I'm making a search engine called MillionGazillion™.

I wrote a crawler that visits web pages, stores a few keywords in a database, and follows links to other web pages. I noticed that my crawler was wasting a lot of time visiting the same pages over and over, so I made a set, `visited`, where I'm storing URLs I've already visited. Now the crawler only visits a URL if it hasn't already been visited.

Thing is, the crawler is running on my old desktop computer in my parents' basement (where I totally don't live anymore), and it keeps running out of memory because `visited` is getting so huge.

How can I trim down the amount of space taken up by `visited`?

Gotchas

Your strategy shouldn't take a hit on runtime.

Replacing common substrings like ".com" and "www" with characters that aren't allowed in URLs definitely wins us something, but we can do even better. How can we even further exploit overlaps or shared prefixes between URLs?

Breakdown

Notice that a boatload of URLs start with "www."

We could make `visited` a nested **hash** where the outer key is the subdomain and the inner key is the rest of the URL, so for example `visited['www.']['google.com'] = true` and `visited['www.']['interviewcake.com'] = true`. Now instead of storing the "www." for each of these URLs, we've just stored it once in memory. If we have $1,000$ URLs and half of them start with "www." then we've replaced $500 * 4$ characters with just 4 characters in memory.

But we can do even better.

What if we used this same approach of separating out shared prefixes recursively? How long should we make the prefixes?

What if we made the prefixes just one character?

Solution

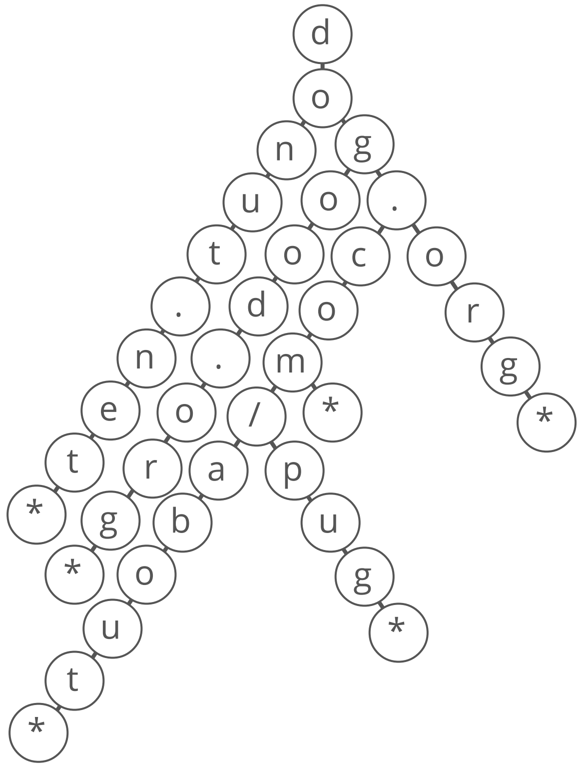
We can use a trie. If you've never heard of a trie, think of it this way:

Let's make `visited` a nested hash where each map has keys of just one character. So we would store 'google.com' as `visited['g']['o']['o']['g']['l']['e']['.']['c']['o']['m']['*'] = true`.

The '*' at the end means 'this is the end of an entry'. Otherwise we wouldn't know what parts of `visited` are real URLs and which parts are just prefixes. In the example above, 'google.co' is a prefix that we might think is a visited URL if we didn't have some way to mark 'this is the end of an entry.'

Now when we go to add 'google.com/maps' to `visited`, we only have to add the characters '/maps', because the 'google.com' prefix is already there. Same with 'google.com/about/jobs'.

We can visualize this as a tree, where each character in a string corresponds to a node. To check if a string is in the trie, we just descend from the root of the tree to a leaf, checking for a node in the tree for each character of in string.



A trie containing "donut.net", "dogood.org", "dog.com", "dog.com/about", "dog.com/pug", and "dog.org"

How could we implement this structure? There are lots of ways! We could use nested hashes, nodes and pointers, or some combination of the two. Evaluating the pros and cons of different options and choosing one is a *great* thing to do in a programming interview.

In our implementation, we chose to use nested hashes. To determine if a given site has been visited, we just call `check_present_and_add()`, which checks if a given string is present in the trie and adds it to the trie if it's not.

```ruby
class Trie

    def initialize
        @root_node = {}
    end

    def check_present_and_add(word)

        current_node = @root_node
        is_new_word = false

        # Work downwards through the trie, adding nodes
        # as needed, and keeping track of whether we add
        # any nodes.
        word.each_char do |char|
            if !current_node.key? char
                is_new_word = true
                current_node[char] = {}
            end
            current_node = current_node[char]
        end

        # Explicitly mark the end of a word.
        # Otherwise, we might say a word is
        # present if it is a prefix of a different,
        # longer word that was added earlier.
        if !current_node.key? "End Of Word"
            is_new_word = true
            current_node["End Of Word"] = {}
        end

        return is_new_word
    end
end
```

If you used a bloom filter, that's a great answer too. Especially if you use run-length encoding.

Complexity

How much space does this save? This is about to get MATHEMATICAL.

How many characters were we storing in our flat hash approach? Suppose `visited` includes *all possible URLs of length 5 or fewer characters*. Let's ignore non-alphabetical characters to simplify, sticking to the standard 26 English letters in lowercase. There are 26^5 different possible 5-character URLs (26 options for the first character, times 26 options for the 2nd character, etc), and of course 26^4 different possible 4-character URLs, etc. If we store each 5-character URL as a normal string in memory, we are storing 5 characters per string, for a total of $5 * 26^5$ characters for all possible 5-character strings (and $4 * 26^4$ total characters for all 4-character strings, etc). **So for all 1, 2, 3, 4, or 5 character URLs, our total number of characters stored is:**

$$5 * 26^5 + 4 * 26^4 + 3 * 26^3 + 2 * 26^2 + 1 * 26^1$$

So for all possible URLs of length n or fewer, our total storage space is:

$$n26^n + (n-1)26^{(n-1)} + ... + 1 * 26^1$$

This is $O(n26^n)$.

How many characters are stored in our trie? The first layer has 26 nodes (and thus 26 characters), one for each possible starting character. On the second layer, each of those 26 nodes has 26 children, for a total of 26^2 nodes. The fifth layer has 26^5 nodes. **To store all 1, 2, 3, 4, or 5 character URLs our trie will have 5 layers. So the total number of nodes is:**

$$26^5 + 26^4 + 26^3 + 26^2 + 26^1$$

So for all URLs of length n or fewer, we have:

$$26^n + 26^{(n-1)} + ... + 26^1$$

This is $O(26^n)$. We've shaved off a factor of n.

Bonus trivia: although the HTTP spec allows for unlimited URL length, in practice many web browsers won't support URLs over 2,000 characters.

What We Learned

We ended up using a trie. Even if you've never heard of a trie before, you can reason your way to deriving one for this question. That's what we did: we started with a strategy for compressing a common prefix ("www") and then we asked ourselves, "How can we take this *idea* even further?" That gave us the idea to treat *each character* as a common prefix.

That strategy—starting with a small optimization and asking, "How can we take this same *idea* even further?"—is hugely powerful. It's one of the keys to unlocking complex algorithms and data structures for problems you've never seen before.
