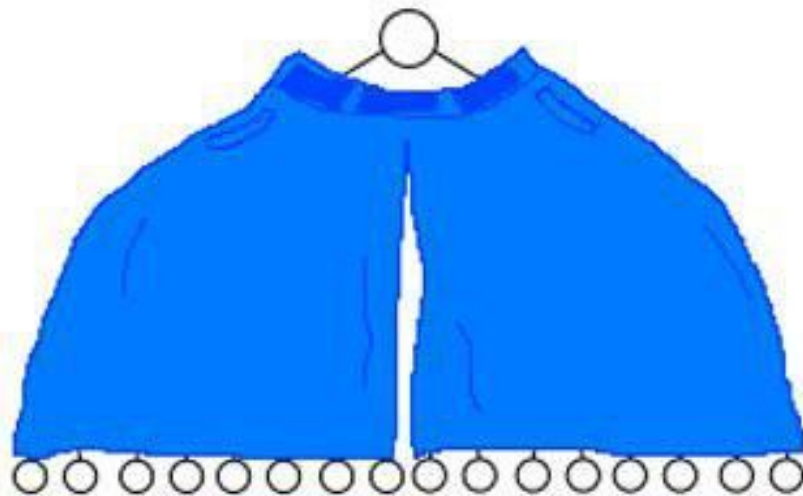
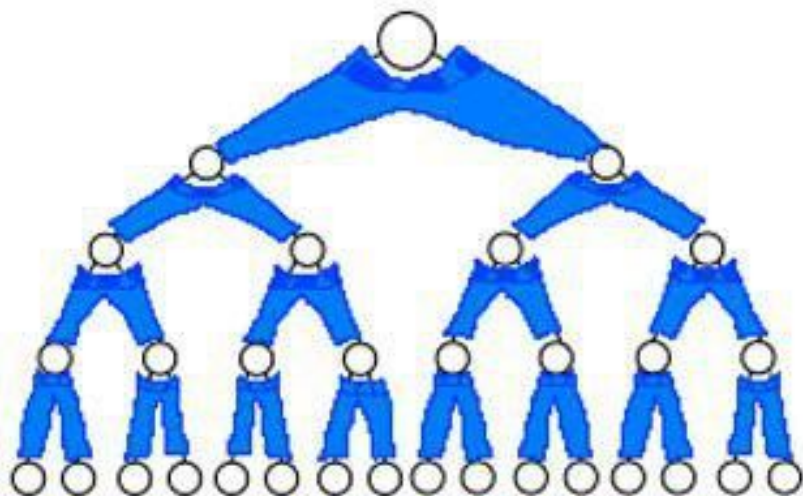




Huffman Coding

Today's question has a visual component, posted on the next slide.



A**B**

If a binary tree wore pants, would it wear them like in picture A or in picture B?

Roadmap

C++ basics

User/client

vectors + grids

stacks + queues

sets + maps

Core
Tools

testing

Object-Oriented Programming

Implementation

arrays

**dynamic memory
management**

linked data structures

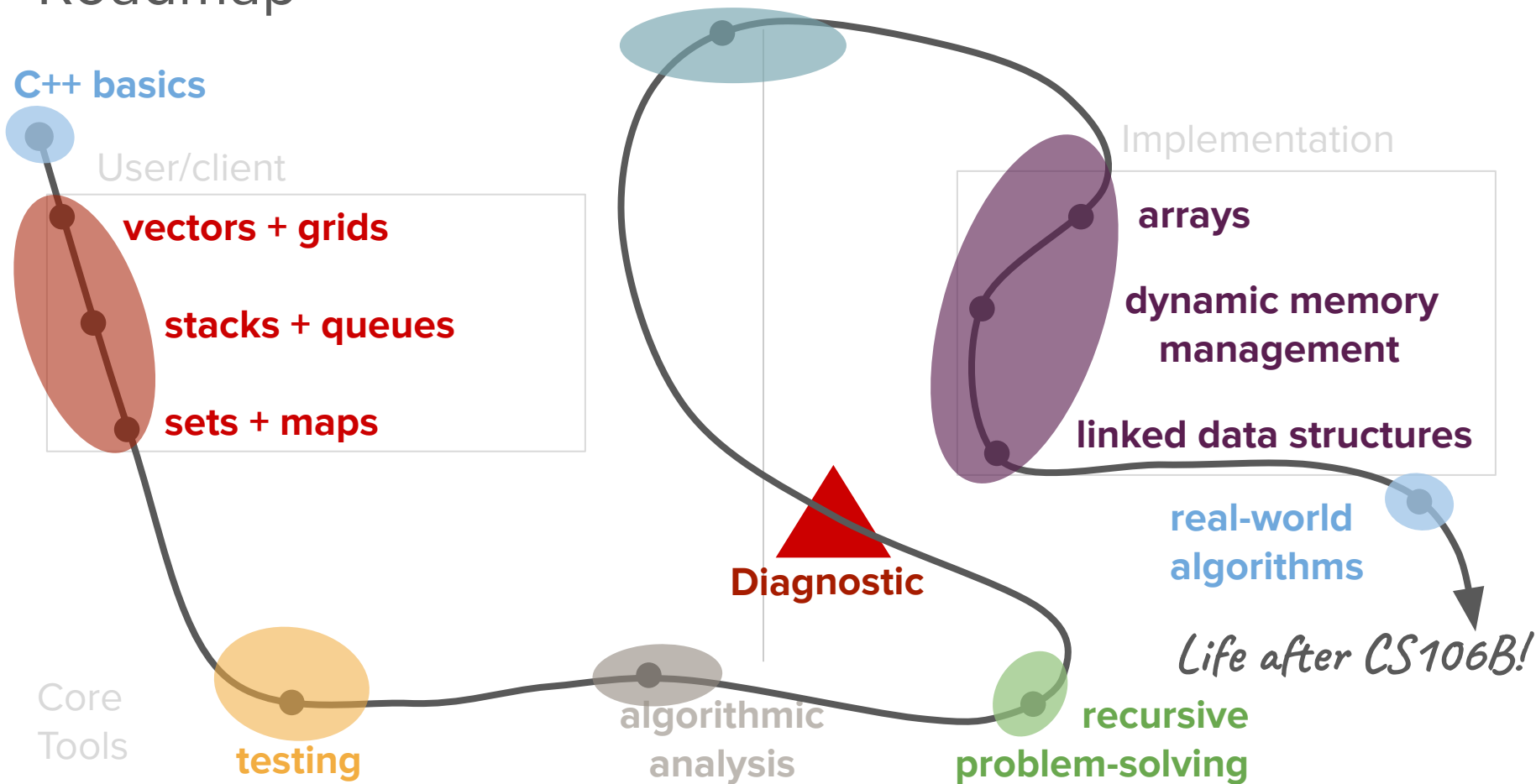
**real-world
algorithms**

Life after CS106B!

Diagnostic

algorithmic
analysis

**recursive
problem-solving**



Roadmap

C++ basics

User/client

vectors + grids

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Life after CS106B!

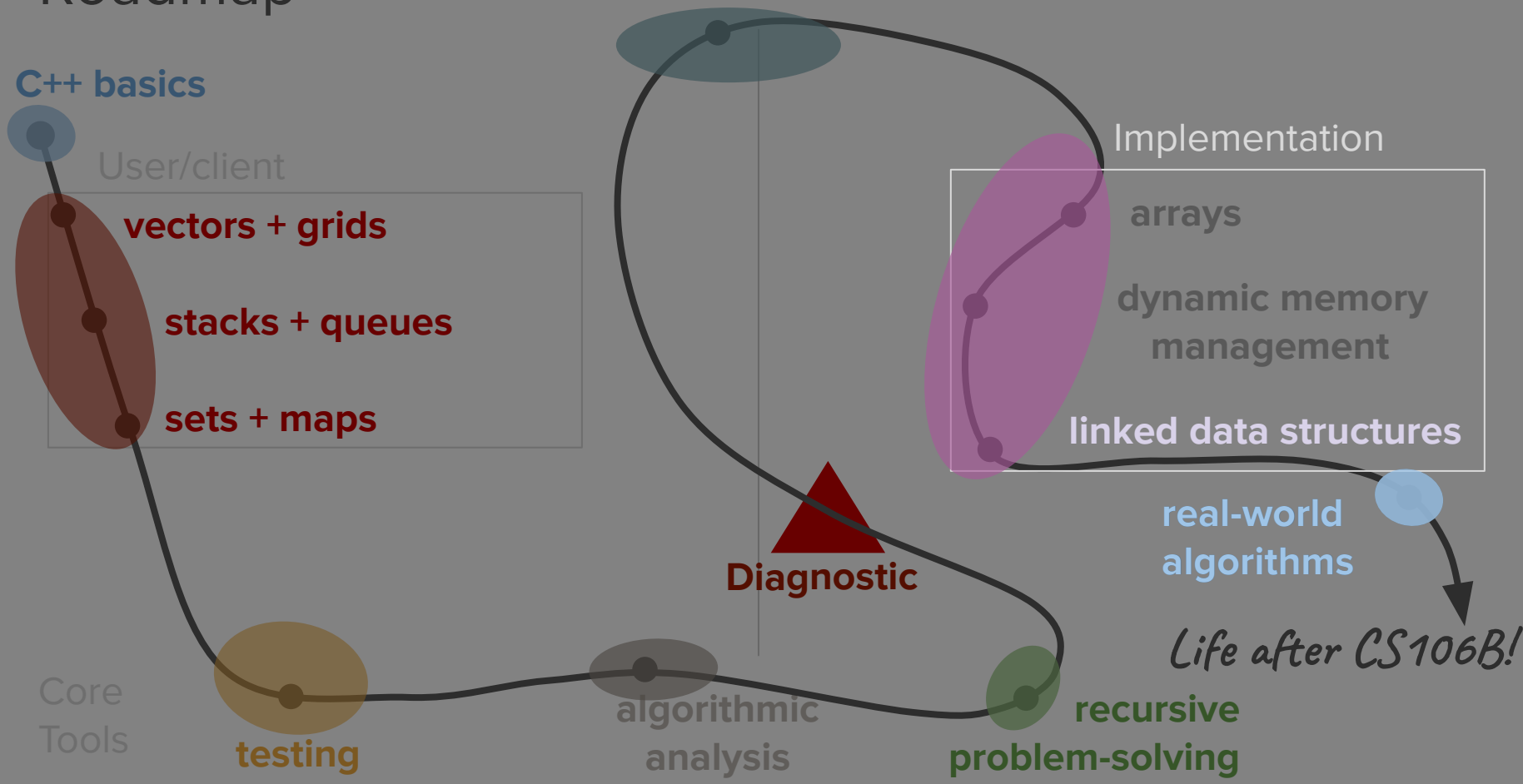
Diagnostic

Core
Tools

testing

algorithmic
analysis

recursive
problem-solving





Today's questions

How can we use trees to
develop more compact and
efficient data
representation techniques?



Today's topics

1. Binary Search Tree Review
2. Data Compression and Encoding
3. Huffman Coding



Review

[binary search trees]



Key Idea: The distance from each element (node) in a tree to the top of the tree (the root) is small, even if there are many elements.

How can we take advantage of trees to structure and efficiently manipulate data?

What is the interface for the user?
(**Sets**, Maps, etc.)



How is our data organized?
(binary heaps, **BSTs**, Huffman trees)

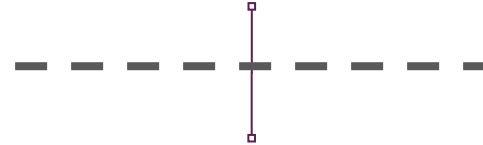


What stores our data?
(arrays, linked lists, **trees**)



How is data represented electronically?
(RAM)

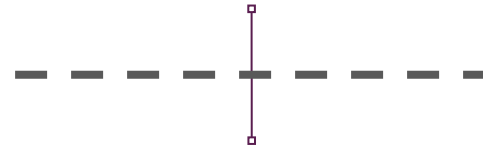
Abstr
Structures



**Data Organization
Strategies**



**Fundamental C++
Data Storage**



**Computer
Hardware**

ADT Big-O Matrix

● Vectors

- `.size()` - $O(1)$
- `.add()` - $O(1)$
- `v[i]` - $O(1)$
- `.insert()` - $O(n)$
- `.remove()` - $O(n)$
- `.clear()` - $O(n)$
- `traversal` - $O(n)$

● Grids

- `.numRows()/.numCols()`
- $O(1)$
- `g[i][j]` - $O(1)$
- `.inBounds()` - $O(1)$
- `traversal` - $O(n^2)$

● Queues

- `.size()` - $O(1)$
- `.peek()` - $O(1)$
- `.enqueue()` - $O(1)$
- `.dequeue()` - $O(1)$
- `.isEmpty()` - $O(1)$
- `traversal` - $O(n)$

● Stacks

- `.size()` - $O(1)$
- `.peek()` - $O(1)$
- `.push()` - $O(1)$
- `.pop()` - $O(1)$
- `.isEmpty()` - $O(1)$
- `traversal` - $O(n)$

● Sets

- `.size()` - $O(1)$
- `.isEmpty()` - $O(1)$
- `.add()` - $O(\log(n))$
- `.remove()` - $O(\log(n))$
- `.contains()` - $O(\log(n))$
- `traversal` - $O(n)$

● Maps

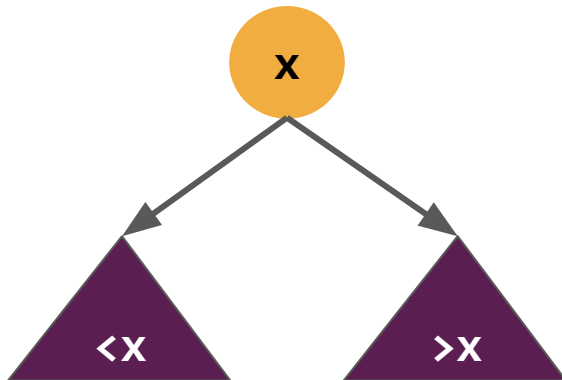
- `.size()` - $O(1)$
- `.isEmpty()` - $O(1)$
- `m[key]` - $O(\log(n))$
- `.contains()` - $O(\log(n))$
- `traversal` - $O(n)$

A binary search tree is either...

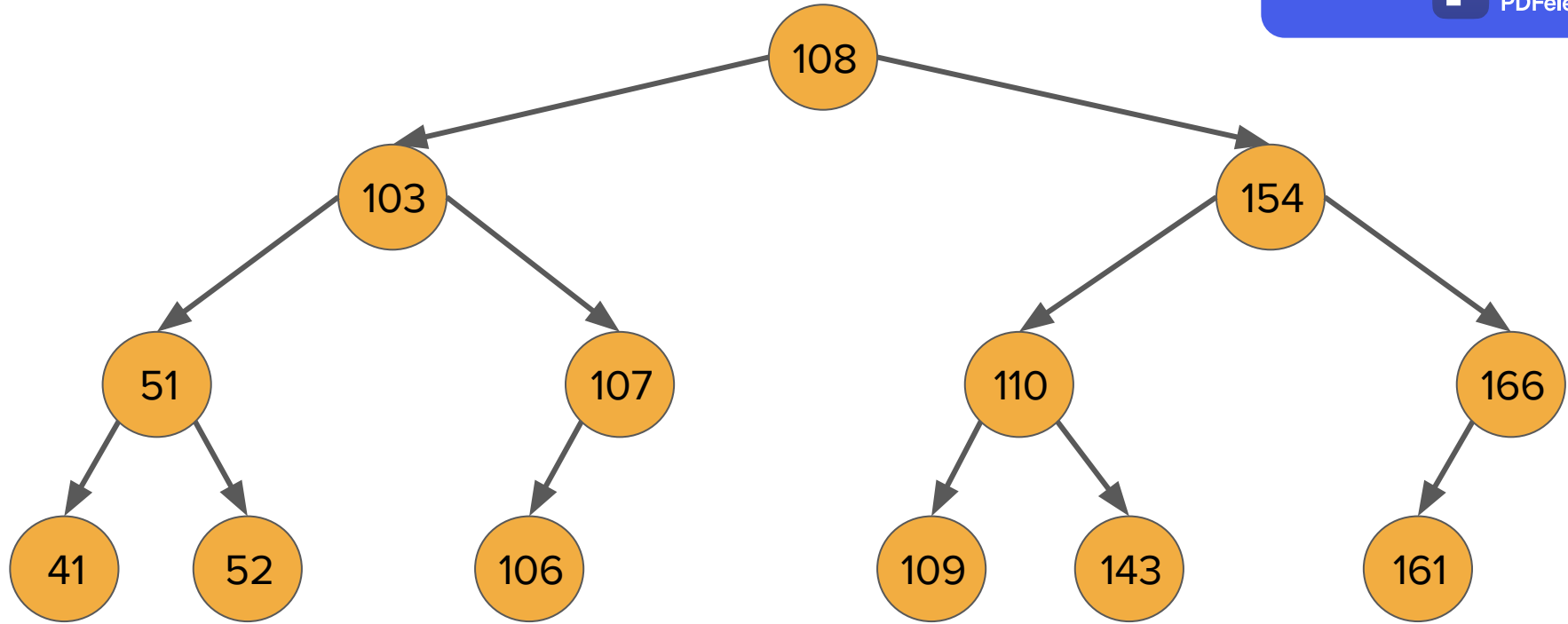
an empty data
structure represented
by nullptr or...



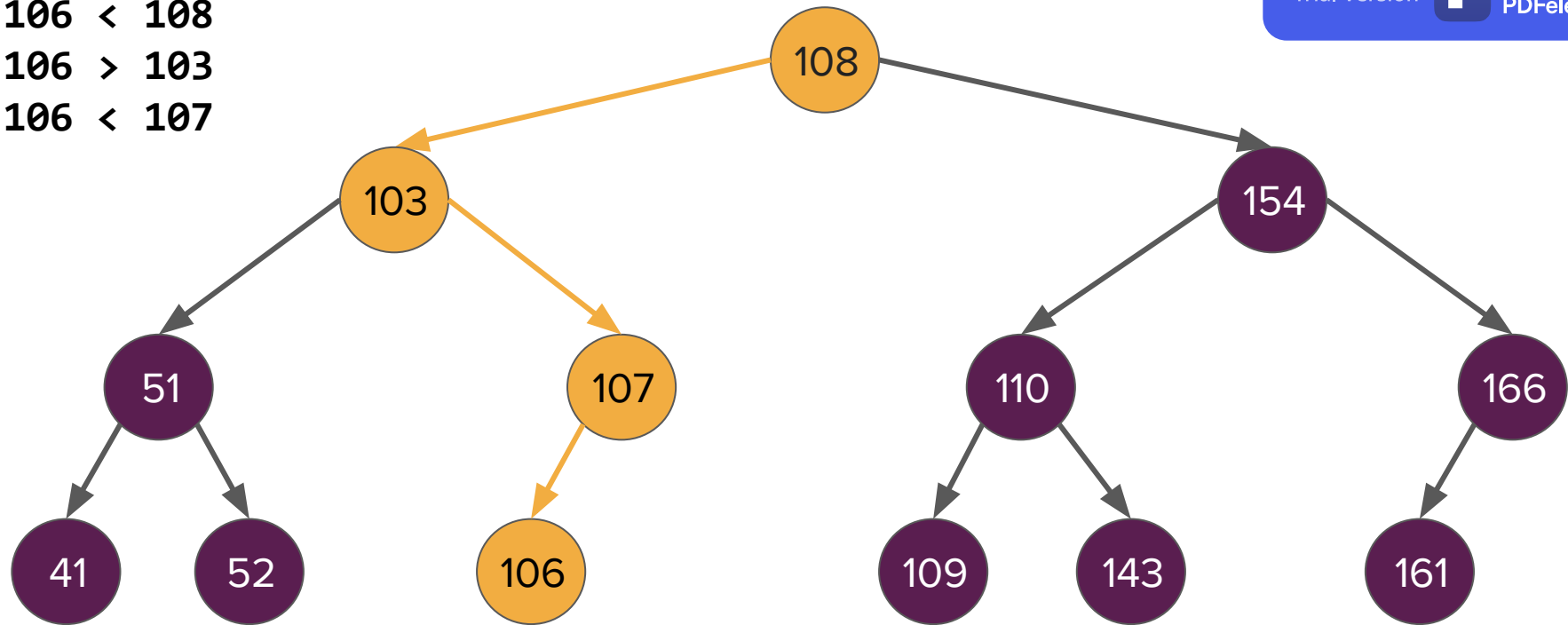
a single node,
whose left subtree is
a BST of smaller
values than **x**...



and whose right
subtree is a BST of
larger values than **x**.



There are **n** nodes in the tree, but
the path to each node is short
 $(\sim O(\log n))!$

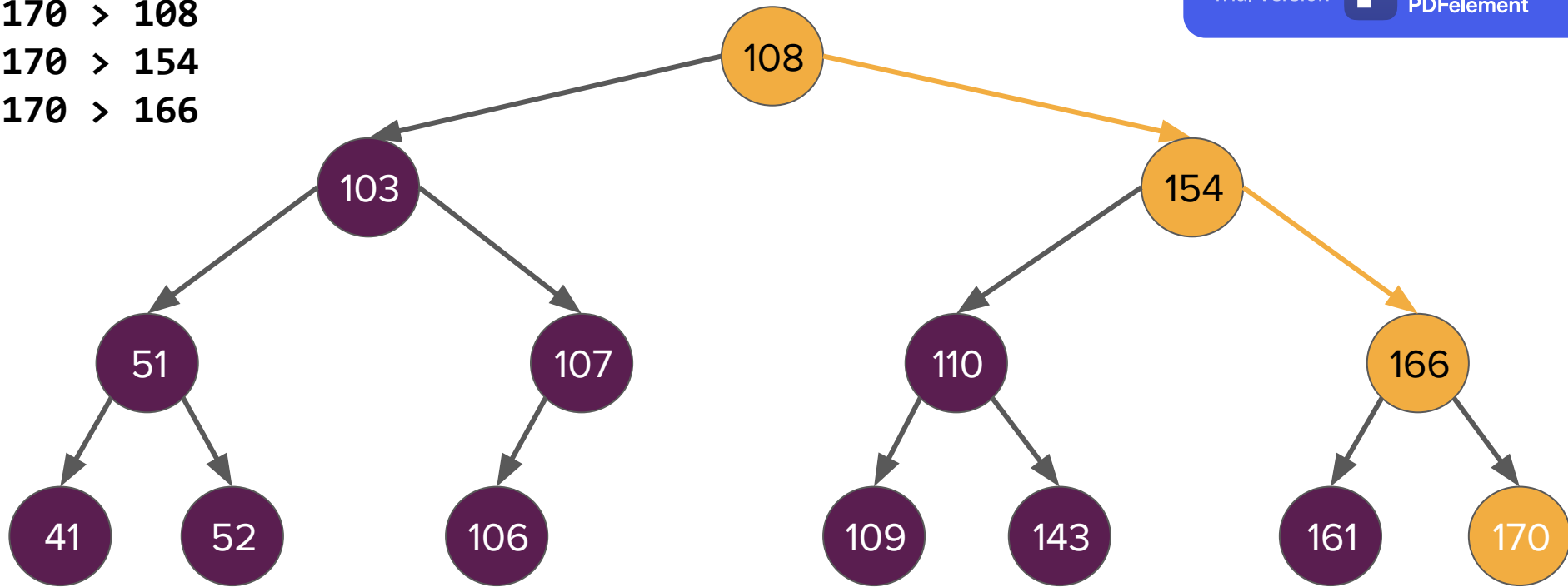
$106 < 108$ $106 > 103$ $106 < 107$ 

How could we check if **106** is in this tree?

170 > **108**

170 > **154**

170 > **166**



How could we add **170** to this tree?

Binary Search Tree Properties

- There are multiple valid BSTs for the same set of data. How you construct the tree/the order in which you add the elements to the tree matters!
- A binary search tree is **balanced** if its height is $O(\log n)$, where n is the number of nodes in the tree (i.e. left/right subtrees don't differ in height by more than 1).
 - An **optimal (balanced) BST** is built by repeatedly choosing the median element as the root node of a given subtree and then separating elements into groups less than and greater than that median.
 - Lookup, insertion, and deletion with balanced BSTs all operate in $O(\log n)$ runtime.
 - A **self-balancing** BST reshapes itself on insertions and deletions to stay balanced (how to do this is beyond the scope of this class).



Implementing a Set with a BST

- Binary search trees are a great backing store for a data structure in which lookup/additional/removal all needs to be fast and the order of elements doesn't matter.
- This makes them a great choice for the internal data storage of a Set or Map ADT!
- Thus, we are able to build our own version of the Set ADT by using a BST to organize the internal structure of the data.



OurSet summary

- Our tree utility functions (**inorderPrint**, **freeTree**) showed up as private member functions/helpers!
 - In-order traversal prints our elements in the correctly sorted order!
- Using a BST allowed us to take advantage of recursion to traverse our data and get an **$O(\log n)$** runtime for our methods.
- Rewiring trees can be complicated!
 - Make sure to consider when nodes need to be passed by reference.
 - Check out the remove method after class if you're interested in seeing an example of tree rewiring (you won't be required to do anything this complex with tree rewiring).

How can we use trees to develop more compact and efficient data representation techniques?

What is the interface for the user?



How is our data organized?
(binary heaps, BSTs, **Huffman trees**)

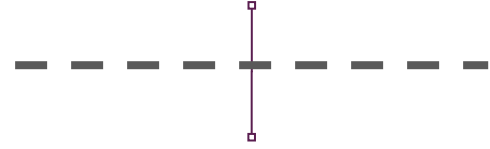


What stores our data?
(arrays, linked lists, **trees**)



How is data represented electronically?
(RAM)

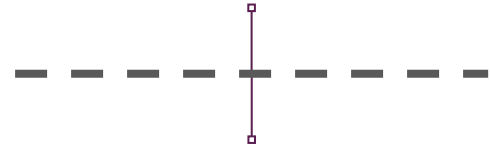
Abstraction Structures



Data Organization Strategies



Fundamental C++ Data Storage



Computer Hardware



Acknowledgement: Many of the following slides were adapted from Keith Schwarz's Winter 2020 "Beyond Data Structures" lecture. Thank you Keith for having such great lecture examples!



Data Storage and Representation

How do computers store and represent data?



How do computers store and represent data?





Just a Little Bit of Magic

- Digital data is stored as **sequences of 0s and 1s**.
 - These sequences are encoded in physical devices by magnetic orientation on small (10nm!) metal particles or by trapping electrons in small gates. This is where the magic happens!
- A single 0 or 1 is called a **bit**.
- A group of eight bits is called a **byte**.

00000000, 00000001, 00000010, ...

00000011, 00000100, 00000101, ...
- There are $2^8 = 256$ different bytes.
 - **Good recursive backtracking practice**: Write a function to list all possible byte sequences!



Binary Representation

- The system of using sequences of 0s and 1s to represent data is called **binary**.
- Similar to how we previously encountered hexadecimal (base-16) numbers, binary numbers can be thought of as expressed in a base-2 system.
 - To produce a number in base 2, **each digit represents a power of 2** (exactly analogous to how in base 10 each digit represents a power of 10).

Binary Representation

- The system of using sequences of 0s and 1s to represent data is called **binary**.
- Similar to how we previously encountered hexadecimal (base-16) numbers, binary numbers can be thought of as expressed in a base-2 system.
- Representing my age in different numerical systems
 - Base 10: **22** = **2** * 10^1 + **2** * 10^0 = 20 + 2 = **22**
 - Base 2: **10110** = **1** * 2^4 + **0** * 2^3 + **1** * 2^2 + **1** * 2^1 + **0** * 2^0 = 16 + 4 + 2 = **22**

ON A SCALE OF 1 TO 10,
HOW LIKELY IS IT THAT
THIS QUESTION IS
USING BINARY?

| ...4?
WHAT'S A 4?)





Representing Text

- We think of strings as being made of characters representing letters, numbers, emojis, etc.
- However, we just said that computers require everything to be written as zeros and ones.
- To bridge the gap, we need to agree on some way of representing characters as sequences of bits.
- **Idea:** Assign each character a sequence of bits called a **code**.



ASCII

- Early (American) computers needed some standard way to send output to their (physical!) printers.
- Since there were fewer than 256 different characters to print (1960's America!), each character was assigned a one-byte value.
 - This initial code was called **ASCII**. Surprisingly, it's still around, though in a modified form.
- For example, the letter A is represented by the byte **01000001** (whose numerical representation is 65). You can still see this in C++:

```
cout << int('A') << endl; // Prints 65
```

B

A

G

ASCII Mystery: 010000100100000101000111

- Here's a small segment from the ASCII encodings for characters.
- What is the mystery word in the title of this slide?

<i>character</i>	<i>code</i>
A	01000001
B	01000010
C	01000011
D	01000100
E	01000101
F	01000110
G	01000111
H	01001000

ASCII Mystery: B A G

- Here's a small segment from the ASCII encodings for characters.
- What is the mystery word in the title of this slide?
- Thus, in the computer's eyes, "BAG" is equivalent to the bit sequence **010000100100000101000111**

<i>character</i>	<i>code</i>
A	01000001
B	01000010
C	01000011
D	01000100
E	01000101
F	01000110
G	01000111
H	01001000



An Observation

- In ASCII, every character has exactly the same number of bits in it.
- Any message with n characters will use up exactly $8n$ bits.
 - Space for **CS106BLECTURE**: 104 bits.
 - Space for **COPYRIGHTABLE**: 104 bits.
- **Question**: Can we reduce the number of bits needed to encode text?

The Star of Today's Show



KIRK'S DIKDIK

A Different Encoding

- ASCII uses one byte per character. There are 256 possible bytes.
- If we're specifically writing the string **KIRK'S DIKDIK**, which has only seven different characters, using full bytes is wasteful.
- Here's a three-bit encoding we can use to represent the letters in **KIRK'S DIKDIK**.
- This uses **37.5% as much space as what ASCII uses**. That's a big improvement!

<i>character</i>	<i>code</i>
K	000
I	001
R	010
'	011
S	100
␣	101
D	110

000	001	010	000	011	100	101	110	001	000	110	001	000
K	I	R	K	'	S	␣	D	I	K	D	I	K



The Journey Ahead

- Storing data using the ASCII encoding is ^{跨系统移植}portable across systems, but is not ^{理想}ideal in terms of space usage.
- Building custom codes for specific strings might let us save space.
- **Idea:** Use this approach to build a **compression algorithm** to reduce the amount of space needed to store text.



Compression Algorithms



Today's Main Idea

- If we can find a way to
 give all characters a bit pattern,
 that both the sender and receiver know about, and
 that can be decoded uniquely,
then we can represent the same piece of text in multiple different ways.
- **Goal:** Find a way to do this that uses less space than the standard ASCII representation.



Compression Algorithms

- Compression algorithms are a whole class of real-world algorithms that are have widespread prevalence and importance.
- In particular, we are interested in algorithms that provide **lossless compression** on a stream of characters or other data.
 - Lossless compression means that we make the amount of data smaller without losing any of the details, and we can decompress the data to exactly the same as it was before compression.



Compression Algorithms

- Compression algorithms are a whole class of real-world algorithms that are have widespread prevalence and importance.
- In particular, we are interested in algorithms that provide **lossless compression** on a stream of characters or other data.
- Virtually everything that you do online involves data compression.
 - When you visit a website, download a file, or transmit video/audio, the data is **compressed** when sending and **decompressed** when receiving.
 - The video stream you're watching on Zoom right now has a compression of roughly 2000:1, meaning that a 2MB image is compressed down to 1000 bytes!

Compression Algorithms

- Compression algorithms are a whole class of real-world algorithms that are have widespread prevalence and importance.
- In particular, we are interested in algorithms that provide **lossless compression** on a stream of characters or other data.
- Virtually everything that you do online involves data compression.
- Compression algorithms **identify patterns in data** and take advantage of those patterns to come up with more efficient representations of that data!

Taking Advantage of Redundancy

- Not all letters have the same frequency in **KIRK'S DIKDIK**.
- The frequencies of each letter are shown to the right.
- So far, we've given each letter a code of the same length.
- **Key Question:** Can we give shorter encodings to more common characters?

character *frequency*

K	4
I	3
D	2
R	1
'	1
S	1
␣	1

Morse Code

- Morse Code is one coding system that makes use of this insight!
- The code for very frequent letters (e, t, a) are much shorter than the codes for very infrequent letters (q, k, j).

International Morse Code

1. The length of a dot is one unit.
2. A dash is three units.
3. The space between parts of the same letter is one unit.
4. The space between letters is three units.
5. The space between words is seven units.

A ● —
B — ● ● ●
C — ● — ●
D — ● ●
E ●
F ● ● — ●
G — — ●
H ● ● ● ●
I ● ●
J ● — — —
K — ● —
L ● — ● ●
M — —
N — ●
O — — —
P ● — — ●
Q — — ● —
R ● — ●
S ● ● ●
T —

U ● ● —
V ● ● ● —
W ● — —
X — ● ● —
Y — ● — —
Z — — ● ●

1 ● — — — —
2 ● ● — — —
3 ● ● ● — —
4 ● ● ● ● —
5 ● ● ● ● ●
6 — ● ● ● ●
7 — — ● ● ●
8 — — — ● ●
9 — — — — ●
0 — — — — —

A First Attempt

Shorter codes for more frequent characters

character	code
K	0
I	1
D	00
R	01
'	10
S	11
␣	100

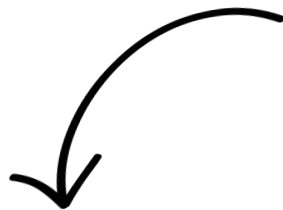
01010101110000100010

How do we decode this if we don't know the original message?

0	1	01	0	10	11	100	00	1	0	00	1	0
K	I	R	K	'	S	␣	D	I	K	D	I	K

A First Attempt

<i>character</i>	<i>code</i>
K	0
I	1
D	00
R	01
'	10
S	11
␣	100



*How do we decode this if
we don't know the
original message?*

01010101110000100010

A First Attempt



<i>character</i>	<i>code</i>
K	0
I	1
D	00
R	01
'	10
S	11
␣	100

01010101110000100010

0	1	01	0	10	11	100	00	1	0	00	1	0
K	I	R	K	'	S	␣	D	I	K	D	I	K

A First Attempt

<i>character</i>	<i>code</i>
K	0
I	1
D	00
R	01
'	10
S	11
␣	100

01010101110000100010



01	01	01	01	1	10	0	00	10	0	0	10
R	R	R	R	I	'	K	D	'	K	K	'



What Went Wrong?

- If we use a different number of bits for each letter, we can't necessarily **uniquely determine the boundaries between letters**.
- We need an encoding that makes it possible to determine where one character stops and the next starts.
- Is this possible? If so, how?

Prefix Codes

- A **prefix code** is an encoding system in which no code is a prefix of another code.
- Here's a sample prefix code for the letters in **KIRK'S DIKDIK**.

<i>character</i>	<i>code</i>
K	10
I	01
D	111
R	001
'	000
S	1101
␣	1100

Prefix Codes Example

10010011000011011100
11101101110110

<i>character</i>	<i>code</i>
K	10
I	01
D	111
R	001
'	000
S	1101
␣	1100

10	01	001	10	000	1101	1100	111	01	10	111	01	10
K	I	R	K	'	S	␣	D	I	K	D	I	K

Prefix Codes Example

10010011000011011100
11101101110110

<i>character</i>	<i>code</i>
K	10
I	01
D	111
R	001
'	000
S	1101
┘	1100

Prefix Codes Example

10010011000011011100
11101101110110

<i>character</i>	<i>code</i>
K	10
I	01
D	111
R	001
'	000
S	1101
┘	1100

Prefix Codes Example

10010011000011011100
11101101110110

<i>character</i>	<i>code</i>
K	10
I	01
D	111
R	001
'	000
S	1101
⌞	1100

Prefix Codes Example

10010011000011011100
11101101110110

10

K

character

code

K	10
I	01
D	111
R	001
'	000
S	1101
┘	1100

Prefix Codes Example

10010011000011011100
11101101110110

10

K

character *code*

K	10
I	01
D	111
R	001
'	000
S	1101
⌞	1100

Prefix Codes Example

10010011000011011100
11101101110110

10

K

character *code*

K	10
I	01
D	111
R	001
'	000
S	1101
⌞	1100

Prefix Codes Example

10010011000011011100
11101101110110

10	01
K	I

<i>character</i>	<i>code</i>
K	10
I	01
D	111
R	001
'	000
S	1101
┘	1100

Prefix Codes Example

10010011000011011100
11101101110110

10	01
K	I

<i>character</i>	<i>code</i>
K	10
I	01
D	111
R	001
'	000
S	1101
⌞	1100

Prefix Codes Example

10010011000011011100
11101101110110

10	01
K	I

<i>character</i>	<i>code</i>
K	10
I	01
D	111
R	001
'	000
S	1101
┘	1100

Prefix Codes Example

10010011000011011100
11101101110110

10	01
K	I

<i>character</i>	<i>code</i>
K	10
I	01
D	111
R	001
'	000
S	1101
┘	1100

Prefix Codes Example

10010011000011011100
11101101110110

10	01	001
K	I	R

<i>character</i>	<i>code</i>
K	10
I	01
D	111
R	001
'	000
S	1101
⌞	1100



Prefix Codes Summary

- Using this prefix code, we can represent **KIRK'S DIKDIK** as the sequence

1001001100001101110011101101110110

- This uses just 34 bits, compared to our initial 104 (using ASCII). Wow!
- Many questions remain: Where did this code come from? How could you come up with codes like this for other strings? What makes a "good" prefix coding scheme? What does this all have to do with trees?



Prefix Codes Summary

- Using this prefix code, we can represent **KIRK'S DIKDIK** as the sequence

1001001100001101110011101101110110

- This uses just 34 bits, compared to our initial 104 (using ASCII). Wow!
- Many questions remain: Where did this code come from? How could you come up with codes like this for other strings? What makes a "good" prefix coding scheme? **What does this all have to do with trees?**



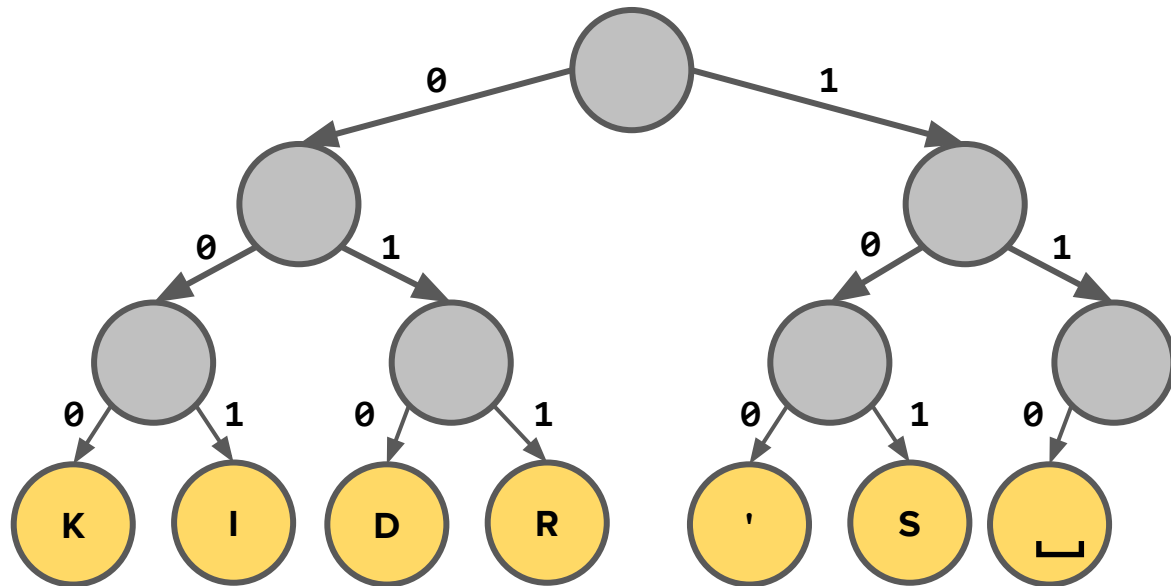
The Trees are Back in Town

- **Main Insight:** We can represent a prefix coding scheme with a binary tree! This special type of binary tree is called a **coding tree**.

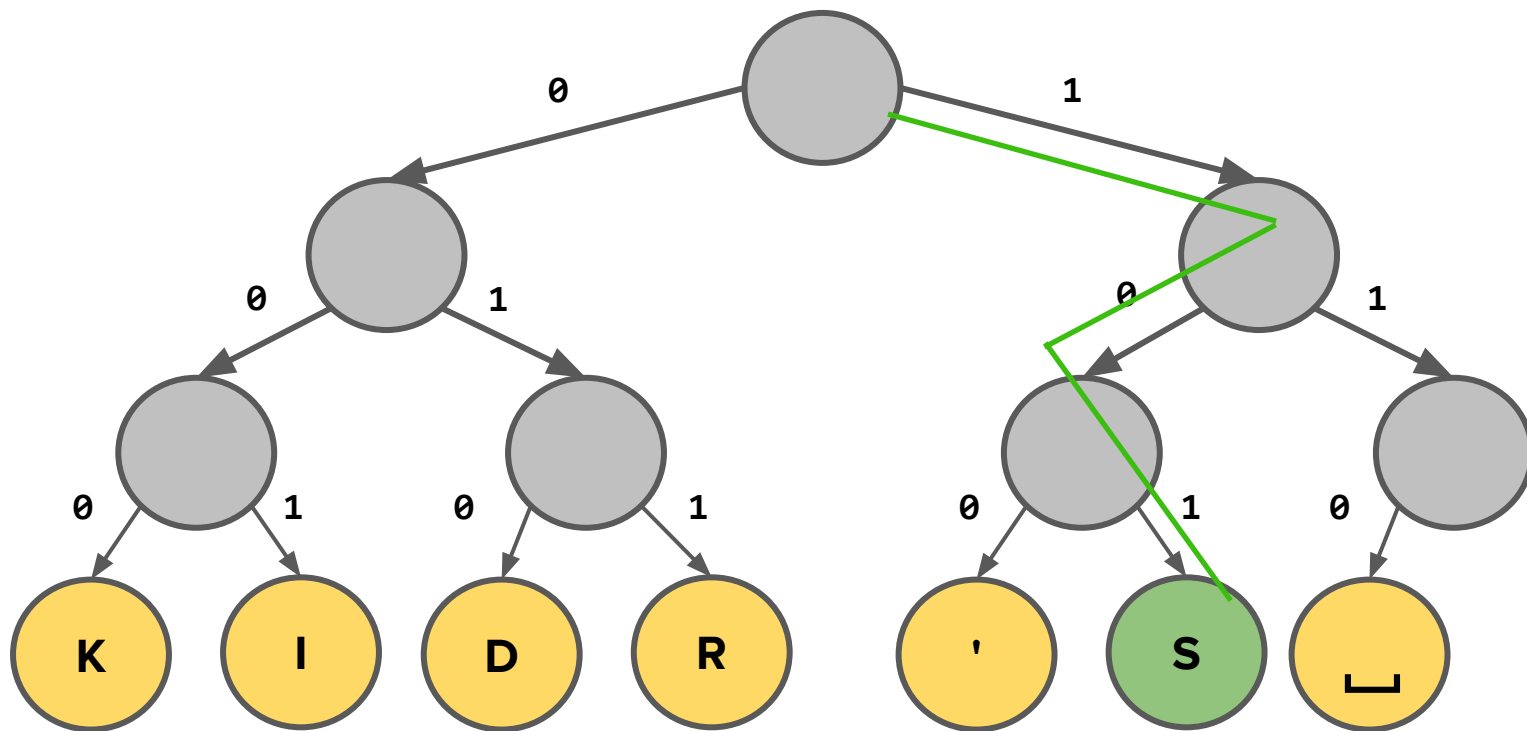
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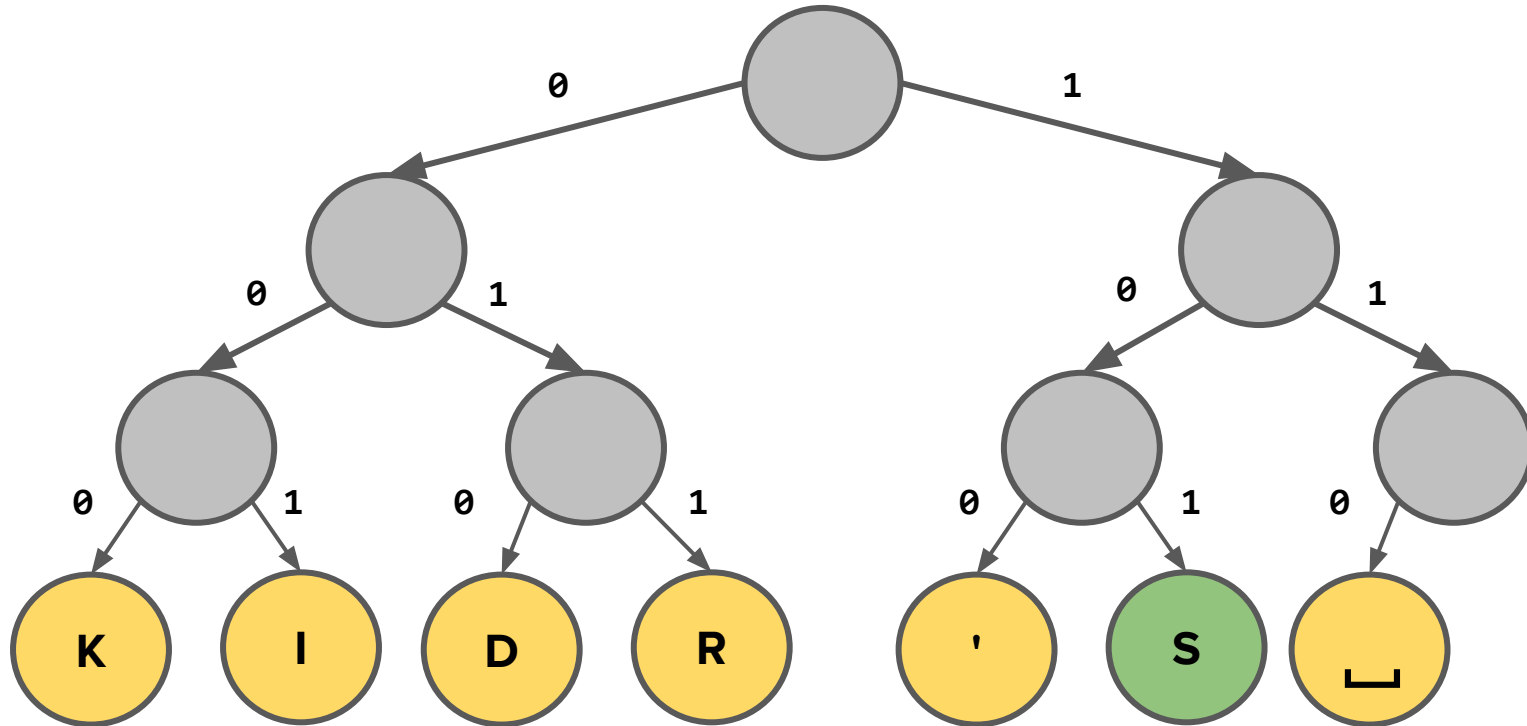
<i>character</i>	<i>code</i>
K	000
I	001
D	010
R	011
'	100
S	101
	110



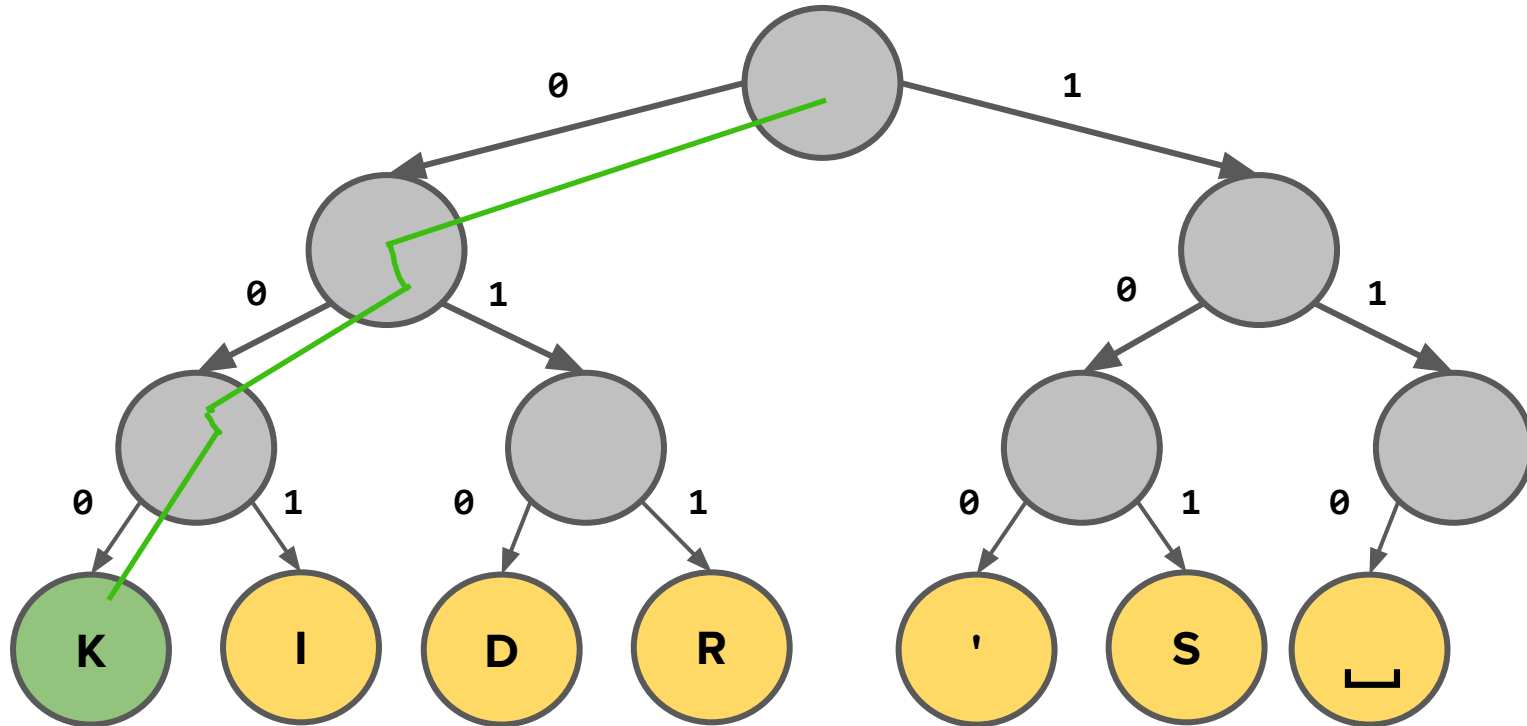
Prefix Coding Mystery: 101000001



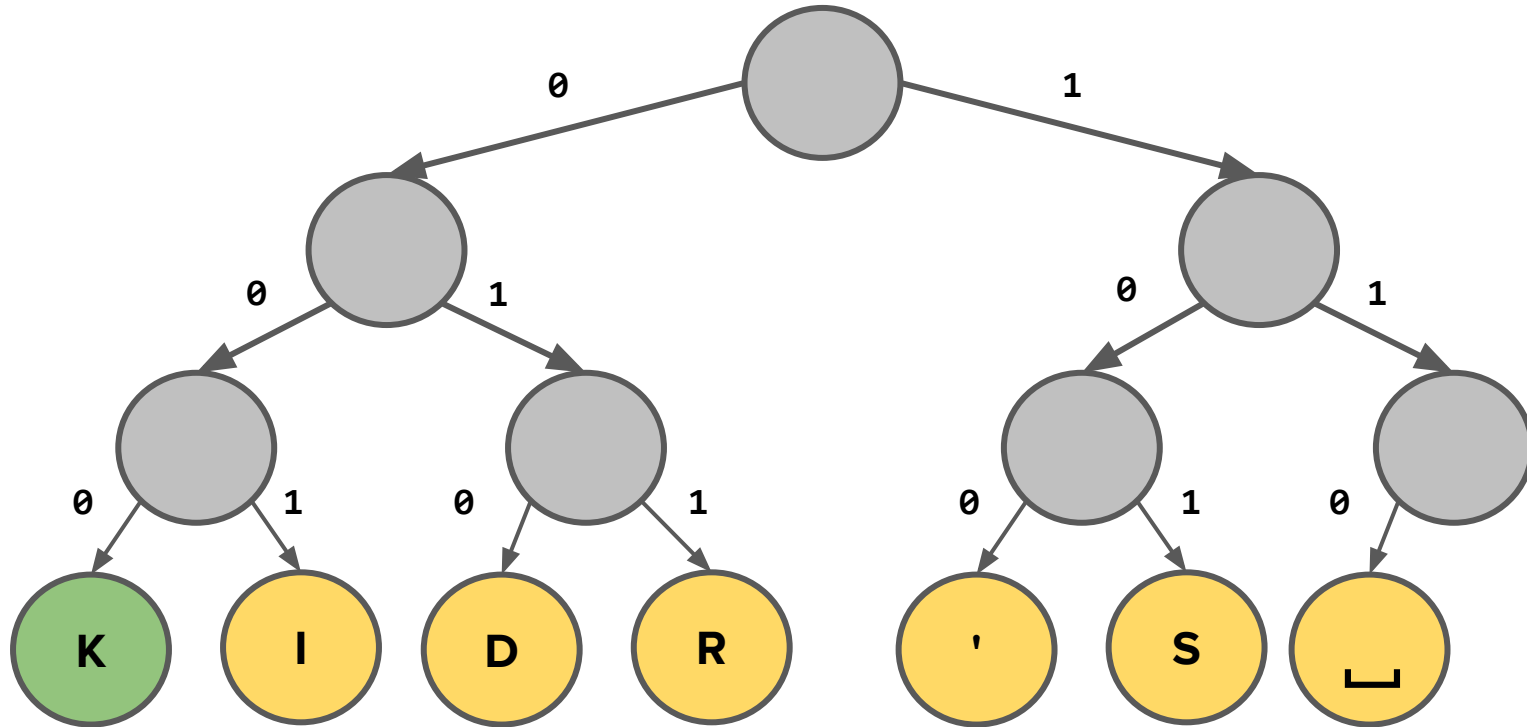
Prefix Coding Mystery: S 000001



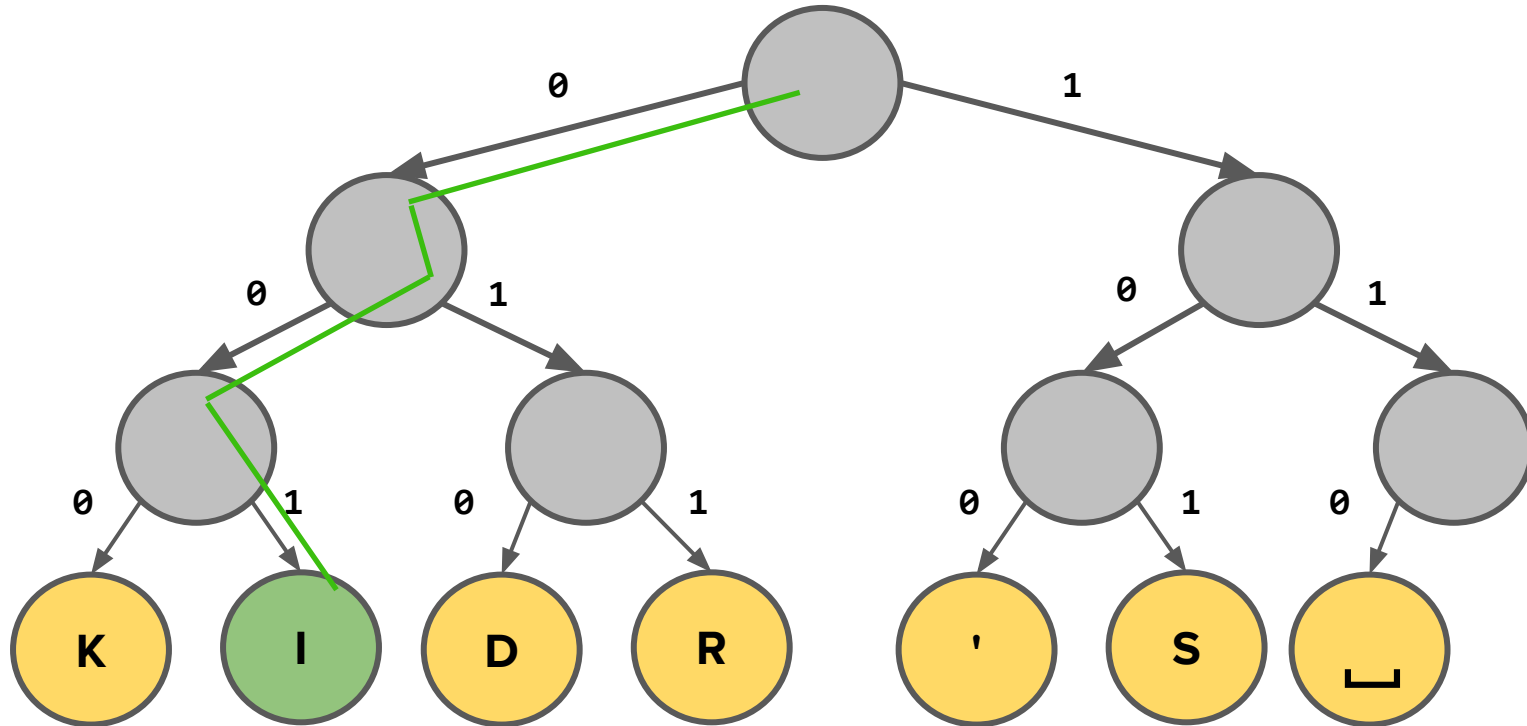
Prefix Coding Mystery: S 000001



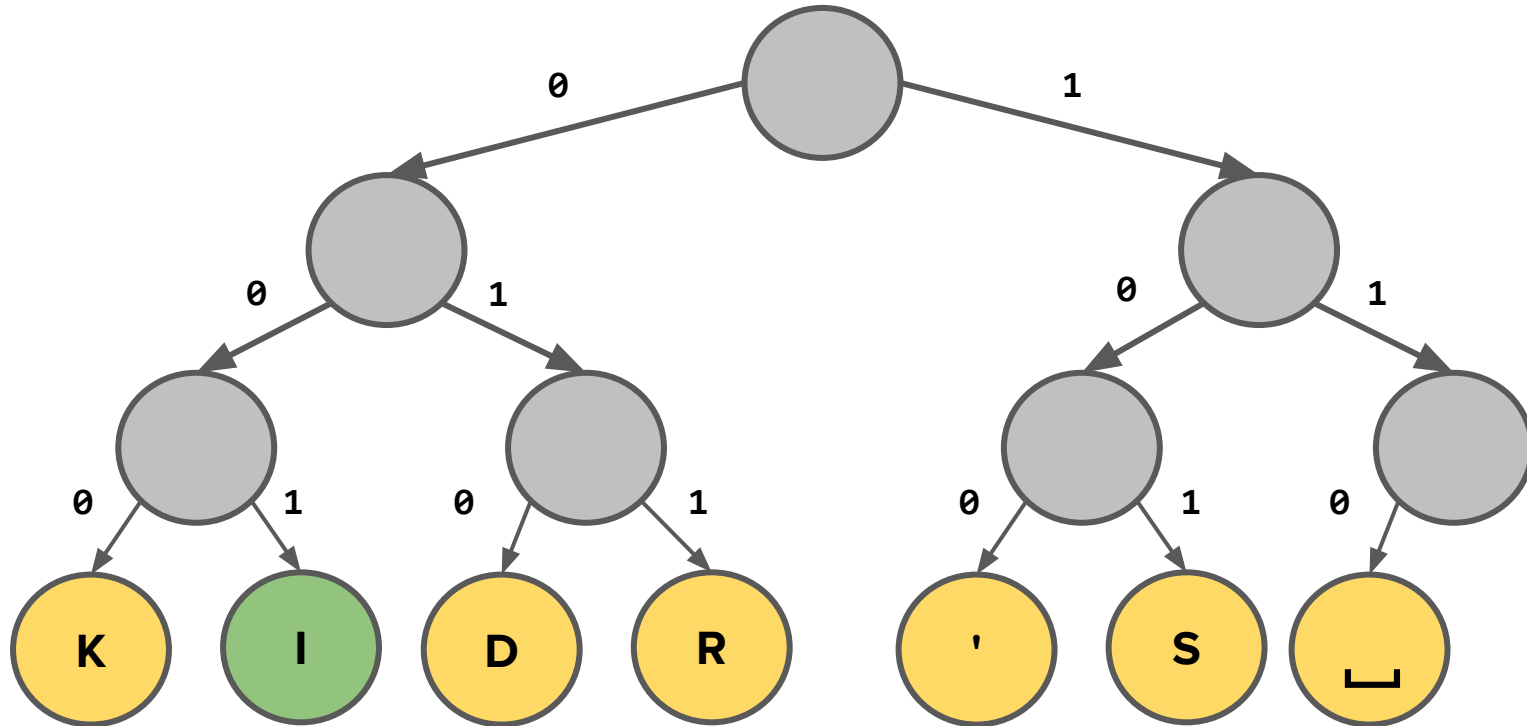
Prefix Coding Mystery: S K 001



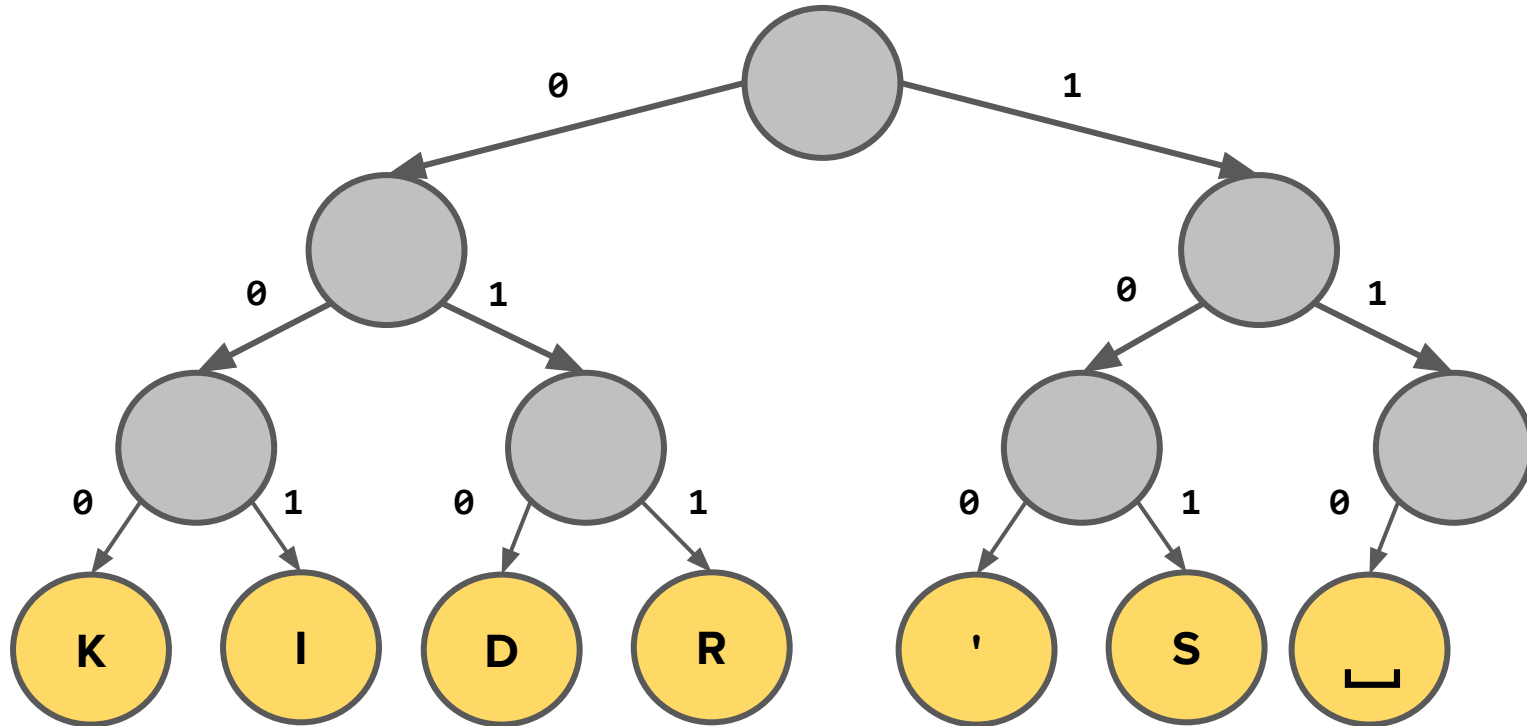
Prefix Coding Mystery: S K 001



Prefix Coding Mystery: S K I

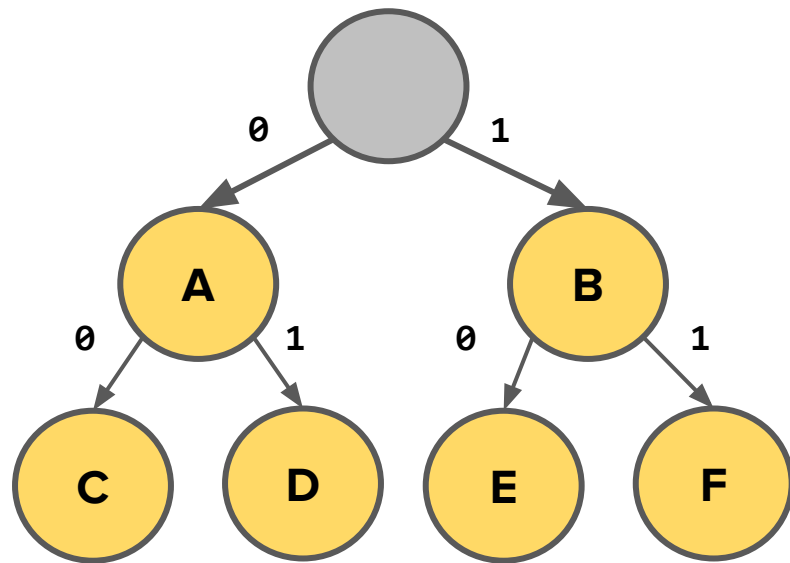


Prefix Coding Mystery: SKI



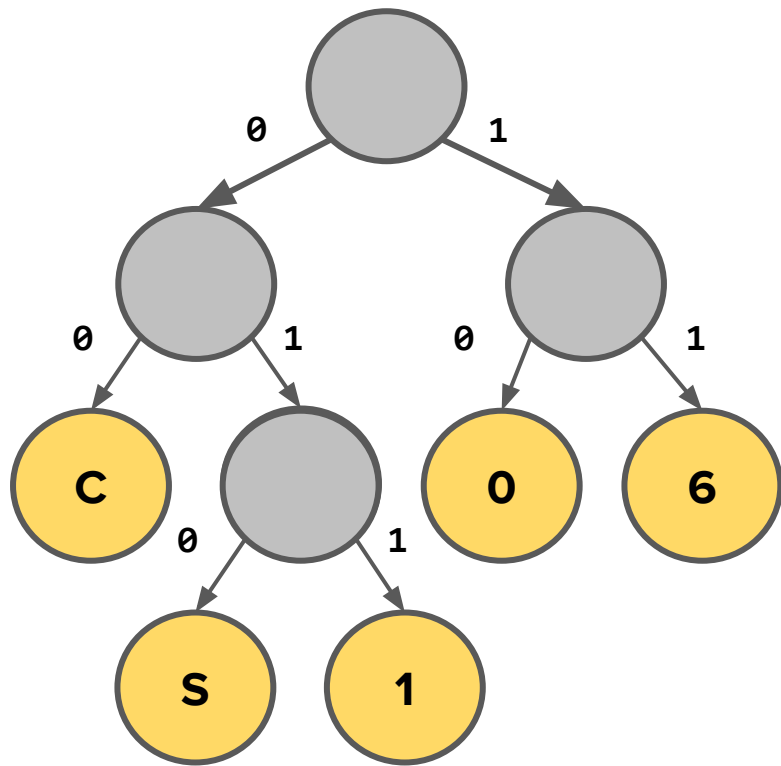
Coding Trees

- Not all binary trees will work as coding trees.
- Why is the one to the right not a valid coding tree?
- **Answer:** It doesn't give a prefix code. The code for A is a prefix for the codes for C and D.



Coding Trees

- A coding tree is valid if all the letters are stored at the **leaves**, with internal nodes just doing the routing.
- **Goal:** Find the best coding tree for a string.
- **Question:** How do we find the best binary tree with this property?





Announcements



Announcements

- Assignment 6 will be released by the end of the day today and will be due on **Wednesday, August 12 at 11:59pm PDT**. This is a hard deadline – there is **no grace period and no submissions will be accepted after this time**.
- Final project reports are due on **Sunday, August 9 at 11:59pm PDT**. You will have the opportunity to schedule your final presentation time after submitting. Reports should be submitted to Paperless and time slot sign-ups will also happen through Paperless.



Huffman Coding



Story Time

Link to full story here:

https://www.maa.org/sites/default/files/images/upload_library/46/Pengelley_projects/Project-14/Huffman.pdf



The Algorithm



Huffman Coding

- Huffman coding is an algorithm for generating a coding tree for a given piece of data that produces a **provably minimal encoding** for a given pattern of letter frequencies.
- Different data (different text, different images, etc.) will each have their own personalized Huffman coding tree.
- The Huffman coding algorithm is a flexible, powerful, adaptive algorithm for data compression. And you will implement it on the final assignment as your capstone accomplishment of the quarter!

Huffman Coding Pseudocode

- To generate the optimal encoding tree for a given piece of text:
 - Build a **frequency table** that tallies the number of times each character appears in the text.
 - Initialize an empty **priority queue** that will hold partial trees (represented as **TreeNode***)
 - Create **one leaf node per distinct character in the input string**. Add each new leaf node to the priority queue. The weight of that leaf is the frequency of the character.
 - While there are two or more trees in the priority queue:
 - Dequeue the two lowest-priority trees.
 - **Combine them together to form a new tree** whose weight is the sum of the weights of the two trees.
 - Add that tree back to the priority queue.



Huffman in Action



Our goal: Build the optimal encoding
tree for **KIRK 'S DIKDIK**

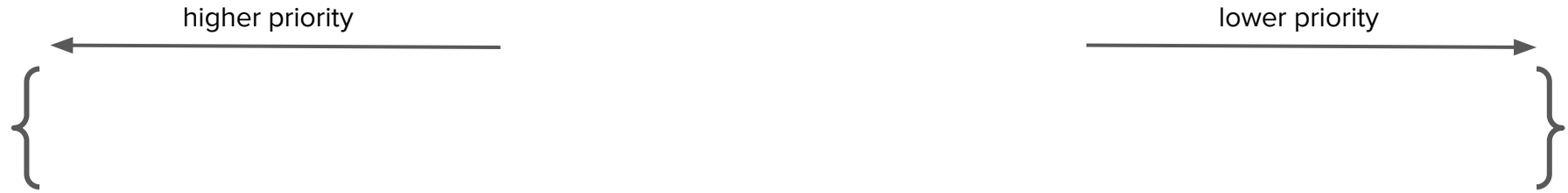
1) Build the frequency table

Input Text: **KIRK'S DIKDIK**

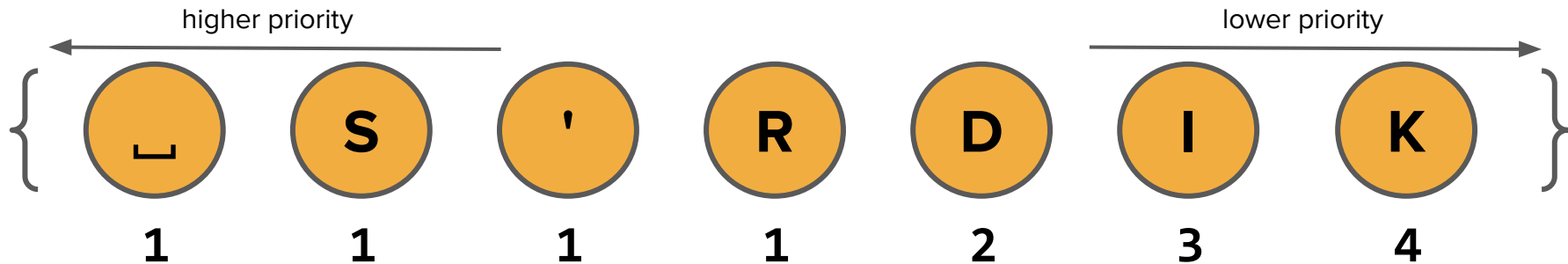
<i>character</i>	<i>frequency</i>
K	4
I	3
D	2
R	1
'	1
S	1
	1



2) Initialize the priority queue



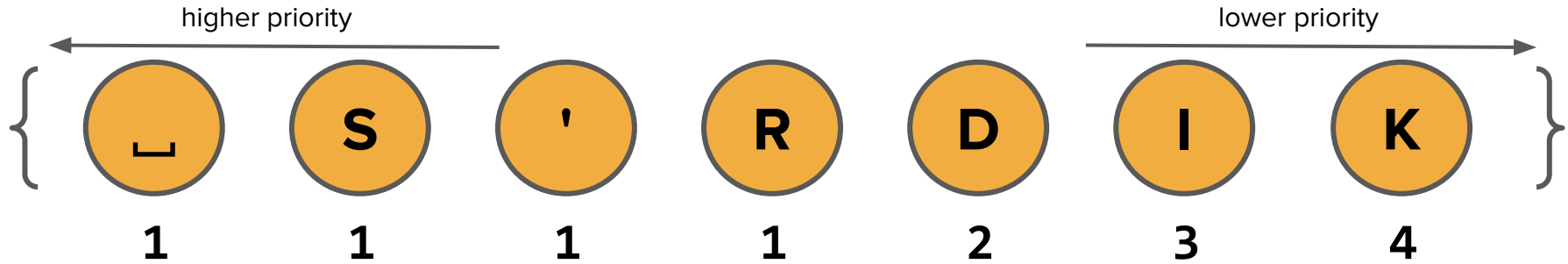
3) Add all unique characters as leaf nodes to queue



character *frequency*

K	4
I	3
D	2
R	1
'	1
S	1
	1

4) Build the Huffman tree by joining adjacent nodes



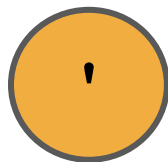
higher priority

Trial Version



Wondershare
PDFelement

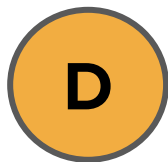
1



1



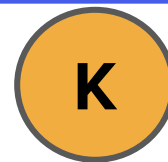
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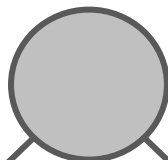
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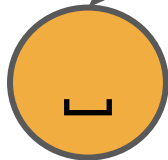
3



2

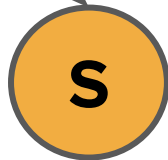


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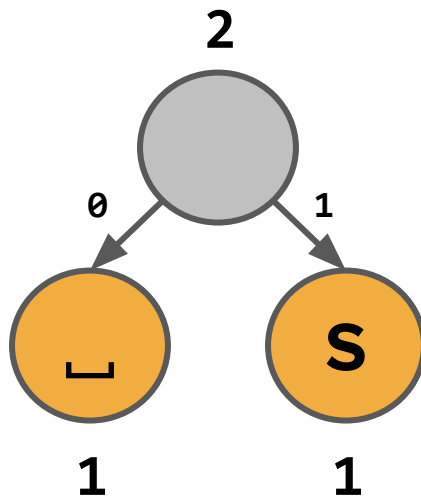


1

1



1

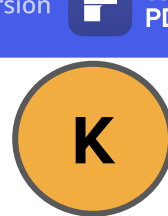
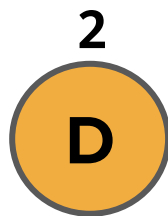
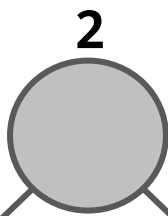
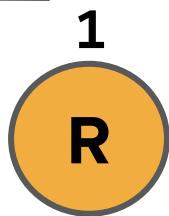
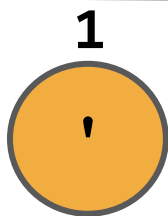


higher priority

Trial Version

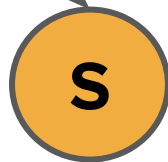
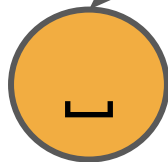


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PDFelement



0

1



1

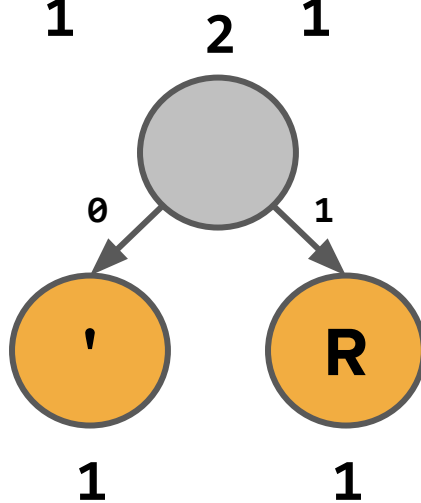
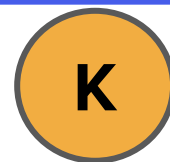
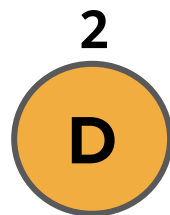
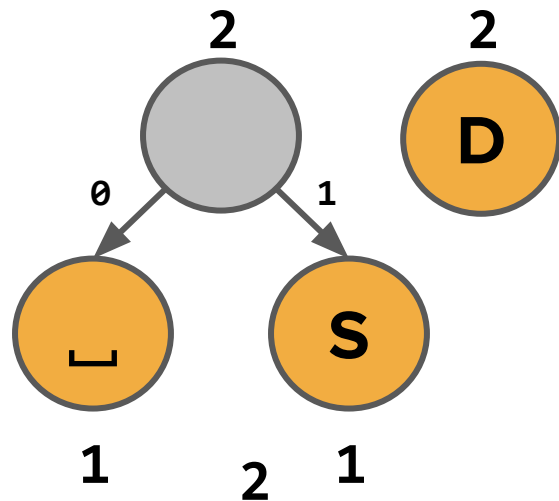
1

higher priority ←

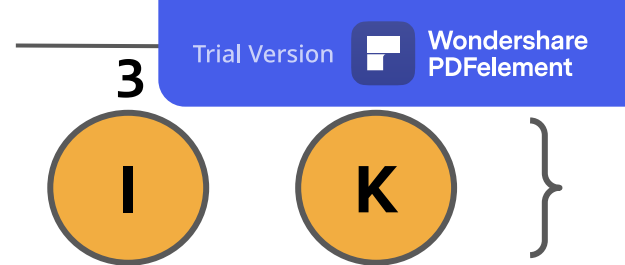
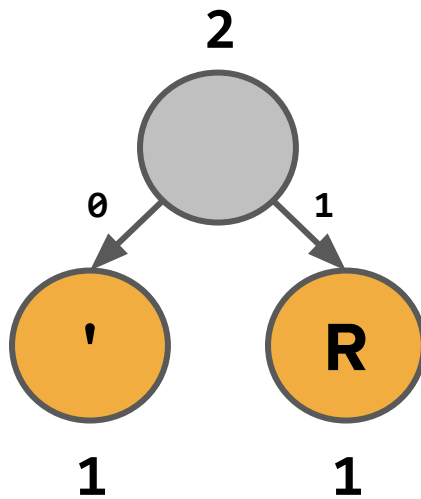
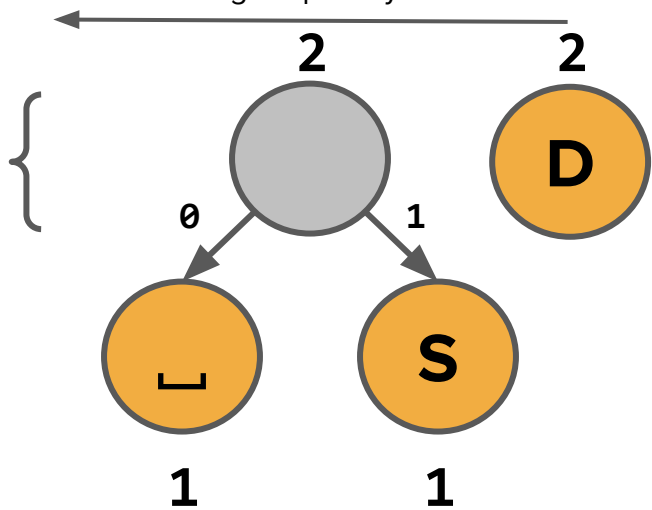
Trial Version



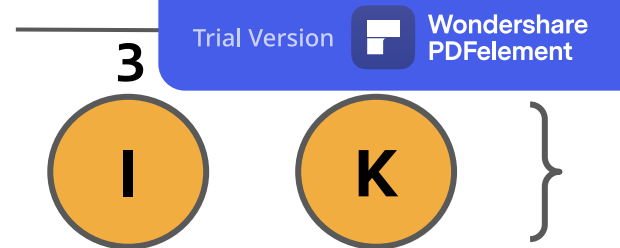
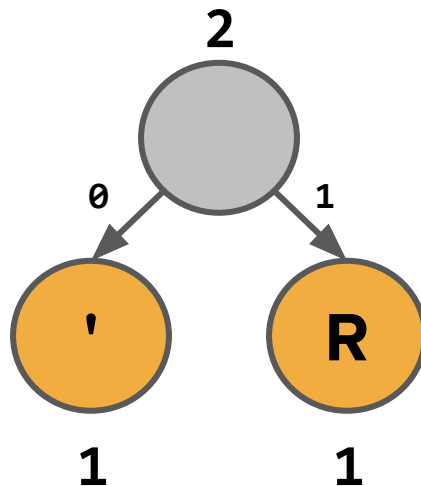
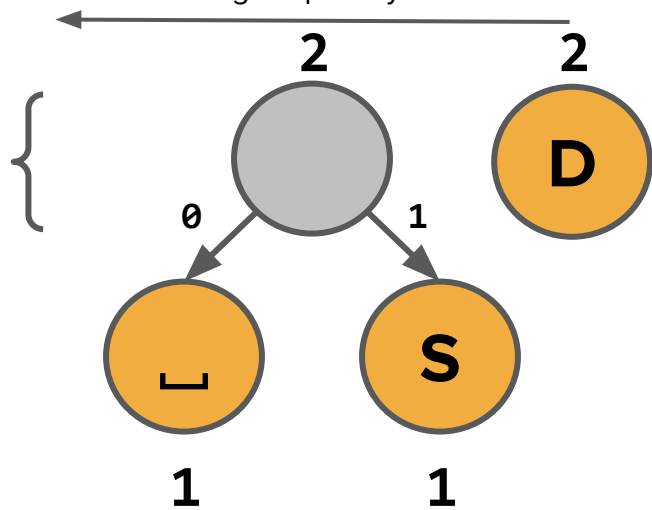
Wondershare
PDFelement



higher priority



higher priority



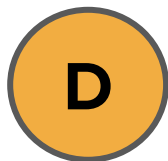
Trial Version



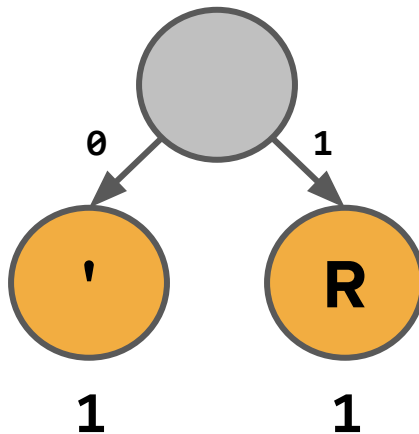
Wondershare
PDFelement

higher priority

2



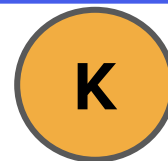
2



3



K



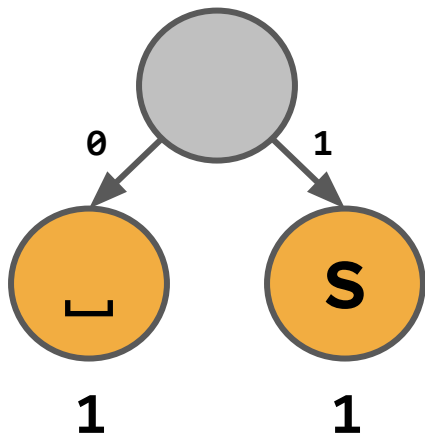
Trial Version



Wondershare
PDFelement

0

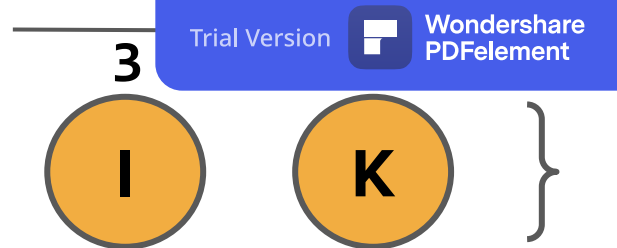
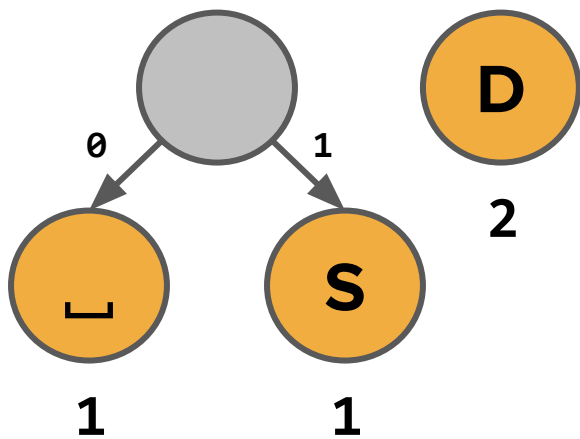
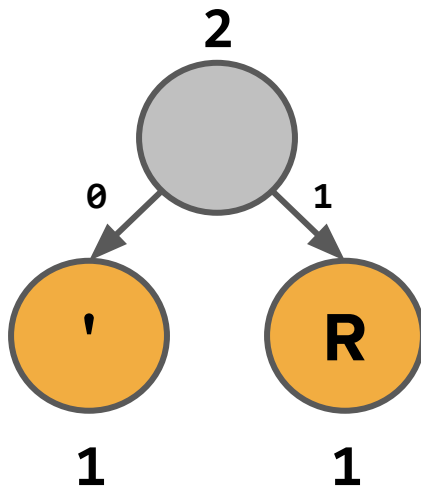
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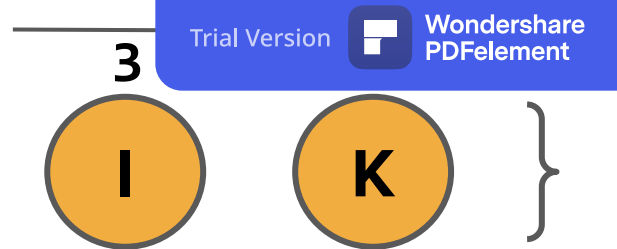
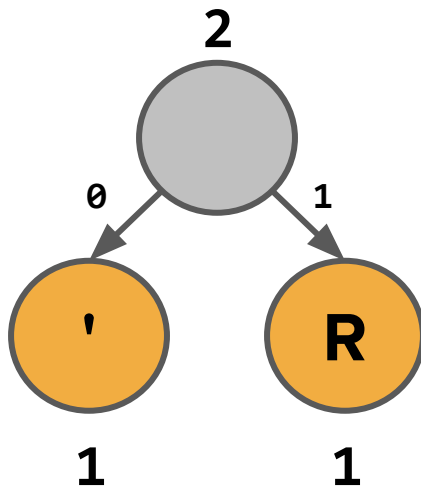
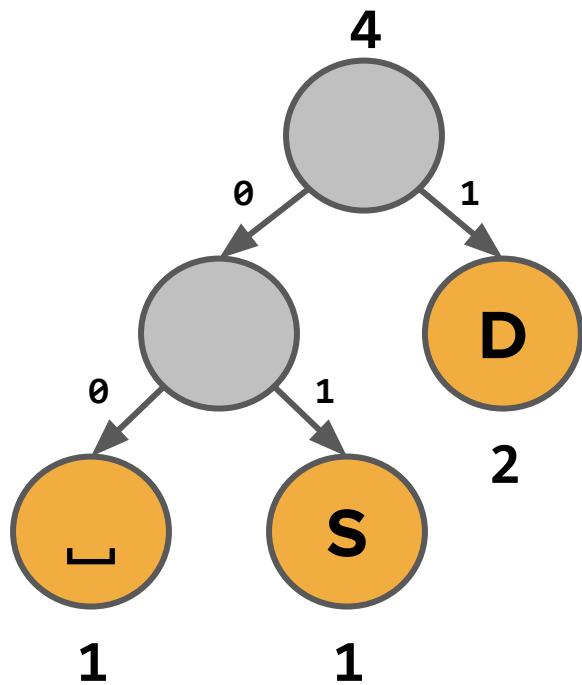
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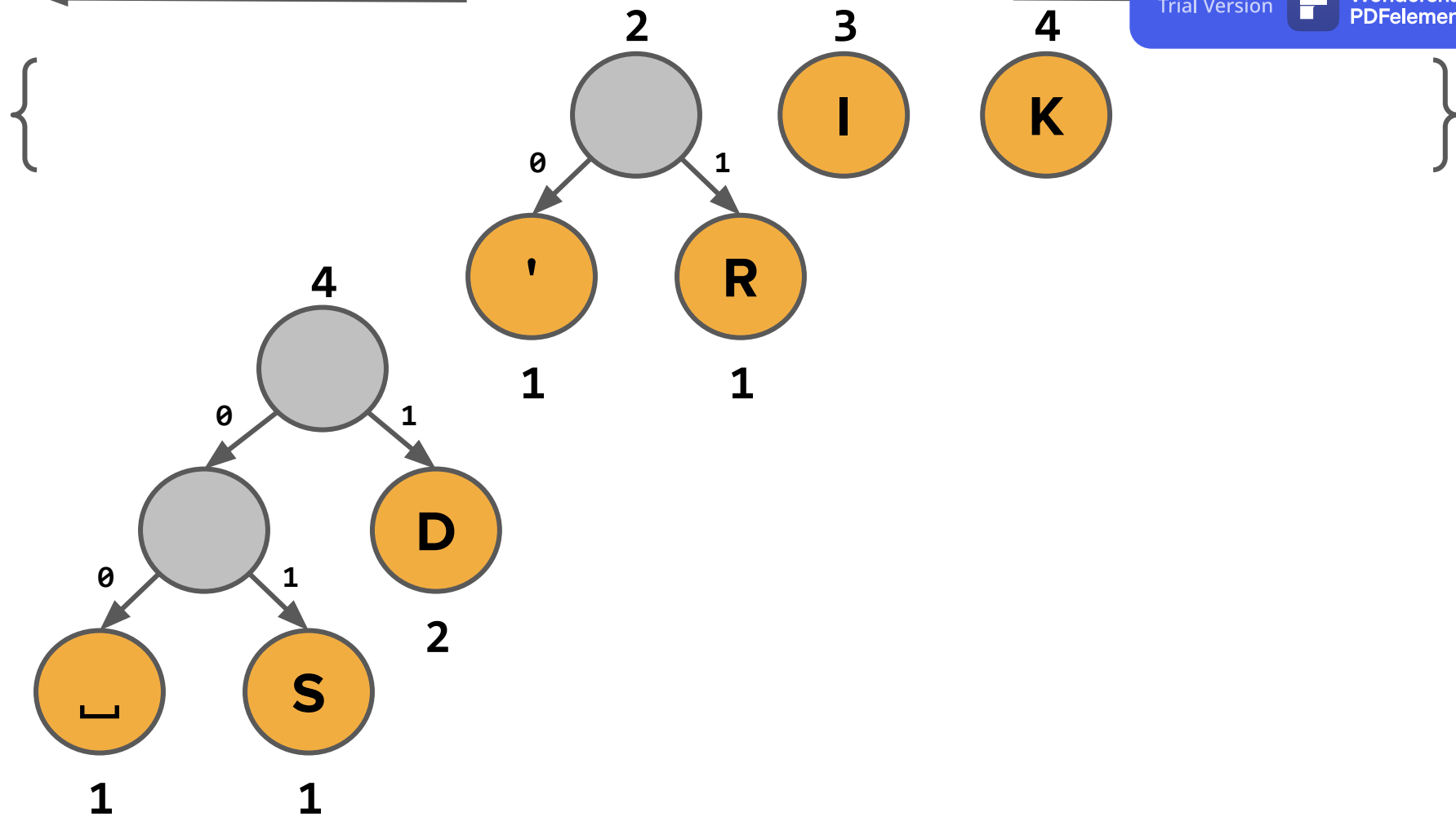
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higher priority



higher priority



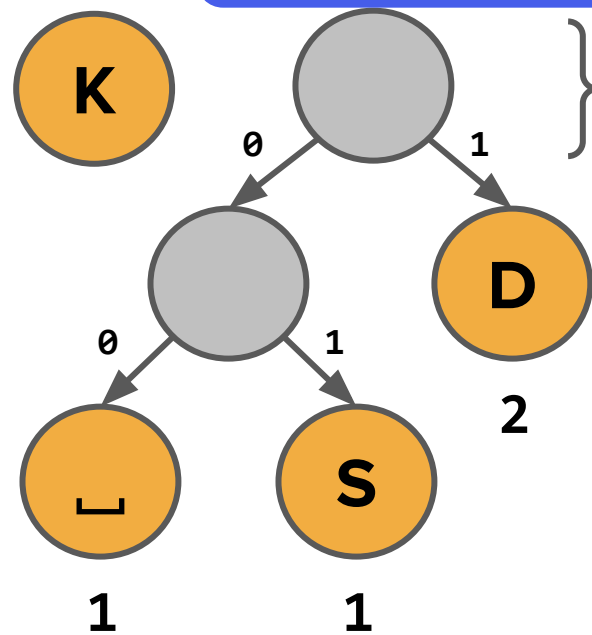
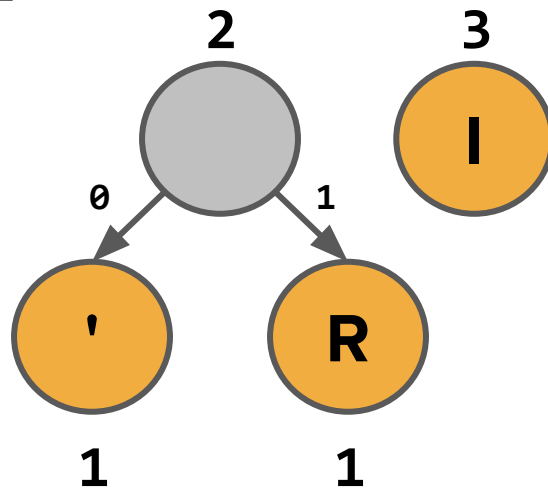


higher priority ←

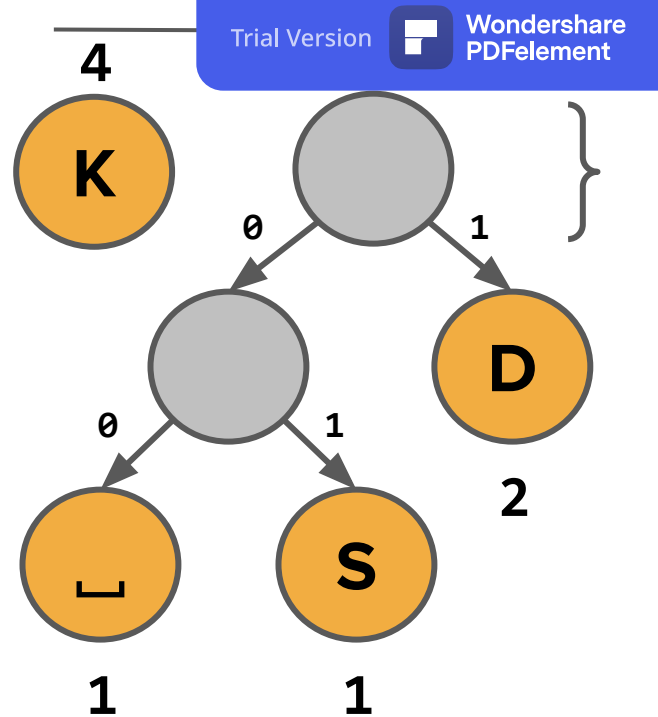
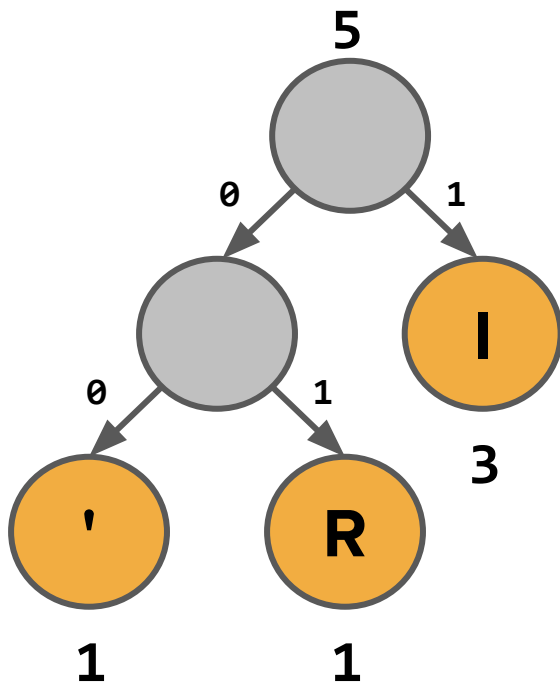
Trial Version



Wondershare
PDFelement



higher priority

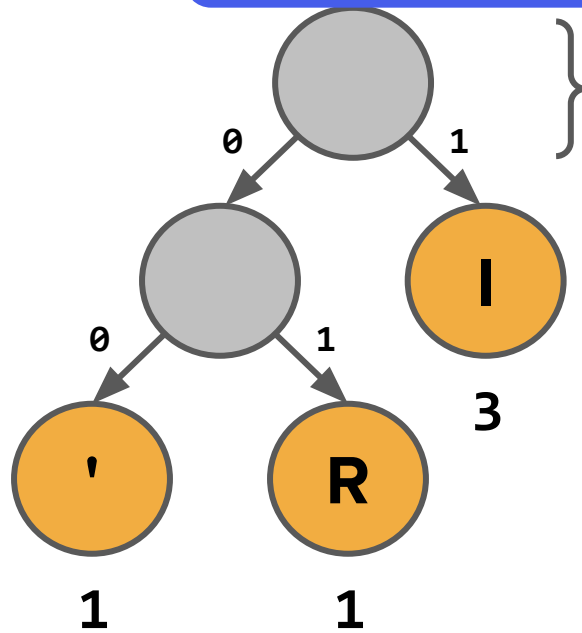
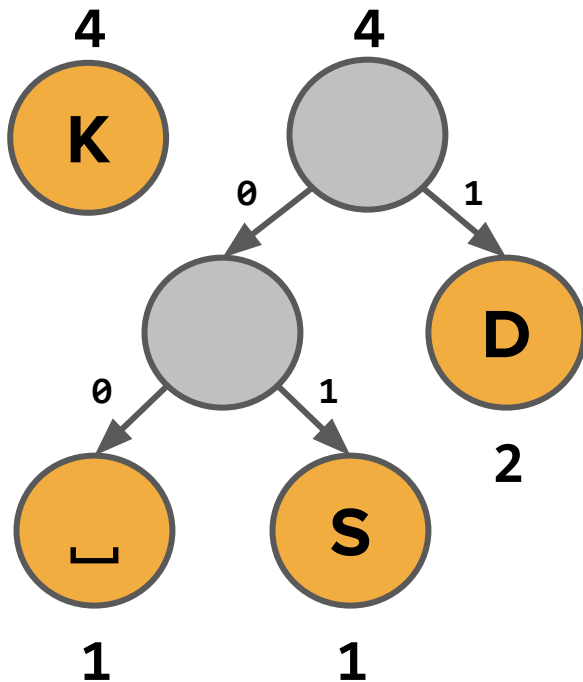


higher priority ←

Trial Version



Wondershare
PDFelement

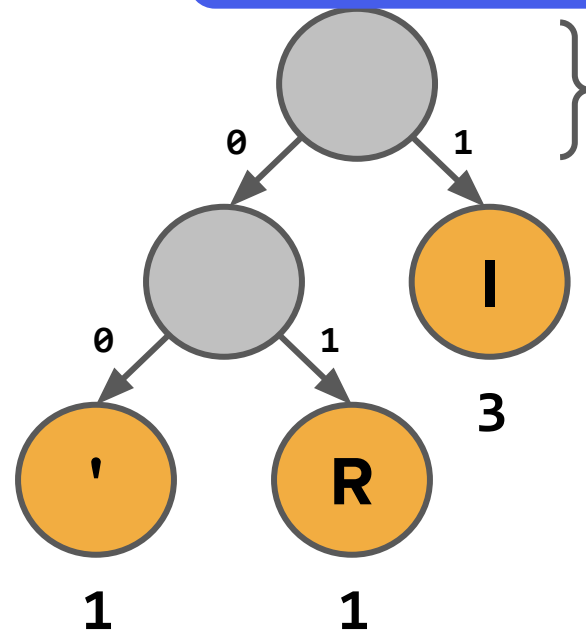
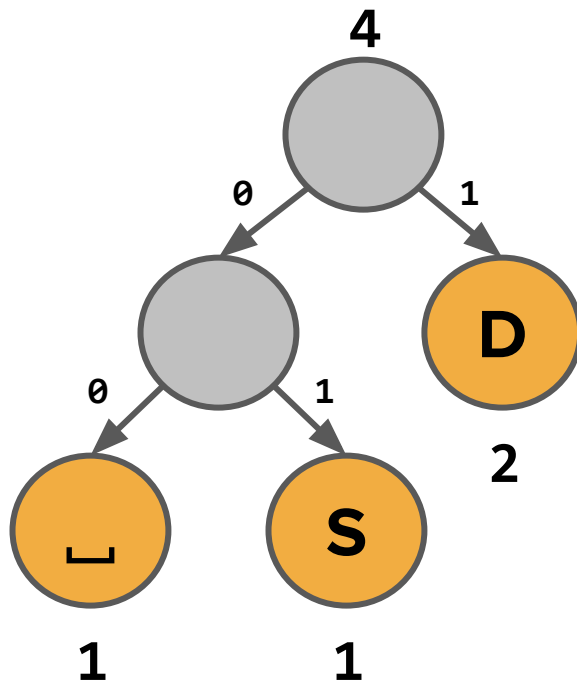
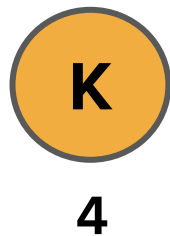


higher priority

Trial Version



Wondershare
PDFelement

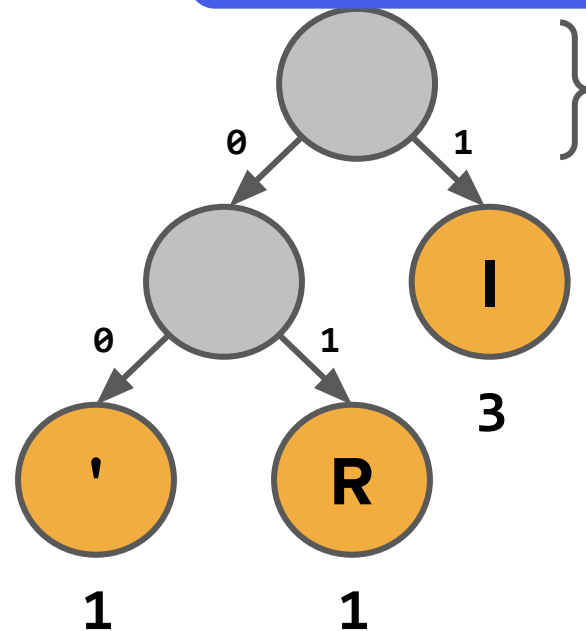
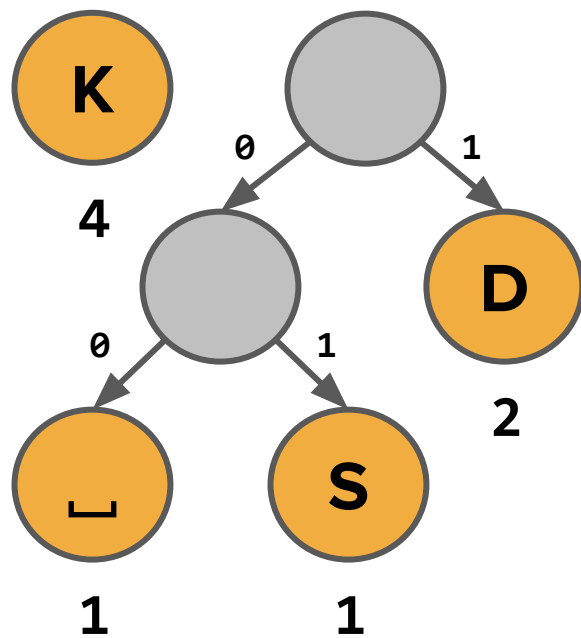


higher priority

Trial Version



Wondershare
PDFelement

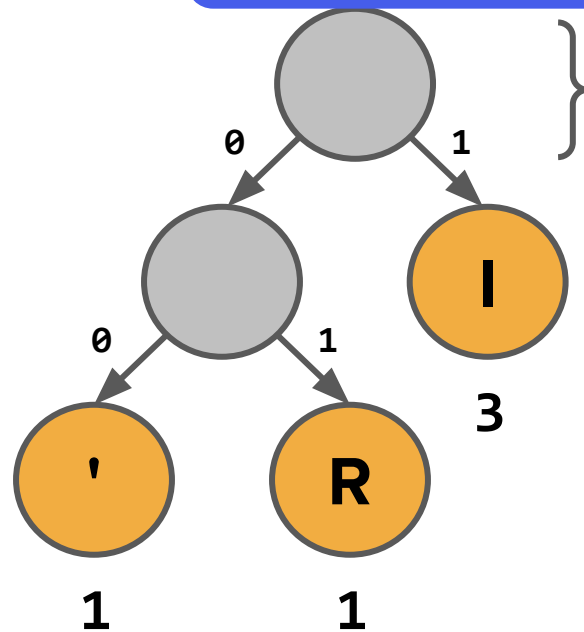
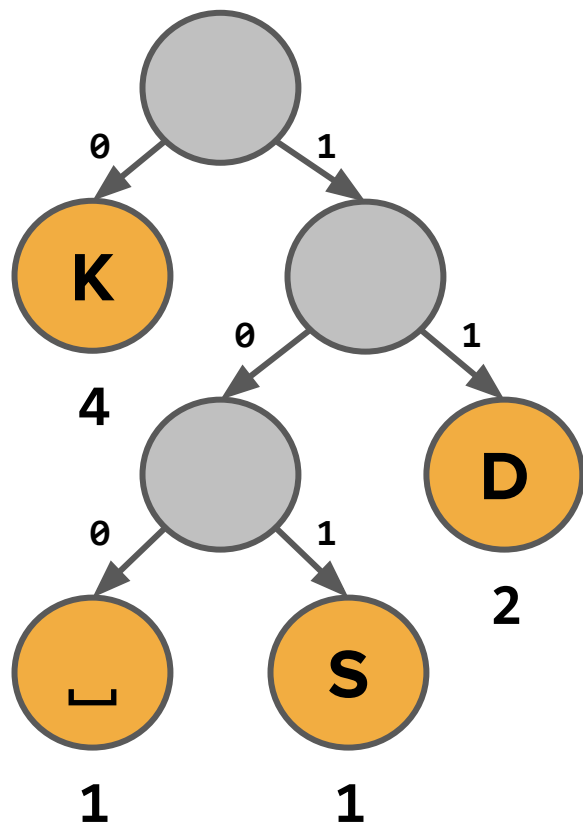


higher priority

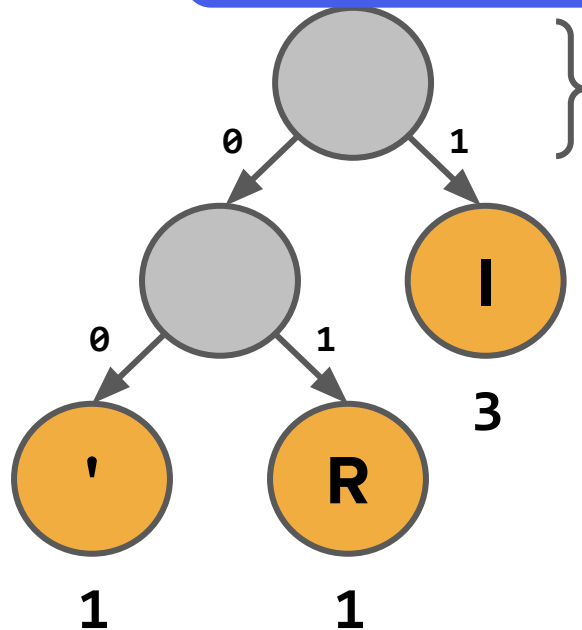
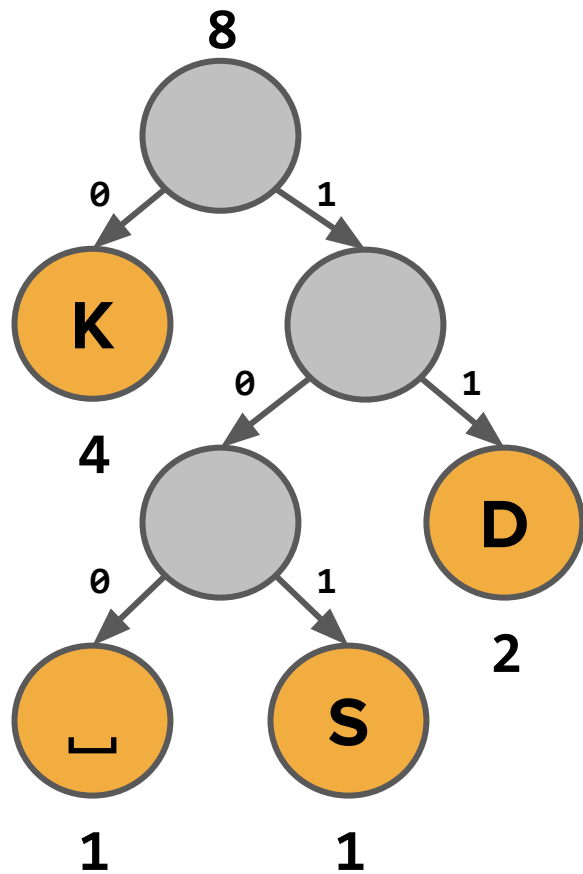
Trial Version



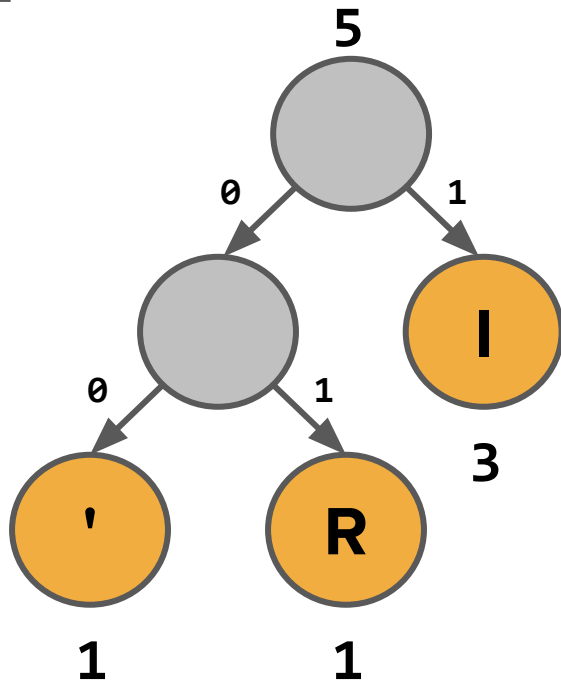
Wondershare
PDFelement



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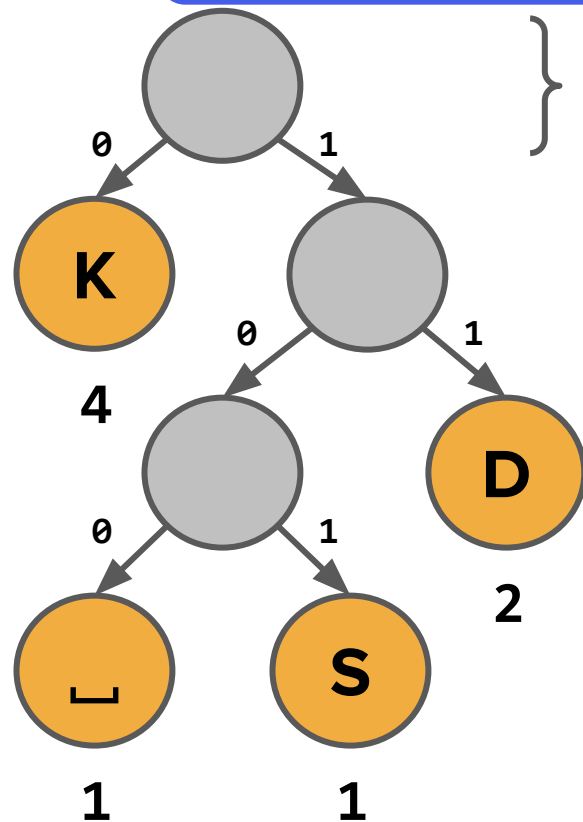
higher priority ←



Trial Version



Wondershare
PDFelement

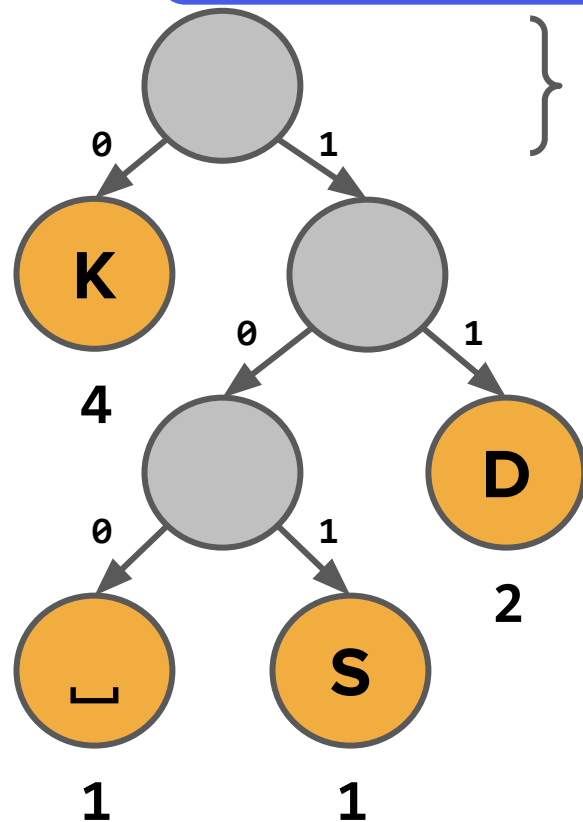
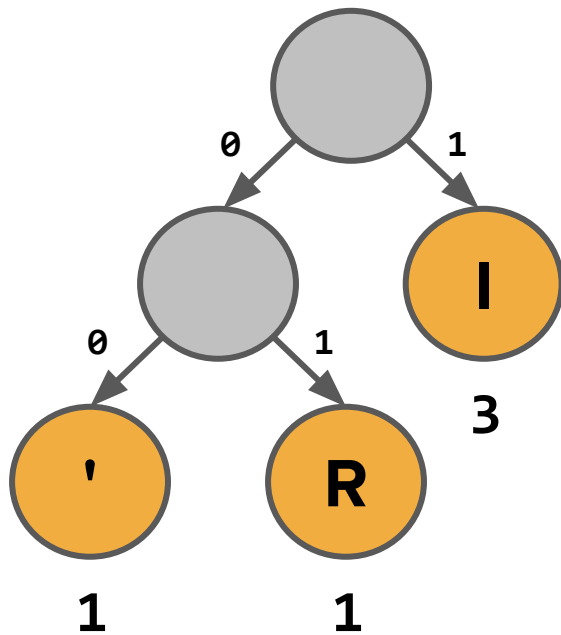


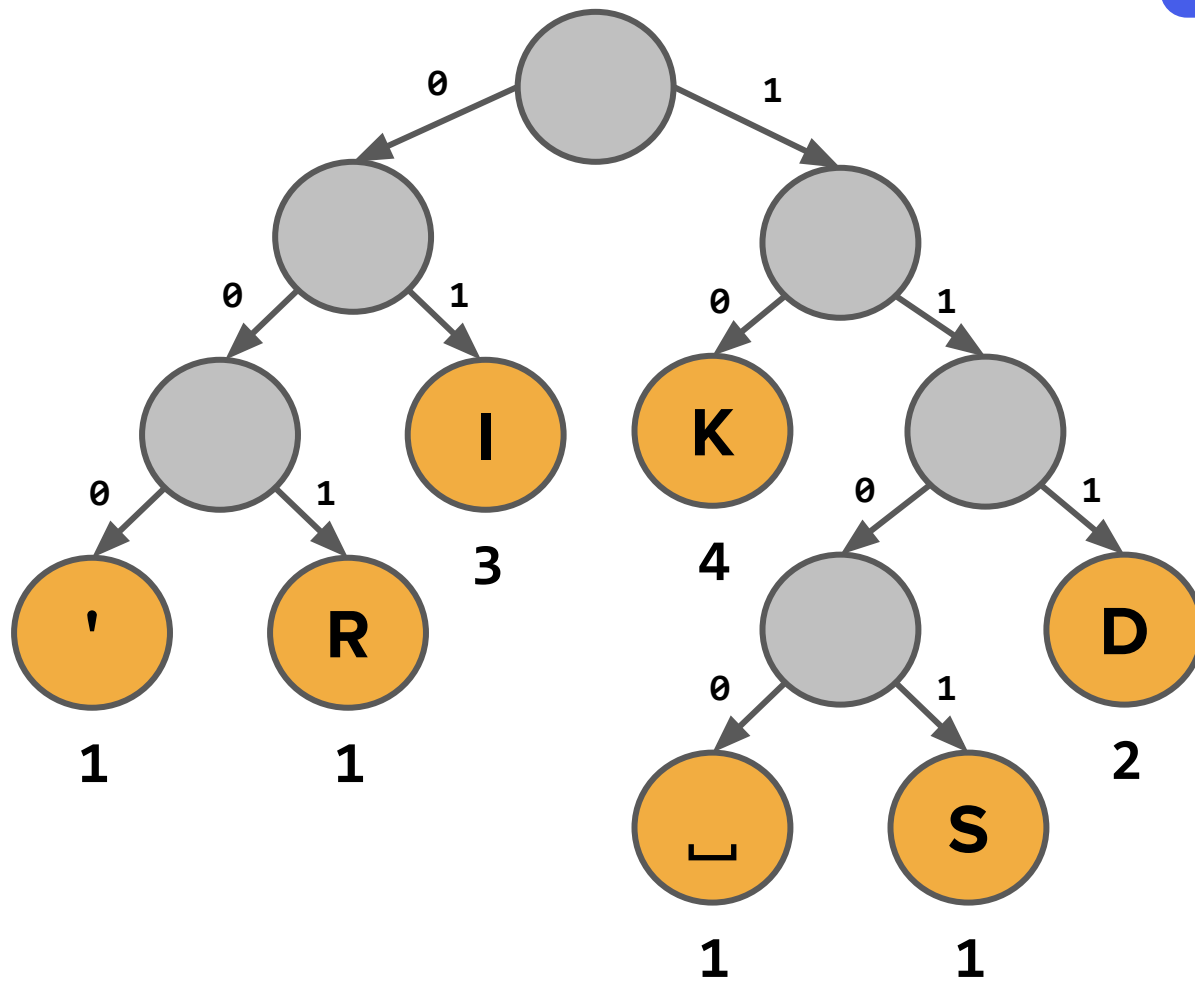
higher priority

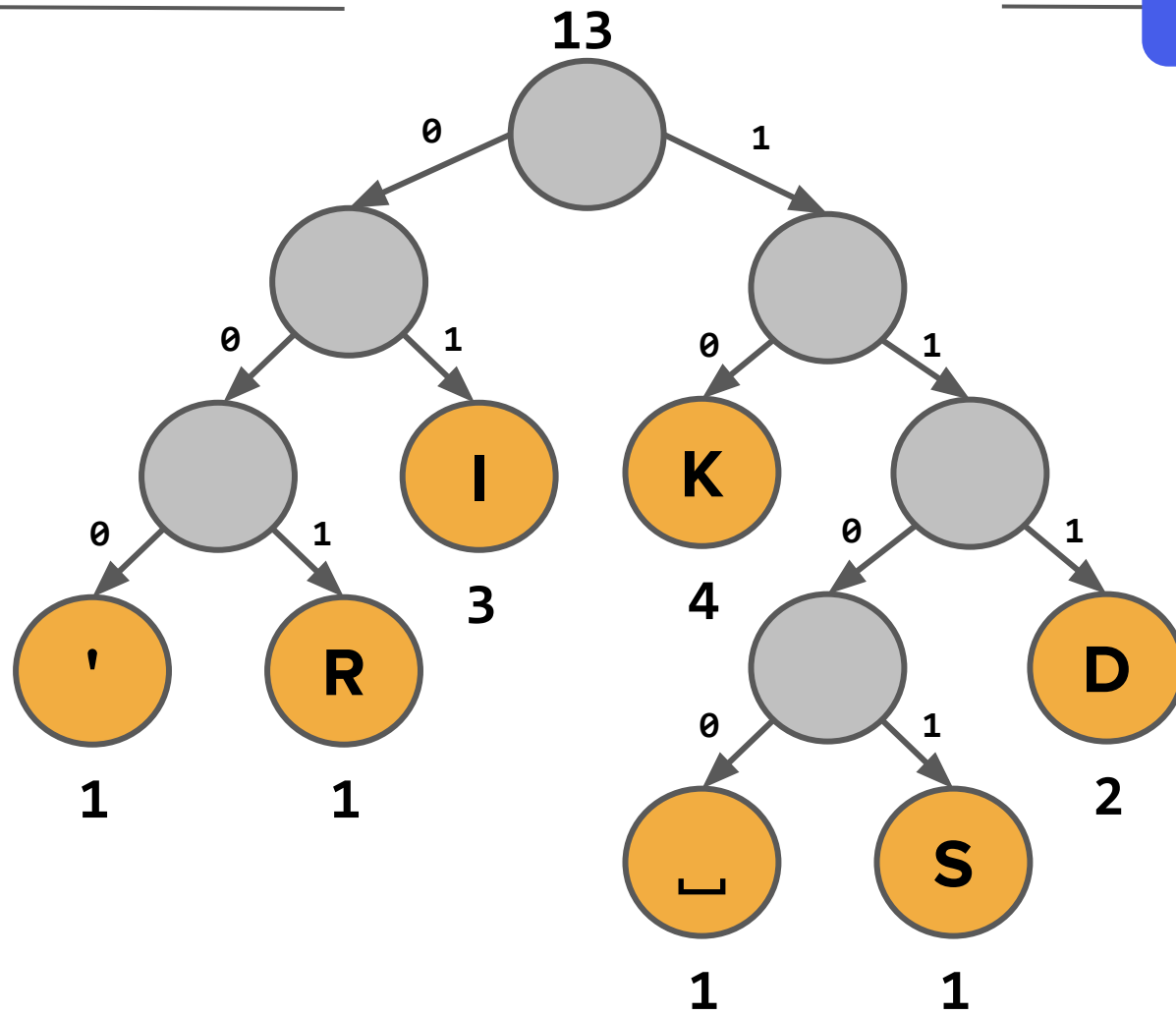
Trial Version

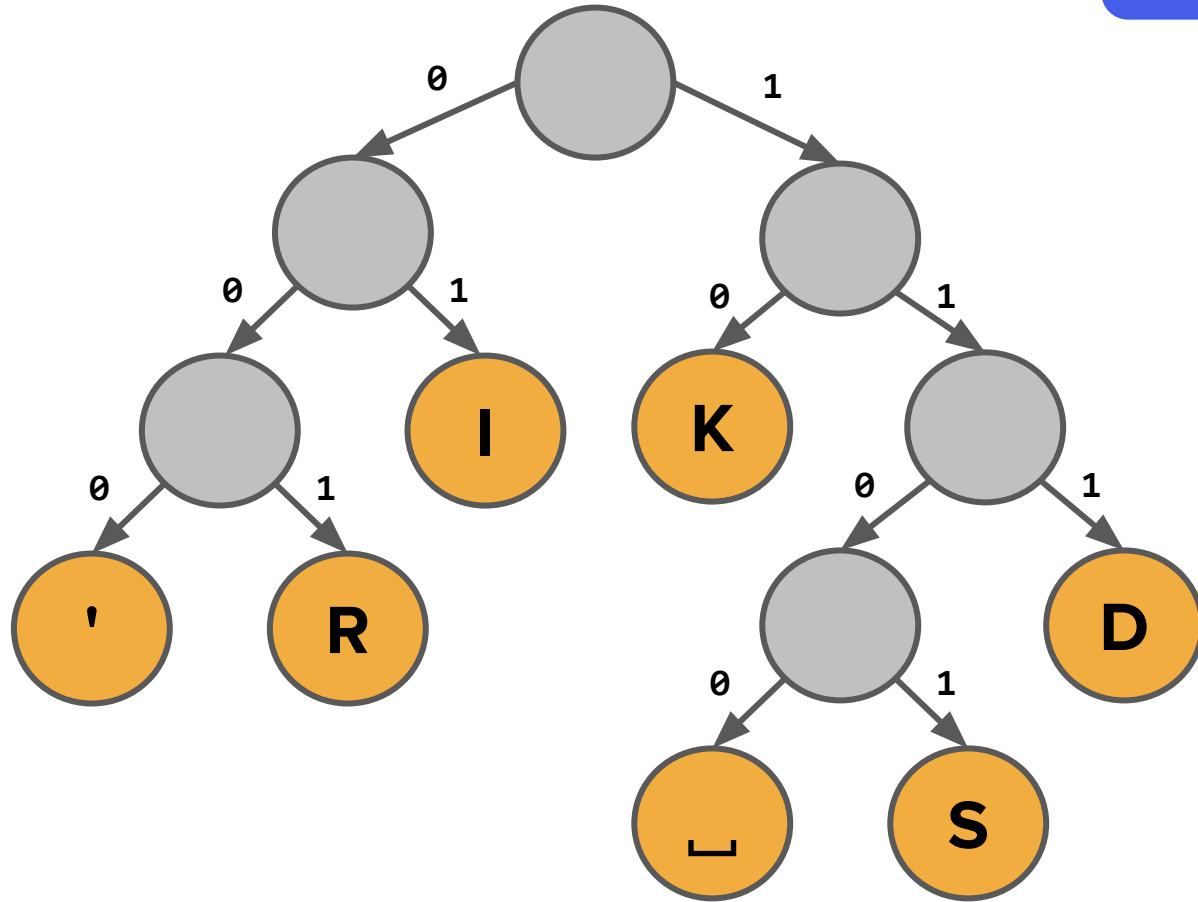


Wondershare
PDFelement

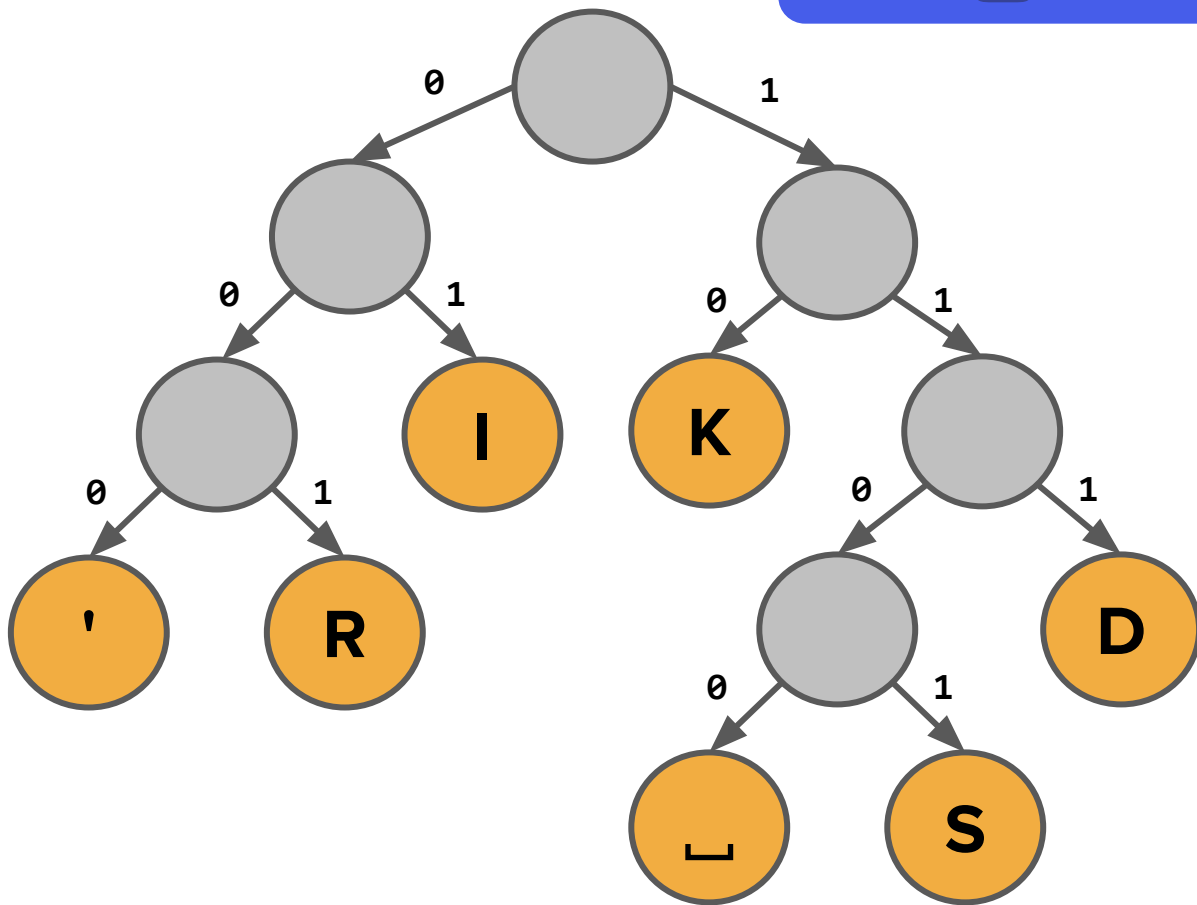




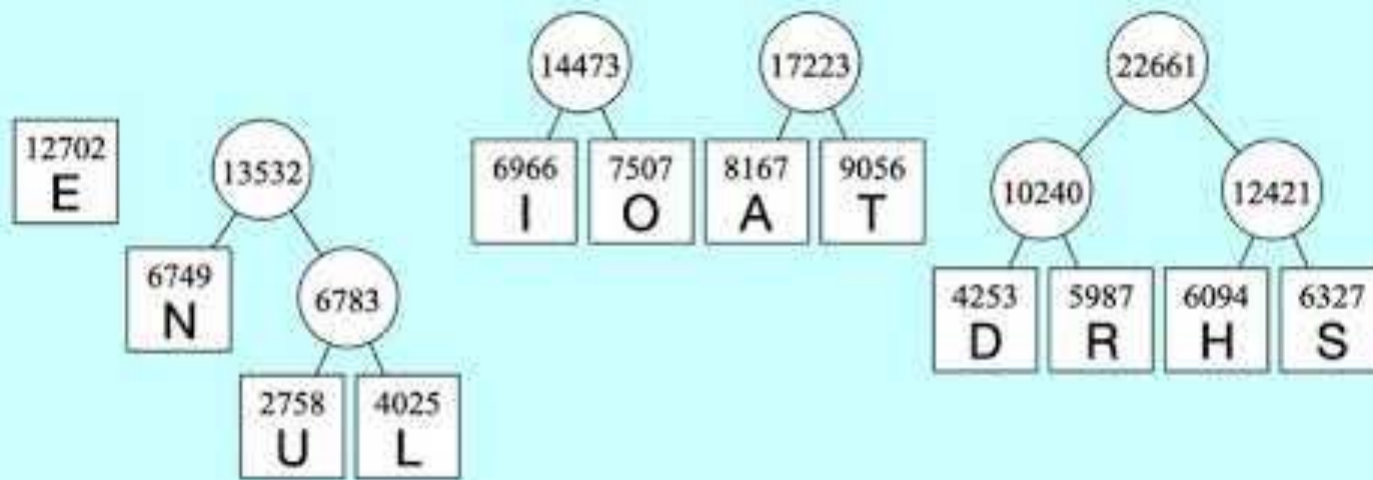




<i>character</i>	<i>code</i>
K	10
I	01
D	111
R	001
'	000
S	1101
L	1100



Illustrating the Huffman Algorithm

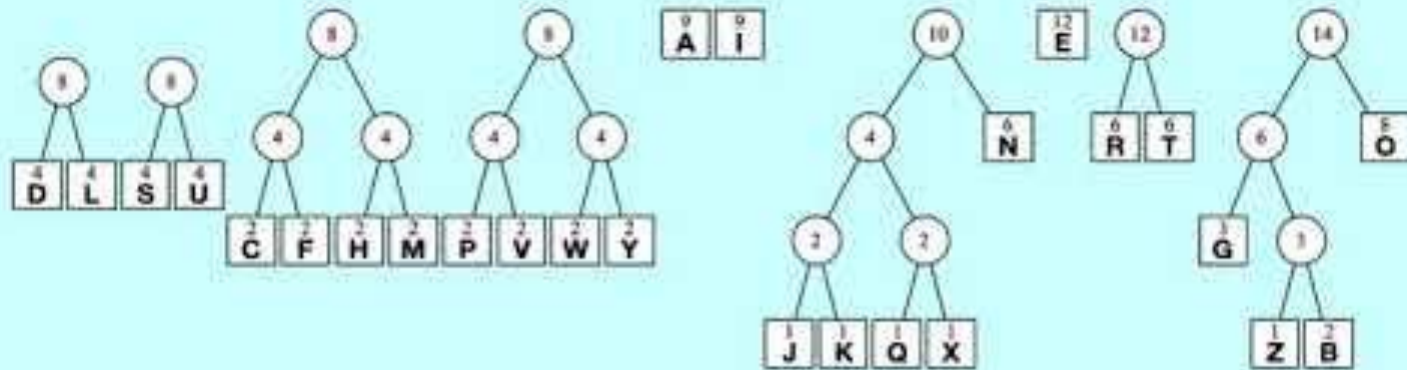


The Huffman Tree for Scrabble T

Trial Version



Wondershare
PDFelement

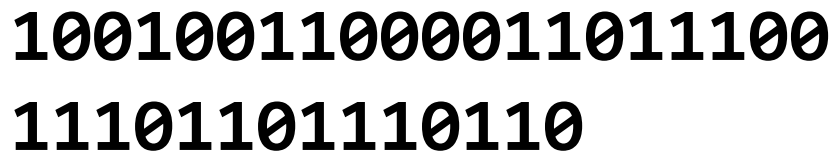




One important final detail...


Prefix Codes Example

So far we've only thought about transmitting the compressed message.



10010011000011011100
11101101110110

*But we need this
information in order to
be able to decompress.*



character	code
K	10
I	01
D	111
R	001
'	000
S	1101
␣	1100

Prefix Codes Example

**10010011000011011100
11101101110110**



Transmitting the Tree

- In order to decompress the text, we have to remember what encoding we used!
- **Idea:** Prefix the compressed data with a header containing information to rebuild the tree. This might increase the total file size in some cases!

Encoded Tree	110111001011101111000100110101011110...
---------------------	---

- **Theorem:** There is no compression algorithm that can always compress all inputs.
 - **Proof:** Take CS103!



Summary



Huffman Encoding Summary

- Data compression is a very important real-world problem that relies on patterns in data to find efficient, compact data representations schemes.
- In order to support variable-length encodings for data, we must use prefix coding schemes. Prefix coding schemes can be modeled as binary trees.
- Huffman encoding uses a greedy algorithm to construct encodings by building a tree from the bottom up, putting the most frequent characters higher up in the coding tree.
- We need to send the encoding table with the compressed message.



More to Explore

- **UTF-8 and Unicode**
 - A variable-length encoding that has since replaced ASCII.
- **Kolmogorov Complexity**
 - What's the theoretical limit to compression techniques?
- **Adaptive Coding Techniques**
 - Can you change your encoding system as you go?
- **Shannon Entropy**
 - A mathematical bound on Huffman coding.
- **Binary Tries**
 - Other applications of trees like these!



What's next?

Roadmap

C++ basics

User/client

vectors + grids

stacks + queues

sets + maps

Object-Oriented Programming

Implementation

arrays

**dynamic memory
management**

linked data structures

**real-world
algorithms**

Life after CS106B!

Diagnostic

Core
Tools

testing

**algorithmic
analysis**

**recursive
problem-solving**

Hashing

