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3.1 SYMBOL TABLES

- *API*
- *elementary implementations*
- *ordered operations*

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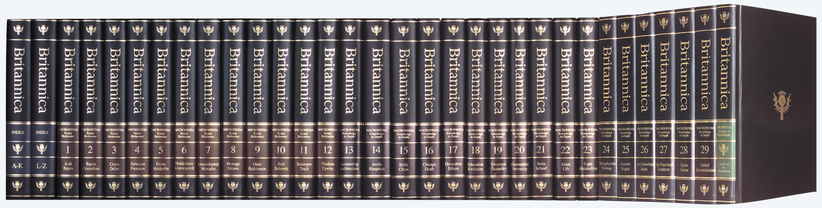
Why are telephone books (and their cousins) obsolete?

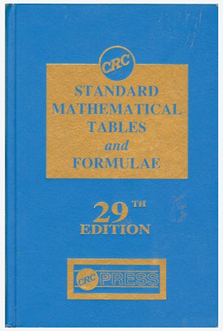
Unsupported phone book operations.

- Add a new name and associated number.
- Remove a given name and associated number.
- Change the number associated with a given name.

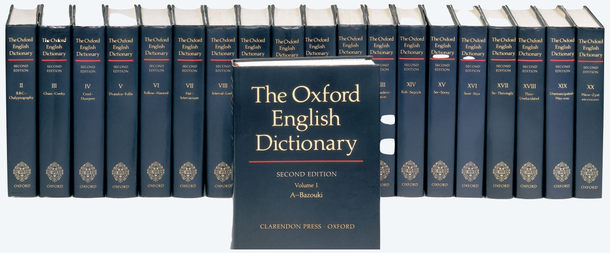


key = term
value = article

key = name
value = phone number



key = math function and input
value = function output



key = word
value = definition

key = time and channel
value = TV show

Symbol tables

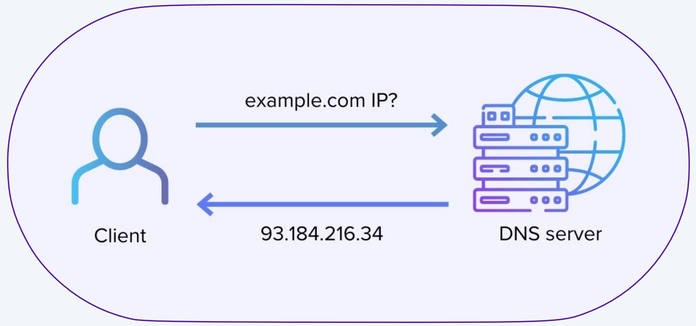
Key–value pair abstraction.

- Insert a value with specified key.
- Given a key, search for the corresponding value.

Ex. DNS lookup.

- Insert domain name with specified IP address.
- Given domain name, find corresponding IP address.

domain name	IP address
www.cs.princeton.edu	128.112.136.61
goprincetontigers.com	67.192.28.17
wikipedia.com	208.80.153.232
google.com	172.217.11.46
↑ *key*	↑ *value*



Symbol table applications

application	purpose of search	key	value
dictionary	*find definition*	word	definition
book index	*find relevant pages*	term	list of page numbers
file share	*find song to download*	name of song	computer ID
financial account	*process transactions*	account number	transaction details
web search	*find relevant web pages*	keyword	list of page names
compiler	*find properties of variables*	variable name	type and value
routing table	*route Internet packets*	destination	best route
DNS	*find IP address*	domain name	IP address
reverse DNS	*find domain name*	IP address	domain name
genomics	*find markers*	DNA string	known positions
file system	*find file on disk*	filename	location on disk

Conventions

- Method `put()` overwrites old value with new value.
- Method `get()` returns `null` if key not present.
- Values are not `null`. ⟵ `java.util.Map` *allows* `null` *values*

> *“ Careless use of null can cause a staggering variety of bugs. Studying the Google code base, we found that something like 95% of collections weren’t supposed to have any null values in them, and having those fail fast rather than silently accept null would have been helpful to developers.”*

https://code.google.com/p/guava-libraries/wiki/UsingAndAvoidingNullExplained

Symbol tables: context

Also known as: maps, dictionaries, associative arrays.

Generalizes arrays. Keys need not be integers between 0 and $n - 1$.

Language support.

- External libraries: C, VisualBasic, Standard ML, bash, …
- Built-in libraries: Java, C#, C++, Scala, Rust, …
- Built-in to language: Python, Go, JavaScript, Swift, Ruby, Awk, Perl, PHP, Tcl, …

```
has_nice_syntax_for_dictionaries['Python'] = True
has_nice_syntax_for_dictionaries['Java']   = False
```

Python code

Basic symbol table API

Associative array abstraction. Associate key-value pairs.

two generic type parameters

```
public class ST<Key extends Comparable<Key>, Value>
```

	`ST()`	*create an empty symbol table*
`void`	`put(Key key, Value val)`	*insert key–value pair* ⟵ `a[key] = val;`
`Value`	`get(Key key)`	*value paired with key* ⟵ `a[key]`
`Iterable<Key>`	`keys()`	*all the keys in the symbol table*
`boolean`	`contains(Key key)`	*is there a value paired with key?*
`void`	`delete(Key key)`	*remove key (and associated value)*
`boolean`	`isEmpty()`	*is the symbol table empty?*
`int`	`size()`	*number of key–value pairs*

Key and value types

Value type. Any generic type.

Key type. Different assumptions.

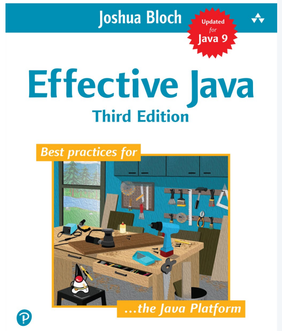
specify `Comparable` *in API*

- This lecture: keys are `Comparable`; use `compareTo()`.
- Hash table lecture: keys are any generic type;
  use `equals()` to test equality and `hashCode()` to scramble key.

Best practices. Use immutable types for symbol-table keys.

immutable	mutable
`String`	`StringBuilder`
`Integer`	`Stack`
`Double`	`ArrayList`
`Color`	`int[]`
⋮	⋮

> *"Classes should be immutable unless there's a very good reason to make them mutable.... If a class cannot be made immutable, you should still limit its mutability as much as possible."*
>
> — Joshua Bloch (Java Collections architect)



ST test client for analysis

Frequency counter. Read a sequence of strings from standard input; print one that occurs most often.

```
~/cos226/st> more tinyTale.txt
it was the best of times
it was the worst of times
it was the age of wisdom
it was the age of foolishness
it was the epoch of belief
it was the epoch of incredulity
it was the season of light
it was the season of darkness
it was the spring of hope
it was the winter of despair

~/cos226/st> java FrequencyCounter 3 < tinyTale.txt
the 10

~/cos226/st> java FrequencyCounter 8 < tale.txt
business 10

~/cos226/st> java FrequencyCounter 10 < leipzig1M.txt
government 24763
```

tiny example (60 *words*, 20 *distinct*)

real example (135,635 *words*, 10,769 *distinct*)

real example (21,191,455 *words*, 534,580 *distinct*)

Frequency counter implementation

```
public class FrequencyCounter {
   public static void main(String[] args) {
      int minLength = Integer.parseInt(args[0]);

      ST<String, Integer> st = new ST<>();          compute frequencies
      while (!StdIn.isEmpty()) {
         String word = StdIn.readString();
         if (word.length() < minLength) continue;
         if (!st.contains(word)) st.put(word, 1);
         else                    st.put(word, st.get(word) + 1);
      }

      String champ = "";          identify and print a string with max frequency
      st.put(champ, 0);
      for (String word : st.keys()) {
         if (st.get(word) > st.get(champ))
            champ = word;
      }
      StdOut.println(champ + " " + st.get(champ));

   }
}
```

overwrites old value with new value (no need to remove)

iterates over all keys in symbol table

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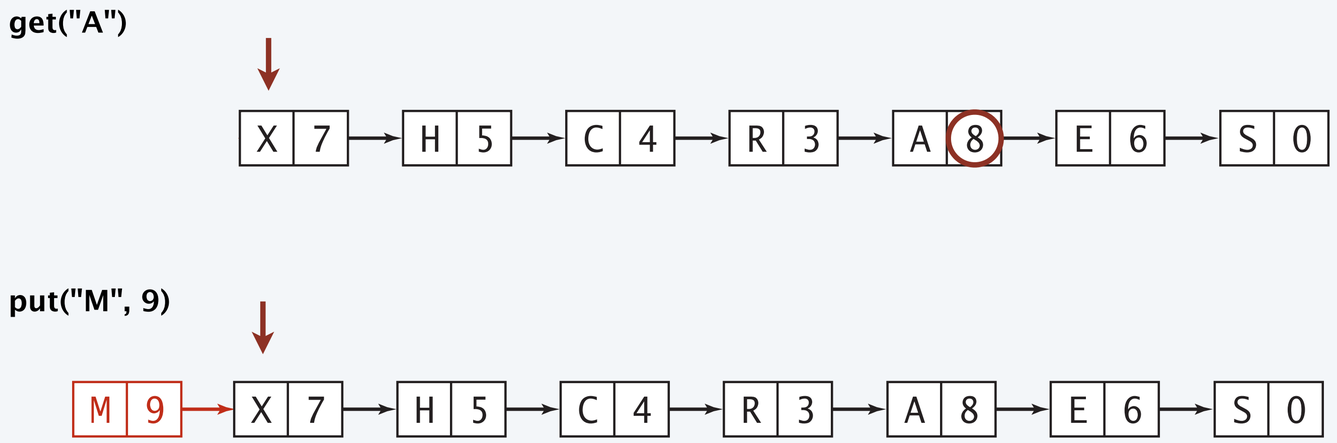
Sequential search in a linked list

Data structure. Maintain an (unordered) linked list of key–value pairs.

Search. Scan through all keys until finding a match.

Insert. Scan through all keys until finding a match; if no match add to front.



Proposition. In the worst case, search and insert each take $\Theta(n)$ time.

Elementary symbol tables: poll 1

Data structure. Maintain parallel arrays for keys and values, sorted by key.

`keys[]`

0	1	2	3	4	5	6	7	8	9
A	C	E	H	L	M	P	R	S	Z

`vals[]`

0	1	2	3	4	5	6	7	8	9
8	4	2	5	11	9	10	3	0	7

What are the worst-case running times for search and insert, respectively?

A. $\Theta(\log n)$ and $\Theta(\log n)$

B. $\Theta(n)$ and $\Theta(\log n)$

C. $\Theta(\log n)$ and $\Theta(n)$

D. $\Theta(n)$ and $\Theta(n)$

Binary search in a sorted array

Data structure. Maintain parallel arrays for keys and values, sorted by key.

Search. Use binary search to find key.

Insert. Use binary search to find place to insert; shift all larger keys over.

get("P")

keys[]	0	1	2	3	4	5	6	7	8	9
	A	C	E	H	L	M	P	R	S	Z

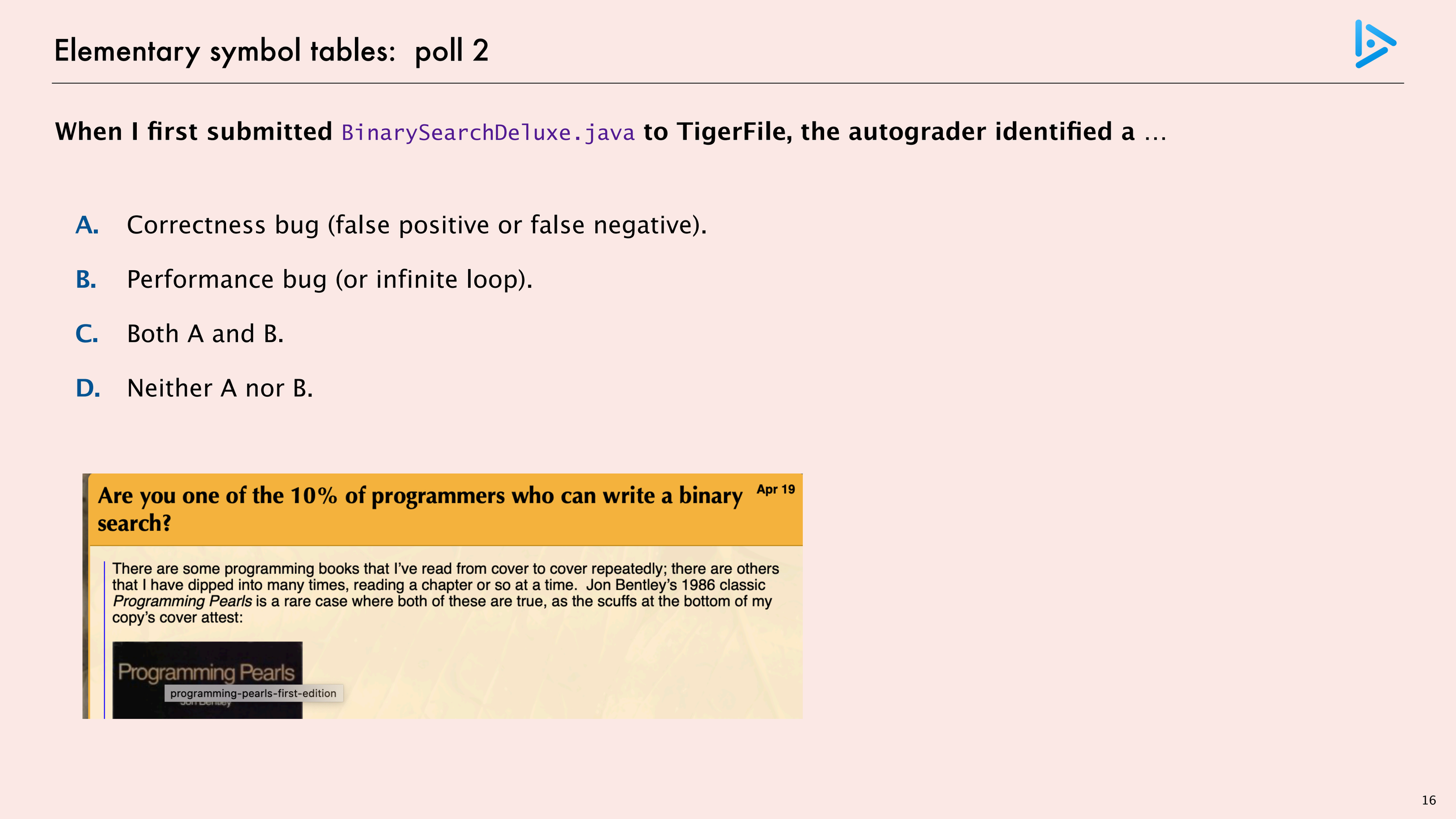
vals[]	0	1	2	3	4	5	6	7	8	9
	8	4	2	5	11	9	10	3	0	7

put("P", 10)

keys[]	0	1	2	3	4	5	6	7	8	9
	A	C	E	H	M	R	S	X	-	-

vals[]	0	1	2	3	4	5	6	7	8	9
	8	4	6	5	9	3	0	7	-	-

Elementary symbol tables: poll 2



When I first submitted `BinarySearchDeluxe.java` to TigerFile, the autograder identified a …

A. Correctness bug (false positive or false negative).

B. Performance bug (or infinite loop).

C. Both A and B.

D. Neither A nor B.

Elementary ST implementations: summary

implementation	worst case		operations on keys
	search	insert	
sequential search (unordered list)	n	n	`equals()`
binary search (sorted array)	$\log n$	n †	`compareTo()`

† *can do with* $\Theta(\log n)$ *compares, but still requires* $\Theta(n)$ *array accesses*

Challenge. Efficient implementations of both search and insert.

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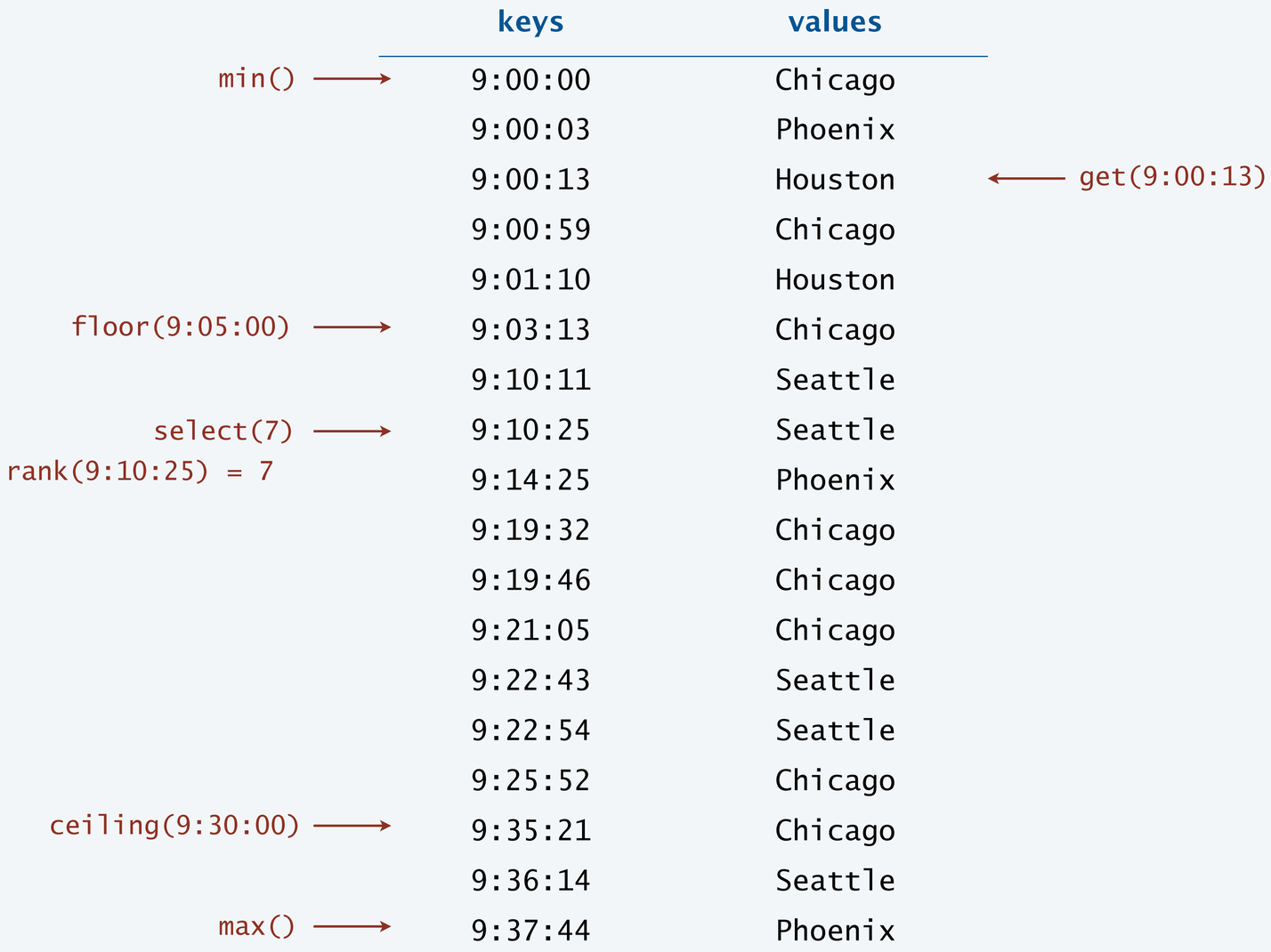
Examples of ordered symbol table API



Ordered symbol table API

Symbol table API. Add these ordered operations when keys are `Comparable`.

```
public class ST<Key extends Comparable<Key>, Value>
```

⋮

`Key`	`min()`	*smallest key*
`Key`	`max()`	*largest key*
`Key`	`floor(Key key)`	*largest key less than or equal to key*
`Key`	`ceiling(Key key)`	*smallest key greater than or equal to key*
`int`	`rank(Key key)`	*number of keys less than key*
`Key`	`select(int k)`	*key of rank k*

Rank in a sorted array

Problem. Given a sorted array of n distinct keys,
find the number of keys strictly less than a given query key.

Q. What if duplicate keys are allowed?

Ordered symbol table operations: performance summary

	sequential search	binary search	goal
search	$\Theta(n)$	$\Theta(\log n)$	$\Theta(\log n)$
insert / delete	$\Theta(n)$	$\Theta(n)$	$\Theta(\log n)$
min / max	$\Theta(n)$	$\Theta(1)$	$\Theta(\log n)$
floor / ceiling	$\Theta(n)$	$\Theta(\log n)$	$\Theta(\log n)$
rank	$\Theta(n)$	$\Theta(\log n)$	$\Theta(\log n)$
select	$\Theta(n)$	$\Theta(1)$	$\Theta(\log n)$

worst-case running time for ordered symbol table operations

Challenge. Efficient implementations of all operations, including insertion/deletion.

Credits

image	source	license
Encyclopedias	Encyclopædia Britannica	
Stack of Phone Books	James Joyner	
CRC Standard Mathematical Tables	CRC Press	
Oxford English Dictionary	Oxford University Press	
TV Guide	TV Guide Magazine	
DNS Server	3hcloud.com	
Effective Java	Addison-Wesley Professional	
Binary Search	The Reinvigorated Programmer	