3.1 Symbol Tables

- API
- sequential search
- binary search
- ordered operations

Symbol tables

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

Ex. DNS lookup.
- Insert URL with specified IP address.
- Given URL, find corresponding IP address.

URL	IP address
www.cs.princeton.edu	128.112.136.11
www.princeton.edu	128.112.128.15
www.yale.edu	130.132.143.21
www.harvard.edu	128.103.060.55
www.simpsons.com	209.052.165.60

↑ 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 given URL	URL	IP address
reverse DNS	find URL given IP address	IP address	URL
genomics	find markers	DNA string	known positions
file system	find file on disk	filename	location on disk

Symbol table API

Associative array abstraction. Associate one value with each key.

`public class ST<Key, Value>`

	`ST()`	*create a symbol table*	
`void`	`put(Key key, Value val)`	*put key-value pair into the table (remove key from table if value is null)*	← `a[key] = val;`
`Value`	`get(Key key)`	*value paired with key (null if key is absent)*	← `a[key]`
`void`	`delete(Key key)`	*remove key (and its value) from table*	
`boolean`	`contains(Key key)`	*is there a value paired with key?*	
`boolean`	`isEmpty()`	*is the table empty?*	
`int`	`size()`	*number of key-value pairs in the table*	
`Iterable<Key>`	`keys()`	*all the keys in the table*	

API for a generic basic symbol table

Conventions

- Values are not `null`.
- Method `get()` returns `null` if key not present.
- Method `put()` overwrites old value with new value.

Intended consequences.

- Easy to implement `contains()`.

```
public boolean contains(Key key)
{  return get(key) != null;  }
```

- Can implement lazy version of `delete()`.

```
public void delete(Key key)
{  put(key, null);          }
```


Keys and values

Value type. Any generic type.

Key type: several natural assumptions.

- Assume keys are `Comparable`, use `compareTo()`.
- Assume keys are any generic type, use `equals()` to test equality.
- Assume keys are any generic type, use `equals()` to test equality and `hashCode()` to scramble key.

specify `Comparable` in API.

built-in to Java (stay tuned)

Best practices. Use immutable types for symbol table keys.

- Immutable in Java: `String`, `Integer`, `Double`, `File`, …
- Mutable in Java: `Date`, `StringBuilder`, `Url`, …

Implementing `equals()` for user-defined types

Seems easy

```
public       class Record
{
   private final String name;
   private final long val;
   ...

   public boolean equals(Record y)
   {





      Record that =          y;
      return (this.val == that.val) &&
             (this.name.equals(that.name));
   }
}
```

check that all significant fields are the same

Implementing `equals()` for user-defined types

Seems easy, but requires some care.

```
public final class Record
{
   private final String name;
   private final long val;
   ...

   public boolean equals(Object y)
   {
      if (y == this) return true;

      if (y == null) return false;

      if (y.getClass() != this.getClass())
         return false;

      Record that = (Record) y;
      return (this.val == that.val) &&
             (this.name.equals(that.name));
   }
}
```

no safe way to use `equals()` with inheritance

must be `Object`. Why? Experts still debate.

optimize for true object equality

check for `null`

objects must be in the same class

check that all significant fields are the same

ST test client for traces

Build ST by associating value i with ith string from standard input.

```
public static void main(String[] args)
{
   ST<String, Integer> st = new ST<String, Integer>();
   String[] a = StdIn.readAll().split("\\s+");
   for (int i = 0; i < a.length; i++)
      st.put(a[i], i);
   for (String s : st.keys())
      StdOut.println(s + " " + st.get(s));
}
```

keys	S	E	A	R	C	H	E	X	A	M	P	L	E
values	0	1	2	3	4	5	6	7	8	9	10	11	12

output

A	8
C	4
E	12
H	5
L	9
M	11
P	10
R	3
S	0
X	7

ST test client for analysis

Frequency counter. Read a sequence of strings from standard input and print out one that occurs with highest frequency.

```
% 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

% java FrequencyCounter 1 < tinyTale.txt
it 10

% java FrequencyCounter 8 < tale.txt
business 122

% 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 minlen = Integer.parseInt(args[0]);
      ST<String, Integer> st = new ST<String, Integer>();
      while (!StdIn.isEmpty())
      {
         String word = StdIn.readString();
         if (word.length() < minlen) continue;
         if (!st.contains(word)) st.put(word, 1);
         else                    st.put(word, st.get(word) + 1);
      }
      String max = "";
      st.put(max, 0);
      for (String word : st.keys())
         if (st.get(word) > st.get(max))
            max = word;
      StdOut.println(max + " " + st.get(max));
   }
}
```

create ST

ignore short strings

read string and update frequency

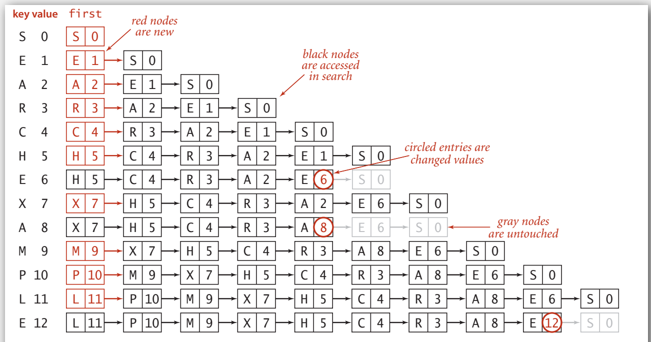
print a string with max freq

- API
- **sequential search**
- binary search
- ordered operations

Sequential search in a linked list

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

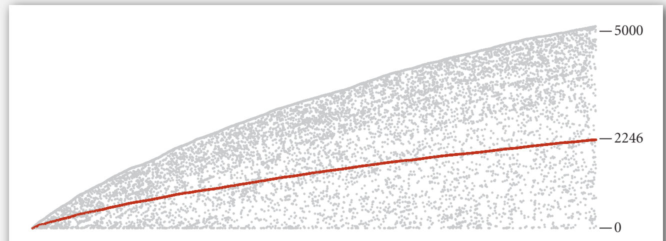
Search. Scan through all keys until find a match.
Insert. Scan through all keys until find a match; if no match add to front.



Trace of linked-list ST implementation for standard indexing client

Elementary ST implementations: summary

ST implementation	worst case		average case		ordered iteration?	operations on keys
	search	insert	search hit	insert		
sequential search (unordered list)	N	N	N / 2	N	no	`equals()`



Costs for `java FrequencyCounter 8 < tale.txt` using `LinkedListST`

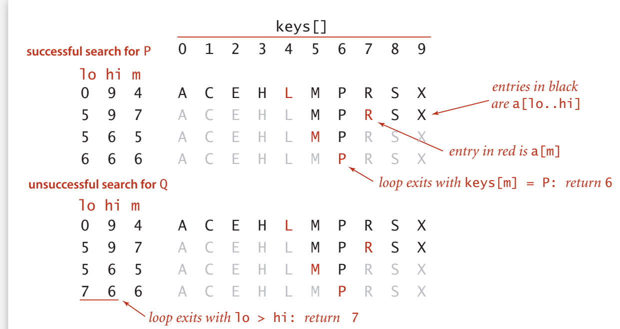
Challenge. Efficient implementations of both search and insert.

- API
- sequential search
- **binary search**
- ordered symbol table ops

Binary search

Data structure. Maintain an ordered array of key-value pairs.

Rank helper function. How many keys < k?



Trace of binary search for rank in an ordered array

Binary search: Java implementation

```
public Value get(Key key)
{
   if (isEmpty()) return null;
   int i = rank(key);
   if (i < N && keys[i].compareTo(key) == 0) return vals[i];
   else  return null;
}
```

```
private int rank(Key key)                          number of keys < key
{
   int lo = 0, hi = N-1;
   while (lo <= hi)
   {
       int mid = lo + (hi - lo) / 2;
       int cmp = key.compareTo(keys[mid]);
       if      (cmp  < 0) hi = mid - 1;
       else if (cmp  > 0) lo = mid + 1;
       else if (cmp == 0) return mid;
  }
  return lo;
}
```


Binary search: mathematical analysis

Proposition. Binary search uses $\sim \lg N$ compares to search any array of size N.

Def. $T(N)$ ≡ number of compares to binary search in a sorted array of size N.

$$\leq T(N/2) + 1$$

left or right half

Binary search recurrence. $T(N) \leq T(N/2) + 1$ for $N > 1$, with $T(1) = 1$.

- Not quite right for odd N.
- Same recurrence holds for many algorithms.

Solution. $T(N) \sim \lg N$.

- For simplicity, we'll prove when N is a power of 2.
- True for all N. [see COS 340]

Binary search recurrence

Binary search recurrence. $T(N) \leq T(N/2) + 1$ for $N > 1$, with $T(1) = 1$.

Proposition. If N is a power of 2, then $T(N) \leq \lg N + 1$.

Pf.

$T(N) \leq T(N/2) + 1$	given
$\leq T(N/4) + 1 + 1$	apply recurrence to first term
$\leq T(N/8) + 1 + 1 + 1$	apply recurrence to first term
$\ldots$	
$\leq T(N/N) + 1 + 1 + \ldots + 1$	stop applying, T(1) = 1
$= \lg N + 1$	

Binary search: trace of standard indexing client

Problem. To insert, need to shift all greater keys over.

		keys[]											vals[]									
key	value	0	1	2	3	4	5	6	7	8	9	N	0	1	2	3	4	5	6	7	8	9
S	0	S										1	0									
E	1	E	S									2	1	0								
A	2	A	E	S								3	2	1	0							
R	3	A	E	R	S							4	2	1	3	0						
C	4	A	C	E	R	S						5	2	4	1	3	0					
H	5	A	C	E	H	R	S					6	2	4	1	5	3	0				
E	6	A	C	E	H	R	S					6	2	4	6	5	3	0				
X	7	A	C	E	H	R	S	X				7	2	4	6	5	3	0	7			
A	8	A	C	E	H	R	S	X				7	8	4	6	5	3	0	7			
M	9	A	C	E	H	M	R	S	X			8	8	4	6	5	9	3	0	7		
P	10	A	C	E	H	M	P	R	S	X		9	8	4	6	5	9	10	3	0	7	
L	11	A	C	E	H	L	M	P	R	S	X	10	8	4	6	5	11	9	10	3	0	7
E	12	A	C	E	H	L	M	P	R	S	X	10	8	4	12	5	11	9	10	3	0	7
		A	C	E	H	L	M	P	R	S	X		8	4	12	5	11	9	10	3	0	7

entries in red were inserted

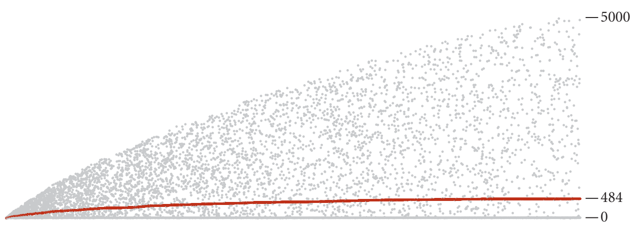
entries in gray did not move

entries in black moved to the right

circled entries are changed values

Elementary ST implementations: summary

ST implementation	worst case		average case		ordered iteration?	operations on keys
	search	insert	search hit	insert		
sequential search (unordered list)	*N*	*N*	*N* / 2	*N*	no	`equals()`
binary search (ordered array)	log *N*	*N*	log *N*	*N* / 2	yes	`compareTo()`



Costs for `java FrequencyCounter 8 < tale.txt` using `OrderedArrayST`

Challenge. Efficient implementations of both search and insert.

- API
- sequential search
- binary search
- **ordered operations**

Ordered symbol table API

operation	*keys*	*values*
`min()` →	09:00:00	Chicago
	09:00:03	Phoenix
	09:00:13	Houston
`get(09:00:13)`	09:00:59	Chicago
	09:01:10	Houston
`floor(09:05:00)` →	09:03:13	Chicago
	09:10:11	Seattle
`select(7)` →	09:10:25	Seattle
	09:14:25	Phoenix
	09:19:32	Chicago
	09:19:46	Chicago
`keys(09:15:00, 09:25:00)` →	09:21:05	Chicago
	09:22:43	Seattle
	09:22:54	Seattle
	09:25:52	Chicago
`ceiling(09:30:00)` →	09:35:21	Chicago
	09:36:14	Seattle
`max()` →	09:37:44	Phoenix

`size(09:15:00, 09:25:00)` *is* 5
`rank(09:10:25)` *is* 7

Examples of ordered symbol-table operations

Ordered symbol table API

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

	`ST()`	*create an ordered symbol table*
`void`	`put(Key key, Value val)`	*put key-value pair into the table (remove* `key` *from table if value is* `null`*)*
`Value`	`get(Key key)`	*value paired with* `key` *(*`null` *if* `key` *is absent)*
`void`	`delete(Key key)`	*remove* `key` *(and its value) from table*
`boolean`	`contains(Key key)`	*is there a value paired with* `key`*?*
`boolean`	`isEmpty()`	*is the table empty?*
`int`	`size()`	*number of key-value pairs*
`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`
`void`	`deleteMin()`	*delete smallest key*
`void`	`deleteMax()`	*delete largest key*
`int`	`size(Key lo, Key hi)`	*number of keys in* `[lo..hi]`
`Iterable<Key>`	`keys(Key lo, Key hi)`	*keys in* `[lo..hi]`*, in sorted order*
`Iterable<Key>`	`keys()`	*all keys in the table, in sorted order*

API for a generic ordered symbol table

Binary search: ordered symbol table operations summary

	sequential search	binary search
search	N	lg N
insert	1	N
min / max	N	1
floor / ceiling	N	lg N
rank	N	lg N
select	N	1
ordered iteration	N log N	N

worst-case running time of ordered symbol table operations