CS 1699: Privacy in the Electronic Society
Project 1 – Side-Channel Attacks

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Contents

Task W0

Problem P: String Comparison

The problem chosen for this assignment is *string comparison*, which involves checking one string for equality with another string. This includes comparing both the **length** and the **content** of each string for a mismatch.
Input: Two strings to be compared.
Output: Boolean indicating if the strings are *equal*.

Task W1

Relevance to Privacy

String comparison has big implications in privacy for such a seemingly innocuous problem. Comparing values is a basic, necessary task for any system involving authentication or user input, which includes most (if not all) privacy-related services. This is especially true of web apps, and string comparison has been mentioned as a potential point of weakness on a number of online resources (more on how this weakness is exploited later). [2]

For example, an application may check if a username exists or a given password is correct by comparing its string value to the stored password for a user, whether in plaintext (unlikely for passwords) or by comparing their

hash values. This typically occurs via a custom comparison for the object in question (potentially still timing sensitive!) or by using simple string comparison (both have been done historically). [1] For example, the Java `MessageDigest.isEqual` method uses a simple byte comparison to check whether two digests are equal, which is essentially the implementation of string comparison for some languages.

Task W4

Algorithm A: Break-on-Inequality

Firstly, let's examine **Algorithm A** so that we can understand how and why this naive algorithm varies in runtime (including for inputs of the same size). In the pseudocode below, first notice that if the strings are different lengths, a 'False' is returned immediately (lines 5-6). This clearly changes the runtime in the case of different-sized inputs, which can reveal private information as discussed below. More subtle is the character-by-character comparison, which breaks as soon as it finds a mismatch between the two strings (line 11). This reveals information about *how* close the two strings are (or in the case of an attacker, how correct the guess was).

```
1  // This method takes two strings, a and b, and returns True if they are equal, False otherwise
2  def algorithm_A (String a, String b)
3
4    // First check that the lengths are the same
5    if a.length != b.length
6      return False
7
8    // Now iterate through characters, comparing one by one
9    int i = 0
10   while i < a.length
11     if a[i] != b[i]
12       return False
13     i = i+1
14
15   // If we make it all the way, they match!
16   return True
```

Results

Benchmarking [4] the above code–implemented in the Ruby programming language–over 1000s of iterations gives the results displayed in the table below. Note that the "different strings of the same length" differed in the first or nearly first characters while the "close strings of the same length" differed only on the final character, for both the sentence and the hash value. The following observations (about real time taken to compare inputs) are plain from the data:

- Comparing different strings of the same length is an order of magnitude slower than strings of different length.
- Comparing nearly-identical strings is *another* order of magnitude slower.
- The difference between two close strings vs. two of the same string is very small, although it becomes more noticeable with a longer input.

Naive

This is a good dog

Test with string	real time (string)	iterations in 5.0s	iterations / second	slower?
Diff String, diff length	0.000255	16.386M	3.263M	
Diff strings, same length	0.002788	1.936M	386.523k	8.44x
Close strings, same length	0.005953	860.031k	170.027k	19.19x
The strings are identical	0.007526	863.582k	171.550k	19.02x

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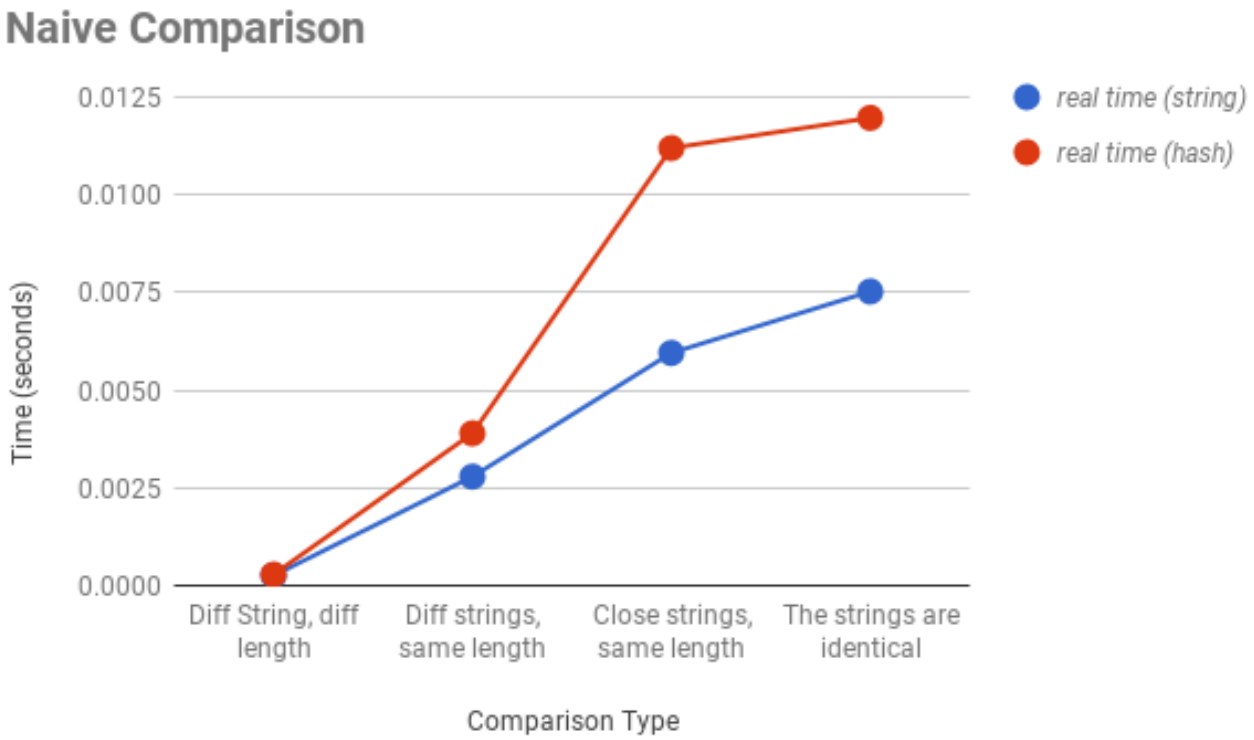
Test with hash	real time (hash)	iterations in 5.0s	i / s	slower?
Diff String, diff length	0.000282	16.203M	3.207M	
Diff strings, same length	0.003896	1.423M	280.709k	11.43x
Close strings, same length	0.011195	534.558k	104.985k	30.55x
The strings are identical	0.011967	518.313k	103.680k	30.94x

This may also be clearer from the following graph of the clock time taken by each comparison type. Notice that the difference between two different strings of the same length and two close strings is more dramatic as the length increases.



Effect on Privacy

It is clear that this measurable difference in string comparison times can be leveraged in a timing attack against some systems that make use of such an algorithm. Although my first speculation was that such an attack could be used to recover a password from a system that allows multiple login attempts, I quickly recalled my computer science class on 'Privacy in the Electronic Society', wherein we learned that it is insecure and foolish to 1) transmit passwords in cleartext, or 2) store cleartext passwords on a secure system. So the best that a timing attack could reveal in this instance (using techniques described below) is the hash of a password, or something that is normally sent in cleartext anyways. But of course, due to the cryptographic properties of any good hash function, recovering the password itself from such information is all but impossible. [3] After further research and armchair rationalization, I determined that there are at least two categories of information that can be gained as a consequence of the above algorithm. The general setup for an attacker requires that:

1. The system being attacked makes use of Algorithm A, above.
2. The attacker be able to choose the input to the algorithm (making this a *chosen plaintext* attack).
3. The attacker has some way of **verifying** whether or not the input was accepted; for example, a login form for a web app must indicate to the user (attacker) whether or not the input was correct, rather than simply sitting without any response.

If the above conditions hold, then the system is functioning (loosely) as what is known as a *verification oracle*, meaning that it will verify as correct or incorrect whatever input you provide, specifically by way of the (vulnerable) algorithm given above. This can leak information by way of a simple attack outlined here:

1. For any given set x of known input characters and $y = y_0 \dots y_n$ unknown, try every possibility for a variable a in the input $x||a||y_1 \dots y_n$ and some fixed filler, say `<underscore>`, for all $y_i \neq y_0$.
2. Sample some dozens (or hundreds) of times on each combination, and then take the mean (or median to mitigate outliers) of the time taken to return an error/False message.

3. Set a to be the character/byte with the greatest mean/median value, add it to x, and then return to step 1.

By repeating this process, first to find the correct length and then to find the correct combination of characters,
Then the system is at risk of leaking one of leaking the following two types of (private) information:

Existential information

This type of information is leaked when an attacker exploits the timing differences in the above algorithm

Specifically, if there is ever a user-facing application that requires input that must be verified, such as a username or password, some type of comparison will be involved. Consider such a system, with a typical login page where a user might enter their credentials, which will then be compared to the system's stored list of credentials using the above naive string comparison. A *chosen plaintext* attack is possible against this portal, say to discover valid usernames. The attacker need only perform these steps:

1. Discover valid usernames for the system.
2. Recover full login info (including passwords) for users.

This may require a more sophisticated timing software than Ruby's built-in benchmarking module, but I believe that it would not be difficult to achieve such an attack, even with (for example) a basic timing program.

Task W7

Algorithm B: Constant-Time Comparison

Now let's examine **Algorithm B** so that we can understand how and why this revised algorithm runs in a more constant-time manner, mitigating some of the effects discussed for Algorithm A above. In the pseudocode below, first notice that before anything else we select a consistent number of iterations to run the byte-wise comparisons for (`len` in the code below, line 5)–this helps ensure that we don't reveal information about the length of the secret value (perhaps a login name), since that was an obvious and large timing difference in our naive algorithm. Next, consider the revised loop through our inputs (lines 9-13). Rather than breaking this loop once we find a mismatch, we continue for the specified length `len` (line 9). Then we check that both of the next characters are even valid to be compared (line 10). If so, we skip to the `else` (line 12) and proceed with the comparison. If either one is *not* valid, we execute a "dummy" comparison to (hopefully) take the same amount of time as a real one (line 11). Finally, we return the resulting boolean.

```
1  // This method takes two strings, a and b, and returns True if they are equal, False otherwise
2  def algorithm_B (String a, String b)
3
4    // We'll assume string a is the "system string" we're comparing the user-input against
5    int len = a.length
6
7    // Now set a boolean and then iterate through characters, comparing each (even on mismatch)
8    boolean bool = (a.length == b.length)
9    for i in 0... len                // for every character in the fixed length
10     if a[i] == null || b[i] == null       // if we've reached the end of one string
11       bool = (a[0] == a[0]) && bool       // compare something anyways
12     else                                  // otherwise
13       bool = (a[i] == b[i]) && bool       // compare the two chars, update the boolean
14
15   return bool
```

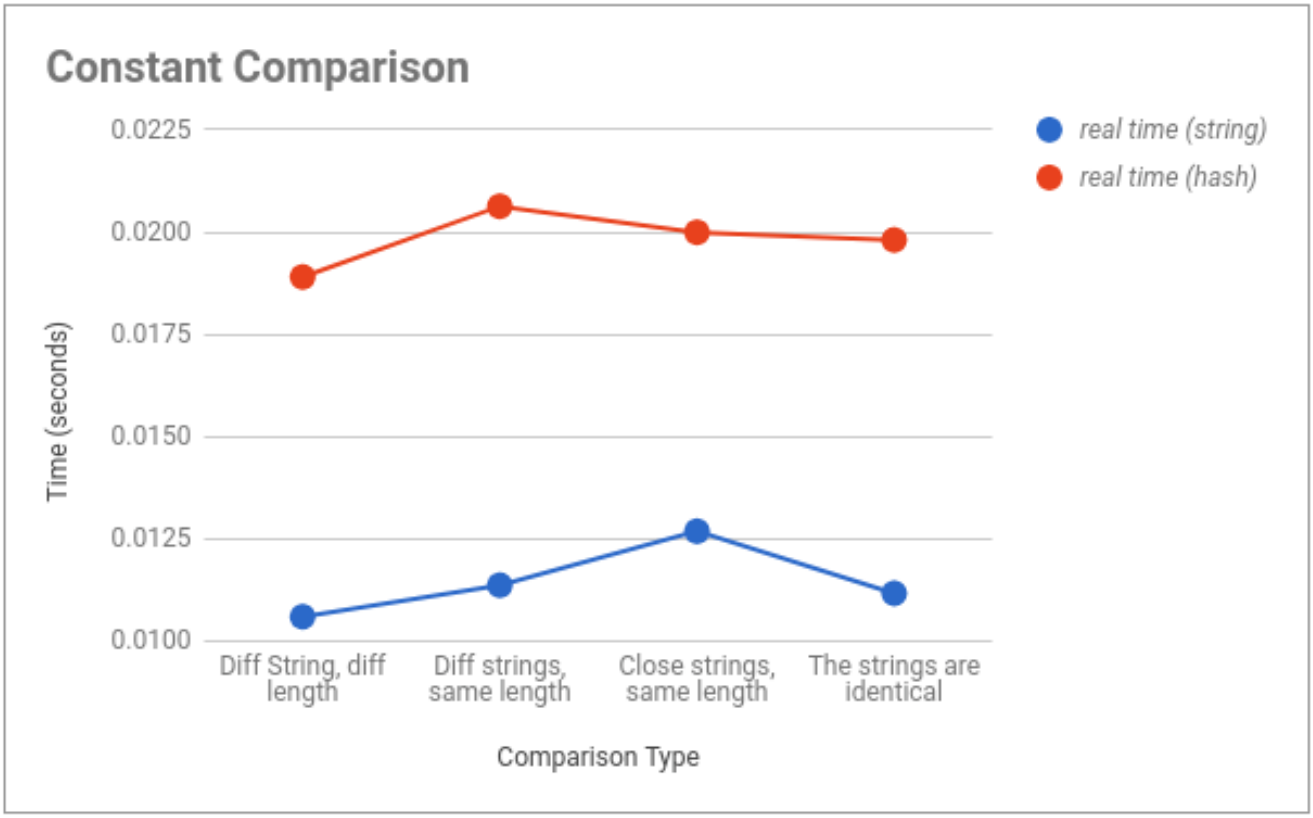
Results

Benchmarking the above code–implemented in Ruby–over 1000s of iterations gives the results displayed in the table below. Note that the timing distinctions between the different types of comparison are almost entirely eliminated for shorter strings, and are statistically insignificant for longer strings/hash values. It is worth noting that comparing strings of different length still seems to be notably faster, especially for shorter inputs. This could reveal the length of a secret, given enough samples.

Constant		This is a good dog			
Test with string		real time (string)	iterations in 5.0s	i / s	slower?
	Diff String, diff length	0.010596	495.144k	97.921k	
	Diff strings, same length	0.011366	431.600k	85.590k	1.14x
	Close strings, same length	0.012686	431.400k	86.376k	1.13x
	The strings are identical	0.011168	439.416k	87.895k	1.11x

	286755fad04869ca523320acce0dc6a4			
Test with hash		real time (hash)	iterations in 5.0s	i / s	slower?
	Diff String, diff length	0.018902	259.632k	52.482k	
	Diff strings, same length	0.020629	255.500k	51.108k	within error
	Close strings, same length	0.019993	260.355k	51.922k	within error
	The strings are identical	0.019806	263.648k	52.152k	within error

The improvement is especially clear given the graph below, which shows much more even timing results across different types of input. In particular, the test on longer (hash) strings shows a slight reversal in the trend across strings of the same length–which could indicate that it would lead an attacker to make incorrect guesses (a desirabe trait).



Trade-Offs & Design Decisions

There is a significant performance cost associated with making constant-time comparisons, especially when trying to obscure even the length of the secret value(s). Notice in the graphs above (INCLUDE EXTRA GRAPH BELOW THAT COMPARES THE TWO) for Naive vs. Constant Comparison that the constant-time algorithm takes nearly twice as long when comparing similar strings and *several times* as long when comparing very different strings. This would be a highly significant cost on a system or web-server that may receive thousands of requests a day/hour/minute.

Additionally, not all the timing difference for comparing strings of different length is mitigated. This could be because the 'else' conditional code (lines 12-13) is not being executed for every null character of the compared

string, resulting in faster overall execution. Some amount of randomness could perhaps be introduced that would further obscure those lines of comparison.

Finally, because the chosen amount of time is based on the *first* string passed to the algorithm, we risk revealing length of secret values anyways if our implementation is known and the attacker can duplicate our system/working environment.

Task W8

Remaining Problems

There is still potential to leak lengths of secret values, and there may be a better way to obscure those lengths that I have not implemented above. –¿ THIS WILL BE EXPANDED

References

[1] 'Coda Hale'. *A Lesson In Timing Attacks*. 2009. URL: `https://codahale.com/a-lesson-in-timing-attacks/`. (accessed 28 Feb 2018).

[2] Nick Malcolm. *Timing Attacks against String Comparison*. 2016. URL: `https://thisdata.com/blog/timing-attacks-against-string-comparison/`. (accessed 1 Mar 2018).

[3] Wikipedia Contributors. *Cryptographic hash function*. Wikipedia, The Free Encyclopedia. URL: `https://en.wikipedia.org/wiki/Cryptographic_hash_function`. (accessed 26 Feb 2018).

[4] Rdoc Generator. *Module: Benchmark (Ruby 2.5.0)*. Ruby-doc.org. URL: `https://ruby-doc.org/stdlib-2.5.0/libdoc/benchmark/rdoc/Benchmark.html`. (accessed 26 Feb 2018).