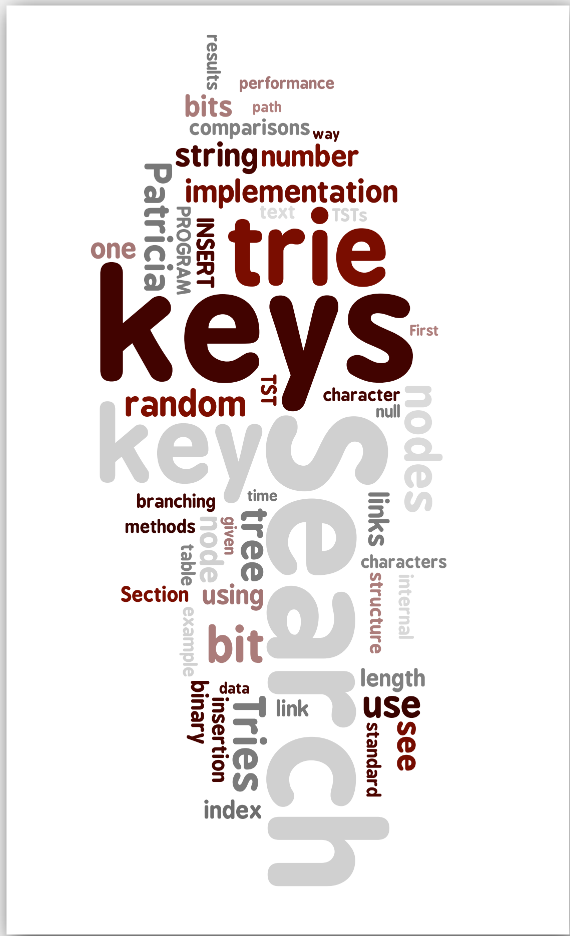
5.2 Tries



- R-way tries
- ternary search tries
- string symbol table API

Review: summary of the performance of symbol-table implementations

Frequency of operations.

implementation	typical case			ordered operations	operations on keys
	search	insert	delete		
red-black BST	1.00 lg N	1.00 lg N	1.00 lg N	yes	`compareTo()`
hashing	1 †	1 †	1 †	no	`equals()` `hashcode()`

† under uniform hashing assumption

Q. Can we do better?

A. Yes, if we can avoid examining the entire key, as with string sorting.

String symbol table basic API

String symbol table. Symbol table specialized to string keys.

`public class StringST<Value>`	
`StringST()`	*create an empty symbol table*
`void put(String key, Value val)`	*put key-value pair into the symbol table*
`Value get(String key)`	*return value paired with given key*
`boolean contains(String key)`	*is there a value paired with the given key?*

Goal. Faster than hashing, more flexible than binary search trees.

String symbol table implementations cost summary

	character accesses (typical case)				dedup	
implementation	search hit	search miss	insert	space (references)	moby.txt	actors.txt
red-black BST	$L + c \lg^2 N$	$c \lg^2 N$	$c \lg^2 N$	4N	1.40	97.4
hashing	L	L	L	4N to 16N	0.76	40.6

file	size	words	distinct
moby.txt	1.2 MB	210 K	32 K
actors.txt	82 MB	11.4 M	900 K

Parameters
- N = number of strings
- L = length of string
- R = radix

Challenge. Efficient performance for string keys.

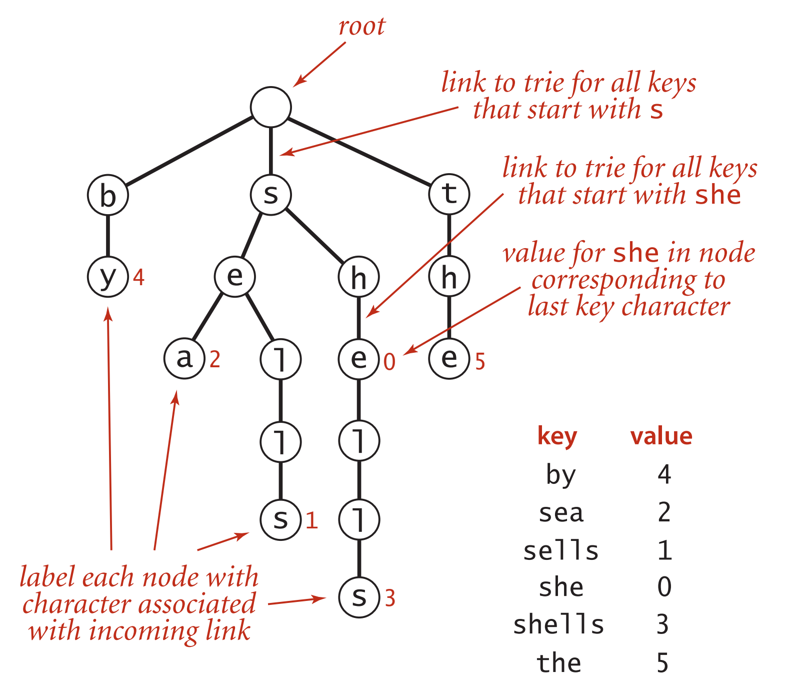
- R-way tries
- ternary search tries
- string symbol table API

Tries

Tries. [from retrieval, but pronounced "try"]

- Store characters and values in nodes (not keys).
- Each node has R children, one for each possible character.
- For now, we do not draw null links.

Ex. `she sells sea shells by the`

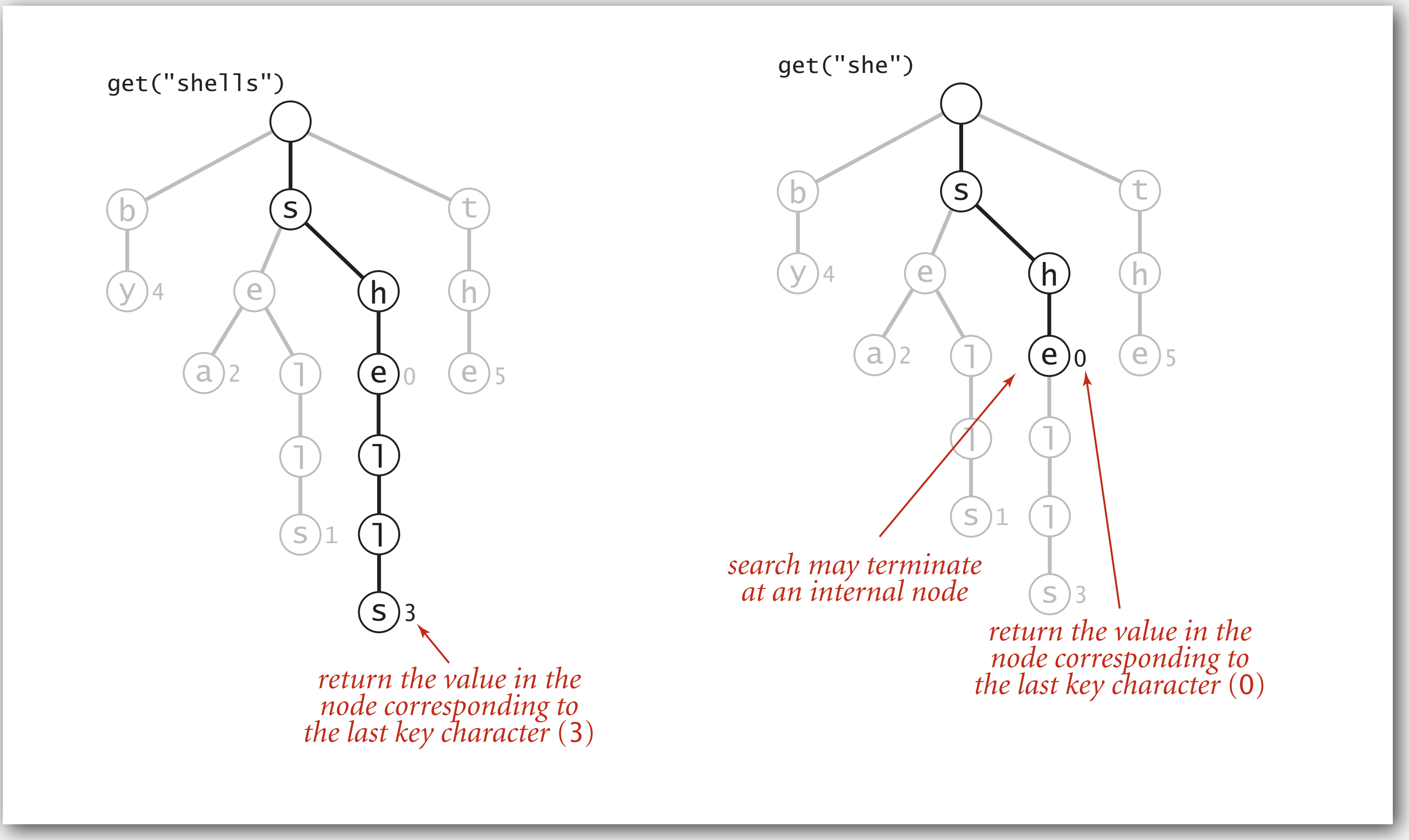


Anatomy of a trie

Search in a trie

Follow links corresponding to each character in the key.

- Search hit: node where search ends has a non-null value.
- Search miss: reach a null link or node where search ends has null value.



Search in a trie

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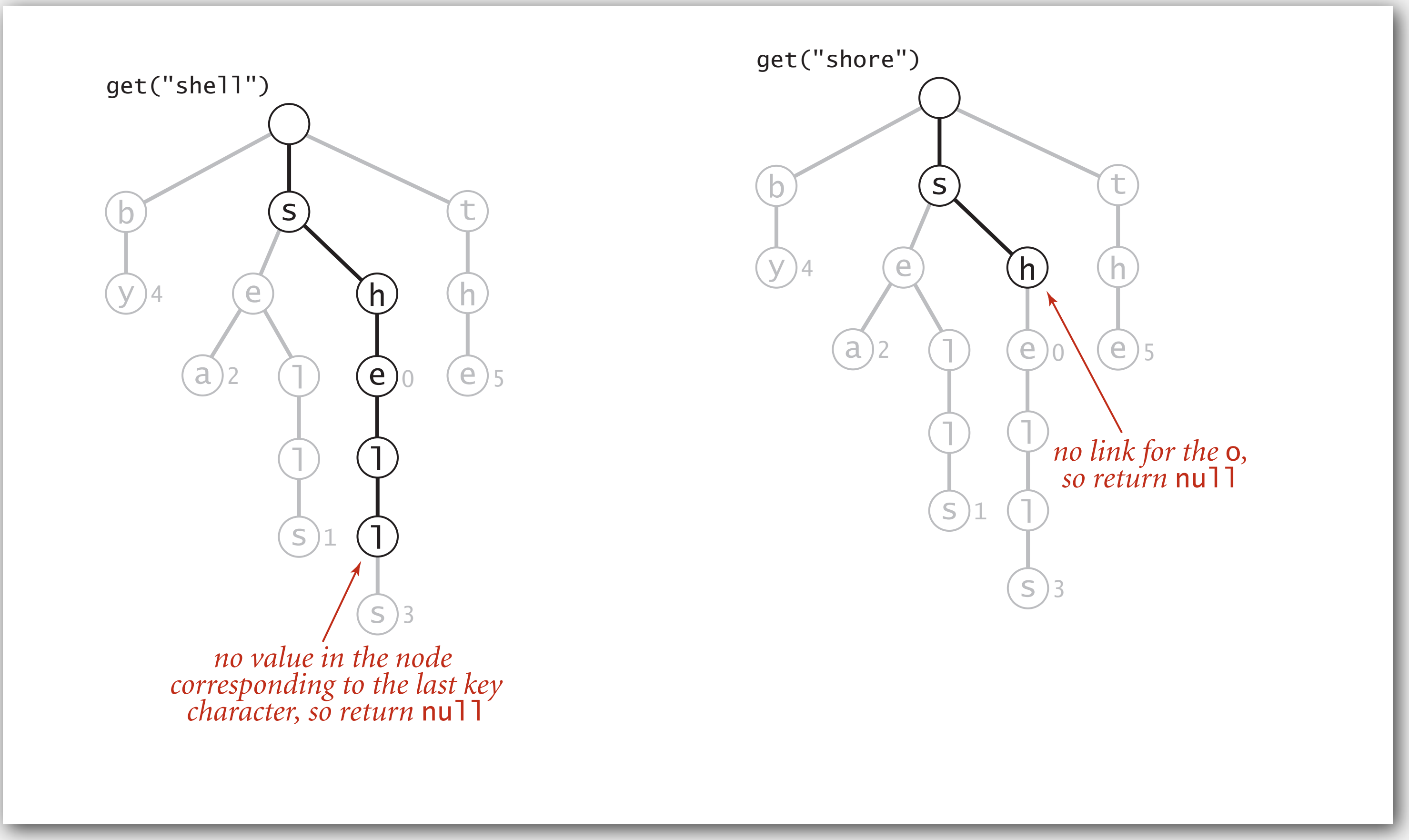
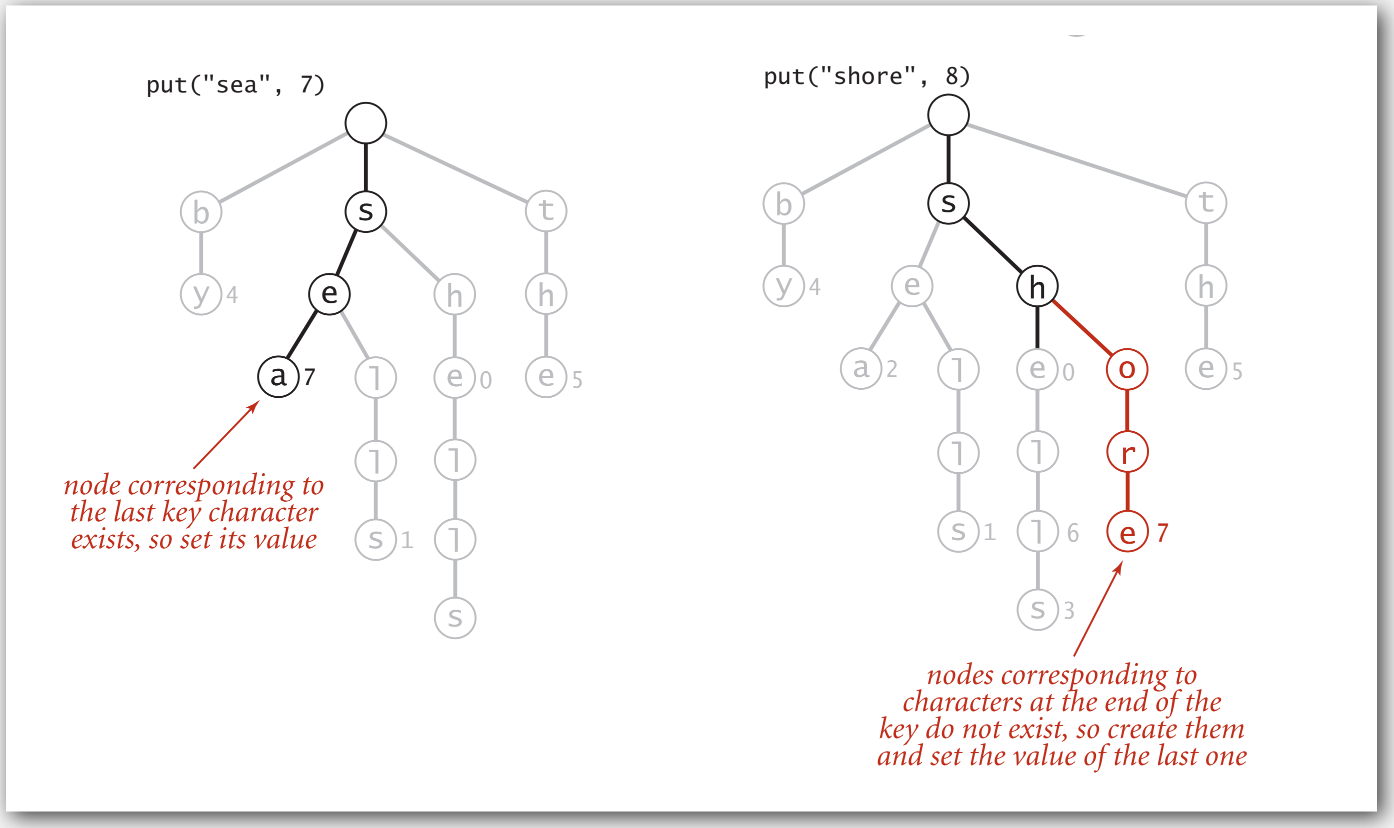


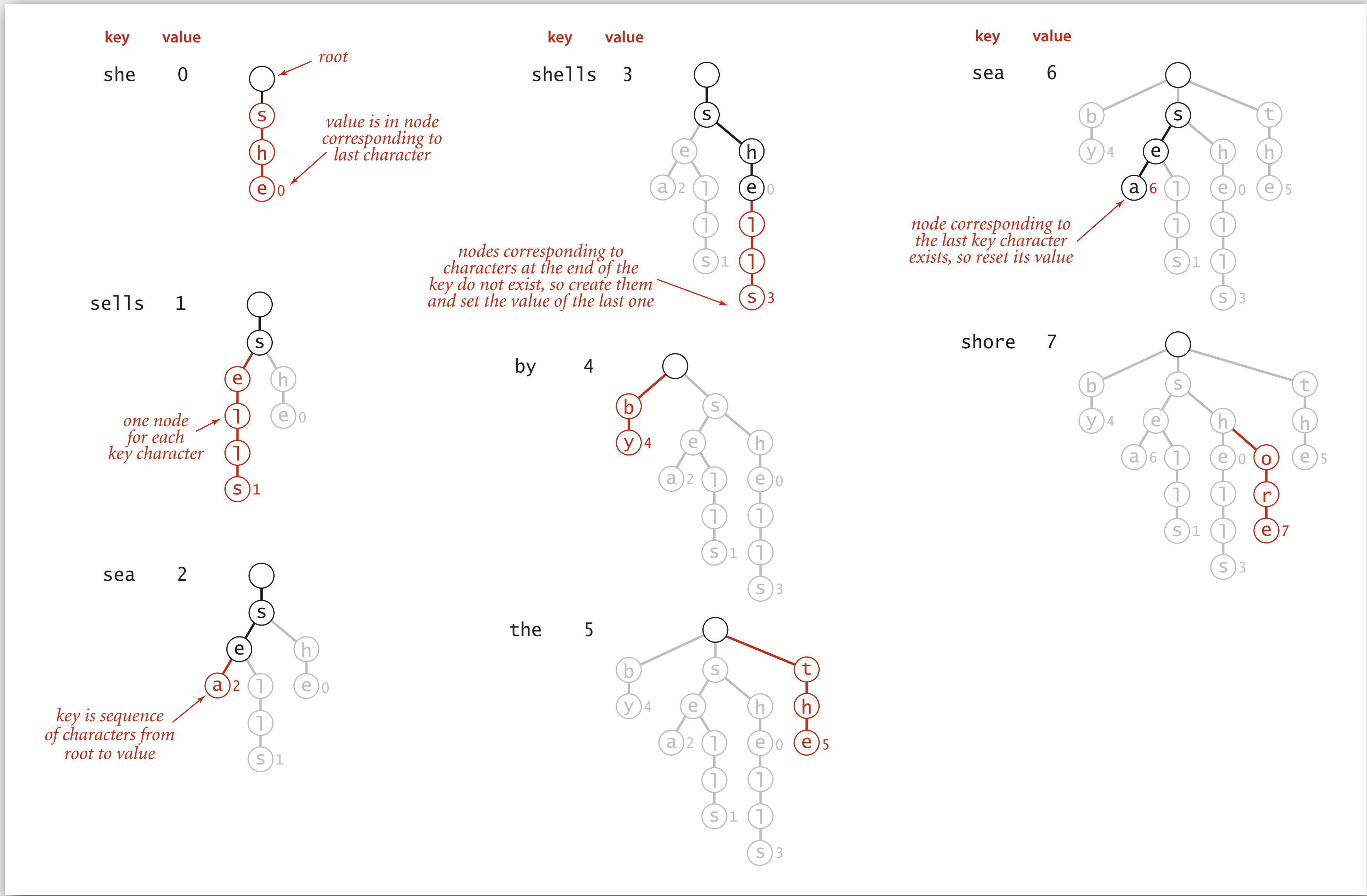
Insertion into a trie

Follow links corresponding to each character in the key.

- Encounter a null link: create new node.
- Encounter the last character of the key: set value in that node.



Trie construction example

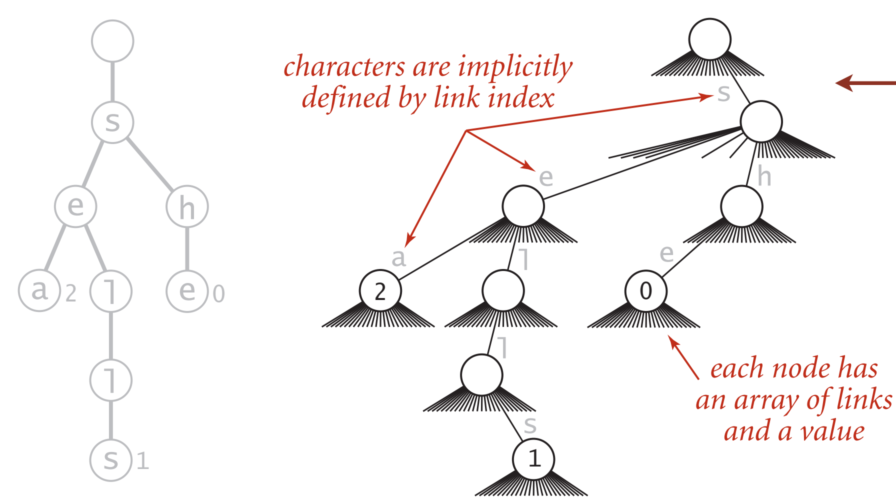


Trie representation: Java implementation

Node. A value, plus references to R nodes.

```
private static class Node
{
   private Object value;
   private Node[] next = new Node[R];
}
```

use **`Object`** instead of **`Value`** since no generic array creation in Java



Trie representation

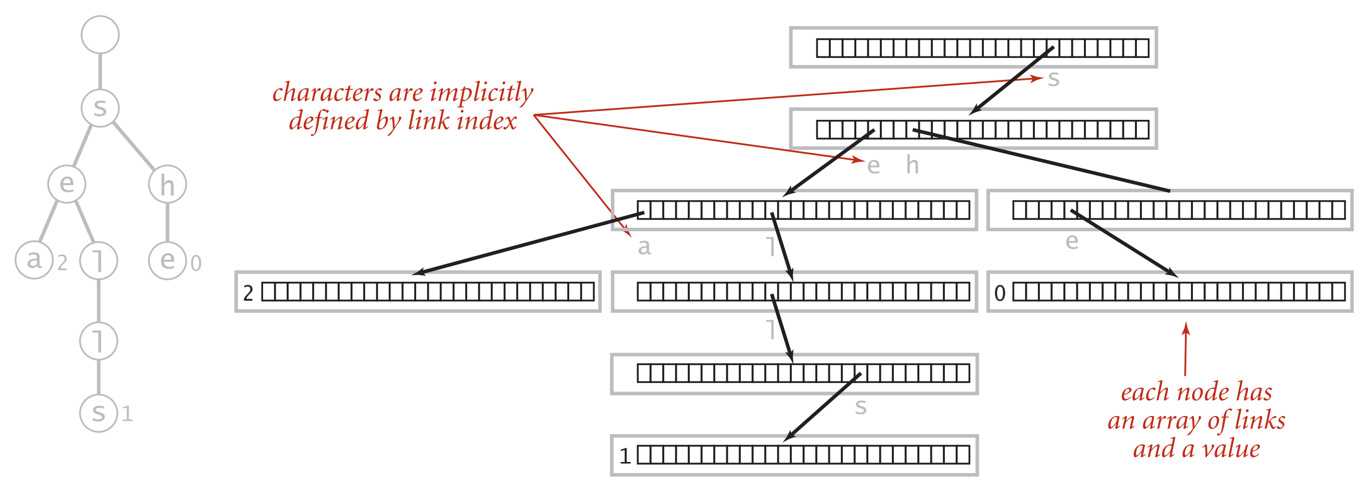
keys are not explicitly stored

Trie representation: Java implementation

Node. A value, plus references to R nodes.

```
private static class Node
{
   private Object value;
   private Node[] next = new Node[R];
}
```

use **Object** instead of **Value** since no generic array creation in Java



Trie representation (R = 26)

R-way trie: Java implementation

```
public class TrieST<Value>
{
   private static final int R = 256;      ← extended ASCII
   private Node root;

   private static class Node
   {  /* see previous slide */   }

   public void put(String key, Value val)
   {  root = put(root, key, val, 0);   }

   private Node put(Node x, String key, Value val, int d)
   {
      if (x == null) x = new Node();
      if (d == key.length()) { x.val = val; return x; }
      char c = key.charAt(d);
      x.next[c] = put(x.next[c], key, val, d+1);
      return x;
   }

}
```

R-way trie: Java implementation (continued)

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

public Value get(String key)
{
   Node x = get(root, key, 0);
   if (x == null) return null;
   return (Value) x.val;        ← cast needed
}

private Node get(Node x, String key, int d)
{
   if (x == null) return null;
   if (d == key.length()) return x;
   char c = key.charAt(d);
   return get(x.next[c], key, d+1);
}
```

Trie performance

Search miss.

- Could have mismatch on first character.
- Typical case: examine only a few characters (sublinear).

Search hit. Need to examine all L characters for equality.

Space. R null links at each leaf.

(but sublinear space possible if many short strings share common prefixes)

Bottom line. Fast search hit and even faster search miss, but wastes space.

String symbol table implementations cost summary

	character accesses (typical case)				dedup	
implementation	search hit	search miss	insert	space (references)	moby.txt	actors.txt
red-black BST	$L + c \lg^2 N$	$c \lg^2 N$	$c \lg^2 N$	$4N$	1.40	97.4
hashing	L	L	L	$4N$ to $16N$	0.76	40.6
R-way trie	L	$\log_R N$	L	$(R+1) N$	1.12	out of memory

R-way trie.

- Method of choice for small R.
- Too much memory for large R.

Challenge. Use less memory, e.g., 65,536-way trie for Unicode!

Digression: out of memory?

" 640 K ought to be enough for anybody. "

— *attributed to Bill Gates, 1981*

(commenting on the amount of RAM in personal computers)

" 64 MB of RAM may limit performance of some Windows XP features; therefore, 128 MB or higher is recommended for best performance. " — *Windows XP manual, 2002*

" 64 bit is coming to desktops, there is no doubt about that. But apart from Photoshop, I can't think of desktop applications where you would need more than 4GB of physical memory, which is what you have to have in order to benefit from this technology. Right now, it is costly. " — *Bill Gates, 2003*

Digression: out of memory?

A short (approximate) history.

machine	year	address bits	addressable memory	typical actual memory	cost
PDP-8	1960s	12	6 KB	6 KB	$16K
PDP-10	1970s	18	256 KB	256 KB	$1M
IBM S/360	1970s	24	4 MB	512 KB	$1M
VAX	1980s	32	4 GB	1 MB	$1M
Pentium	1990s	32	4 GB	1 GB	$1K
Xeon	2000s	64	enough	4 GB	$100
??	future	128+	enough	enough	$1

" 512-bit words ought to be enough for anybody. "
— RS, 1995

A modest proposal

Number of atoms in the universe (estimated). $\leq 2^{266}$.

Age of universe (estimated). 14 billion years ~ 2^{59} seconds $\leq 2^{89}$ nanoseconds.

Q. How many bits address every atom that ever existed?

A. Use a unique 512-bit address for every atom at every time quantum.

266 bits	89 bits	157 bits
atom	time	cushion for whatever

Ex. Use 256-way trie to map each atom to location.

- Represent atom as 64 8-bit chars (512 bits).
- 256-way trie wastes 255/256 actual memory.
- Need better use of memory.

- R-way tries
- **ternary search tries**
- string symbol table API

Ternary search tries

TST. [Bentley-Sedgewick, 1997]

- Store characters and values in nodes (not keys).
- Each node has three children: smaller (left), equal (middle), larger (right).

TST. [Bentley-Sedgewick, 1997]

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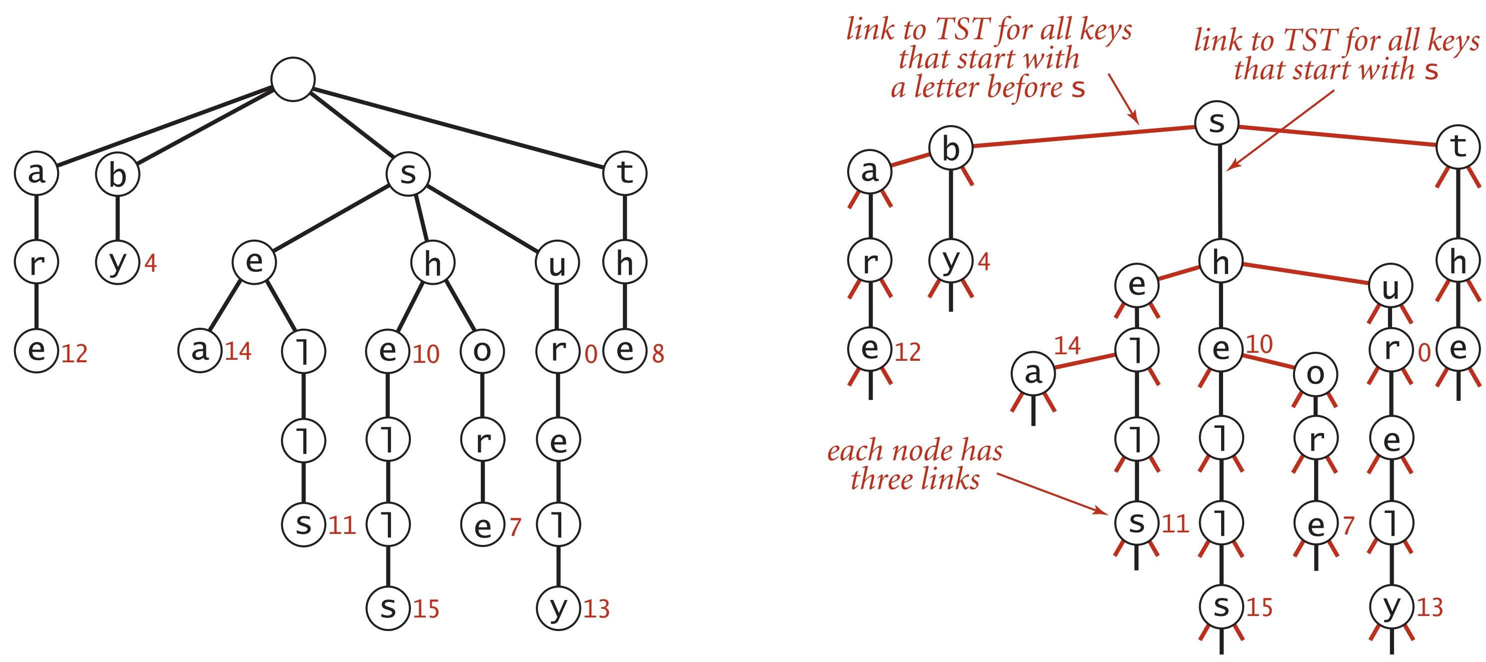


TST representation of a trie

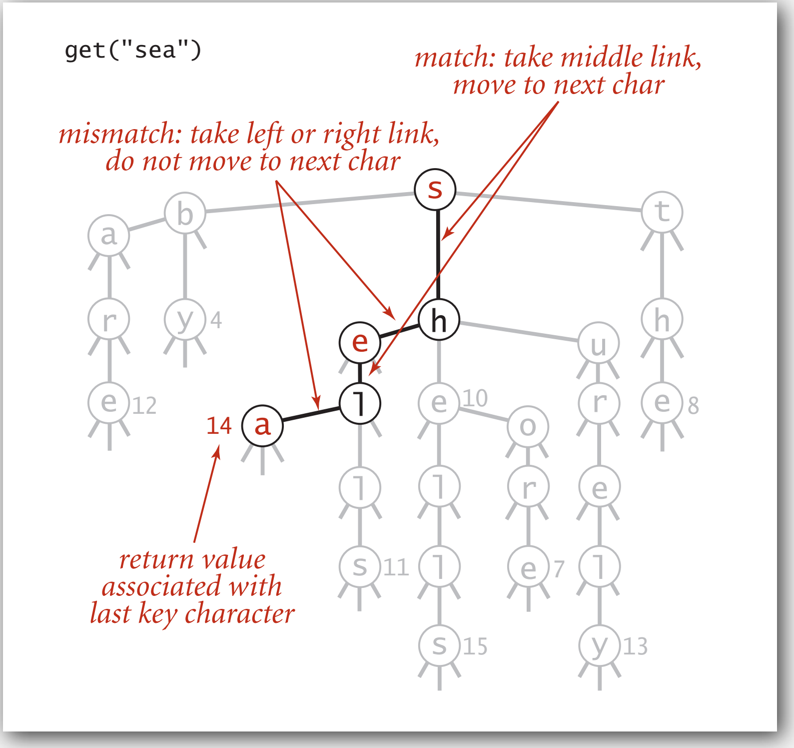
Search in a TST

Follow links corresponding to each character in the key.

- If less, take left link; if greater, take right link.
- If equal, take the middle link and move to the next key character.

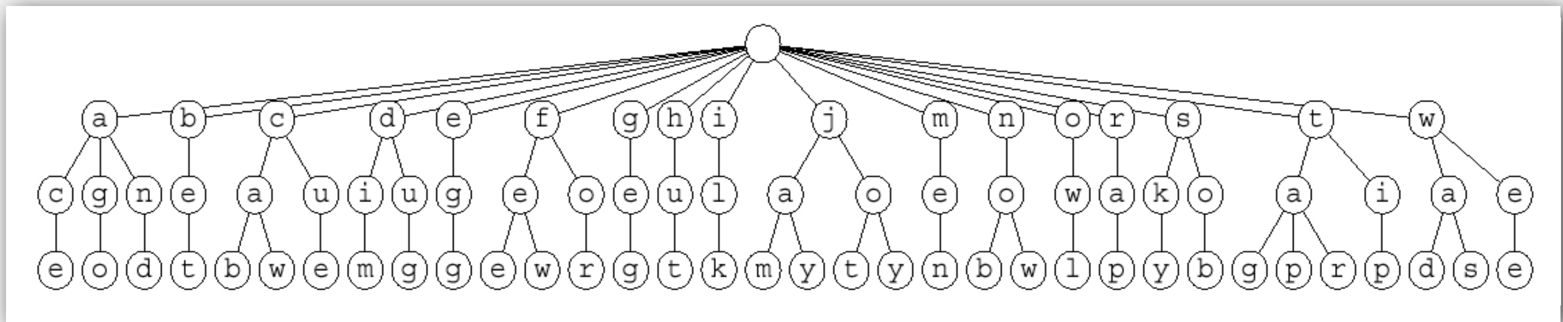
Search hit. Node where search ends has a non-null value.

Search miss. Reach a null link or node where search ends has null value.



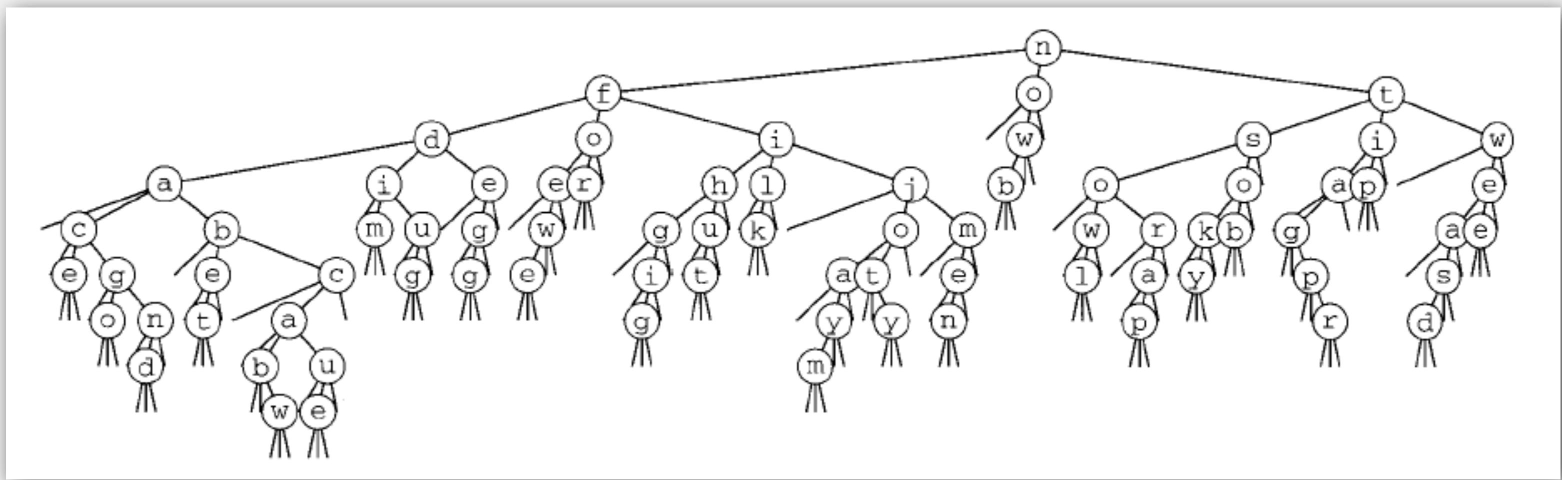
26-way trie vs. TST

26-way trie. 26 null links in each leaf.



26-way trie (1035 null links, not shown)

TST. 3 null links in each leaf.



TST (155 null links)

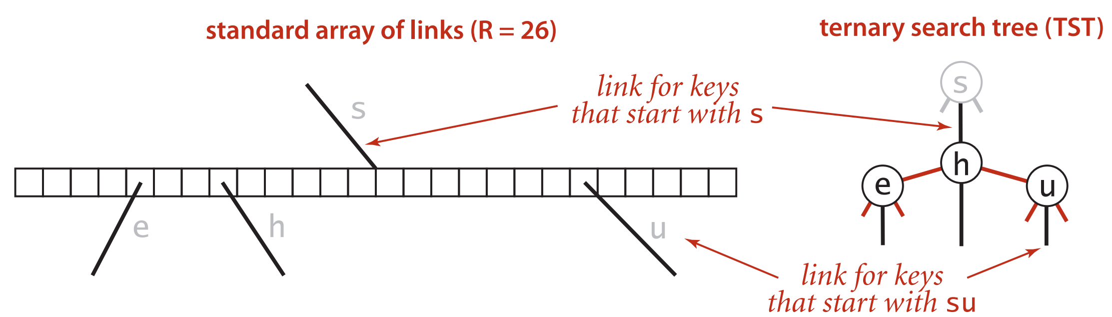
now
for
tip
ilk
dim
tag
jot
sob
nob
sky
hut
ace
bet
men
egg
few
jay
owl
joy
rap
gig
wee
was
cab
wad
caw
cue
fee
tap
ago
tar
jam
dug
and

TST representation in Java

A TST node is five fields:

- A value.
- A character c.
- A reference to a left TST.
- A reference to a middle TST.
- A reference to a right TST.

```
private class Node
{
   private Value val;
   private char c;
   private Node left, mid, right;
}
```



Trie node representations

TST: Java implementation

```
public class TST<Value>
{
   private Node root;

   private class Node
   {  /* see previous slide */   }

   public void put(String key, Value val)
   {  root = put(root, key, val, 0);   }

   private Node put(Node x, String key, Value val, int d)
   {
      char c = key.charAt(d);
      if (x == null) {  x = new Node(); x.c = c;   }
      if      (c < x.c)              x.left  = put(x.left,  key, val, d);
      else if (c > x.c)              x.right = put(x.right, key, val, d);
      else if (d < s.length() - 1) x.mid   = put(x.mid,   key, val, d+1);
      else                           x.val   = val;
      return x;
   }

}
```

TST: Java implementation (continued)

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

public Value get(String key)
{
   Node x = get(root, key, 0);
   if (x == null) return null;
   return x.val;
}

private Node get(Node x, String key, int d)
{
   if (x == null) return null;
   char c = key.charAt(d);
   if      (c < x.c)              return get(x.left,  key, d);
   else if (c > x.c)              return get(x.right, key, d);
   else if (d < key.length() - 1) return get(x.mid,   key, d+1);
   else                           return x;
}
```

String symbol table implementation cost summary

	character accesses (typical case)				dedup	
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red-black BST	$L + c \lg^2 N$	$c \lg^2 N$	$c \lg^2 N$	$4N$	1.40	97.4
hashing	L	L	L	$4N$ to $16N$	0.76	40.6
R-way trie	L	$\log_R N$	L	$(R + 1) N$	1.12	out of memory
TST	$L + \ln N$	$\ln N$	$L + \ln N$	$4N$	0.72	38.7

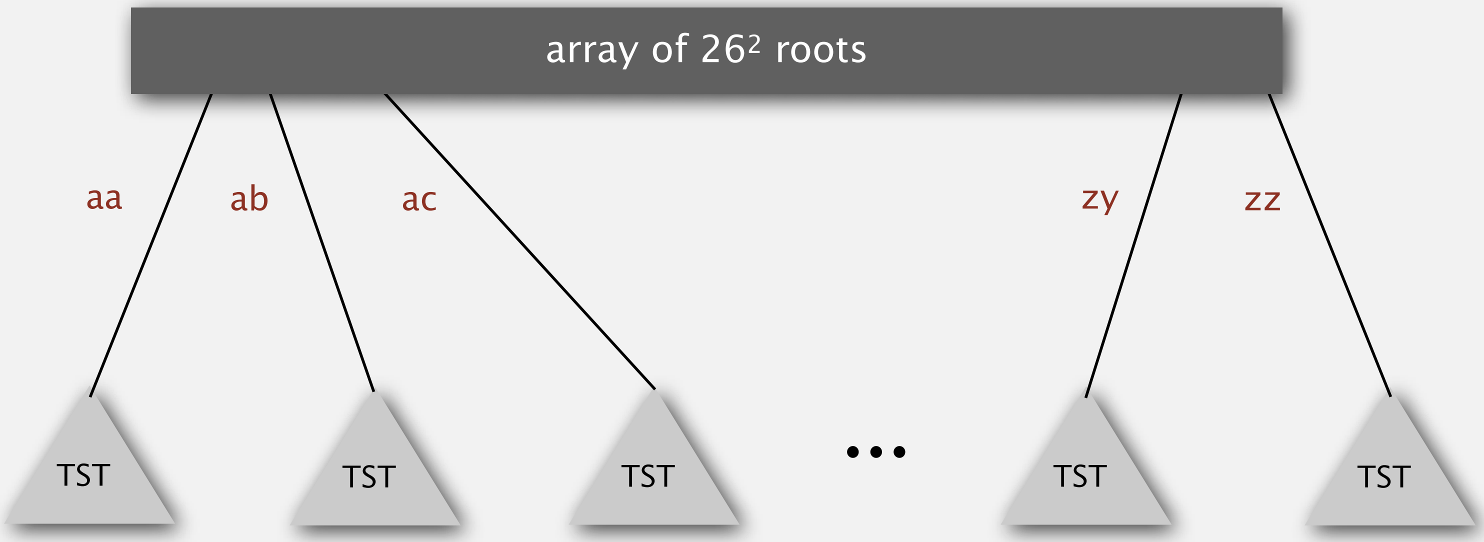
Remark. Can build balanced TSTs via rotations to achieve $L + \log N$ worst-case guarantees.

Bottom line. TST is as fast as hashing (for string keys), space efficient.

TST with R^2 branching at root

Hybrid of R-way trie and TST.

- Do R^2-way branching at root.
- Each of R^2 root nodes points to a TST.



Q. What about one- and two-letter words?

String symbol table implementation cost summary

	character accesses (typical case)				dedup	
implementation	search hit	search miss	insert	space (references)	moby.txt	actors.txt
red-black BST	$L + c \lg^2 N$	$c \lg^2 N$	$c \lg^2 N$	$4N$	1.40	97.4
hashing	L	L	L	$4N$ to $16N$	0.76	40.6
R-way trie	L	$\log_R N$	L	$(R + 1) N$	1.12	out of memory
TST	$L + \ln N$	$\ln N$	$L + \ln N$	$4N$	0.72	38.7
TST with R^2	$L + \ln N$	$\ln N$	$L + \ln N$	$4N + R^2$	0.51	32.7

TST vs. hashing

Hashing.

- Need to examine entire key.
- Search hits and misses cost about the same.
- Need good hash function for every key type.
- No help for ordered symbol table operations.

TSTs.

- Works only for strings (or digital keys).
- Only examines just enough key characters.
- Search miss may only involve a few characters.
- Can handle ordered symbol table operations (plus others!).

Bottom line. TSTs are:

- Faster than hashing (especially for search misses).
  More flexible than red-black trees (next).

- R-way tries
- ternary search tries
- **string symbol table API**

String symbol table API

Character-based operations. The string symbol table API supports several useful character-based operations.

```
by sea sells she shells shore the
```

Prefix match. Keys with prefix `"sh"`: `"she"`, `"shells"`, and `"shore"`.

Longest prefix. Key that is the longest prefix of `"shellsort"`: `"shells"`.

Wildcard match. Keys that match `".he"`: `"she"` and `"the"`.

String symbol table API

```
public class StringST<Value>
```

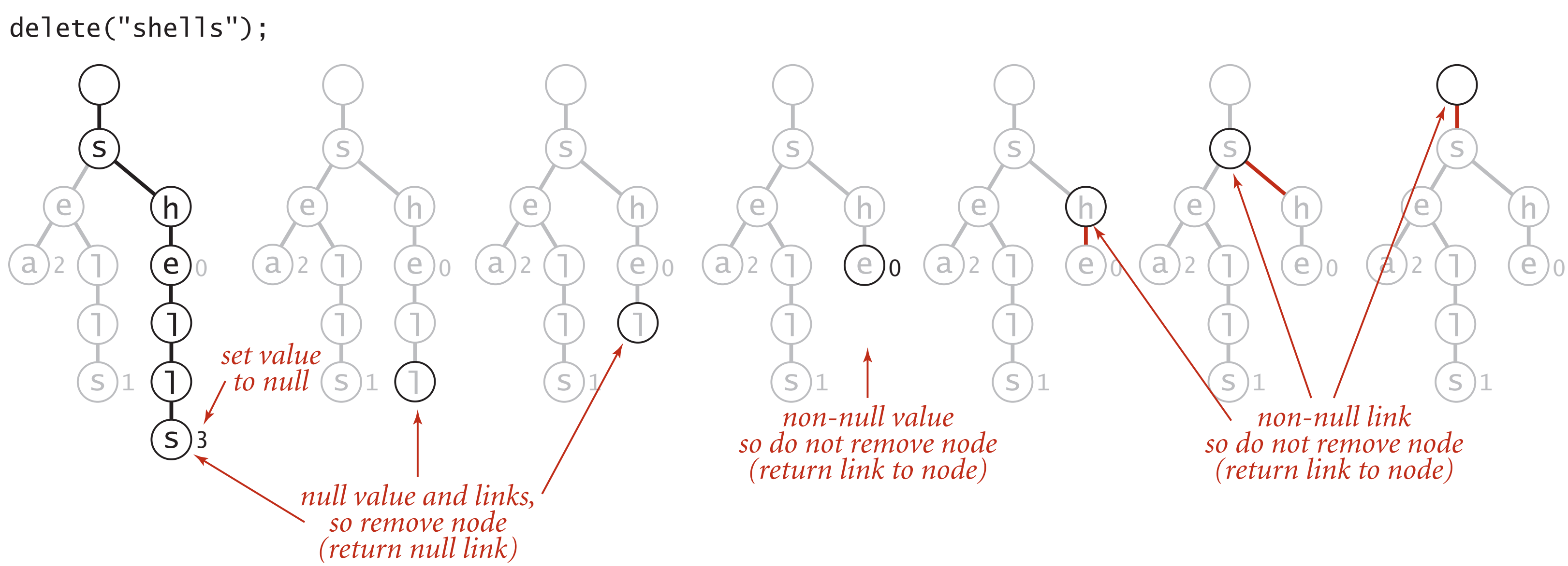
	`StringST()`	*create a symbol table with string keys*
	`StringST(Alphabet alpha)`	*create a symbol table with string keys whose characters are taken from* `alpha`.
`void`	`put(String key, Value val)`	*put key-value pair into the symbol table (remove* `key` *from table if value is* `null`*)*
`Value`	`get(String key)`	*value paired with* `key` *(*`null` *if* `key` *is absent)*
`void`	`delete(String key)`	*remove* `key` *(and its value) from table*
`boolean`	`contains(String key)`	*is there a value paired with* `key`*?*
`boolean`	`isEmpty()`	*is the table empty?*
`String`	`longestPrefixOf(String s)`	*return the longest key that is a prefix of* `s`
`Iterable<String>`	`keysWithPrefix(String s)`	*all the keys having* `s` *as a prefix.*
`Iterable<String>`	`keysThatMatch(String s)`	*all the keys that match* `s` *(where* `.` *matches any character).*
`int`	`size()`	*number of key-value pairs in the table*
`Iterable<String>`	`keys()`	*all the keys in the symbol table*

Remark. Can also add other ordered ST methods, e.g., **`floor()`** and **`rank()`**.

Deletion in an R-way trie

To delete a key-value pair:

- Find the node corresponding to key and set value to null.
- If that node has all null links, remove that node (and recur).



Deleting a key (and its associated value) from a trie

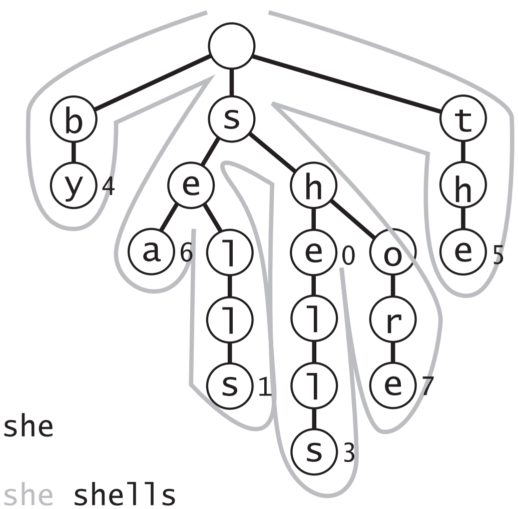
Ordered iteration

To iterate through all keys in sorted order:

- Do inorder traversal of trie; add keys encountered to a queue.
- Maintain sequence of characters on path from root to node.

```
keysWithPrefix("");
```

key	q
b	
by	by
s	
se	
sea	by sea
sel	
sell	
sells	by sea sells
sh	
she	by sea sells she
shell	
shells	by sea sells she shells
sho	
shor	
shore	by sea sells she shells shore
t	
th	
the	by sea sells she shells shore the



Collecting the keys in a trie (trace)

Ordered iteration: Java implementation

To iterate through all keys in sorted order:

- Do inorder traversal of trie; add keys encountered to a queue.
- Maintain sequence of characters on path from root to node.

```
public Iterable<String> keys()
{
   Queue<String> queue = new Queue<String>();
   collect(root, "", queue);
   return queue;
}

private void collect(Node x, String prefix, Queue<String> q)
{
   if (x == null) return;
   if (x.val != null) q.enqueue(prefix);
   for (char c = 0; c < R; c++)
      collect(x.next[c], prefix + c, q);
}
```

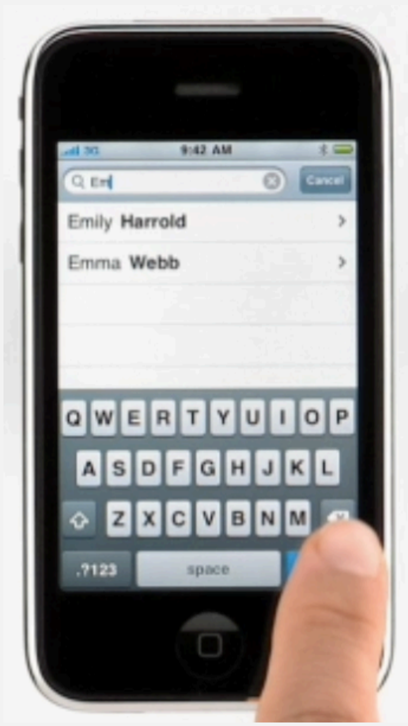
sequence of characters on path from root to x

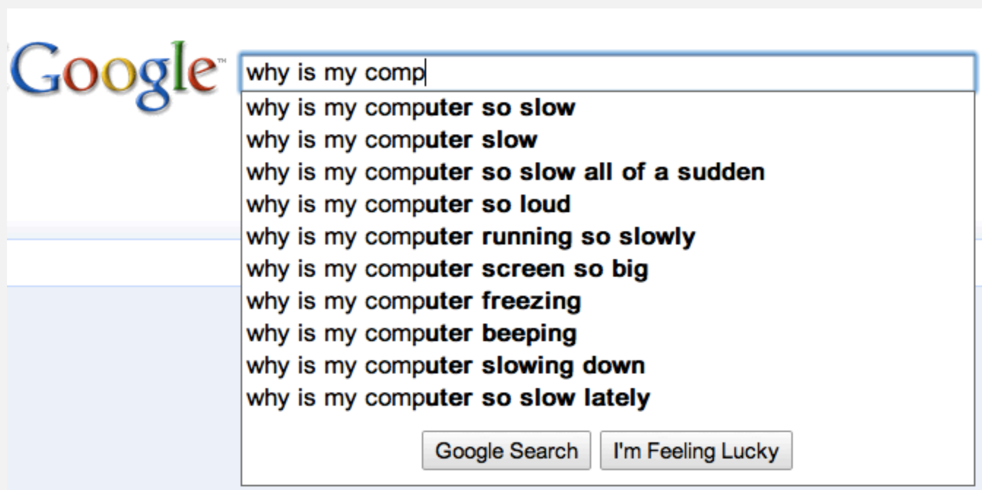
Prefix matches

Find all keys in symbol table starting with a given prefix.

Ex. Autocomplete in a cell phone, search bar, text editor, or shell.

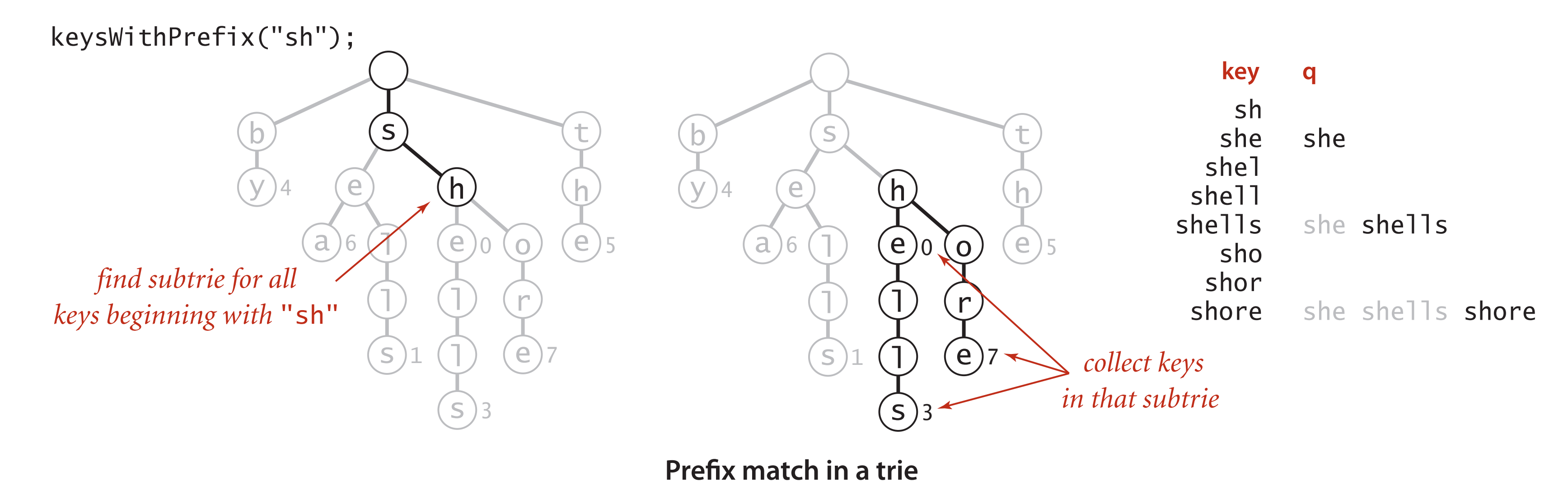
- User types characters one at a time.
- System reports all matching strings.





Prefix matches

Find all keys in symbol table starting with a given prefix.



Prefix match in a trie

```
public Iterable<String> keysWithPrefix(String prefix)
{
   Queue<String> queue = new Queue<String>();
   Node x = get(root, prefix, 0);
   collect(x, prefix, queue);
   return queue;
}
```

root of subtrie for all strings beginning with given prefix

Wildcard matches

Use wildcard . to match any character in alphabet.

```
coalizer
coberger
codifier
cofaster
cofather
cognizer
cohelper
colander
coleader
...
compiler
...
composer
computer
cowkeper
```

`co....er`

```
acresce
acroach
acuracy
octarch
science
scranch
scratch
scrauch
screich
scrinch
scritch
scrunch
scudick
scutock
```

`.c...c.`

Wildcard matches

Search as usual if character is not a period;

go down all R branches if query character is a period.

```
public Iterable<String> keysThatMatch(String pat)
{
   Queue<String> queue = new Queue<String>();
   collect(root, "", 0, pat, queue);
   return queue;
}
```

```
private void collect(Node x, String prefix, String pat, Queue<String> q)
{
   if (x == null) return;
   int d = prefix.length();
   if (d == pat.length() && x.val != null) q.enqueue(prefix);
   if (d == pat.length()) return;
   char next = pat.charAt(d);
   for (char c = 0; c < R; c++)
       if (next == '.' || next == c)
           collect(x.next[c], prefix + c, pat, q);
}
```

Longest prefix

Find longest key in symbol table that is a prefix of query string.

Ex. Search IP database for longest prefix matching destination IP, and route packets accordingly.

```
"128"
"128.112"
"128.112.055"
"128.112.055.15"
"128.112.136"
"128.112.155.11"
"128.112.155.13"
"128.222"
"128.222.136"

prefix("128.112.136.11") = "128.112.136"
prefix("128.166.123.45") = "128"
```

represented as 32-bit binary number for IPv4 (instead of string)

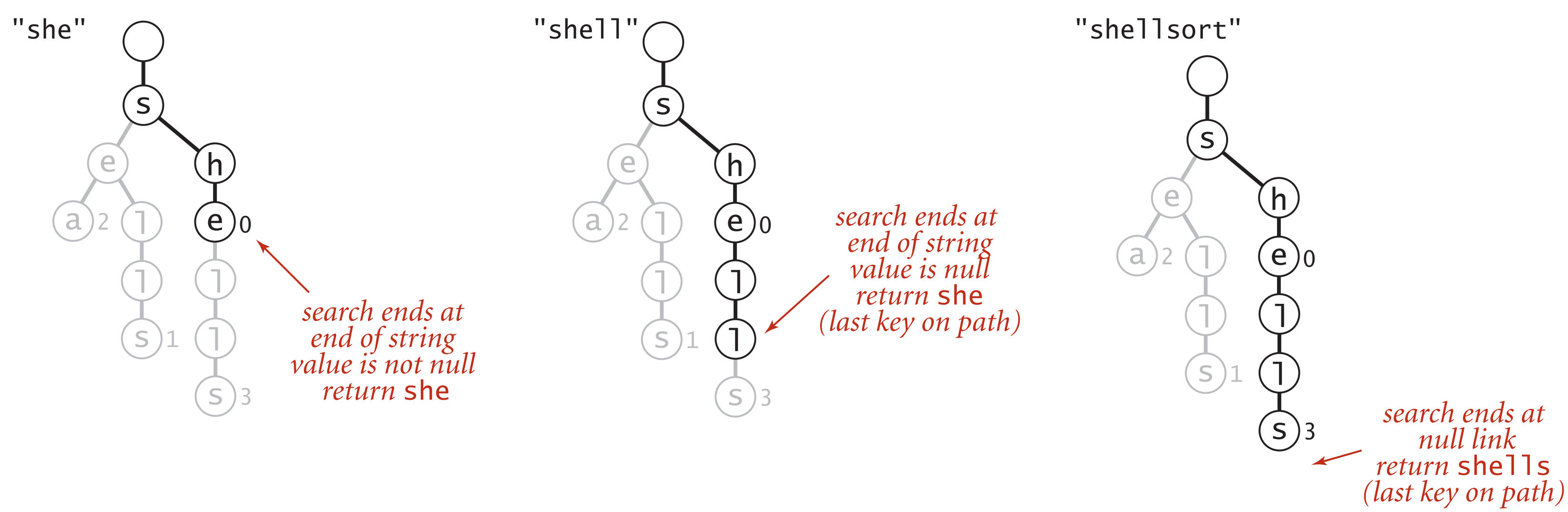
Note. Not the same as floor.

```
prefix("128.112.100.16") = "128.112"
 floor("128.112.100.16") = "128.112.055.15"
```

Longest prefix

Find longest key in symbol table that is a prefix of query string.

- Search for query string.
- Keep track of longest key encountered.



Possibilities for `longestPrefixOf()`

Longest prefix: Java implementation

Find longest key in symbol table that is a prefix of query string.

- Search for query string.
- Keep track of longest key encountered.

```
public String longestPrefixOf(String query)
{
   int length = search(root, query, 0, 0);
   return query.substring(0, length);
}

private int search(Node x, String query, int d, int length)
{
   if (x == null) return length;
   if (x.val != null) length = d;
   if (d == query.length()) return length;
   char c = query.charAt(d);
   return search(x.next[c], query, d+1, length);
}
```

T9 texting

Goal. Type text messages on a phone keypad.

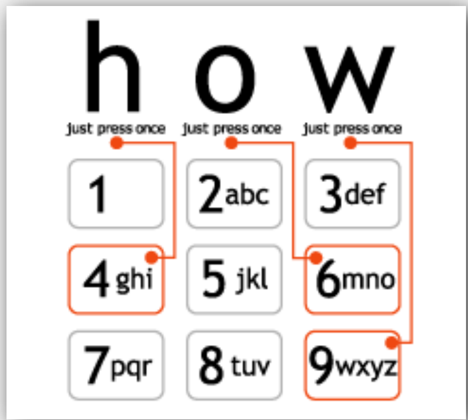
Multi-tap input. Enter a letter by repeatedly pressing a key until the desired letter appears.

T9 text input. ["A much faster and more fun way to enter text."]

- Find all words that correspond to given sequence of numbers.
- Press 0 to see all completion options.

Ex. **`hello`**

- Multi-tap: `4 4 3 3 5 5 5 5 5 5 6 6 6`
- T9: `4 3 5 5 6`



www.t9.com

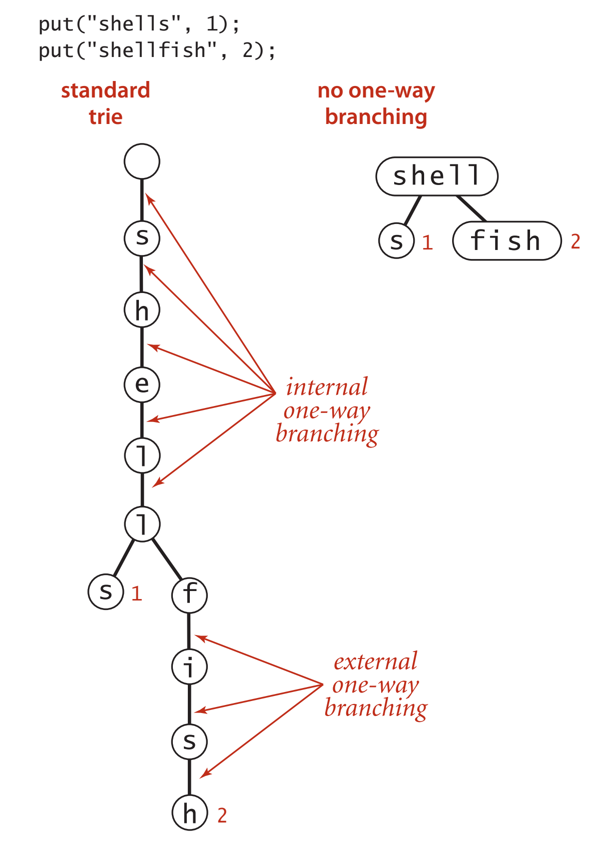
Compressing a trie

Collapsing 1-way branches at bottom.

Internal node stores character; leaf node stores suffix (or full key).

Collapsing interior 1-way branches.

Node stores a sequence of characters.

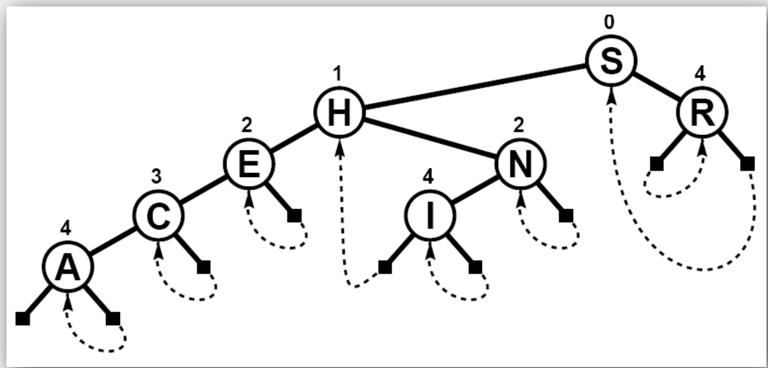


Removing one-way branching in a trie

A classic algorithm

Patricia tries. [Practical Algorithm to Retrieve Information Coded in Alphanumeric]

- Collapse one-way branches in binary trie.
- Thread trie to eliminate multiple node types.

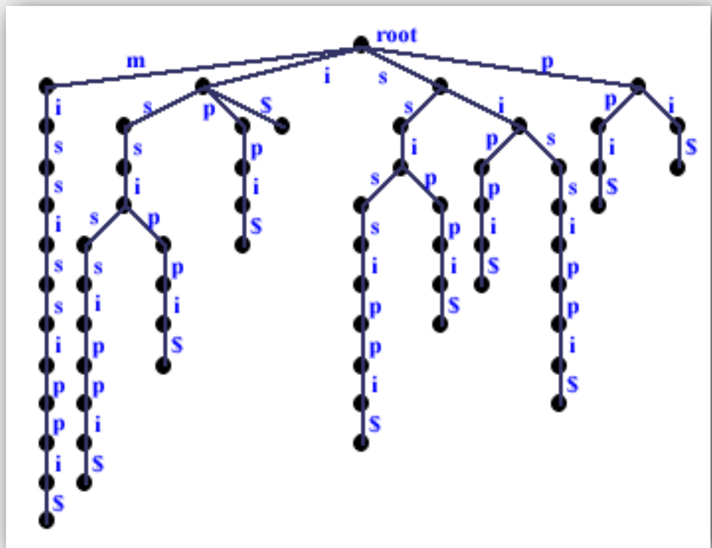


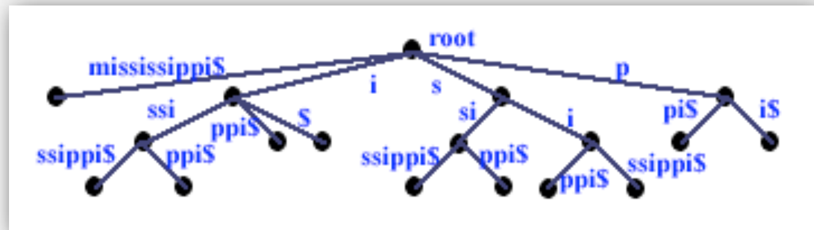
Applications.

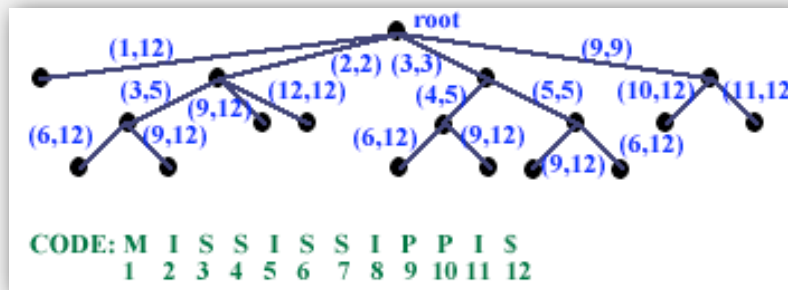
- Database search.
- P2P network search.
- IP routing tables: find longest prefix match.
- Compressed quad-tree for N-body simulation.
- Efficiently storing and querying XML documents.

Implementation. One step beyond this lecture.

Suffix tree. Threaded trie with collapsed 1-way branching for string suffixes.







Applications.

- Linear-time longest repeated substring.
- Computational biology databases (BLAST, FASTA).

Implementation. One step beyond this lecture.

String symbol tables summary

A success story in algorithm design and analysis.

Red-black BST.

- Performance guarantee: $\log N$ key compares.
- Supports ordered symbol table API.

Hash tables.

- Performance guarantee: constant number of probes.
- Requires good hash function for key type.

Tries. R-way, TST.

- Performance guarantee: $\log N$ characters accessed.
- Supports character-based operations.

Bottom line. You can get at anything by examining 50-100 bits (!!!)