing and connection to Java
Rehashing

• As with array-based stacks/queues/lists, if table gets too full, create a bigger table and copy everything over

• With separate chaining, we get to decide what “too full” means
  – Keep load factor reasonable (e.g., < 1)?
  – Consider average or max size of non-empty chains?

• For open addressing, half-full is a good rule of thumb

• New table size
  – Twice-as-big is a good idea, except, uhm, that won’t be prime!
  – So go about twice-as-big
  – Can have a list of prime numbers in your code since you probably won’t grow more than 20-30 times, and then calculate after that
More on rehashing

- What if we copy all data to the same indices in the new table?
  - Will not work; we calculated the index based on TableSize

- Go through table, do standard insert for each into new table
  - Iterate over old table: O(n)
  - n inserts / calls to the hash function: \( n \cdot O(1) = O(n) \)

- Is there some way to avoid all those hash function calls?
  - Space/time tradeoff: Could store \( h(key) \) with each data item
  - Growing the table is still \( O(n) \); saving \( h(key) \) only helps by a constant factor
Hashing and comparing

• Our use of int key can lead to us overlooking a critical detail:
  – We initially hash E to get a table index
  – While chaining or probing we need to determine if this is the E that I am looking for. Just need equality testing.

• So a hash table needs a hash function and a equality testing
  – In the Java library each object has an equals method and a hashCode method

```java
class Object {
    boolean equals(Object o) {...}
    int hashCode() {...}
    ...
}
```
Equal objects must hash the same

- The Java library (and your project hash table) make a very important assumption that clients must satisfy...

- Object-oriented way of saying it:
  
  ```java
  if a.equals(b), then we must require
  a.hashCode() == b.hashCode()
  ```

- Function object way of saying it:
  
  ```java
  if c.compare(a, b) == 0, then we must require
  h.hash(a) == h.hash(b)
  ```

- If you ever override equals
  - You need to override hashCode also in a consistent way
  - See CoreJava book, Chapter 5 for other "gotchas" with equals
By the way: comparison has rules too

We have not emphasized important “rules” about comparison for:
   – All our dictionaries
   – Sorting (next major topic)

Comparison must impose a consistent, total ordering:

For all \( a, b, \) and \( c, \)
   – If \( \text{compare}(a,b) < 0 \), then \( \text{compare}(b,a) > 0 \)
   – If \( \text{compare}(a,b) == 0 \), then \( \text{compare}(b,a) == 0 \)
   – If \( \text{compare}(a,b) < 0 \) and \( \text{compare}(b,c) < 0 \),
     then \( \text{compare}(a,c) < 0 \)
A Generally Good `hashCode()`

```java
int result = 17; // start at a prime

foreach field f
    int fieldHashcode =
        boolean: (f ? 1: 0)
        byte, char, short, int: (int) f
        long: (int) (f ^ (f >>> 32))
        float: Float.floatToIntBits(f)
        double: Double.doubleToLongBits(f), then above
        Object: object.hashCode()

    result = 31 * result + fieldHashcode;

return result;
```
Final word on hashing

• The hash table is one of the most important data structures
  – Efficient find, insert, and delete
  – Operations based on sorted order are not so efficient
  – Useful in many, many real-world applications
  – Popular topic for job interview questions

• Important to use a good hash function
  – Good distribution, Uses enough of key’s values
  – Not overly expensive to calculate (bit shifts good!)

• Important to keep hash table at a good size
  – Prime #
  – Preferable $\lambda$ depends on type of table

• What we skipped: Perfect hashing, universal hash functions, hopscotch hashing, cuckoo hashing

• Side-comment: hash functions have uses beyond hash tables
  – Examples: Cryptography, check-sums