CS 240 – Data Structures and Data Management

Module 6: Dictionaries for special keys

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Based on lecture notes by many previous cs240 instructors

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Outline

1. Dictionaries for special keys
   - Lower bound
   - Interpolation Search
   - Tries
     - Standard Tries
     - Variations of Tries
     - Compressed Tries

Outline

Lower bound for search

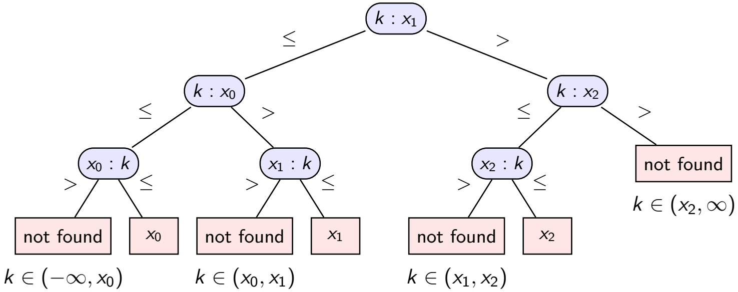
The fastest realizations of *ADT Dictionary* require $\Theta(\log n)$ time to search among n items. Is this the best possible?

Lower bound for search

The fastest realizations of *ADT Dictionary* require $\Theta(\log n)$ time to search among n items. Is this the best possible?

Theorem: In the comparison model (on the keys),
$\Omega(\log n)$ comparisons are required to search a size-n dictionary.

Proof: via decision tree



But can we beat the lower bound for special keys?

Outline

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     - Variations of Tries
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Binary Search

Recall the run-times in a *sorted array*:

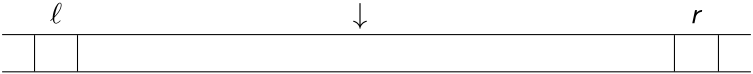
- *insert, delete*: $\Theta(n)$
- *search*: $\Theta(\log n)$

binary-search(A, n, k)
A: Sorted array of size n, k: key

```
ℓ ← 0, r ← n − 1
while (ℓ ≤ r)
    m ← ⌊(ℓ+r)/2⌋
    if (A[m] == k) then return "found at A[m]"
    else if (A[m] < k) then ℓ ← m + 1
    else r ← m − 1
return "not found, but would be between A[ℓ−1] and A[ℓ]"
```

Interpolation Search: Motivation

binary-search$(A[\ell, r], k)$: Compare at index $\lfloor \frac{\ell+r}{2} \rfloor = \ell + \lfloor \frac{1}{2}(r - \ell) \rfloor$



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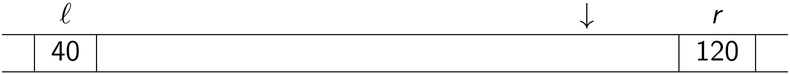

Question: If keys are *numbers*, where would you expect key $k = 100$?

Interpolation Search: Motivation

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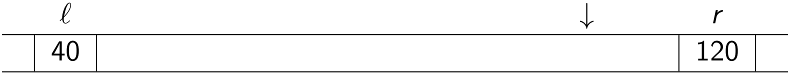

Question: If keys are *numbers*, where would you expect key $k = 100$?

interpolation-search$(A[\ell, r], k)$: Compare at index $\ell + \left\lfloor \frac{k - A[\ell]}{A[r] - A[\ell]}(r - \ell) \right\rfloor$

Interpolation Search

- Code very similar to binary search, but compare at interpolated index
- Need a few extra tests to avoid crash during computation of m.

interpolation-search(A, n, k)
A: Sorted array of size n, k: key

```
ℓ ← 0, r ← n − 1
while (ℓ ≤ r)
    if (k < A[ℓ] or k > A[r]) return "not found"
    if (k = A[r]) then return "found at A[r]"
    m ← ℓ + ⌊(k − A[ℓ])) / (A[r] − A[ℓ]) · (r − ℓ)⌋
    if (A[m] == k) then return "found at A[m]"
    else if (A[m] < k) then ℓ ← m + 1
    else r ← m − 1
// We always return from somewhere within while-loop
```

Interpolation Search Example

0	1	2	3	4	5	6	7	8	9	10
0	1	2	3	449	450	600	800	1000	1200	1500

interpolation-search(A[0..10],449):

Interpolation Search Example

0	1	2	3	4	5	6	7	8	9	10
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ℓ		$\uparrow$								r

interpolation-search(A[0..10],449):

- Initially $\ell = 0,\ r = n - 1 = 10,\ m = \ell + \lfloor \frac{449-0}{1500-0}(10 - 0) \rfloor = \ell + 2 = 2$

Interpolation Search Example

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- $\ell = 3,\ r = 10,\ m = \ell + \lfloor \frac{449-3}{1500-3}(10-3) \rfloor = \ell + 2 = 5$

Interpolation Search Example

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- Initially $\ell = 0$, $r = n - 1 = 10$, $m = \ell + \lfloor \frac{449-0}{1500-0}(10-0) \rfloor = \ell + 2 = 2$
- $\ell = 3$, $r = 10$, $m = \ell + \lfloor \frac{449-3}{1500-3}(10-3) \rfloor = \ell + 2 = 5$
- $\ell = 3$, $r = 4$, found at $A[4]$

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- $\ell = 3$, $r = 10$, $m = \ell + \lfloor \frac{449-3}{1500-3}(10 - 3) \rfloor = \ell + 2 = 5$
- $\ell = 3$, $r = 4$, found at $A[4]$

Works well if keys are *uniformly* distributed:

- Can show: Recurrence relation is $T^{(\text{avg})}(n) = T^{(\text{avg})}(\sqrt{n}) + \Theta(1)$.
- This resolves to $T^{(\text{avg})}(n) \in \Theta(\log \log n)$.

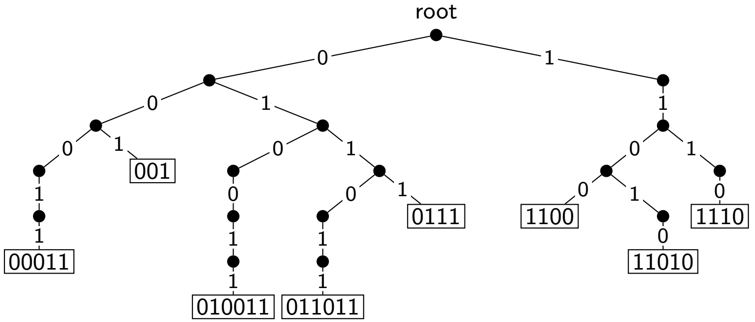
But: Worst case performance $\Theta(n)$

Outline

Tries: Introduction

Trie (also know as **radix tree**): A dictionary for bitstrings.
(Should know: string, word, $|w|$, alphabet, prefix, suffix, comparing words,....)

- Comes from retrieval, but pronounced "try"
- A tree based on *bitwise comparisons*: Edge labelled with corresponding bit
- Similar to *radix sort*: use individual bits, not the whole key

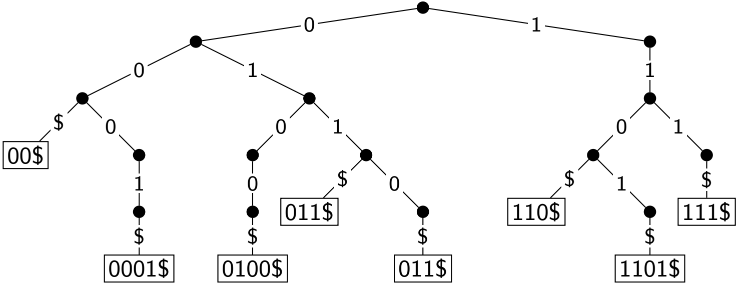


More on tries

Assumption: Dictionary is **prefix-free**: no string is a prefix of another

- Assumption satisfied if all strings have the same length.
- Assumption satisfied if all strings end with 'end-of-word' character \$.

Example: A trie for $\{00\$, 0001\$, 0100\$, 011\$, 0110\$, 110\$, 1101\$, 111\$\}$



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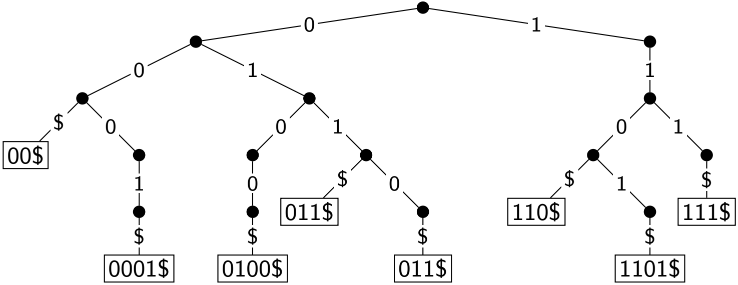


Then items (keys) are stored *only* in the leaf nodes

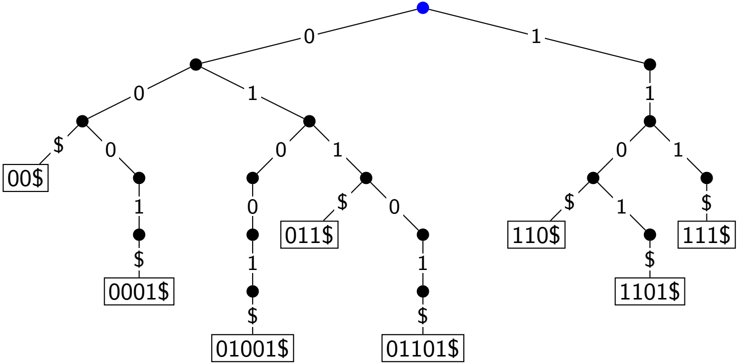
Tries: Search

- start from the root and the most significant bit of x
- follow the link that corresponds to the current bit in x; return failure if the link is missing
- return success if we reach a leaf (it must store x)
- else recurse on the new node and the next bit of x

```
Trie::search(v ← root, d ← 0, x)
v: node of trie; d: level of v, x: word stored as array of chars
    if v is a leaf
        return v
    else
        let v′ be child of v labelled with x[d]
        if there is no such child
            return "not found"
        else Trie::search(v′, d + 1, x)
```

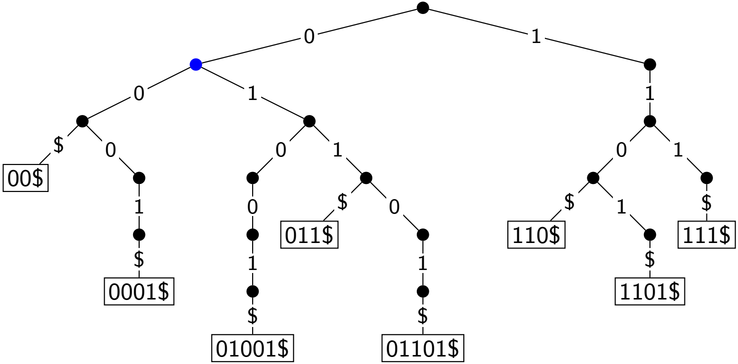
Tries: Search Example

Example: Trie::search(011$)



Tries: Search Example

Example: Trie::search(011$)



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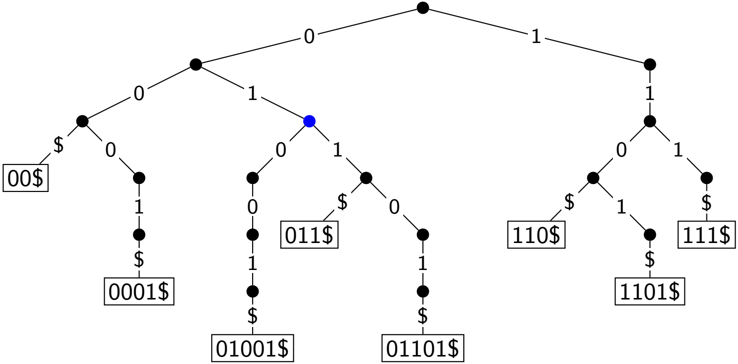
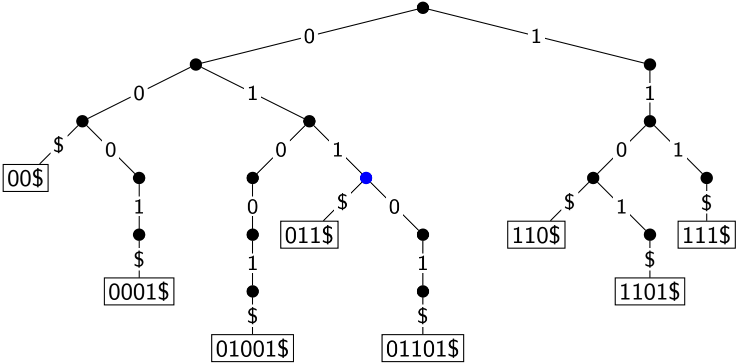


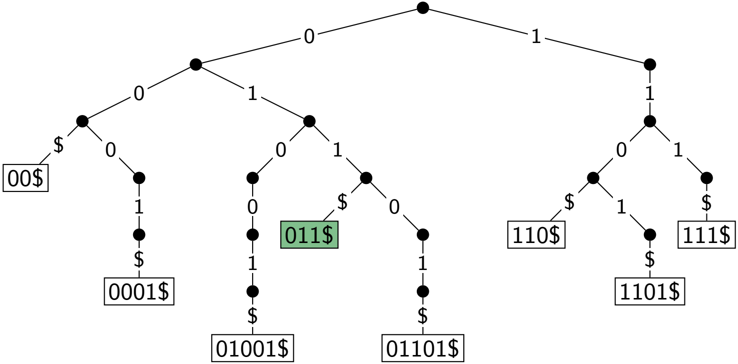
Tries: Search Example

Example: Trie::search(011$)



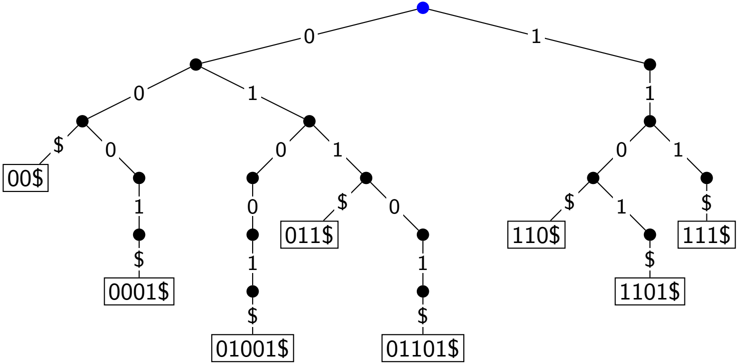
Tries: Search Example

Example: Trie::search(011$) successful



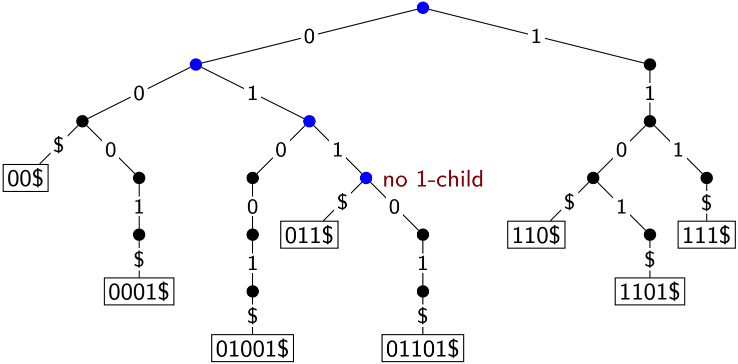
Tries: Search Example

Example: Trie::search(0111$)



Tries: Search Example

Example: Trie::search(0111$) unsuccessful

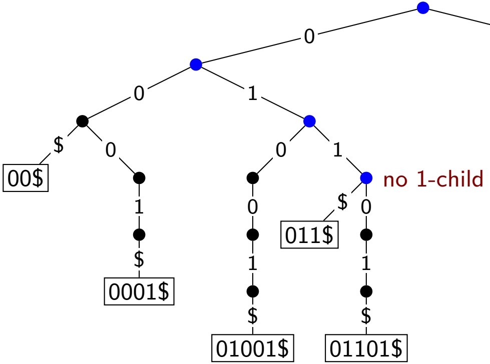


Tries: Insert & Delete

- *Trie::insert(x)*
  - Search for x, this should be unsuccessful
  - Suppose we finish at a node v that is missing a suitable child. Note: x has extra bits left.
  - Expand the trie from the node v by adding necessary nodes that correspond to extra bits of x.
- *Trie::delete*(x)
  - Search for x
  - let v be the leaf where x is found
  - delete v and all ancestors of v until we reach an ancestor that has two children.
- **Time Complexity** of all operations: $\Theta(|x|)$
  $|x|$: length of binary string x, i.e., the number of bits in x

Tries: Insert Example

Example: *Trie::insert*(0111$)



Tries: Insert Example

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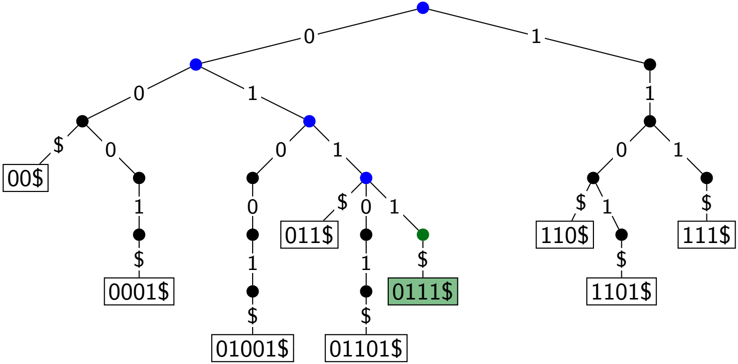
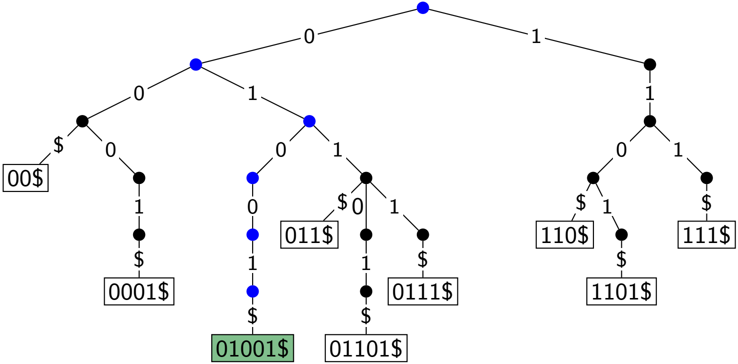


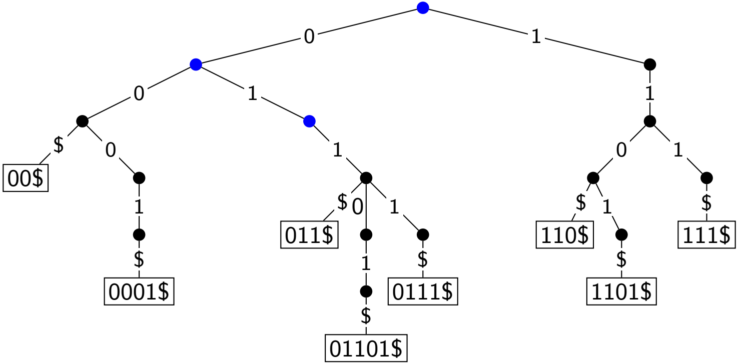
Tries: Delete Example

Example: *Trie::delete*(01001$)



Tries: Delete Example

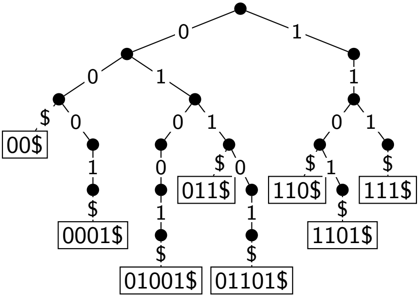
Example: *Trie::delete*(01001$)

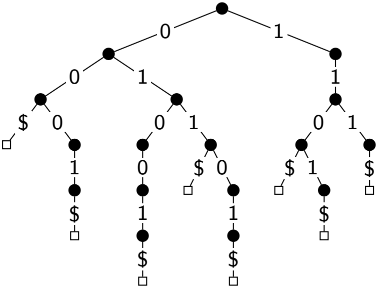


Variation 1 of Tries: No leaf labels

Do not store actual keys at the leaves.

- The key is stored implicitly through the characters along the path to the leaf. It therefore need not be stored again.
- This halves the amount of space needed.

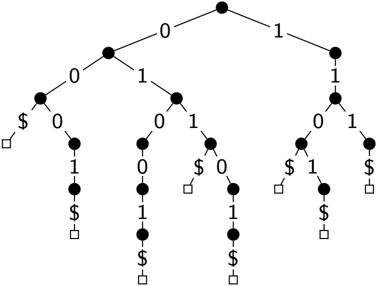


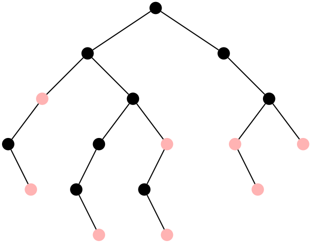


Variation 2 of Tries: Allow Proper Prefixes

Allow prefixes to be in dictionary.

- Internal nodes may now also represent keys.
  Use a *flag* to indicate such nodes.
- No need for end-of-word character $
- Now a trie of bitstrings is a binary tree. Can express 0-child and 1-child implicitly via left and right child.
- More space-efficient.

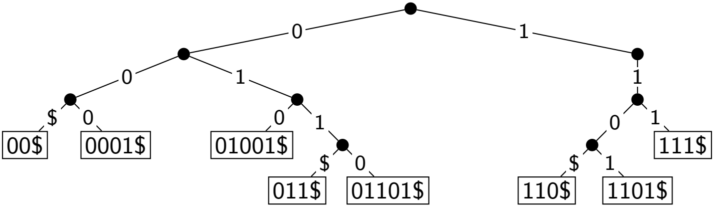




Variations 3 of Tries

Pruned Trie: Stop adding nodes to trie as soon as the key is unique.

- A node has a child only if it has at least two descendants.
- Note that now we *must* store the full keys (why?)
- Saves space if there are only few bitstrings that are long.
- Could even store infinite bitstrings (e.g. real numbers)

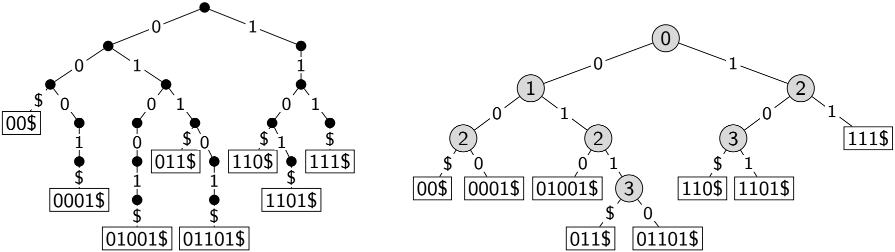


This is in practice the most efficient version of tries, but the operations get a bit more complicated.

Variation 4 of Tries

Compressed Trie: compress paths of nodes with only one child

- Each node stores an *index*, corresponding to the depth in the uncompressed trie.
  - This gives the next bit to be tested during a search
- A compressed trie with n keys has at most $n - 1$ internal nodes



Also known as **Patricia-Tries**:
P̲ractical A̲lgorithm t̲o R̲etrieve I̲nformation C̲oded i̲n A̲lphanumeric

Compressed Tries: Search

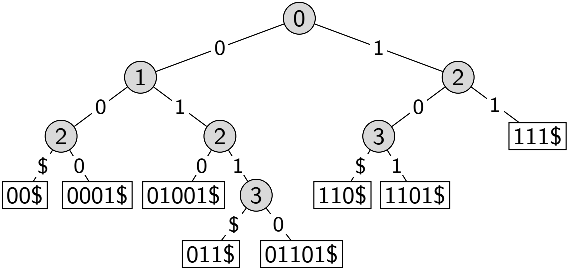
- start from the root and the bit indicated at that node
- follow the link that corresponds to the current bit in x;
  return failure if the link is missing
- if we reach a leaf, expicitly check whether word stored at leaf is x
- else recurse on the new node and the next bit of x

CompressedTrie::search($v \leftarrow$ root, x)
v: node of trie; x: word

    if v is a leaf
        return *strcmp*(x, $v.key$)
    $d \leftarrow$ index stored at v
    if x has at most d bits
        return "not found"
    $v' \leftarrow$ child of v labelled with $x[d]$
    if there is no such child
        return "not found"
    CompressedTrie::search(v', x)

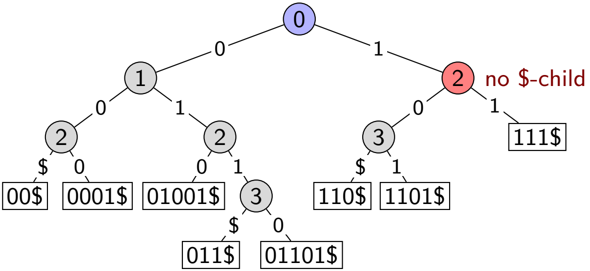
Compressed Tries: Search Example

Example: CompressedTrie::search(10$)



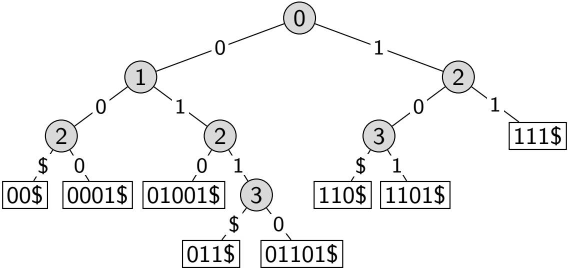
Compressed Tries: Search Example

Example: CompressedTrie::search(10$) unsuccessful



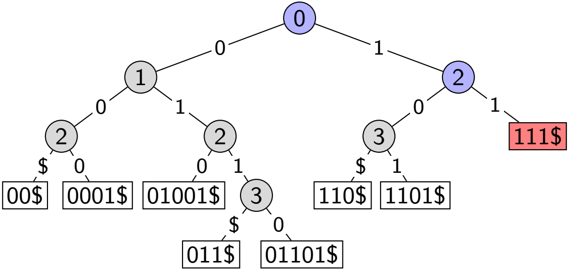
Compressed Tries: Search Example

Example: CompressedTrie::search(101$)



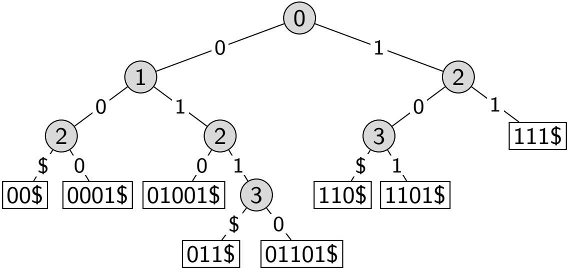
Compressed Tries: Search Example

Example: CompressedTrie::search(101$) unsuccessful



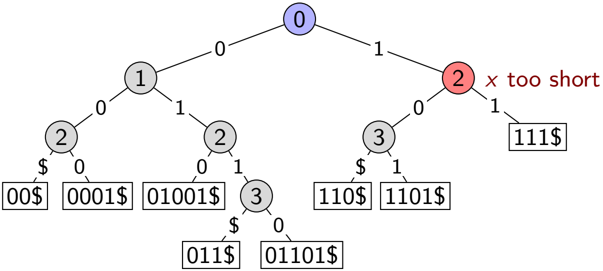
Compressed Tries: Search Example

Example: CompressedTrie::search(1$)



Compressed Tries: Search Example

Example: CompressedTrie::search(1\$) unsuccessful



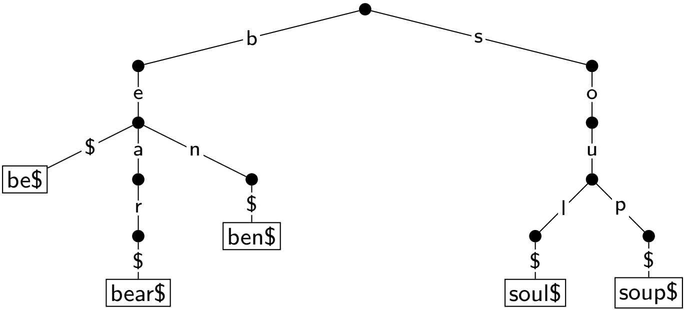
Compressed Tries: Insert & Delete

- *CompressedTrie::delete*(x):
  - Perform *search*(x)
  - Remove the node v that stored x
  - Compress along path to v whenever possible.
- *CompressedTrie::insert*(x):
  - Perform *search*(x)
  - Let v be the node where the search ended.
  - Conceptually simplest approach:
    - ★ Uncompress path from root to v.
    - ★ Insert x as in an uncompressed trie.
    - ★ Compress paths from root to v and from root to x.

    But it can also be done by only adding those nodes that are needed, see the textbook for details.
- All operations take $O(|x|)$ time.

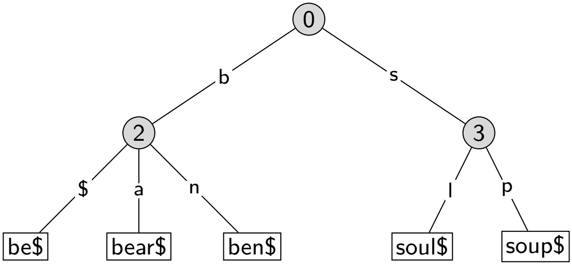
Multiway Tries: Larger Alphabet

- To represent *strings* over any *fixed alphabet* Σ
- Any node will have at most $|\Sigma| + 1$ children (one child for the end-of-word character \$)
- Example: A trie holding strings $\{$bear\$, ben\$, be\$, soul\$, soup\$$\}$



Compressed Multiway Tries

- **Variation**: Compressed multi-way tries: compress paths as before
- Example: A compressed trie holding strings {bear$, ben$, be$, soul$, soup$}



Multiway Tries: Summary

- Operations *search*(x), *insert*(x) and *delete*(x) are exactly as for tries for bitstrings.
- Run-time $O(|x| \cdot (\text{time to find the appropriate child}))$

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- Operations *search*(x), *insert*(x) and *delete*(x) are exactly as for tries for bitstrings.
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Each node now has up to $|\Sigma| + 1$ children. How should they be stored?

Solution 1: Array of size $|\Sigma| + 1$ for each node.
Complexity: $O(1)$ time to find child, $O(|\Sigma| n)$ space.

Solution 2: List of children for each node.
Complexity: $O(|\Sigma|)$ time to find child, $O(\#\text{children})$ space.

Solution 3: Dictionary (AVL-tree?) of children for each node.
Complexity: $O(\log(\#\text{children}))$ time, $O(\#\text{children})$ space.
Best in theory, but not worth it in practice unless $|\Sigma|$ is huge.

In practice, use *hashing* (keys are in (typically small) range Σ).