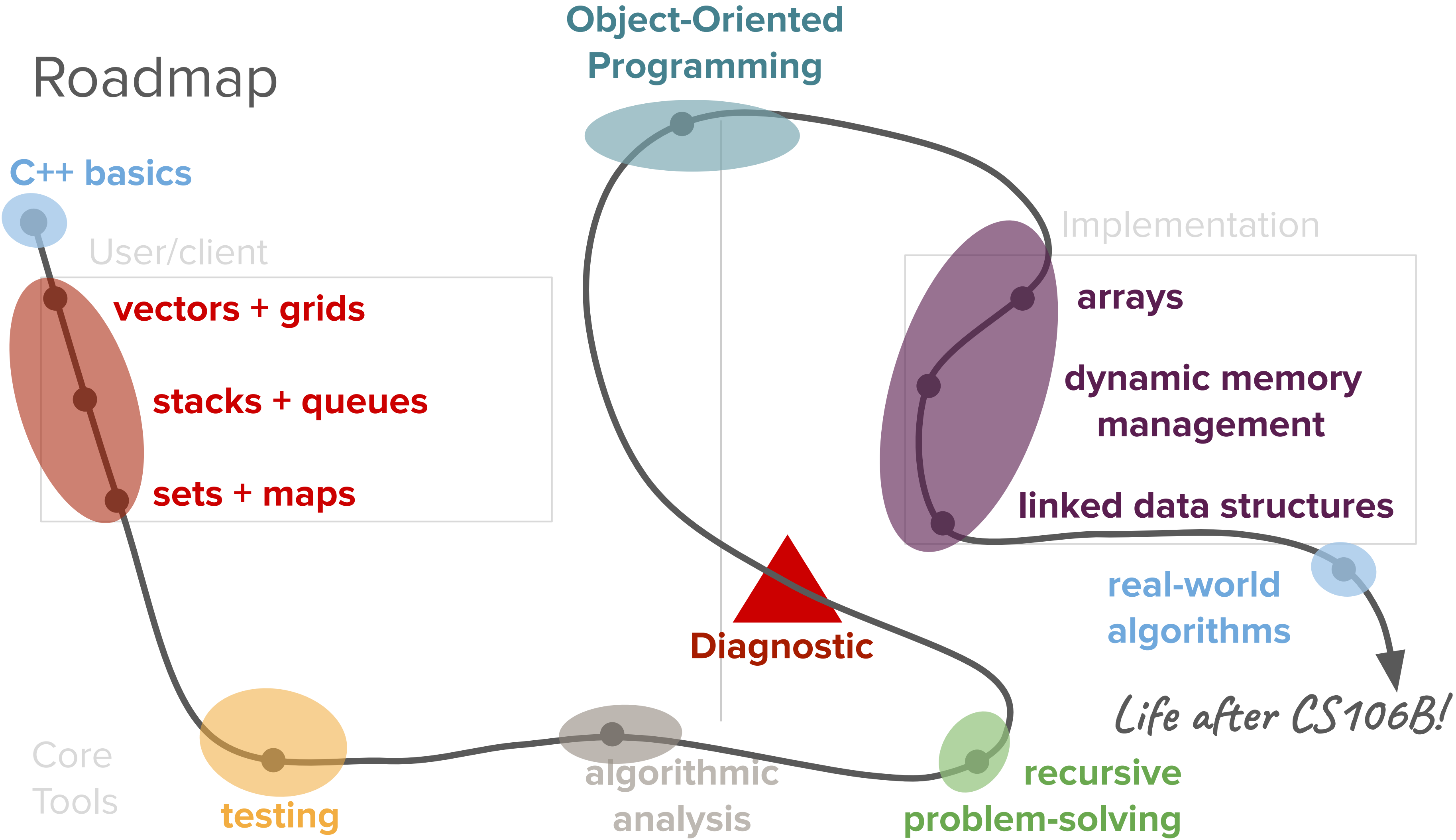
Using Abstractions: Breadth-First Search

What new data structures have you recently noticed in your day-to-day life?

(put your answers the chat)

Roadmap


Object-Oriented Programming
C++ basics
User/client
vectors + grids
stacks + queues
sets + maps
Implementation
arrays
dynamic memory management
linked data structures
real-world algorithms
Diagnostic
Life after CS106B!
Core Tools
testing
algorithmic analysis
recursive problem-solving

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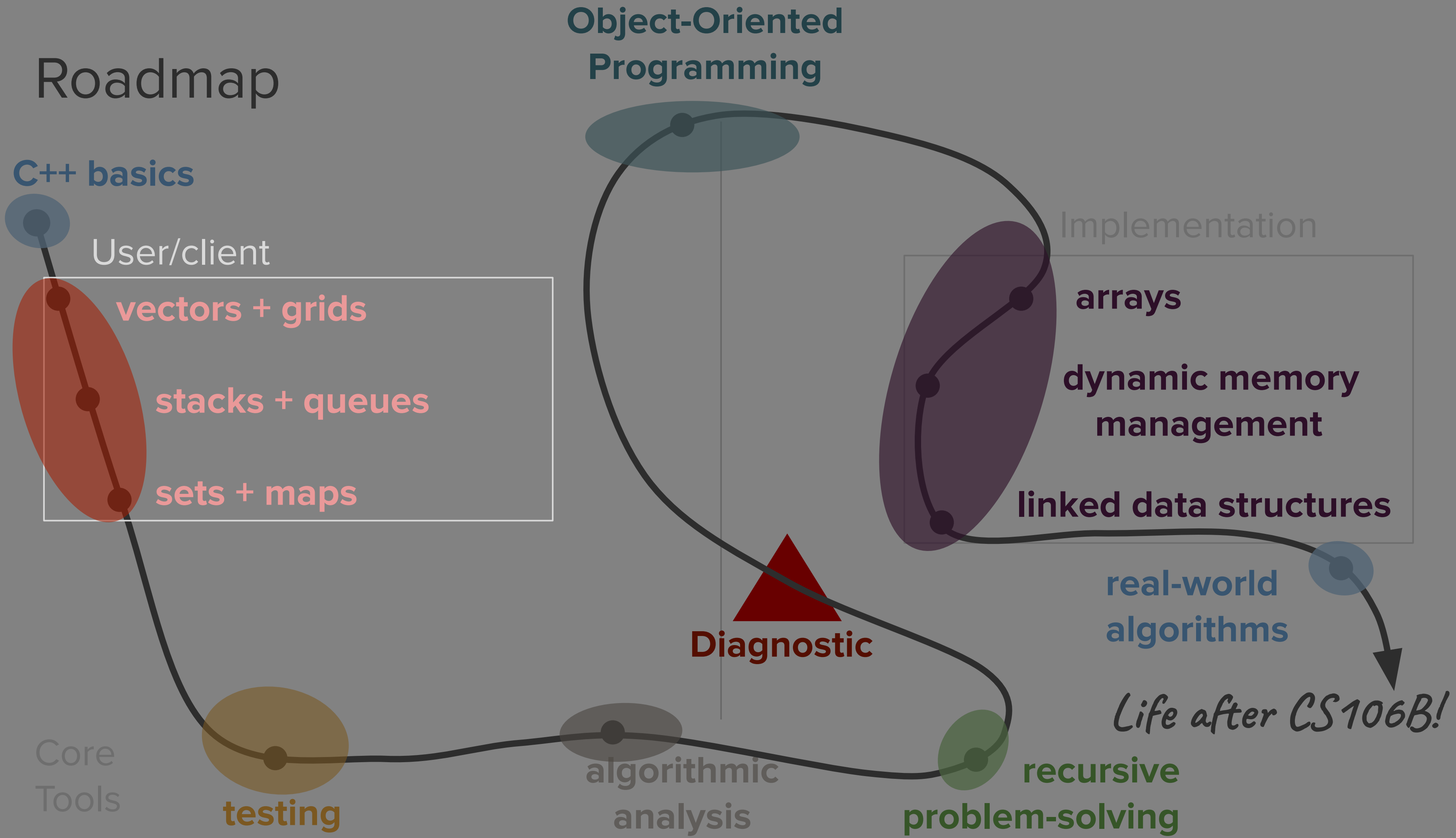
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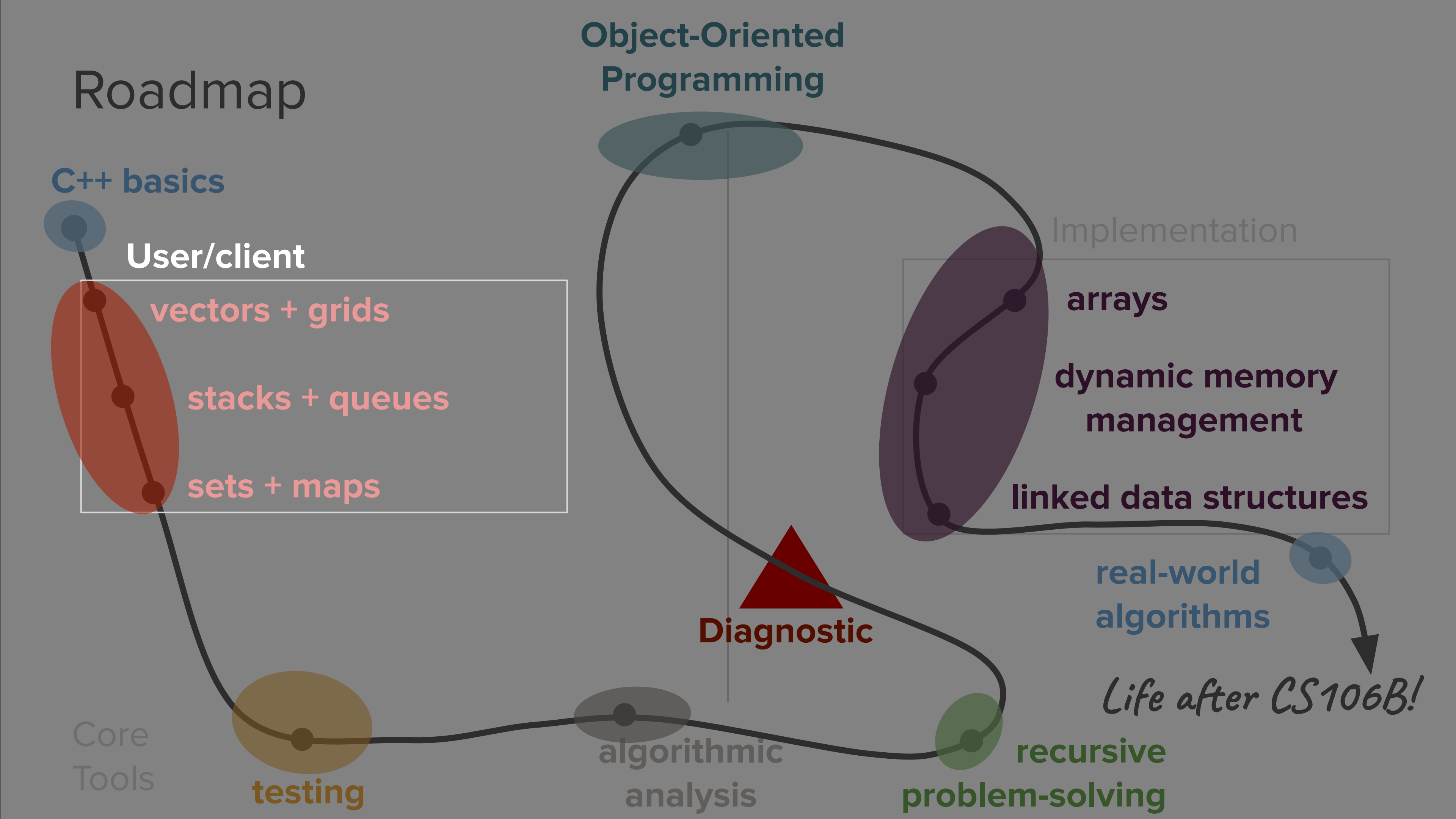
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Today's question

How can we use the unique properties of different abstractions to solve problems?

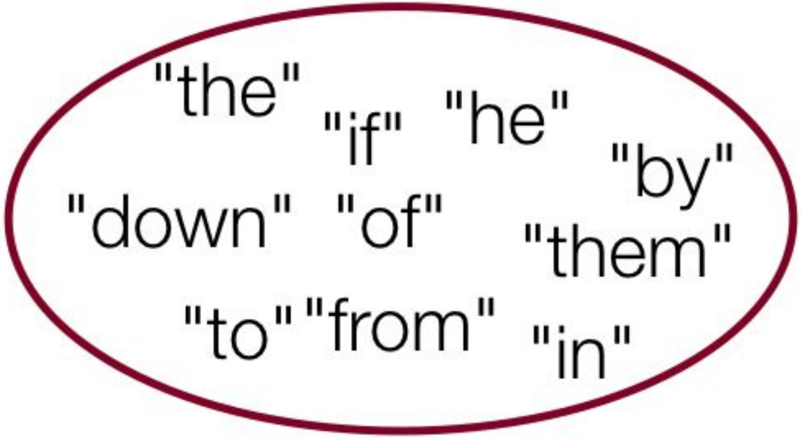
Today's topics

1. Review
2. Implementing Breadth-First Search
3. Nested Data Structures (time-permitting)

Review

(sets and maps)

What is a set?

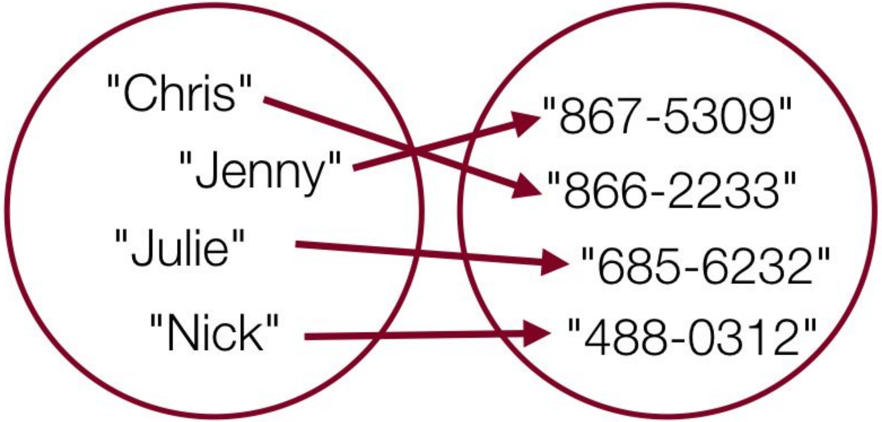


- A set is a collection of elements with no duplicates.

- Sets are faster than ordered data structures like vectors – since there are no duplicates, it's faster for them to find things.
  - (Later in the quarter we'll learn about the details of the underlying implementation that makes this abstraction efficient.)
  - We'll formally define "faster" on Thursday.

- Sets don't have indices!

What is a map?



- A map is a collection of key/value pairs, and the key is used to quickly find the value.

- Other terms you may hear for a map are dictionary (Python) or associative array.

- A map is an alternative to an ordered data structure, where the “indices” no longer need to be integers.

Ordered ADTs

Elements accessible by indices:

- Vectors (1D)
- Grids (2D)

Elements not accessible by indices:

- Queues (FIFO)
- Stacks (LIFO)

Unordered ADTs

- Sets (elements unique)
- Keys (keys unique)

Useful when numerical ordering of data isn't optimal

Activity:
`Counting Sort`

Counting Sort

- Sorting is a fundamental topic in computer science and one that we will revisit in more depth later this quarter

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  - How can we take advantage of some of the data structures we've recently learned about to meaningfully structure the data that we want to sort?

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  - How can we take advantage of some of the data structures we've recently learned about to meaningfully structure the data that we want to sort?

- Idea: If we can tally up how many times each of the letters from 'a' to 'z' shows up, we can then build a new string composed of the correct number of 'a's, followed by the correct number of 'b's, ... etc.

Counting Sort Example

Counting Sort Example

b	**a**	**n**	**a**	**n**	**a**

Example and slides taken from a slide deck by Keith Schwarz

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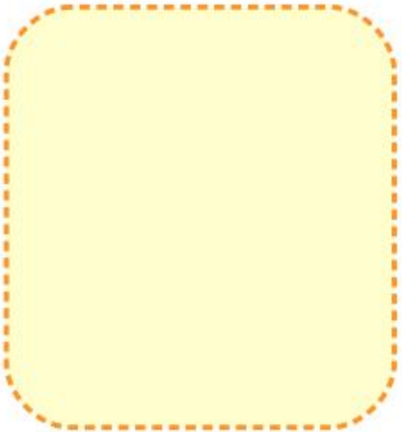

letterFreq

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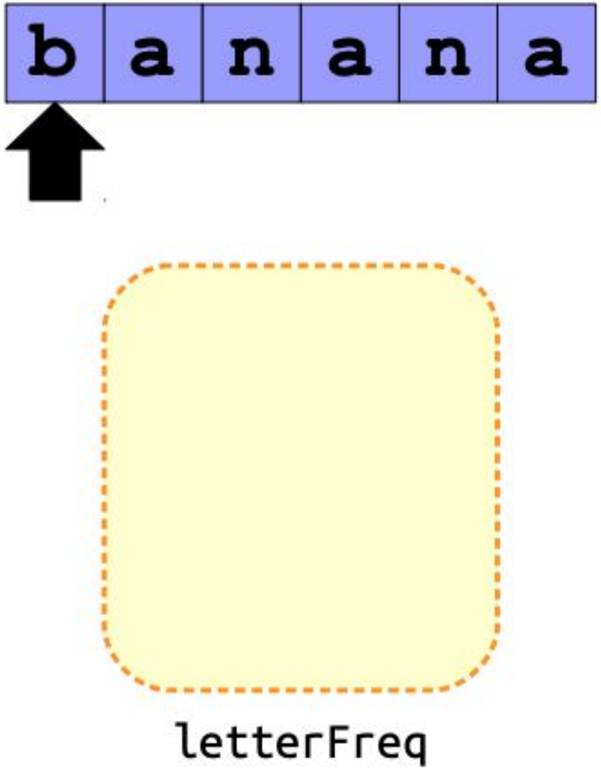

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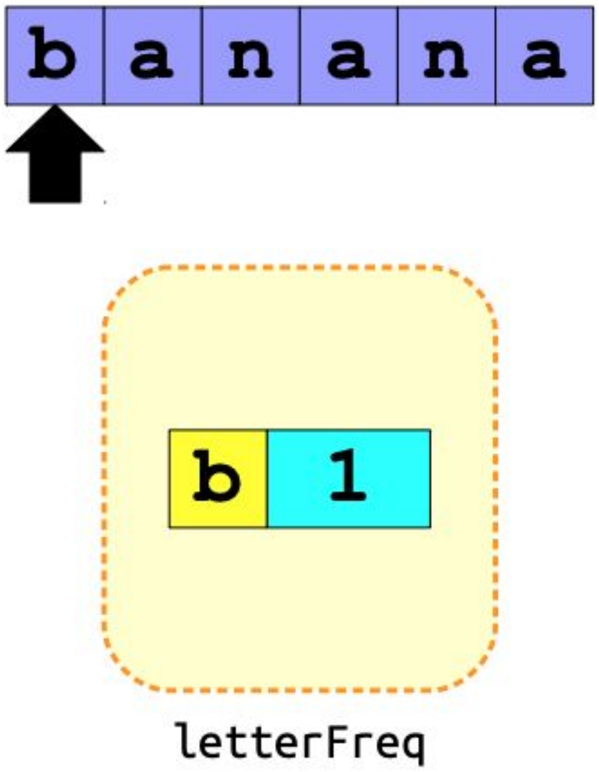

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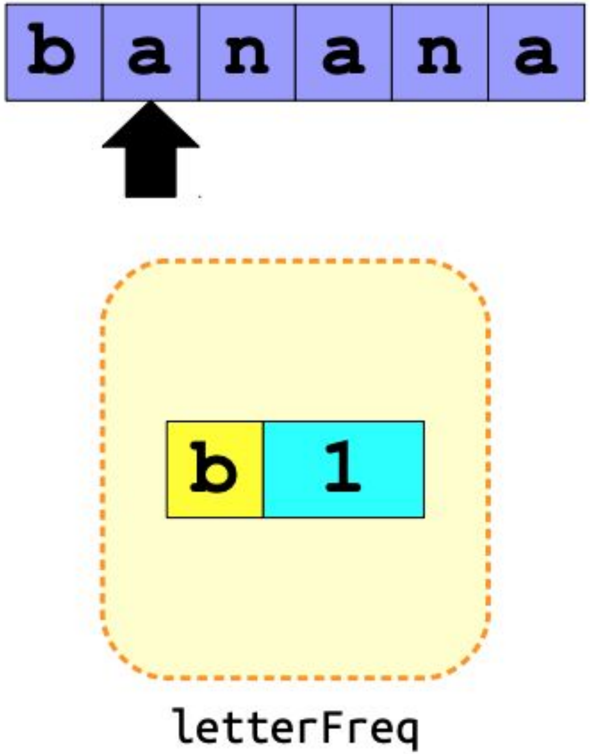

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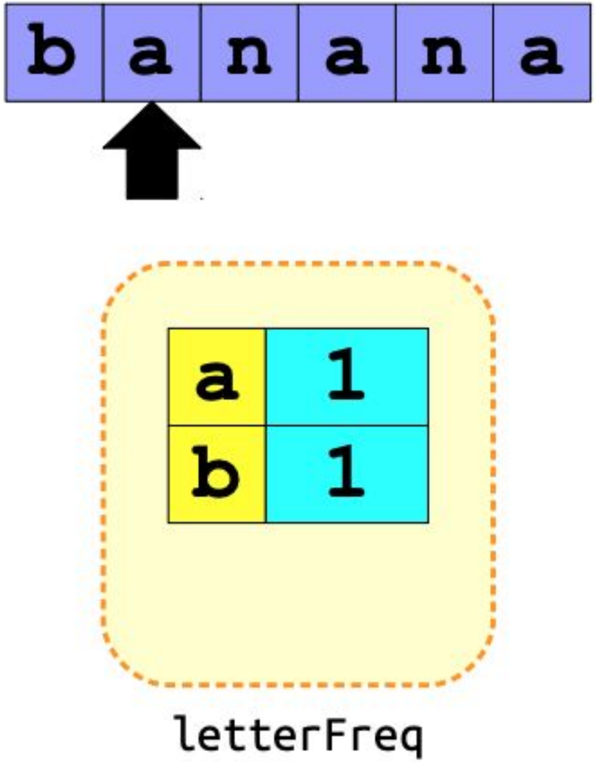

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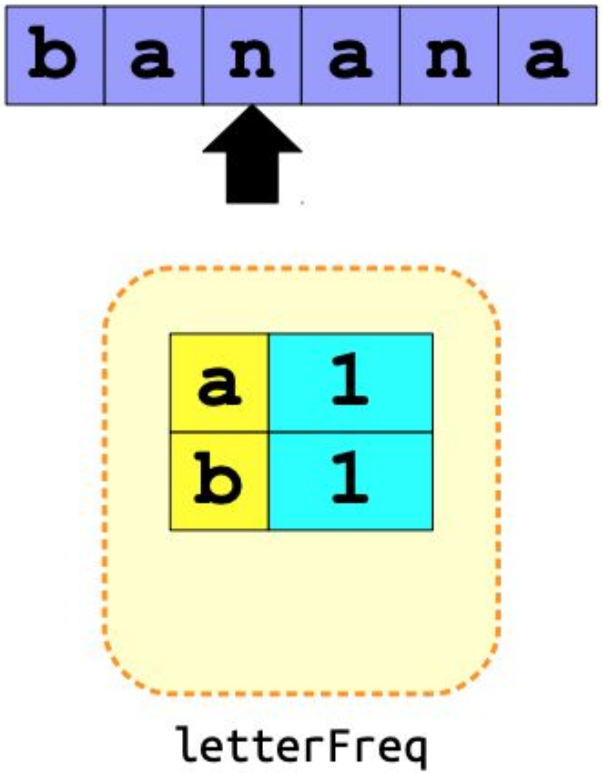

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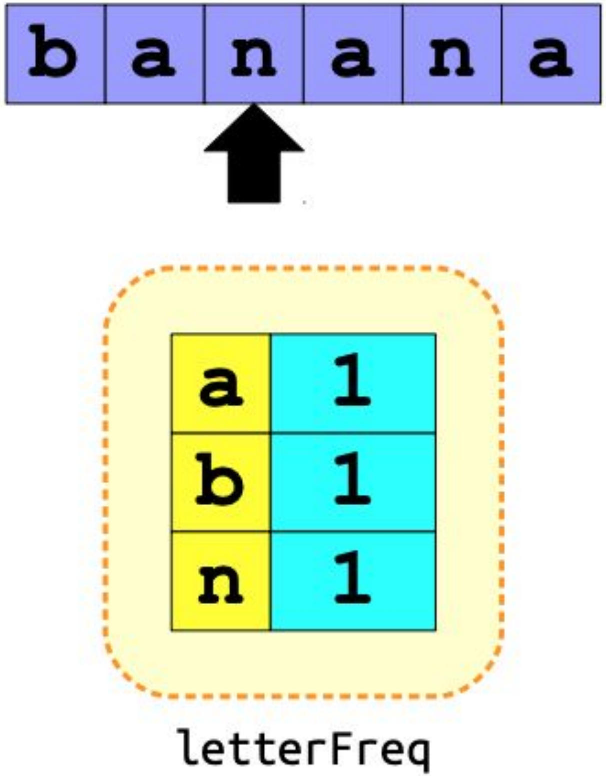

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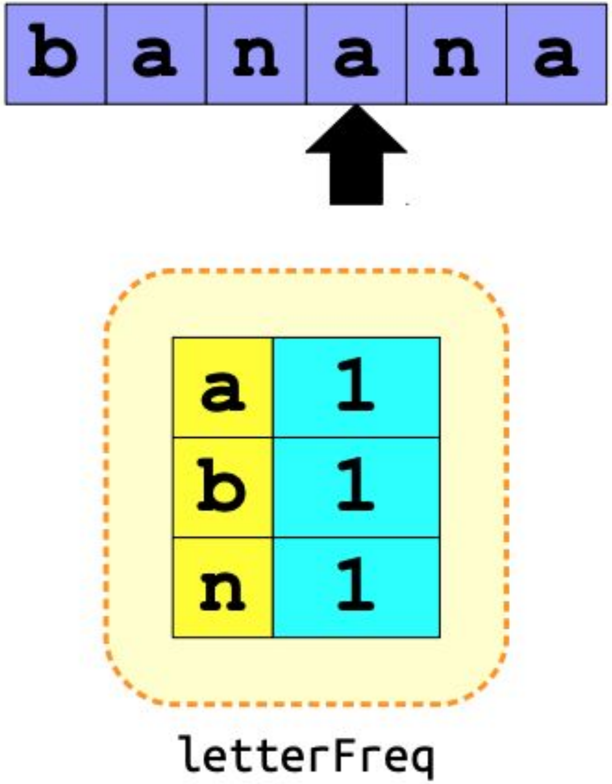

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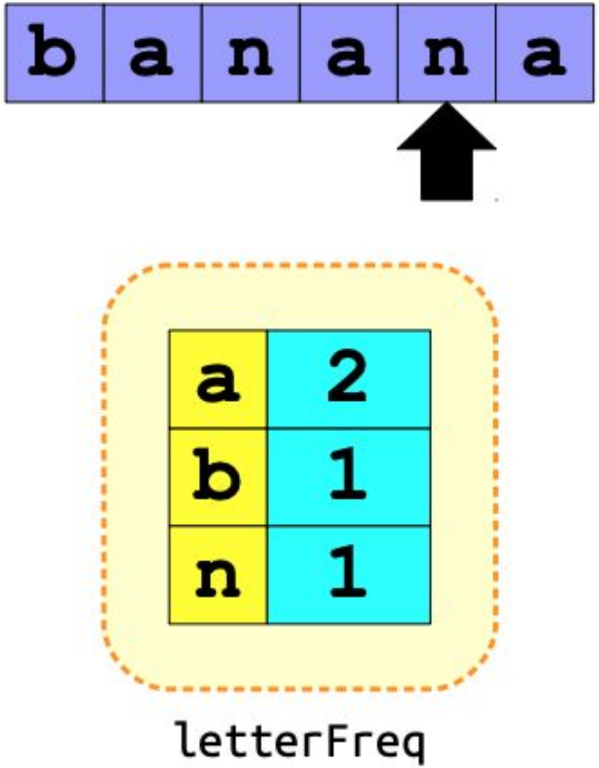

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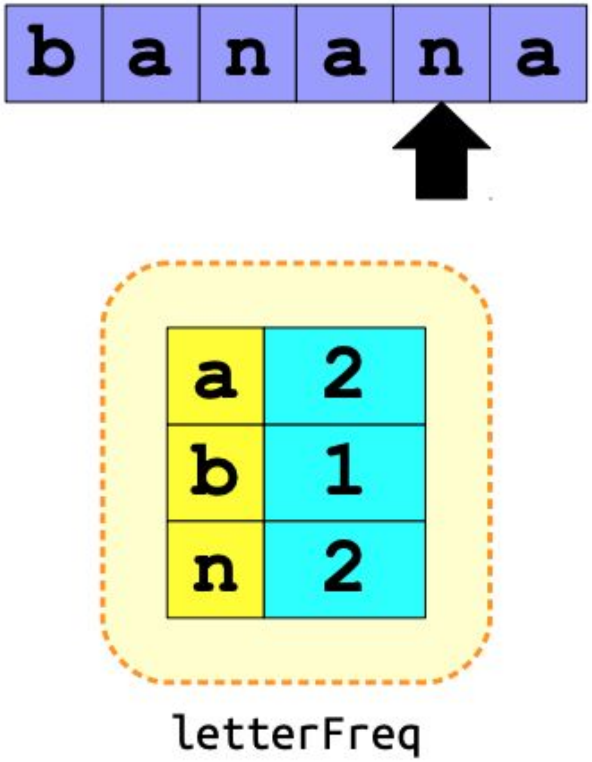

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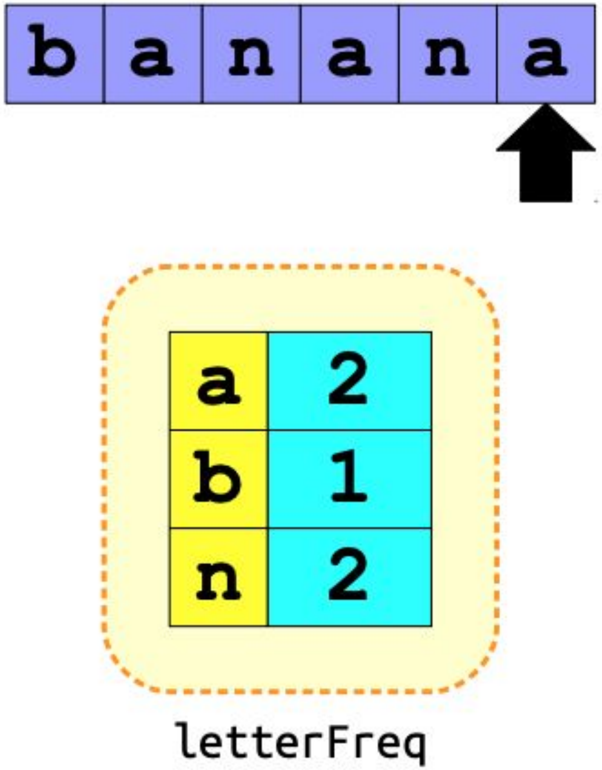

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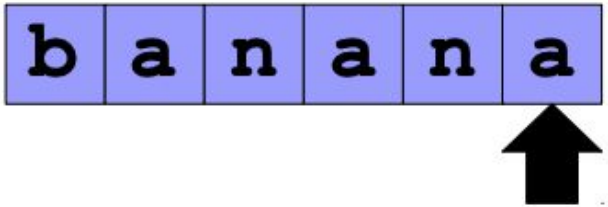

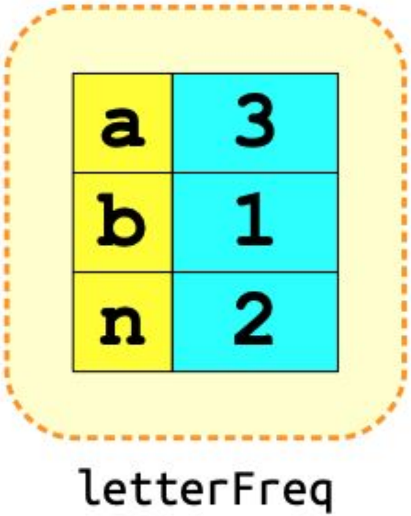

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Counting Sort Example

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a	3
b	1
n	2

letterFreq

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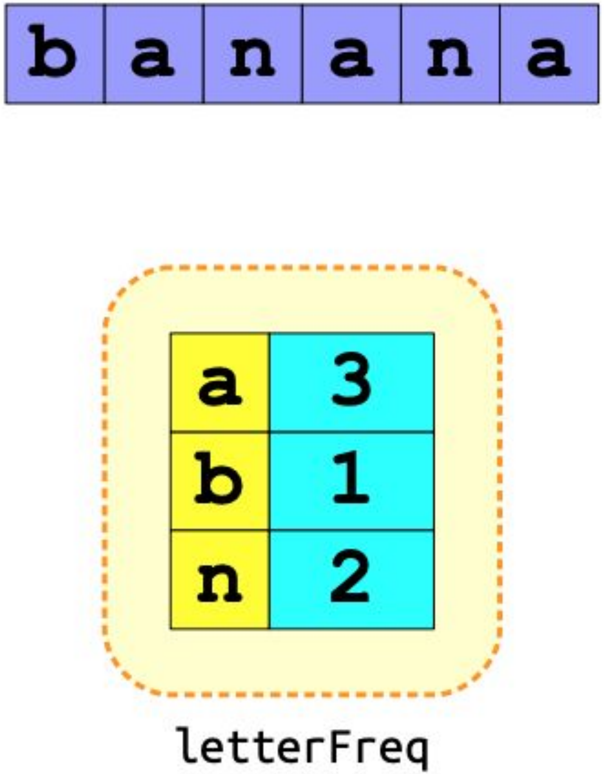

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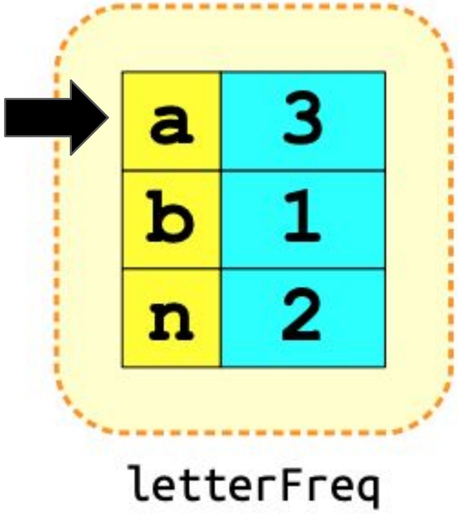

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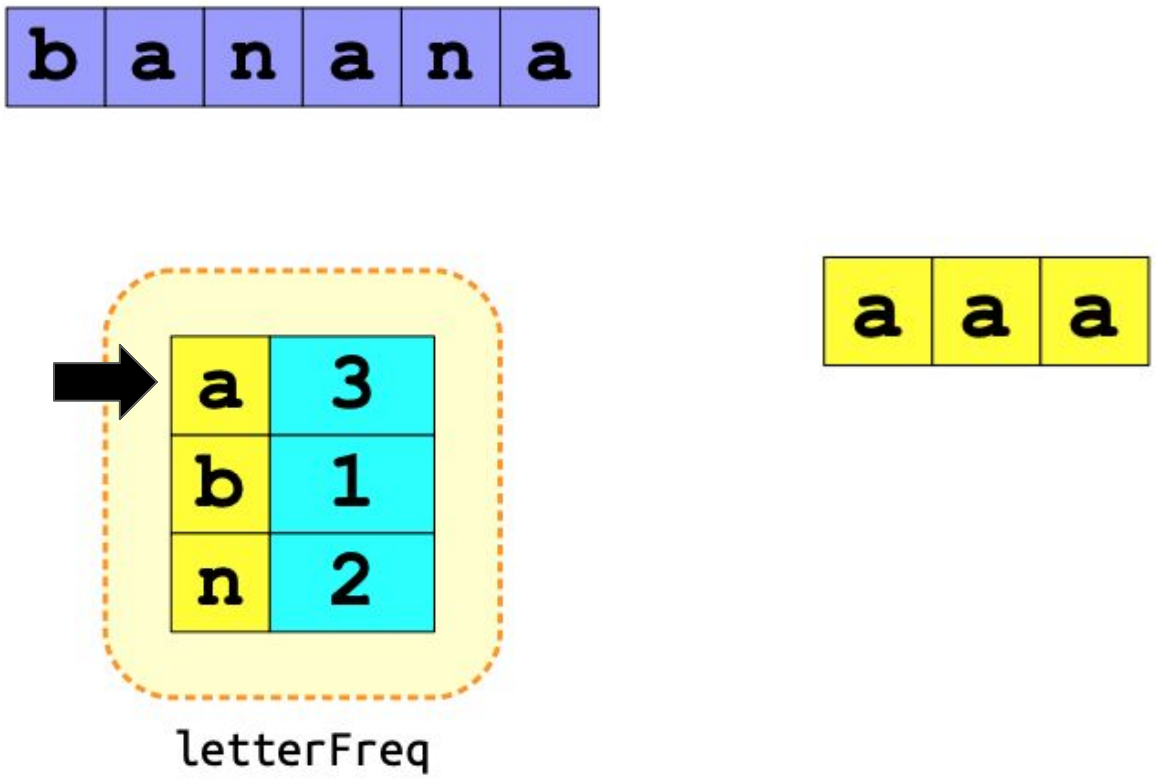

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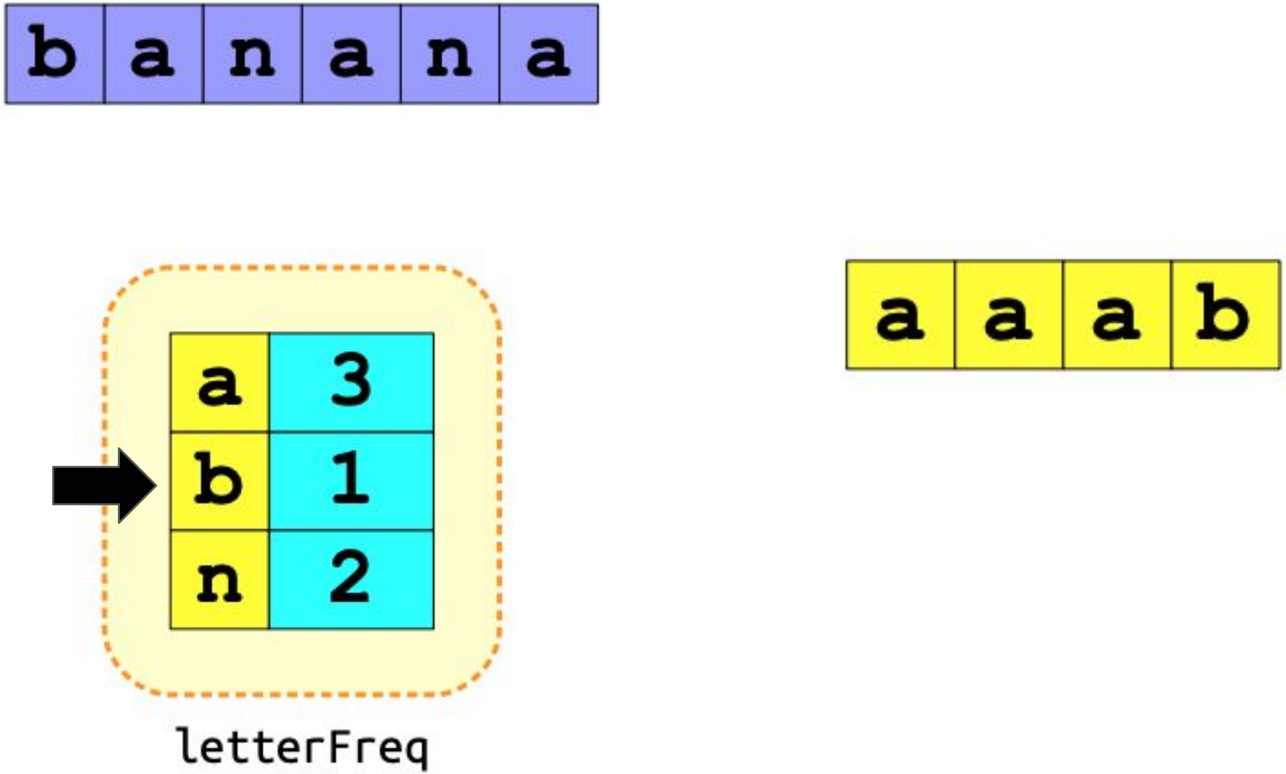

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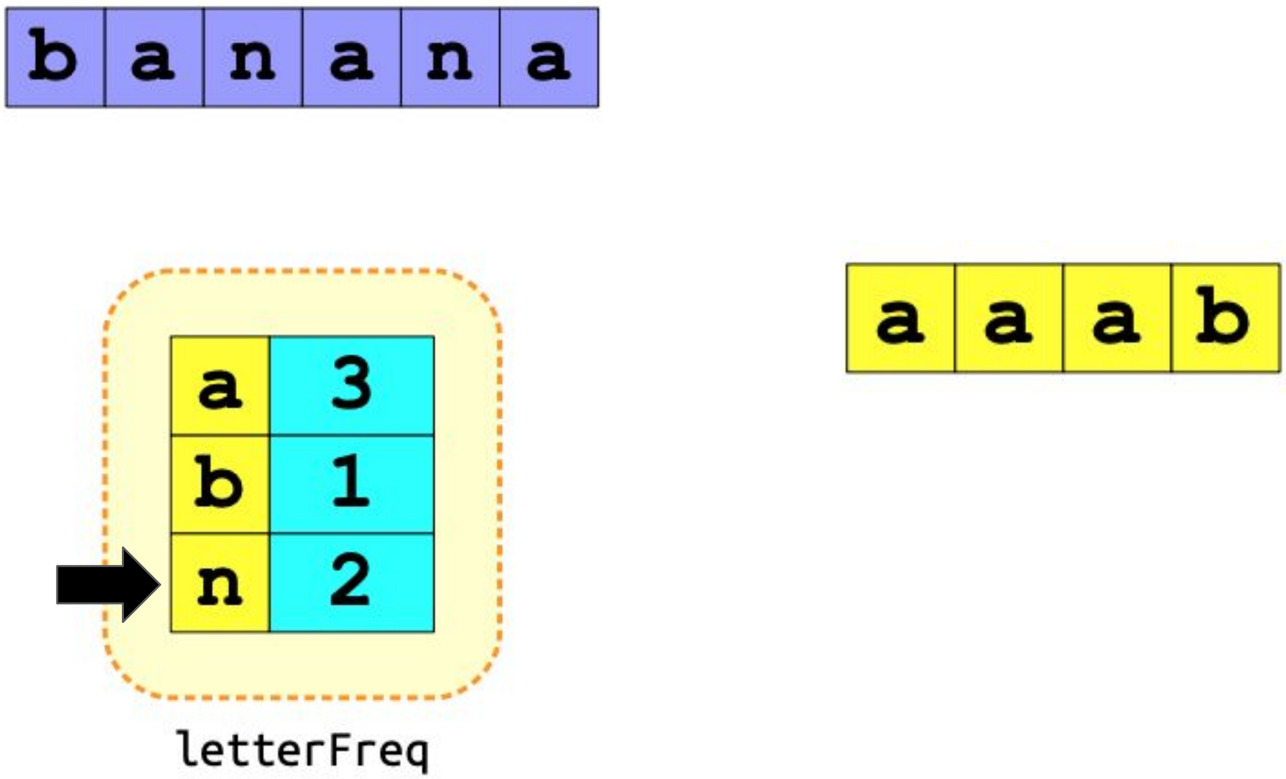

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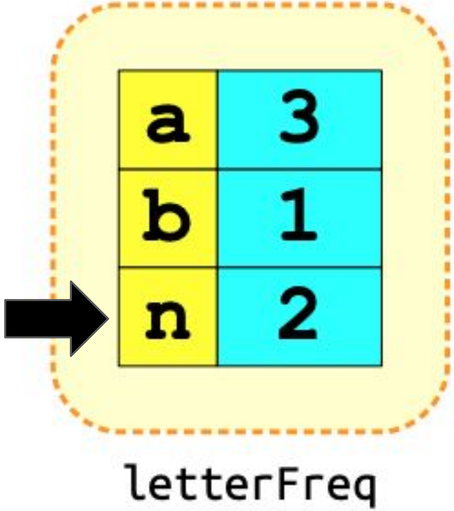

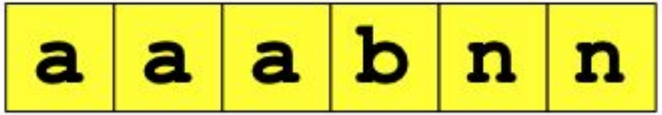

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Counting Sort Example

b	a	n	a	n	a

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letterFreq

a	a	a	b	n	n

Mission Accomplished!

Counting Sort Pseudocode

- Loop over the word and build a frequency map of all letters that appear in the original string
- Loop through all letters from 'a' to 'z' and build up a new string with the right amount of each letter
- Return the newly generated string

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Provided Code

```
string countingSort(string s) {
    Map<char, int> freqMap;
    for (char ch: s) {
        freqMap[ch] = freqMap[ch] + 1;
    }

    string sortedString;
    for (char ch = 'a'; ch <= 'z'; ch++) {

    }
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Activity: Write pseudocode to complete the algorithm

[breakout rooms + Ed workspaces]

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Challenge for home: What other types of data could you efficiently sort in this manner?

Counting Sort Code

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        // taking advantage of map auto-insertion!
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    for (char ch = 'a'; ch <= 'z'; ch++) {
        if (freqMap.containsKey(ch)) {
            for (int i = 0; i < freqMap[ch]; i++) {
                sortedString += charToString(ch);
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This check isn't strictly required, but it does avoid unnecessary things being added to the map via auto-insertion

How can we use the unique properties of different abstractions to solve problems?

Examples of interesting problems to solve using ADTs

- Simulate potential impacts of flooding on a topographical landscape (how does water flow outwards from a source and settle into the surrounding areas)
- Generate simulated text in the style of a certain author. Similarly, do textual analysis to determine who the author of a provided piece of text was.
- Spell check and autocomplete for a word document editor
- Manage information about the natural landmarks and state parks in California to help tourists plan their trip to the state
- Develop a ticketing management system for Stanford Stadium
- Aggregate and analyze reviews for an online shopping website
- Solve fun puzzles

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Word Ladders

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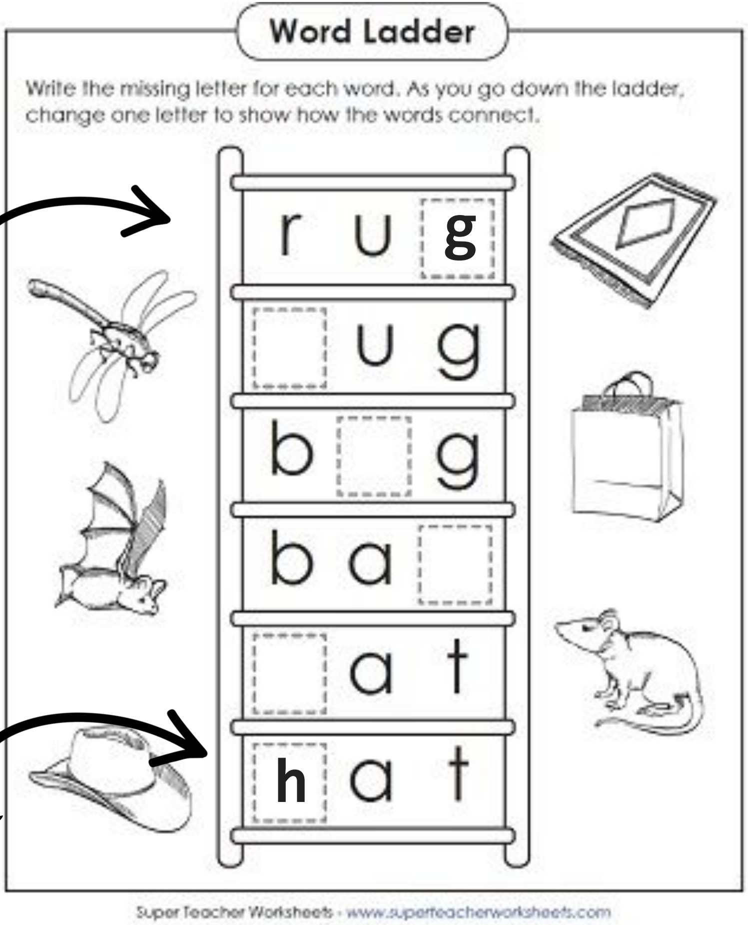

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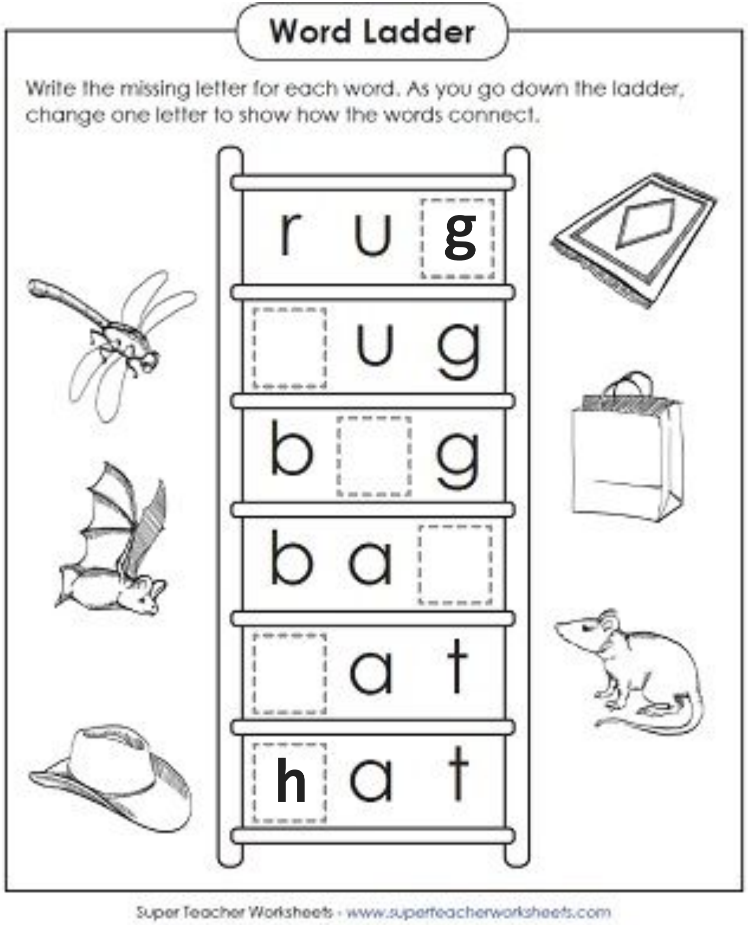

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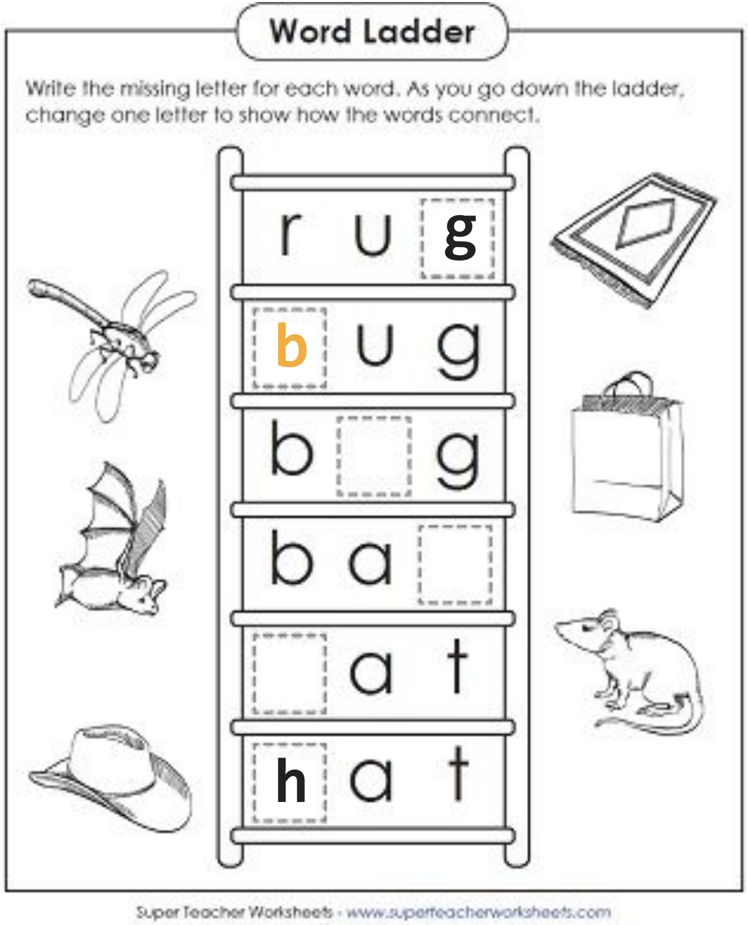

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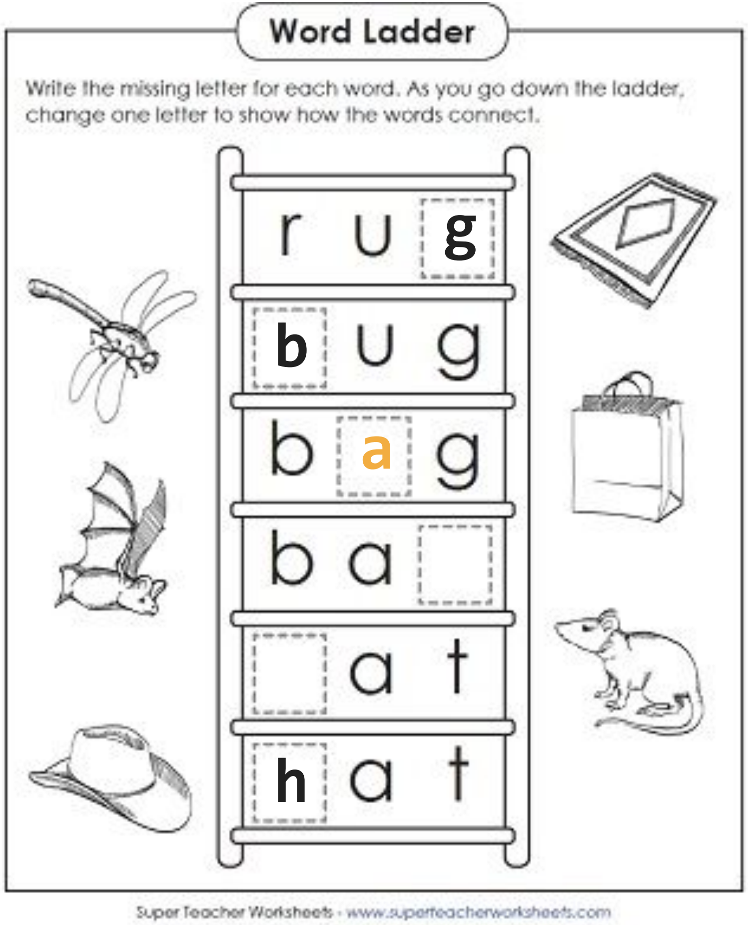

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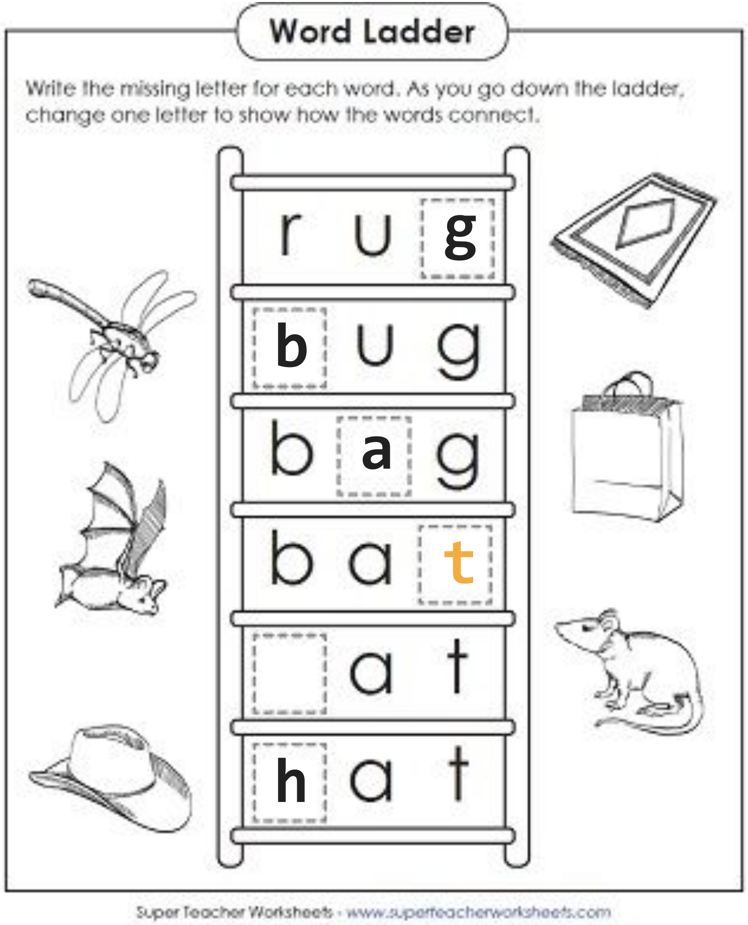

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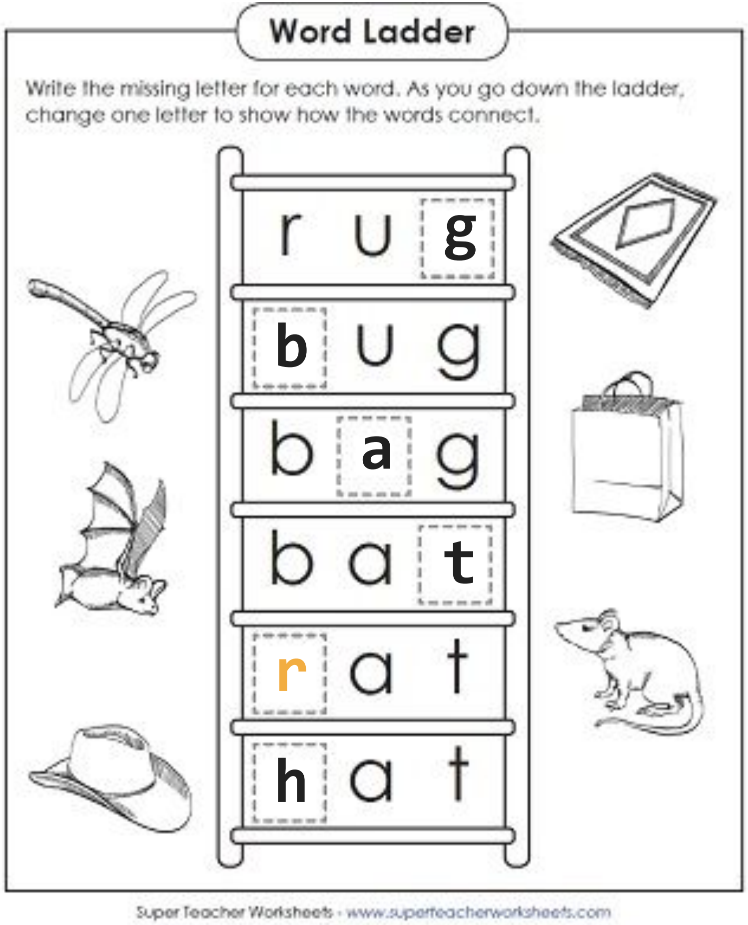

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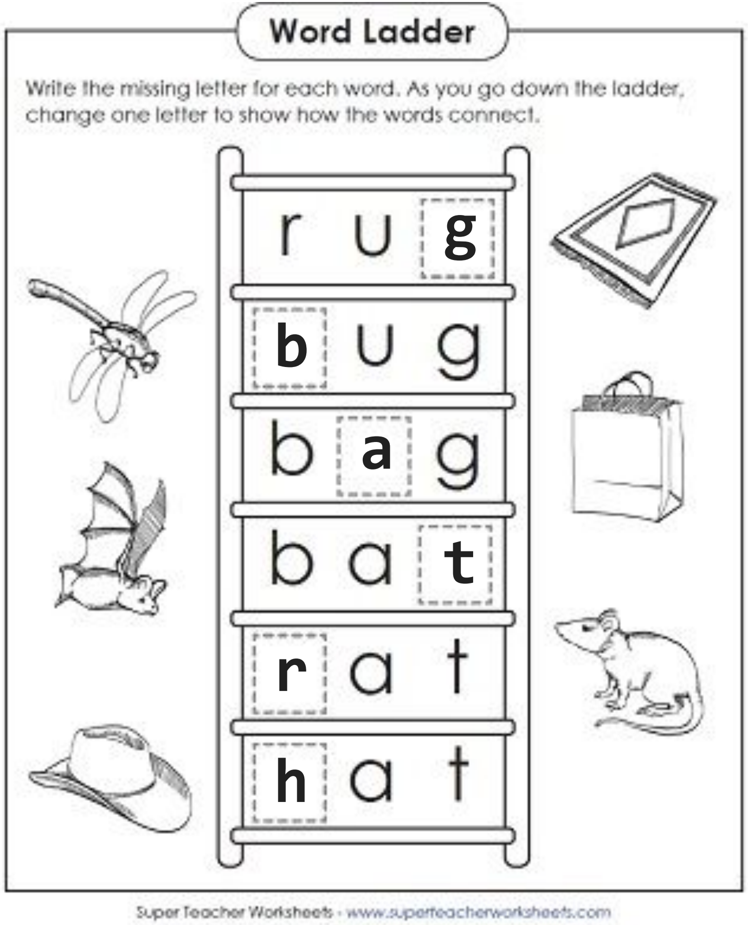

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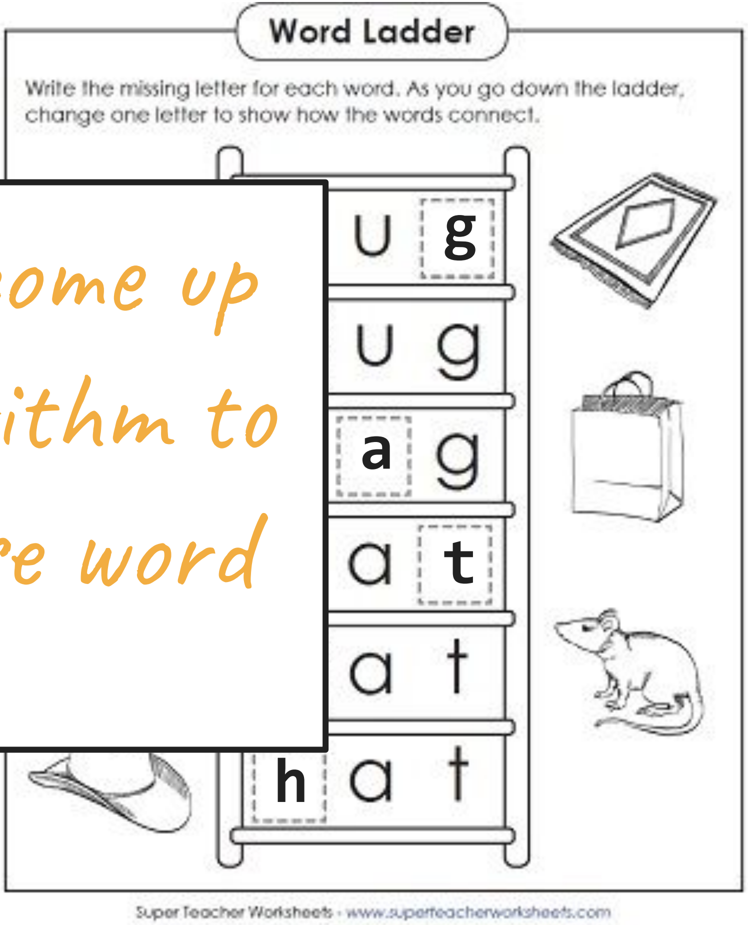
How can we come up with an algorithm to generate these word ladders?



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  - From there, make another educated guess about which letter to change and modify that letter
  - Keep repeating this process until you reach the target word (unlikely) or hit a dead end (likely)
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  - If you hit a dead end, start over again, taking a different first step
- What are the issues with this approach?
  - Requires intuition – does a computer have intuition?
  - Unorganized – no organized strategy for the exploration
  - No guarantee that you'll ever find a solution!

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- **Important observation: In order to keep our search organized, we first explore all word ladders of "length" 1 before we explore any word ladders of "length" 2, and so on.**

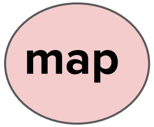
BFS Example

Breadth-First Search Example

- Let's try to apply this approach to find a word ladder starting at the word "map" and ending at the word "way"

Breadth-First Search Example

start: map
destination: way



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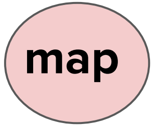

0 steps away

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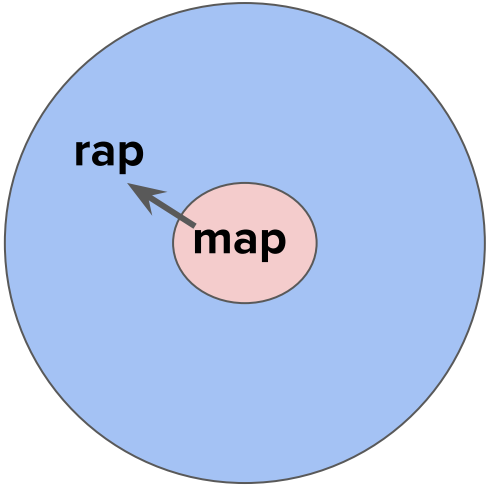

0 steps away
1 step away

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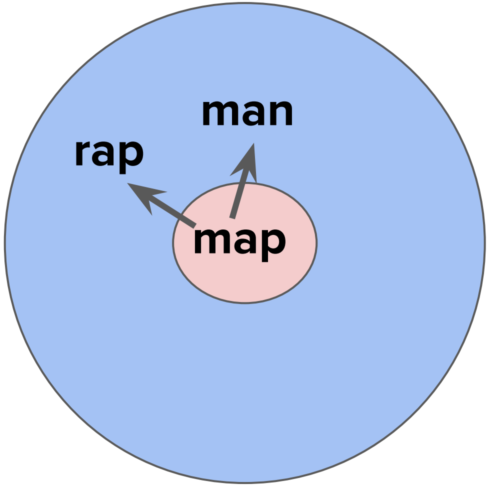

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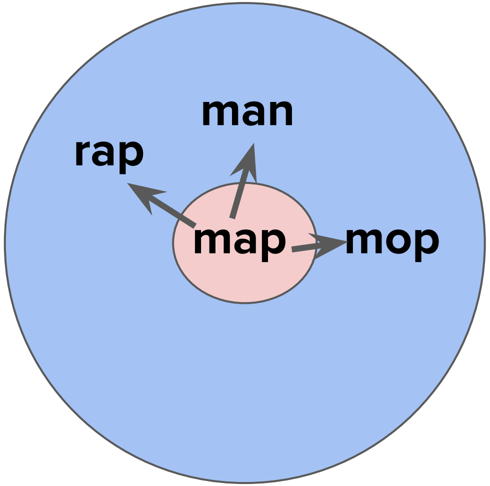
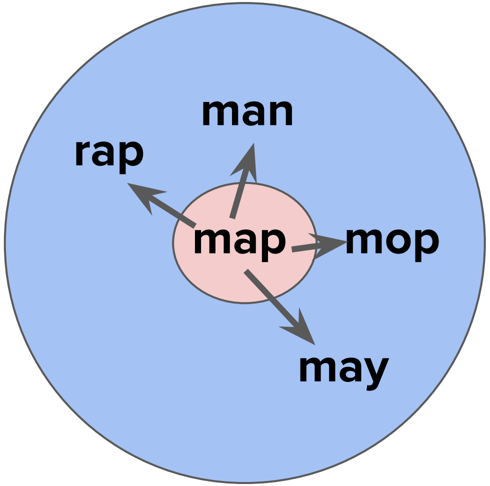
start: map
destination: way



0 steps away
1 step away

Breadth-First Search Example

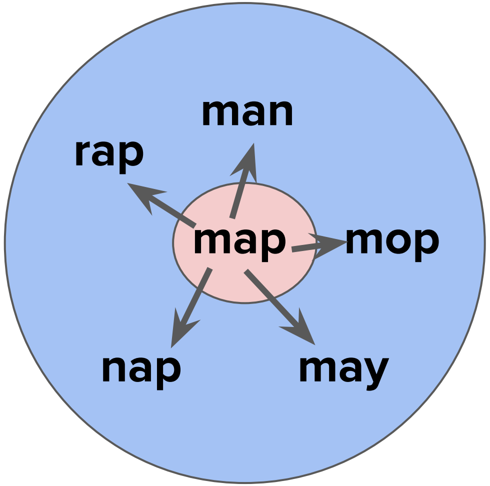
start: map
destination: way



0 steps away
1 step away

Breadth-First Search Example

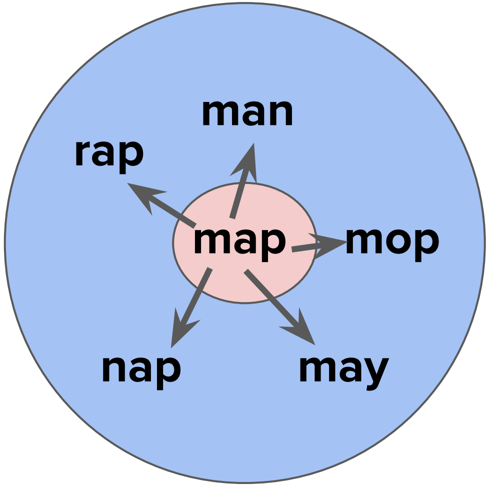
start: map
destination: way



0 steps away
1 step away

Breadth-First Search Example

start: map
destination: way

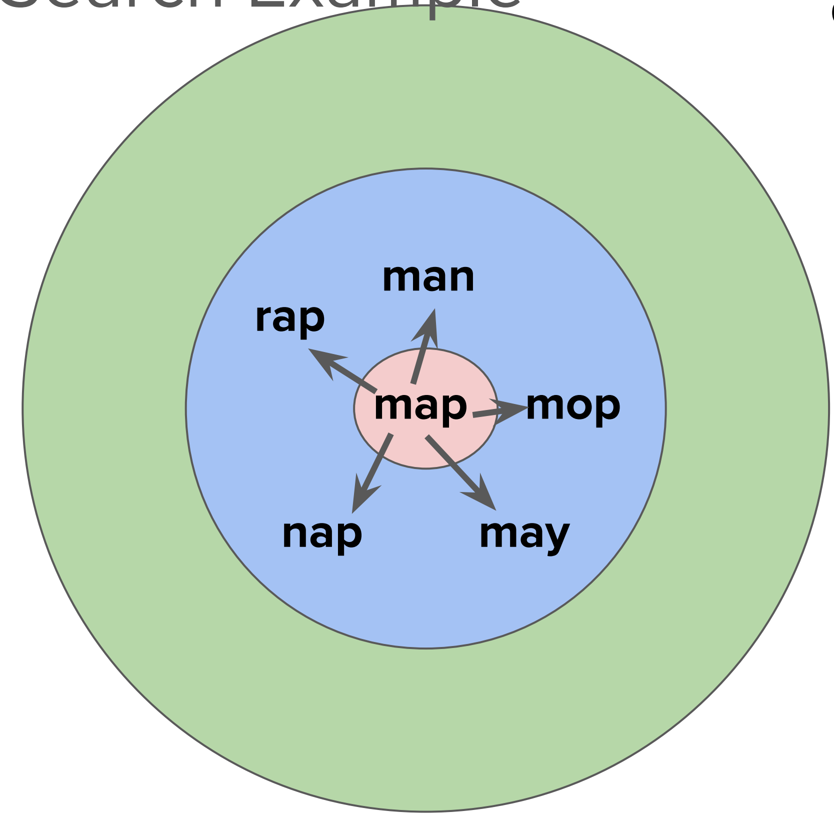


0 steps away
1 step away

Note: For the sake of brevity/demonstration, we will not enumerate all possible words that are 1 step away

Breadth-First Search Example

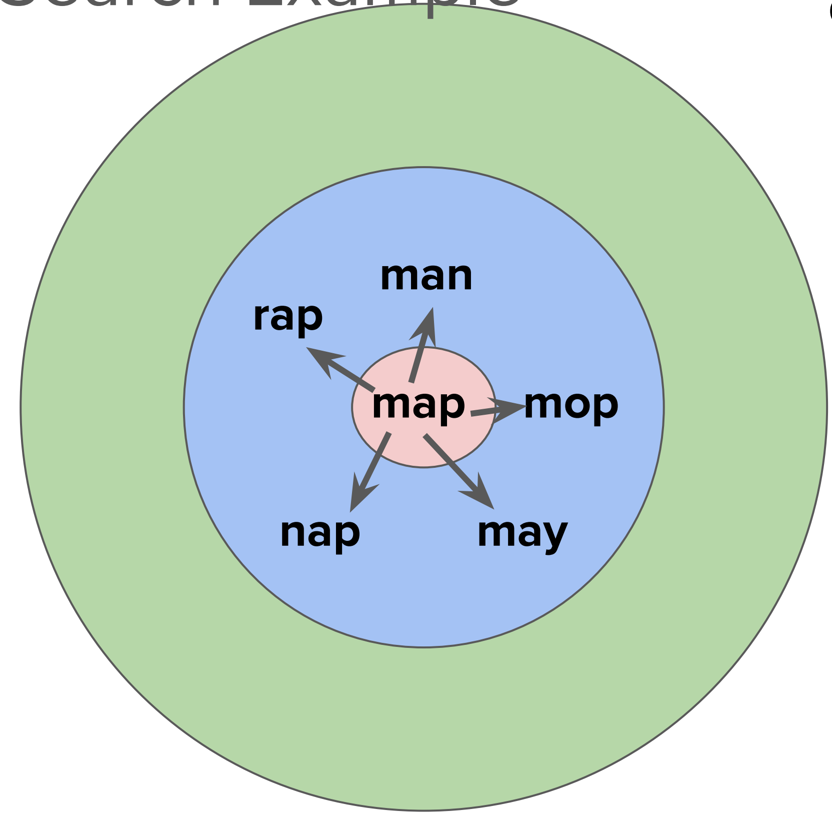
start: map
destination: way



0 steps away
1 step away

Breadth-First Search Example

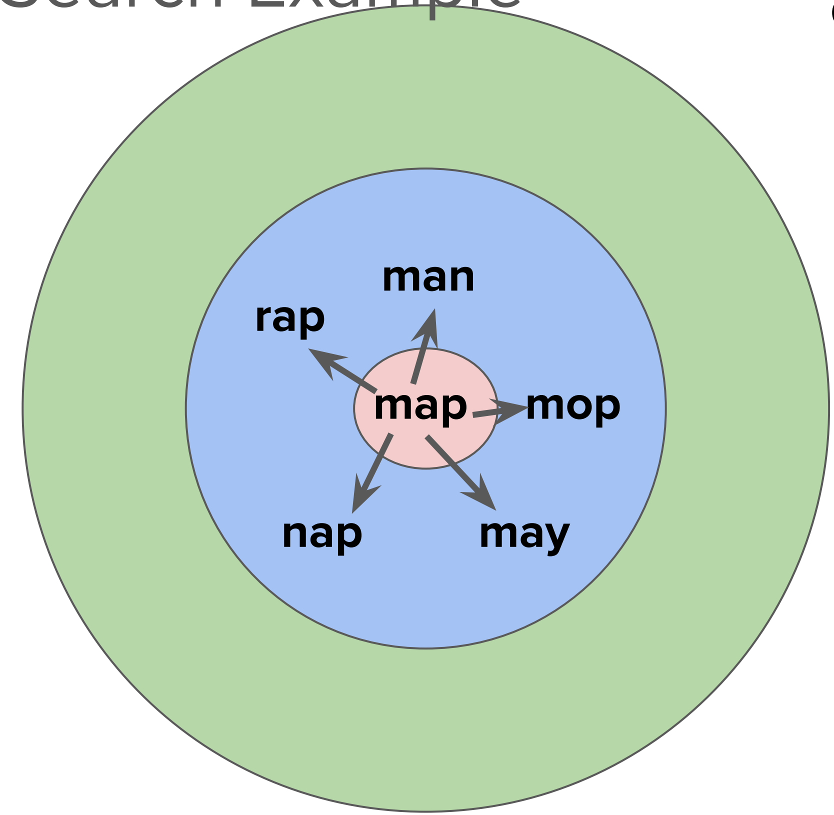
start: map
destination: way



0 steps away
1 step away
2 steps away

Breadth-First Search Example

start: map
destination: way

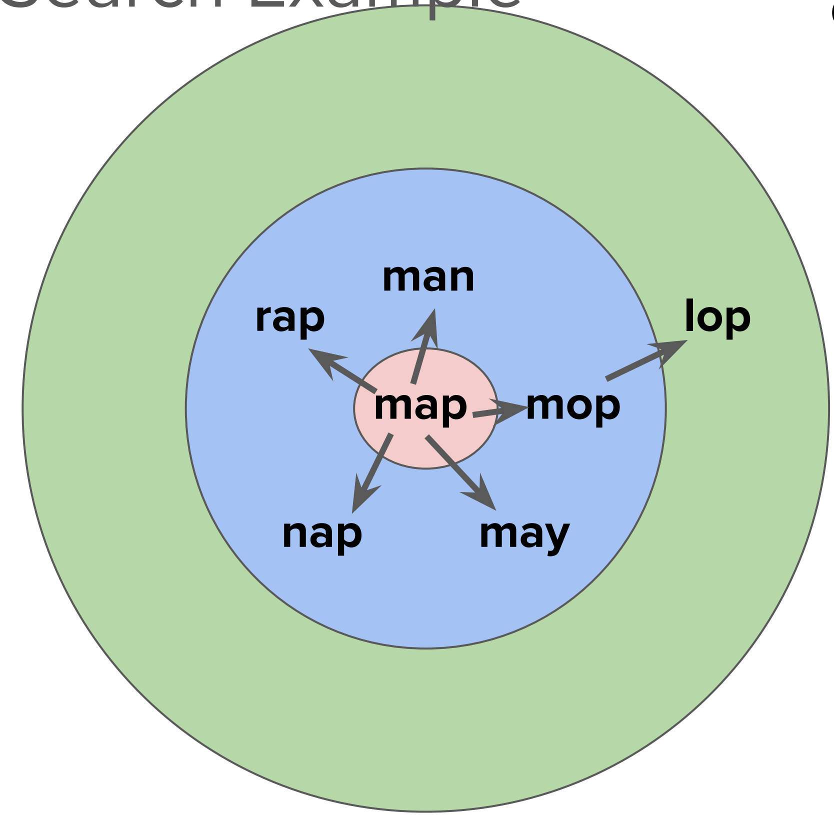


Observation: 2 steps away from "map" is really just 1 step away from any of its neighbors

0 steps away
1 step away
2 steps away

Breadth-First Search Example

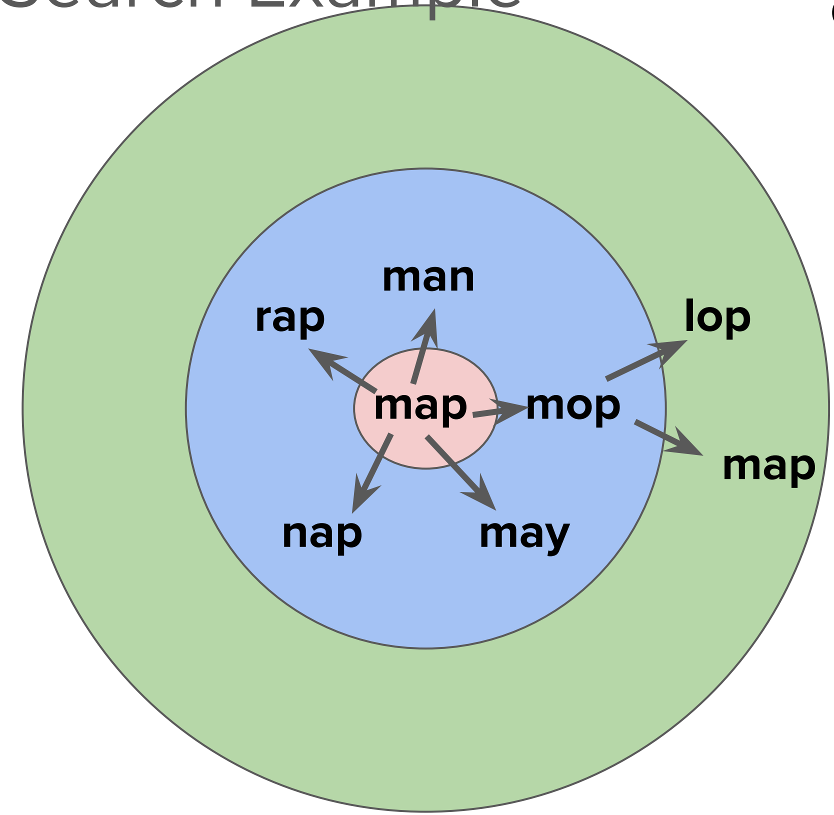
start: map
destination: way



0 steps away
1 step away
2 steps away

Breadth-First Search Example

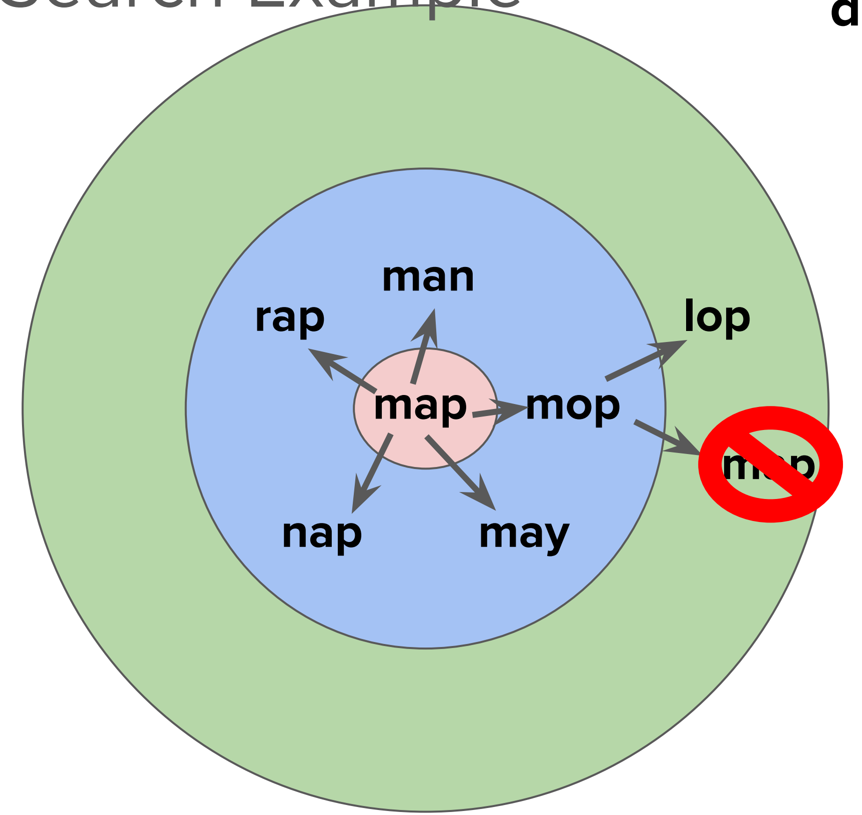
start: map
destination: way



0 steps away
1 step away
2 steps away

Breadth-First Search Example

start: map
destination: way

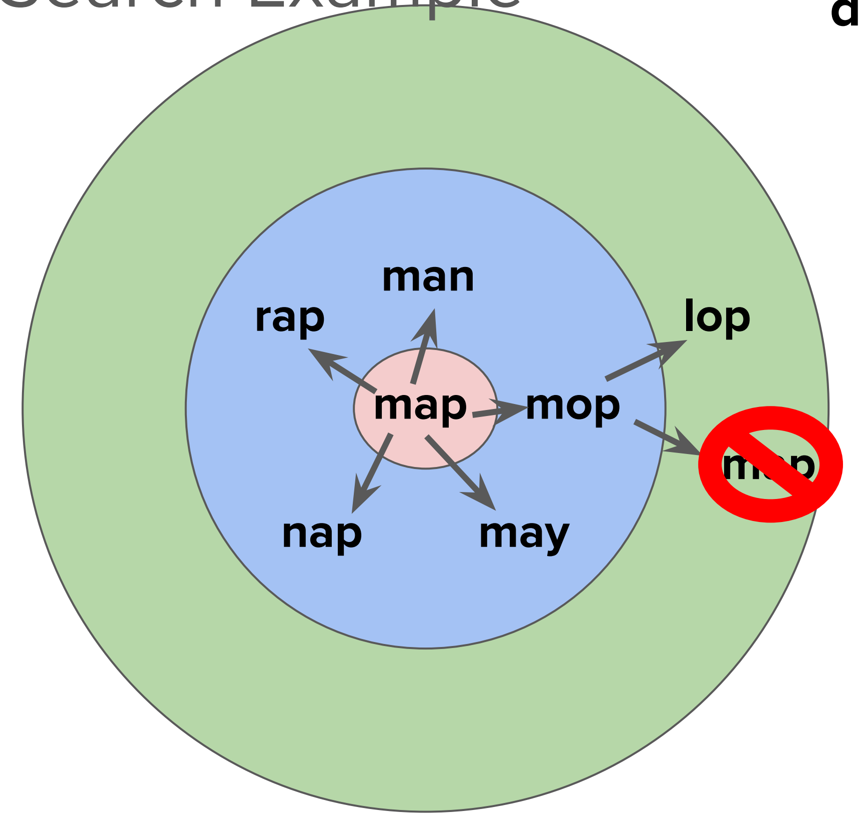


Visiting a word we've already been at before is basically like going backwards in our search. We want to avoid this at all costs!

0 steps away
1 step away
2 steps away

Breadth-First Search Example

start: map
destination: way

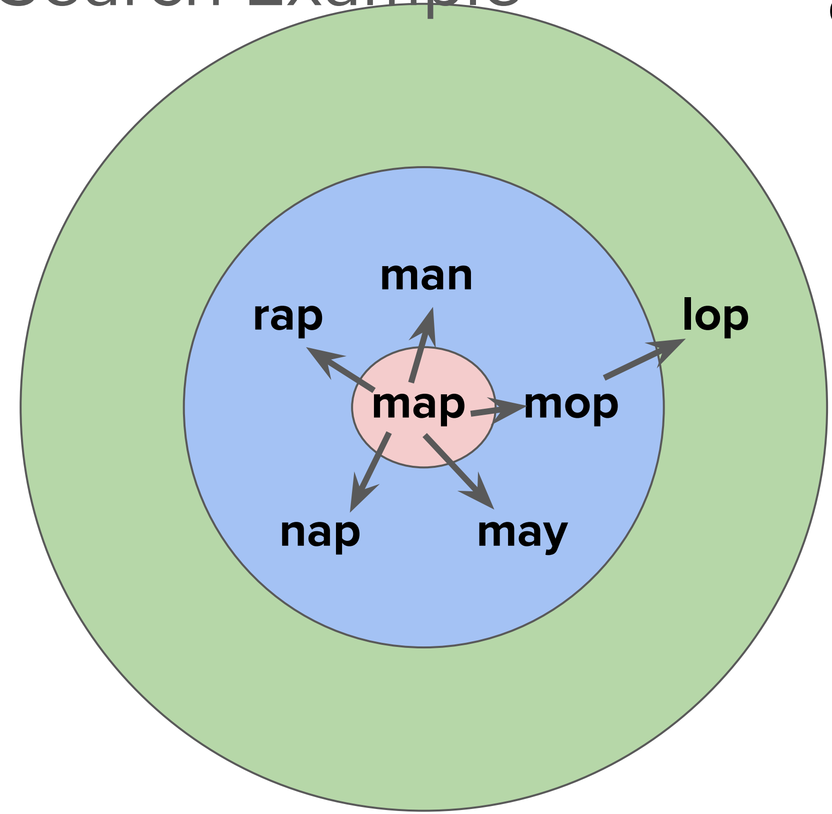


Idea: Keep track of a collection of visited words, and don't double visit

0 steps away
1 step away
2 steps away

Breadth-First Search Example

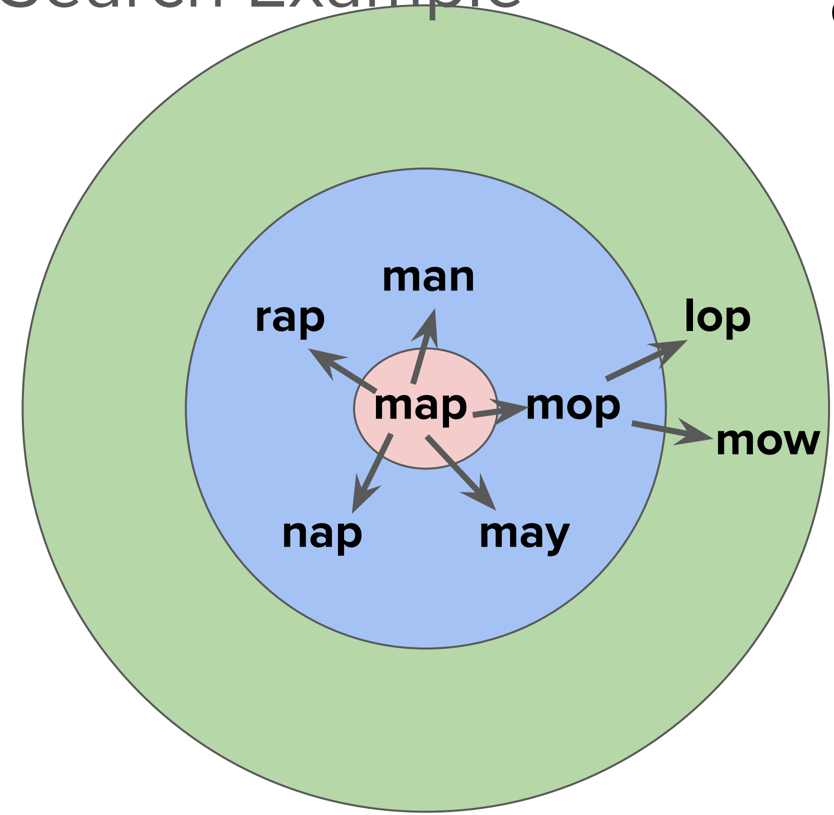
start: map
destination: way



0 steps away
1 step away
2 steps away

Breadth-First Search Example

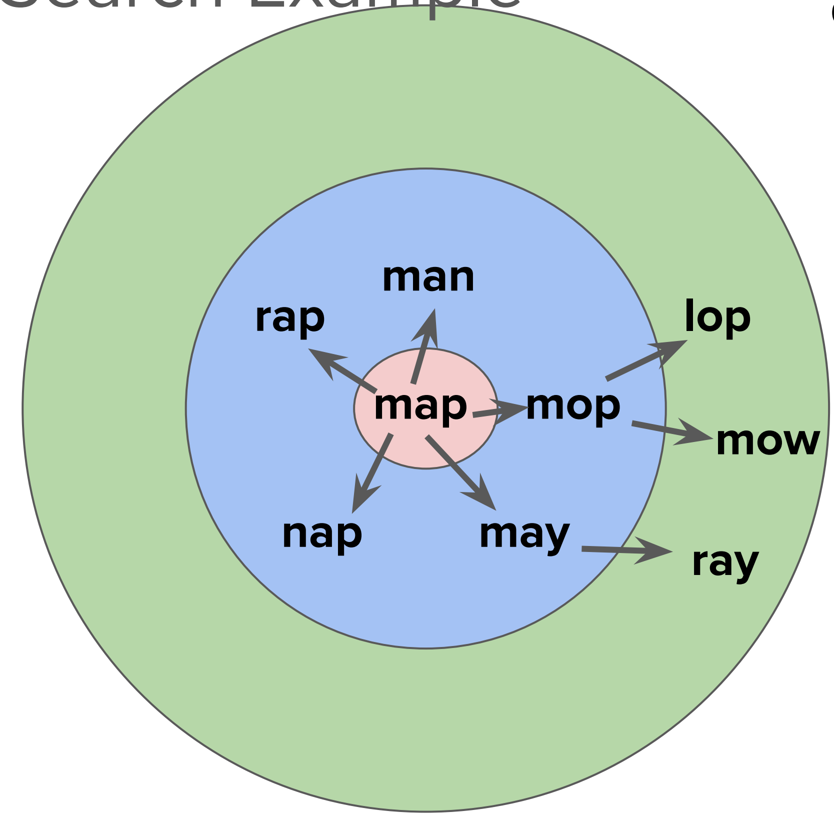
start: map
destination: way



0 steps away
1 step away
2 steps away

Breadth-First Search Example

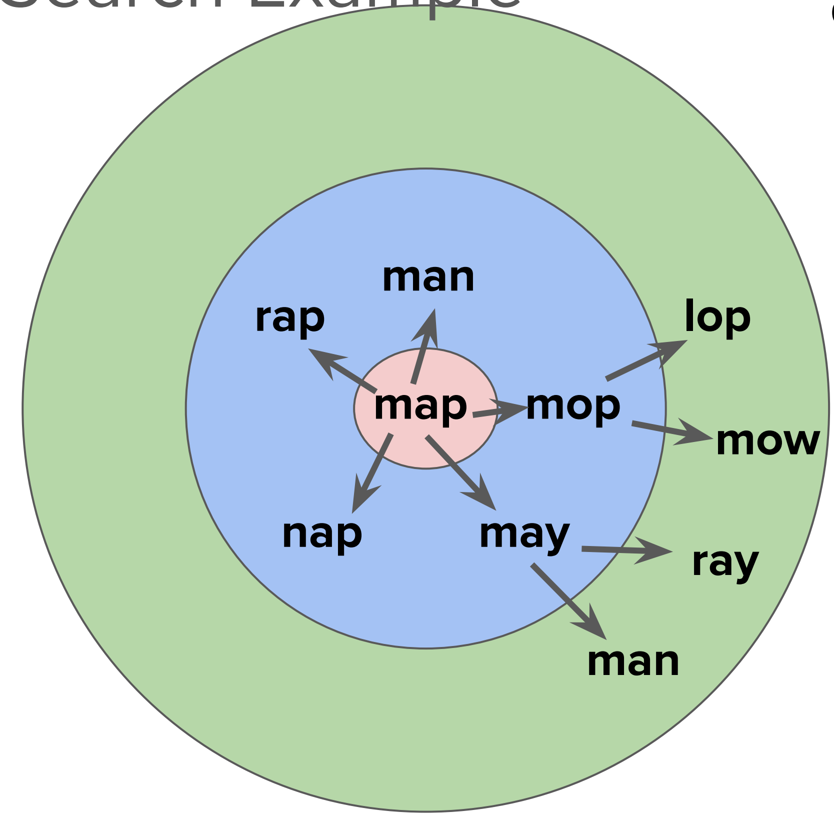
start: map
destination: way



0 steps away
1 step away
2 steps away

Breadth-First Search Example

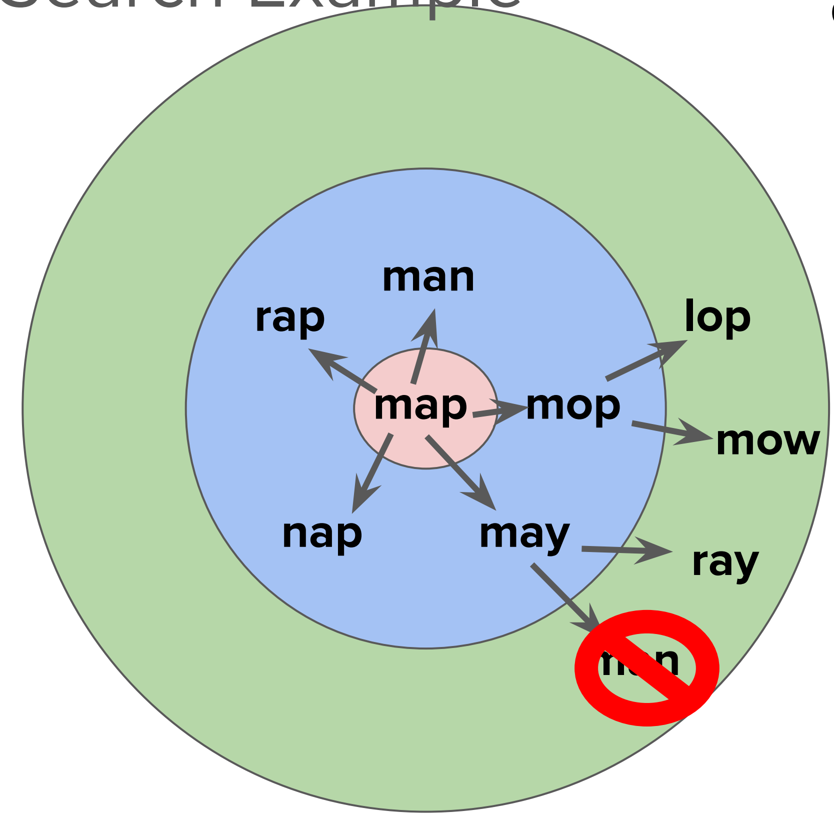
start: map
destination: way



0 steps away
1 step away
2 steps away

Breadth-First Search Example

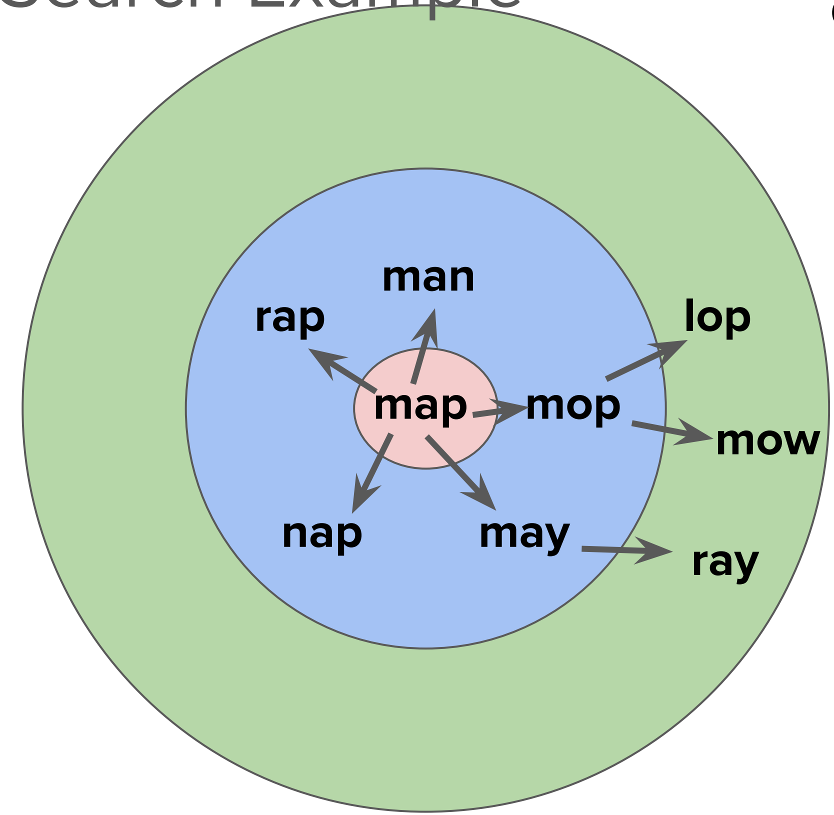
start: map
destination: way



0 steps away
1 step away
2 steps away

Breadth-First Search Example

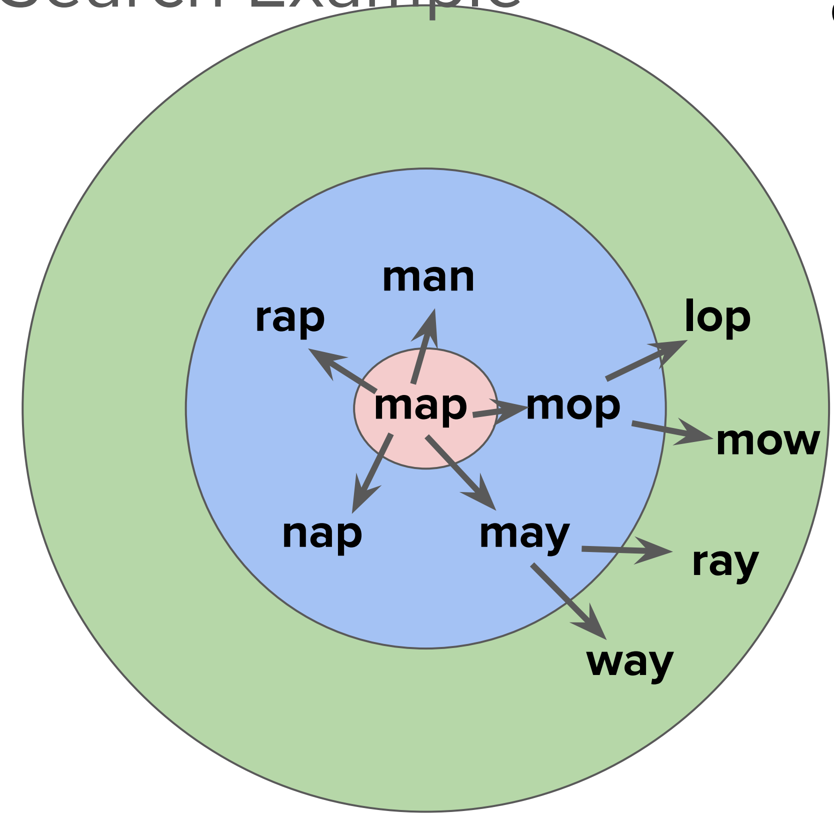
start: map
destination: way



0 steps away
1 step away
2 steps away

Breadth-First Search Example

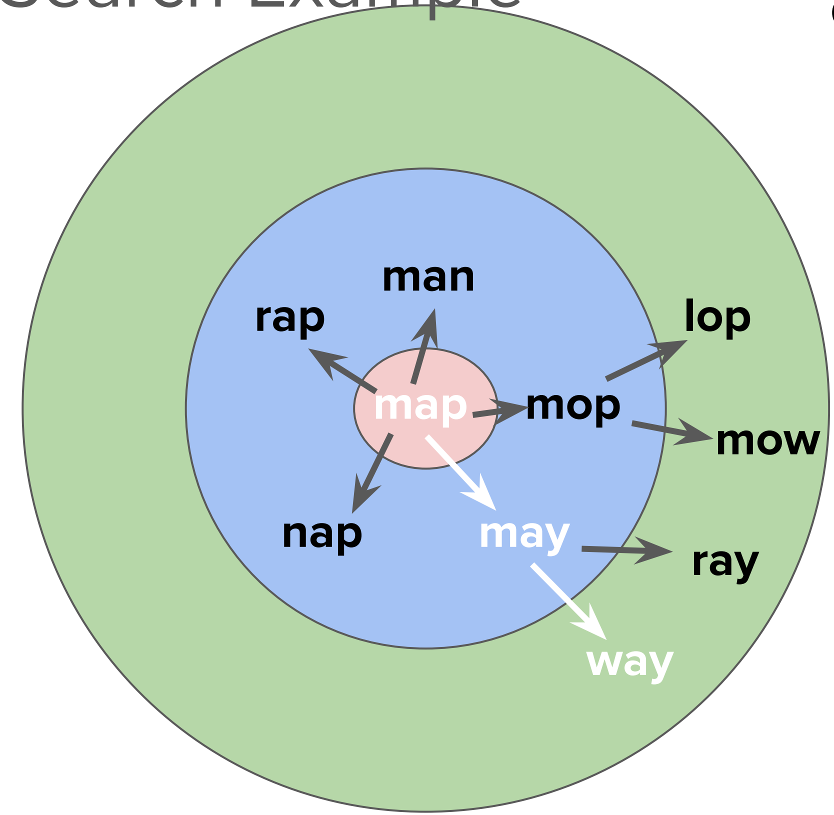
start: map
destination: way



0 steps away
1 step away
2 steps away

Breadth-First Search Example

start: map
destination: way



0 steps away
1 step away
2 steps away

Success! We have found a valid word ladder
map -> may -> way

Announcements

Announcements

- The Assignment 1 grace period expires tonight at 11:59pm in your timezone. We cannot accept any submissions after the grace period expires, barring extenuating circumstances.

- Assignment 2 will be out by the end-of-the-day today.
    - YEAH hours: Hosted by Trip this Thursday, 7/2 at 7pm PDT. The Zoom info is posted on the Zoom details page of the course website

- If you haven't checked it out yet, the C++ survey follow-up thread we posted over the weekend is a super awesome resource to learn more about C++ and get tips on your transition to C++ from other programming languages.

Formalizing BFS

Breadth-First Search Data Structures

We need...

- A data structure to represent (partial word) ladders
  - Desired characteristics: We should be able to easily access the most recent word added to the word ladder

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  - Desired characteristics: We want to maintain an ordering of ladders such that all ladders of a certain length get explored before ladders of longer length get explored

Breadth-First Search Data Structures

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- A data structure to store all the partial word ladders that we have generated so far and have yet to explore
  - Desired characteristics: We want to maintain an ordering of ladders such that all ladders of a certain length get explored before ladders of longer length get explored
- A data structure to keep track of all the words that we've explored so far, so that we avoid getting stuck in loops
  - Desired characteristics: We want to be able to quickly decide whether or not a word has been seen before.

Activity: Discuss which data structures to use

[breakout rooms]

Breadth-First Search Data Structures

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  - Desired characteristics: We should be able to easily access the most recent word added to the word ladder
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Breadth-First Search Data Structures

We need...

- A data structure to represent (partial word) ladders
  - **`Stack<string>`**
- A data structure to store all the partial word ladders that we have generated so far and have yet to explore
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Breadth-First Search Data Structures

We need...

- A data structure to represent (partial word) ladders
  - **`Stack<string>`**
- A data structure to store all the partial word ladders that we have generated so far and have yet to explore
  - **`Queue<Stack<string>>`**
- A data structure to keep track of all the words that we've explored so far, so that we avoid getting stuck in loops
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Breadth-First Search Data Structures

We need...

- A data structure to represent (partial word) ladders
  - `Stack<string>`
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  - `Queue<Stack<string>>`
- A data structure to keep track of all the words that we've explored so far, so that we avoid getting stuck in loops
  - `Set<string>`

Breadth-First Search Pseudocode

Breadth-First Search Pseudocode

```
Create an empty queue and an empty set of visited locations
Create an initial word ladder containing the starting word and add it to the
queue
```

Breadth-First Search Pseudocode

```
Create an empty queue and an empty set of visited locations
Create an initial word ladder containing the starting word and add it to the queue
While the queue is not empty
```

Breadth-First Search Pseudocode

```
Create an empty queue and an empty set of visited locations
Create an initial word ladder containing the starting word and add it to the queue
While the queue is not empty
    Remove the next partial ladder from the queue
    Set the current search word to be the word at the top of the ladder
    If the current word is the destination, then return the current ladder
```

Breadth-First Search Pseudocode

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    Remove the next partial ladder from the queue
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    If the current word is the destination, then return the current ladder
    Generate all "neighboring" words that are valid English words and one
    letter away from the current word
    Loop over all neighbor words
```

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    letter away from the current word
    Loop over all neighbor words
        If the neighbor hasn't yet been visited
```

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queue
While the queue is not empty
    Remove the next partial ladder from the queue
    Set the current search word to be the word at the top of the ladder
    If the current word is the destination, then return the current ladder
    Generate all "neighboring" words that are valid English words and one
    letter away from the current word
    Loop over all neighbor words
        If the neighbor hasn't yet been visited
            Create a copy of the current ladder
            Add the neighbor to the top of the new ladder and mark it visited
            Add the new ladder to the back of the queue of partial ladders
```

Live Coding:
Implementing BFS

[Qt Creator]

Live Coding: Implementing BFS

[Qt Creator]

We hope that you find this to be a helpful resource when working on Assignment 2. However, we do not encourage trying to copy the code as a starting point. The problems are distinctly different, and you will benefit from explicitly developing your own problem-specific pseudocode first.

Nested Data Structures

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- We've already seen one example of nested data structures when we used the **`Queue<Stack<string>>`** to keep track of our search for word ladders.

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- Nesting data structures (using one ADTs as the data type inside of another ADT) is a great way of organizing data with complex structure.

Nested Data Structures

- We've already seen one example of nested data structures when we used the **`Queue<Stack<string>>`** to keep track of our search for word ladders.

- Nesting data structures (using one ADTs as the data type inside of another ADT) is a great way of organizing data with complex structure.

- You will thoroughly explore nested data structures (specifically nested Sets and Maps) in Assignment 2!

Nested Data Structures Example

- Imagine we are designing a system to keep track of feeding times for the different animals at a zoo

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- Imagine we are designing a system to keep track of feeding times for the different animals at a zoo
- Requirements: We need to be able to quickly look up the feeding times associated with an animal if we know it's name. We need to be able to store multiple feeding times for each animal. The feeding times should be stored in the order in which the feedings should happen.

Nested Data Structures Example

- Imagine we are designing a system to keep track of feeding times for the different animals at a zoo
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- Data Structure Declaration
    - `Map<string, Vector<string>>`

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- Data Structure Declaration
  - ```
    Map<string, Vector<string>>
    ```

Quick lookup by animal name
    ```

Nested Data Structures Example

- Imagine we are designing a system to keep track of feeding times for the different animals at a zoo
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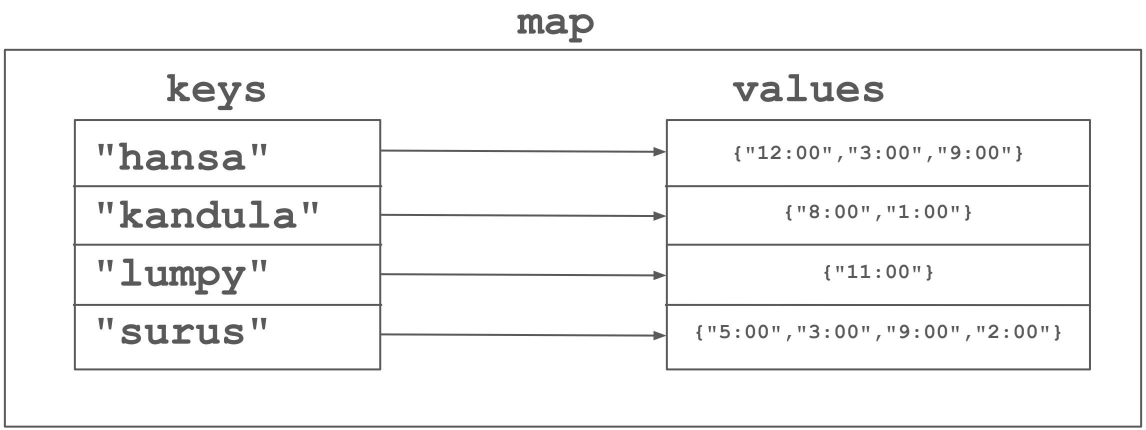
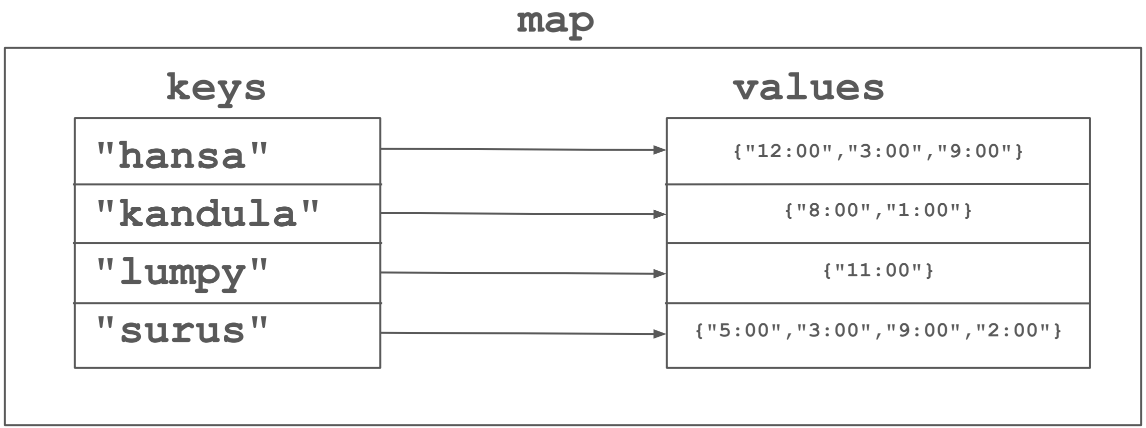
- Data Structure Declaration
    - **Map<string, Vector<string>>**

Store multiple, ordered feeding times per animal

Nested Data Structures Example



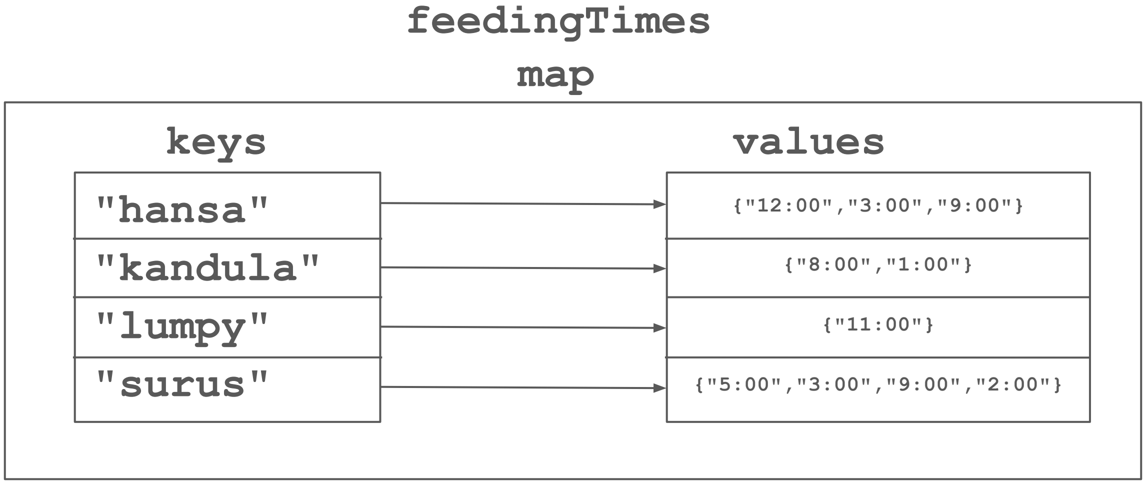
Nested Data Structures Example



How do we use modify the internal values of this map?

Nested Data Structures Example

Goal: We want to add a second feeding time of 4:00 for "lumpy".

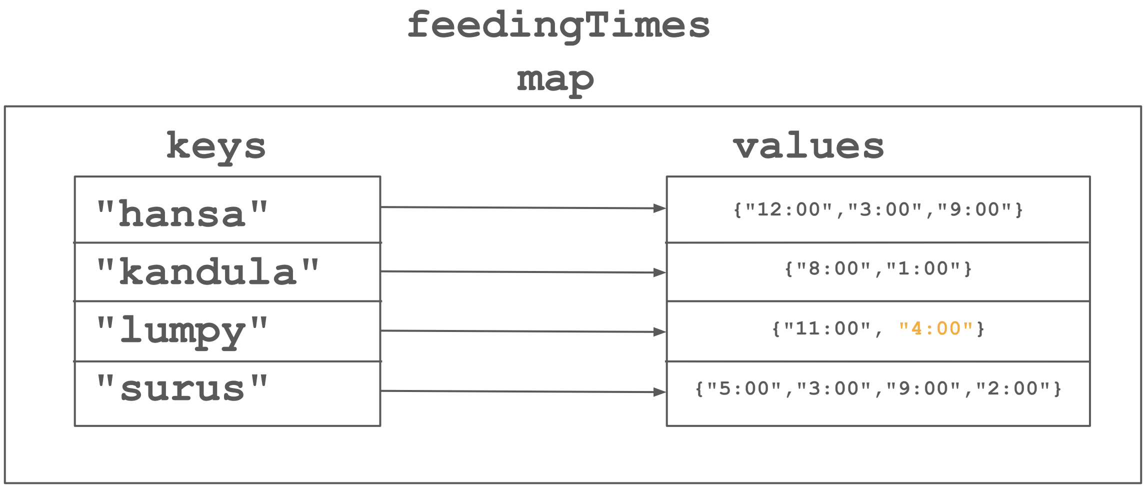


Nested Data Structures Example

Goal: We want to add a second feeding time of 4:00 for "lumpy".

Which of the following three snippets of code will correctly update the state of the map?

1. `feedingTimes["lumpy"].add("4:00");`
2. `Vector<string> times = feedingTimes["lumpy"]; times.add("4:00");`
3. `Vector<string> times = feedingTimes["lumpy"]; times.add("4:00"); feedingTimes["lumpy"] = times;`



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   ```
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   ```
3. ```
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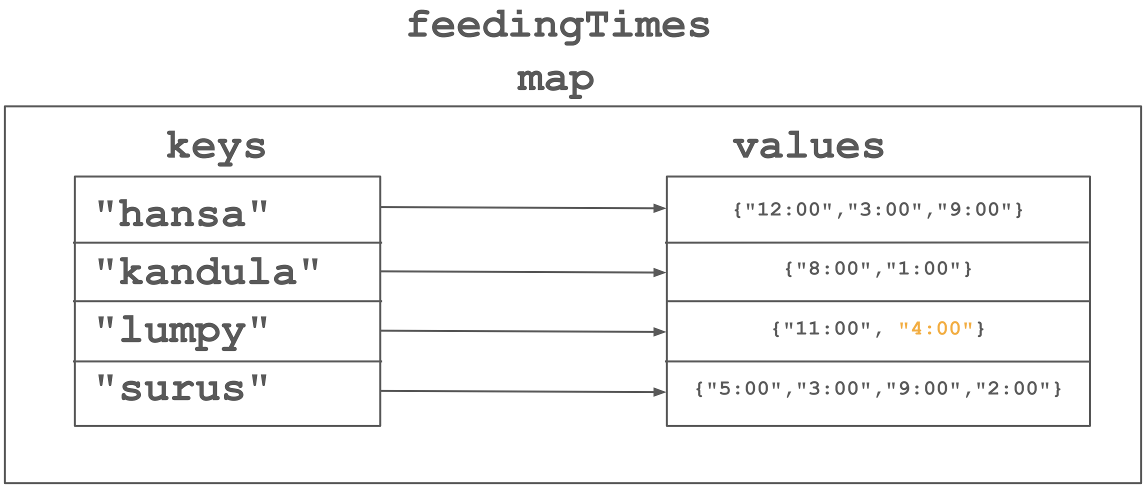
   times.add("4:00");
   feedingTimes["lumpy"] = times;
   ```


   ```

[] Operator and = Operator Nuances

- When you use the [] operator to access an element from a map, you get a reference to the map, which means that any changes you make to the reference will be persistent in the map.
  - `feedingTimes["lumpy"].add("4:00");`

[] Operator and = Operator Nuances

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  - `feedingTimes["lumpy"].add("4:00");`
- However, when you use the = operator to assign the result of the [] operator to a variable, you get a copy of the internal data structure.
  -
    ```
    Vector<string> times = feedingTimes["lumpy"]; // this makes a copy
    times.add("4:00"); // modifies the copy, not the actual map value!!!
    ```

[] Operator and = Operator Nuances

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  - ```
    feedingTimes["lumpy"].add("4:00");
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- However, when you use the = operator to assign the result of the [] operator to a variable, you get a copy of the internal data structure.
  - ```
    Vector<string> times = feedingTimes["lumpy"]; // this makes a copy
    times.add("4:00"); // modifies the copy, not the actual map value!!!
    ```
- If you choose to store the internal data structure in a variable, you must do an explicit reassignment to get your changes to persist
  - ```
    Vector<string> times = feedingTimes["lumpy"]; // this makes a copy
    times.add("4:00"); // modifies the copy
    feedingTimes["lumpy"] = times; // stores the modified copy in the map
    ```
    ```

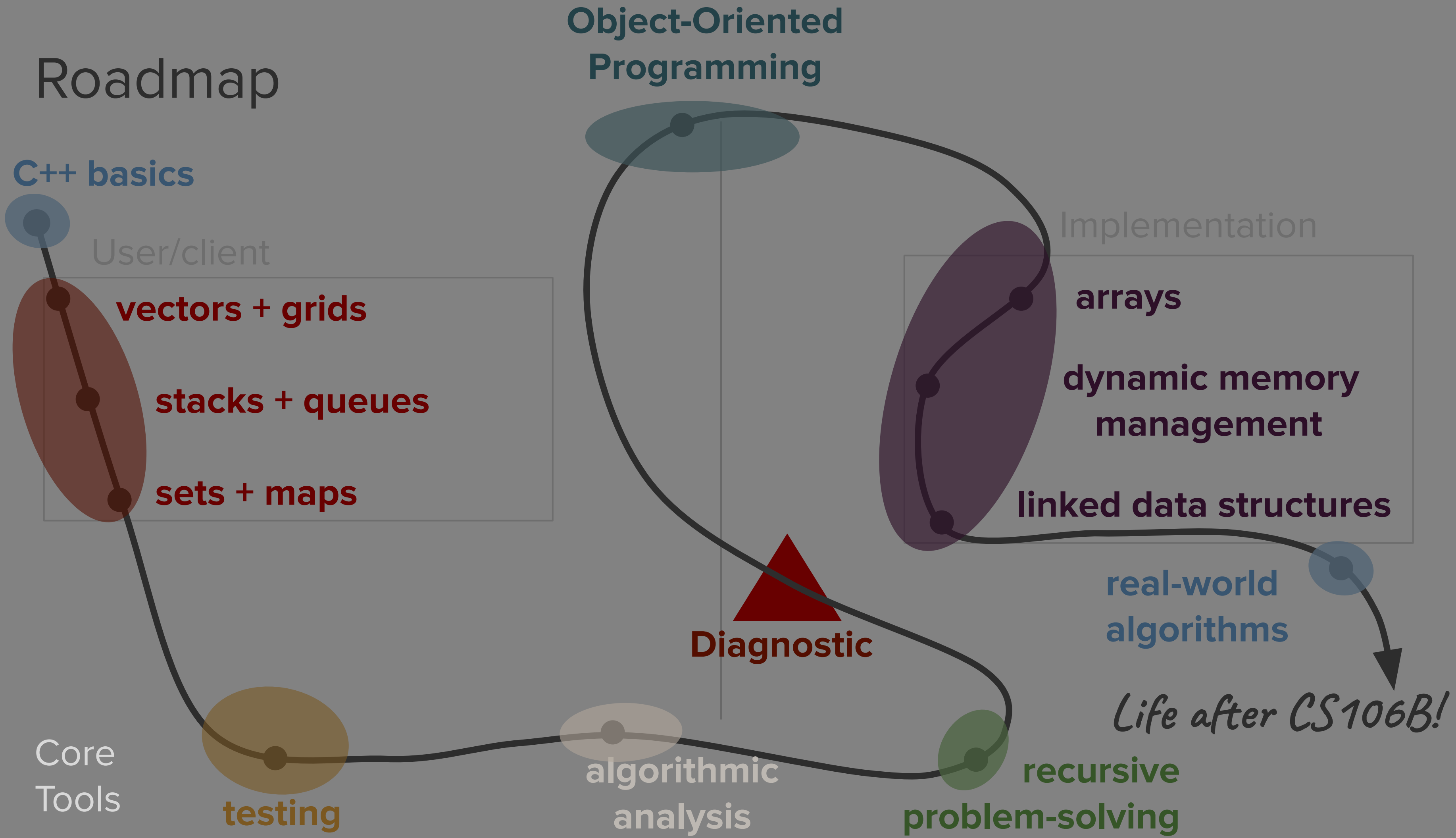
Nested ADTs Summary

- Powerful
  - Can express highly structured and complex data
  - Used in many real-world systems

- Tricky
  - With increased complexity comes increased cognitive load in differentiating between the levels of information stored at each level of the nesting
  - Specifically in C++, working with nested data structures can be tricky due to the fact that references and copies show up at different points in time. Follow the correct paradigms presented earlier to stay on track!

What's next?

Roadmap



Object-Oriented Programming
C++ basics
User/client
vectors + grids
stacks + queues
sets + maps
Implementation
arrays
dynamic memory management
linked data structures
real-world algorithms
Life after CS106B!
Diagnostic
Core Tools
testing
algorithmic analysis
recursive problem-solving

Big O and Algorithmic Analysis