

Department of Computer Science



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MSc in Cybersecurity.

Investigating the Security of $p \equiv p$'s Trustwords

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Abstract

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Acknowledgements

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1 Introduction

The increasing use of public-key cryptography by instant messaging and secure email means key-fingerprint verification is an ever more important task.

One of the most significant risks to the security of the communication channel is a Man-in-the-middle (MiTM) attack. A MiTM attack involves an attacker impersonating one or both sides of a connection. MiTM attacks can entirely circumvent the encryption as it allows an attacker to read all of the encrypted data.

A countermeasure for the threat of MiTM attacks is the verification of each parties' fingerprint. A fingerprint is a small string of characters that is unique to each key and, thus, can be used to identify.

Fingerprints can come in several different encodings such as Hexadecimal, words, and even procedurally generated avatars. Previous research has shown that the average human can only hold around 7-digits (± 2) worth of data in their working memory[1]. Consequently, this makes the designing of user-friendly schemes a task of utmost importance.

Humans are commonly considered the most vulnerable part of any computer system. Solutions, therefore, have been proposed to remove this manual verification with examples such as PGP's web-of-trust[2] and Namecoin[3]. However, these suffer from user adoption due to perceived complexity. Manual verification is, consequently, left in a difficult position, due in part to proposed solutions needing to sacrifice either usability or security. Therefore, research into improving or creating a more secure and user-friendly fingerprint encoding remains an important task.

This report evaluates the security and feasibility of attacking a fingerprint encoding known as "Trustwords." The motivation for this is due in part to the shortage of justification behind some fundamental design choices.

The report is structured as follows:

Chapter 2 provides any required background knowledge alongside a review of all relevant literature.

1 Introduction

Chapter 3 formally defines the aim of this report alongside the research questions the project aims to answer.

Chapter 4 documents the proposed designs required to answer the research questions proposed in Chapter 3.

Chapter 5 discusses the significant implementation details of the designs formalized in Chapter 4.

Chapter 6 presents and analyses all experimentation results of the project.

Chapter 7 evaluates the success of the project alongside a discussion into proposed further work. The research aims proposed earlier in Chapter 3 are used as evaluative metrics.

Chapter 8 concludes the project with a culmination of the findings of the paper alongside any relevant conclusions.

2 Background

The chapter explains aspects required to fully comprehend the project's achievements alongside an evaluation of current literature and the respective gaps.

The chapter contains the following sections:

- **Project context**
Provides the user with the base knowledge required to understand the context and purpose of the following literature review.
- **Definition of terms**
Specific definitions relevant to the literature review are initially defined.
- **Literature Review**
A review of currently available literature on relevant topics. Recommendations and research gaps are identified and discussed.

2.1 Project context

To fully understand the literature review, it is necessary to introduce and explain the base knowledge before continuing.

Public-key Cryptography and Key Exchange

Asymmetric cryptography facilitates the secure encryption of messages in end-to-end encryption (E2EE), verification of digital signatures, and sharing of pre-communication secrets, among others.

The asymmetry stems from the use of "Public" and "Private" keys. The public-key is used to encrypt data that only the respective private-key can decrypt. Hence, this means that sharing the keys required to encrypt can be performed across insecure channels.

An E2EE connection uses the key types discussed previously to exchange messages between verified parties securely. However, this hinges

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on the verification of the initial parties, if one party impersonates another and receives sensitive communication, the secure encryption is completely circumvented. Therefore, the correct identification of parties is crucial to maintaining security. The exploitation of this is known as a Man-in-the-middle (MiTM) attack. This attack is commonly bidirectional, and if executed correctly, there is often no discerning change to the user experience. Figure 2.1 contains a visual representation of this attack.

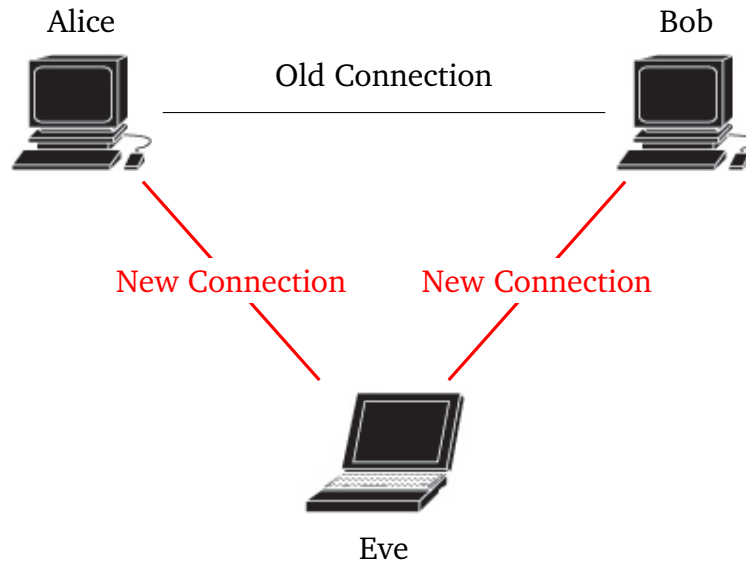


Figure 2.1: Photo depicting a MITM attack

Due to the assumption that the attacking party (Eve) does not have the same public-private key pair as either party (Alice or Bob), the fingerprint of the public keys are, therefore, different, and, thus can be used for identification. There are, however, issues in how a user should link a key's fingerprint to a real-world entity. This paper will, however, assume that users have access to the respective parties' correct fingerprint, as the protocols used to achieve this are outside the project's scope.

The fingerprint of the key is generated by running the main key components through a secure one-way hash function such as SHA-1. This process produces a digest of a fixed length that can be used to compare keys. Therefore, the comparison of expected and actual fingerprints can be used to detect MiTM attacks. Historically these have been represented as a hexadecimal string whereon verification fingerprints are compared between two substrates, for example, a monitor screen and a business card. This process is known as the “*authentication ceremony*.” System

designers are, however, moving away from this structure and are now implementing a combined key. This change is due to the assumed increase in usability. Users now compare a single fingerprint, instead of two sets separately. In the case of WhatsApp for example, the connection fingerprint of two parties keys is the first 30 bytes of an SHA-512¹ hash of each parties' identity key, these are then both concatenated together to form a single key[4]. This process produces a unique-key communication pair.

Due to the manual comparison of the fingerprint, length, and format is a core design consideration. Prior research has shown that the average human can only hold around 7-digits worth of data in their working memory[1]. This rules out the possibility of comparing complete digests. For example, SHA-1 is 40 hex digits (160-bit) and, therefore, difficult to effectively compare. Therefore, if human interaction is required; there is a need for schemes that work effectively with consideration to individual limitations.

Research in this area has taken various encoding schemes and compared their fallibility to impersonated attacks. The main elements of comparison have been the "accuracy of attack detection" and "time to compare." In this paper, these are considered the metrics of "security" and "usability," respectively.

2.2 Definition of terms

Throughout the paper, various terms are used to define elements of the authentication ceremony relevant to fingerprints verification. Explicit descriptions are, therefore, stated in this section. These are used to remove ambiguity and underlying associations readers may have for the words chosen.

Encoding schemes - are the physical method of encoding used to represent the fingerprint. For example, "Hexadecimal" or "Words" are a unique way to represent a fingerprint and thus, are encoding schemes.

Method of comparison - is the way a user assesses the encoding scheme. The most common example and the one used as default is "Compare-and-Confirm" (CaC). CaC, as the name suggests, is the *comparison* of two fingerprints on different devices or mediums that are then *confirmed*. The following sections explain alternative methods of comparisons.

¹5200 iterations

2.3 Literature Review

This section discusses the current research around the proposed topic.

The organisation of the section is as follows:

- **Authentication ceremony performance**
This section explains the current research on the performance of various encoding schemes and methods of comparison, alongside an assessment of the literature's experimental design.
- **Encoding schemes**
The following section then discusses research around the design of an encoding scheme. The focus of the section is the technical details regarding the creation and design of schemes.
- **Attacks on encoding schemes**
The final section discusses literature that investigates the creation of actual attacks against encoding schemes.

2.3.1 Authentication ceremony performance

Encoding scheme performance

Results from the literature consistently show the effectiveness of language-based encodings such as Words or Sentences with accuracies ranging up from 94% [5][6][7]. In all cases, these were the best schemes from the sets assessed. The exception to this is the work performed by **Hsiao et al.** [8] in 2009 with Words achieving an abnormal accuracy of 63%.

Aside from textual representations were graphical schemes. Examples of schemes assessed were: Random Art[9], Flag[10], T-Flag[11], Vash², OpenSSH visual host key and Unicorns³, among others. These schemes had mixed accuracy with ranges as large as 50% - 94% in work by **Hsiao et al.** [8]. The only other paper assessing graphical representations was the work of **Tan et al.** [6] where they also achieved mixed results with accuracies ranging from 46% to 90%.

In terms of usability of graphical schemes, the literature concurred on their high usability. The comparison speed of these schemes were all among the quickest (See Table 2.1 for an overview of timings). Other work also indirectly agreed with graphical encodings having significantly quicker comparison times compared to non-graphical schemes [5][7]. In

²<https://github.com/thevash/vash>

³<https://unicornify.pictures/>

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Scheme	Hsu-Chun[8]	Kainda[7]	Dechand[5]	Tan[6]
Bit-Length	28 bits	20-40-bits	122-bits	128-bits
Hexadecimal			11.20	9.00
Numerical		6.00	10.60	9.00
Base32	3.51	6.00	10.20	
Words	4.63	7.00	8.70	7.00
Scentences		11.00	12.30	8.00
Chinese Symbols	5.01			
Japanese Symbols	5.07			
Korean Symbols	4.92			
Random Art	3.21			
Flag	4.28			
T-Flag	4.00			
Flag Ext.	4.02			
OpenSSH'				5.00
Unicorns				3.00
Vash				3.00

Table 2.1: Timing results in seconds for the related schemes

terms of research into the performance of graphical schemes, the literature does not contain an extensive review with literature only containing two papers. There is also no overlap in the schemes assessed with each paper reviewing a unique set. This area is, therefore, a promising candidate for further research.

One unique paper in this research area was the work by **M. Shirvanian et al.**[12] produced in the context of secure messaging pairing. This paper was unique for several reasons. First was to consideration for “remote-vs-proximity” pairing where this is the first consideration of this aspect found in the literature. There is room for further research to compare encoding schemes in the context of “remote-vs-proximity.” Another unique aspect was the end-to-end encryption context of the study.

The findings from the paper showed a high false-negative rate for all the schemes. This consideration is also missing from the literature. Alongside this, results for usability were lower in a remote setting for all the schemes. The author, however, comments on the expected nature of this result.

Images were identified as being the most secure method of authentication in the remote setting but voted as the method with the worst usability. This conclusion is highly inconsistent with all other work in this area. However, this could be due to the unique setting of remote verification, resulting in distinct results from user studies. Without further

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work in this area, it is difficult to validate these results conclusively.

Alongside this, it was shown in work by **Hsiaoet al.** [8] that age and gender do not affect the accuracy of the scheme. However, younger participants were considerably faster. Furthermore, findings also showed that language comprehension helped in discerning small differences between schemes encoded in Chinese, Japanese, Korean, or English. Subsequently, knowledge of the language did not assist in differentiating more significant changes in the schemes as these had high accuracy regardless. These were unique considerations. Further work could aim to corroborate these conclusions.

Scheme⁴	Hsu-Chun[8]	Kainda[7]	Dechand[5]	Tan[6]	M. Shirvanian[12]
Hexadecimal			90%	79%	
Numerical		100%	94%	65%	97%
Base32	86%	90%	92%		
Words	63%	100%	94%	94%	
Scentences		100%	97%	94%	
Chinese Symbols	59%				
Japanese Symbols	57%				
Korean Symbols	54%				
Random Art	94%				
Flag	50%				
T-Flag	85%				
Flag Ext.	88%				
OpenSSH ⁴				90%	
Unicorns				46%	
Vash				88%	

Table 2.2: Accuracy of correct comparison for the encoding schemes assessed

Tables 2.1 & 2.2 contain the accuracy results of all papers assessed; this is to aid in visual comparison. Each paper used a different metric for measuring accuracy. Therefore, all results have been translated into “overall accuracy.”

Methods of comparison performance

Aside from “Compare-and-Confirm” (CaC), there is “Compare-and-Select” (CaS) and “Compare-and-Enter” (CaE). CaS is the method where one device displays the fingerprint, and the other user is provided with several options. The user then has to choose the correct value from the list

⁴All values have been rounded to the nearest whole percentage

of candidates. If there is no match, the user must deny the connection attempt. The creation of CaS was due to concerns that CaC would be “too easy” for users leading to complacency and errors[13]. The design of CaE is for scenarios where both devices might not have a display, i.e., pairing between a phone and a keyboard. One device displays the checksum. This checksum is then entered into the other device. The first device then compares the entered string and checks for a match.

Research has assessed the performance of these schemes and how they affect the security of the authentication ceremony. The literature agrees on CaC being the best overall scheme to compare fingerprints [6][13] with CaS highlighted for its poor security and usability. CaE has had conflicting results. [13] discarded it after one round due to “poor usability.” However, [6] considered it the best method overall for usability and security. These conflicting results, therefore, show polarisation in the results of CaE. However, this could be due to the different overall use-cases of the studies. Validation of results from either study would, therefore, be an area of additional study.

Experimentation methodology comparison

To further look into the validity of previously discussed results, it is necessary to assess how the respective studies reached their conclusions. Areas for consideration are scheme entropy, attacker strength, and participant demographics.

The starkest limitations of the literature are the range of participants and encoding entropy. The worst studies tested only 22-bits of entropy. This lack of entropy makes it challenging to compare results directly. One of the papers this most affects is the early work by Hsiao *et al.* [8] where their highest entropy is 28-bits. This level of entropy was inadequate even at the time of publication. There is an attempt by the authors’ to address this issue in the later stages of the paper where they write: “[...] increasing entropy is not a solution because it sacrifices usability and accuracy. With more entropy, representations will contain longer sequences of characters or more minute details which will lead to increased time and errors during comparisons.”. This statement is backed up with no empirical evidence, and the authors fail to consider how the low entropy would affect the overall security of the schemes.

Attacker strength is also another metric used to compare results concluded by each paper. Some papers failed to address their attacker strength consideration directly, but the overall strength has been inferred from the changes made to their schemes. For example, if they decided to change a single character in a 40-digit (160-bit) SHA-1 hex digest, they are indirectly stating that the attacker can control 39-digits

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(156-bit). To achieve this, the attacker would have to compute 2^{156} SHA-1 compressions to find a key match. In the literature, this element ranged from 2^{28} to around 2^{242} . However, this has some relation to the size of the encoding schemes used. This substantial range makes it challenging to compare and confer results confidently. Further work could exclusively look into the effects that attacker strength has on the success of attacks. Moreover, all the papers assessed failed to fully consider the feasibility of attacks in terms of computer and storage requirements.

All of the studies considered demographical data when presenting their results. Their average ages were all around ~ 35 years old with the majority of participants educated with at least a bachelor degree. Alongside, the equal split between male and female participants.

One consideration of note is that made by Dechand *et al.* [5] where they briefly consider medical conditions such as ADHD and reading or visual disorders and the way they affect the comparison's effectiveness. The results highlight a slight reduction in overall accuracy, however, due to their small sample size, the results cannot be considered conclusive. This aspect is unique to all literature assessed. Further work would be required to produce conclusive results. Therefore, highlighting a gap in the literature.

One glaring issue with the demographical health of Ersin Uzun *et al.* [13] study is the use of two entirely different groups of participants. Not only were their demographics different, but they were from different countries (America and Finland). Different cultures contain inherent biases and assumptions. Changes were made pragmatically regarding the results from the first round of 40 participants. These were then re-assessed, alongside the direct comparison of results. This aspect casts vast doubts on the validity of the results with no consideration made by the authors to control external factors that may affect the performance of the method of comparison.

Hexadecimal and numerical schemes were not included as encoding schemes in work by Hsiao *et al.* [8] (some of the most widespread encoding schemes). The justification was the schemes similarities to Base32 alongside "well-known deficiencies". This point was provided with no further justification or quantified. Moreover, it is also inconsistent with available research, for example, in "*Empirical Study of Textual Key-Fingerprint Representations*" [5] it was shown numerical representations performed significantly better than that of Base32.

Table 2.3 has been provided to compare the different aspects of the papers' parameters visually. It can be seen from the table the substantial

⁵Some attacker strengths are estimations due to the lack of quantification in some papers.

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	Hsu-Chun[8]	Kainda[7]	Dechand[5]	Tan[6]	M. Shirvanian[12]
Attacker Strength ⁵	$\sim 2^{28}$	$\sim 2^{40}$	2^{80}	2^{60}	$\sim 2^{242}$
Entropy Range	22-28 bits	20-40 bits	122 bits	128 bits	160-256 bits
No° Participants	436	30	1001	661	25

Table 2.3: Paper attribute comparison

ranges in participant size, entropy and attacker strength.

Topic conclusion

Overall, this review has identified several key areas suitable for further work. The first is the performance assessment of graphical encoding schemes. Recreation of pre-existing results from [8][6] is required to corroborate current conclusions and validate results. Another gap in the research is the consideration into the utilisation of encoding schemes in realistic conditions, i.e. “remove vs proximity.” This topic was initially covered by [12], but their scope was limited. Further work, therefore, could increase the scope and touch upon a large number of schemes in these settings. The final aspect for further work is the limited consideration into the feasibility of attacks on encoding schemes. All of the papers assessed simulated attacks and had minimal consideration for the execution of these attacks. Therefore, further work could delve into the implementation and feasibility of such attacks.

2.3.2 Encoding schemes

Another area of research is investigations into the actual physical encodings of the hash digest. This section discusses the current research on the creation and security of actual encoding schemes. The technical details of the operation of the schemes are outside the scope of this literature review. Therefore, minimal attention is allocated to these details.

Some of the oldest preliminary work into visual encoding schemes is by **Adrian Perrig *et al.*** [9] in the creation of their scheme “Random Art” in 1999. The motivation for creating such a scheme was the perceived flaws in the ways humans verify and compare written information. As mentioned in previous sections, visual encoding schemes have been shown to have mixed success, with low security being one of their most alarming flaws. This research laid the foundation for further work in analysing the security of visual encoding schemes.

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Further research into the creation of unique visual hash schemes has been performed by **C Ellison et al.** [10] (Flag), **Yue-Hsun Lin et al.** [11] (T-Flag) and work by **M. Olembo et al.** [14]. Each publication has provided a new way to represent a key fingerprint visually. Alongside the academic literature, there are informally presented methods of visual fingerprints such as Unicorns⁶ and Robots⁷. This list is by no means exhaustive but is used to depict the amount of research and work invested into graphical hash representations.

One paper of note is the preliminary work performed by **D Loss et al.** [15] in their “*An analysis of the OpenSSH fingerprint visualisation algorithm*” where they aimed to spur on further research with their initial findings into the security of the OpenSSH scheme. The authors claim that the use of the algorithm in OpenSSH is only heuristically justified, and a more formal proof is required.

The paper proposed several ways to generate similar fingerprints. The methods proposed were: Naive brute force, Graph Theory, and brute force of a full visual set. They were only able to produce only initial results and have proposed a large amount of potential further work. Since the paper’s publication in 2009, there seems to have been no research building on the work of the authors.

Minimal research has also focused on elemental textual fingerprint representations and their security. Work by **A. Karole** and **N. Saxena** [16] looked into ways to improve the security of a textual representation. This research aim was to improve the secure device pairing process of comparing two numerical values. The devices used (Nokia 6030b; Mid-range devices at the time of publication) and the SAS (Short Authentication String) compared results in findings that are not directly applicable in a fingerprint comparison context.

A more specific subsection of textual fingerprints is the use of words and sentences to encode hash digests. Some of the first work in this area was by **Juola** and **Zimmermann** [17]. Their work aimed to produce a word list where phonetic distinctiveness was prioritised. Each word is mapped to a single byte. The unique aspect of the word list is the separation of “even” and “odd” words where “even” byte indices are sample from the even-list and “odd” from the odd-list. This technique effectively creates two sub-word lists. A genetic algorithm was used to maximise linguistic distance. The paper also includes a study on effective measures of “linguistic distances” of words and provided an in-depth discussion into these areas.

Overall the paper provides a foundation for formalising the creation of effective wordlists. A limitation is the lack of empirical data gathered on

⁶<https://unicornify.pictures/>

⁷<https://github.com/e1ven/Robohash>

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the performance. However, this was later evaluated in work by Dechand *et al.* [5] and shown to be an effective encoding scheme.

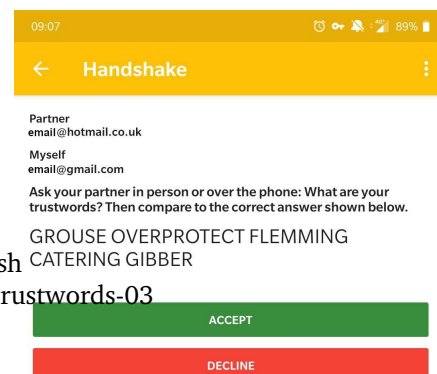
Other research of note is work by **M. Goodrich *et al.*** [18] called *Loud and Clear: Human-Verifiable Authentication Based on Audio*. As the name suggests, the authors were researching ways to improve current methods of secure device pairing. The unique aspect of this work is the use of a Text-to-Speech system reading out syntactically correct English sentences. MadLibs⁸ was the base for these sentences. MadLibs is where static placeholders are replaced with a list potential words. This work is an extension to work performed by Juola and Zimmermann [17] as they aimed to emulate the techniques used in PGPfone. The paper's findings are limited by the lack of empirical data backing up claims made by the author the performance of the system, and security is only theoretically assessed.

Aside from this research, there have been further informal implementations of fingerprint encodings. The first being by **Michael Rogers**⁹. Rogers' implementation is a program designed to map fingerprints to pseudo-random poems. This implementation was again, empirically evaluated by Dechand *et al.* [5]. Earlier work by **N. Haller** with the S/KEY [19] shows the implementation of a system designed to represent a hash as a series of six short words. However, this system is designed for a one-time-password purpose and only provides word mappings for basic human usability of the password and not within a fingerprint verification context. Therefore, the wordlist has not been designed with pronounceability in mind.

Pretty Easy Privacy

A very recent implementation of a word list can be found in Pretty Easy Privacy ($p \equiv p$) implementation of TrustWords¹⁰. $p \equiv p$ is a data encryption system that utilises PGP encryption to provide E2EE on all common channels of communication such as email or SMS. The embedded design principles state that above all the systems should be easy to install, use and understand.

$p \equiv p$ deals with the threat of MiTM attacks by having users compare the respective key fingerprints encoded as a set of words. Figure 2.2 shows the $p \equiv p$ Android implementation of



⁸https://en.wikipedia.org/wiki/Mad_Libs

⁹<https://github.com/akwizgran/basic-english>

¹⁰<https://tools.ietf.org/html/draft-birk-pep-trustwords-03>

Figure 2.2: Trustword fingerprint verification

2 Background

Trustwords. The users then authenticate the words on an OOB (Out of Band) channel such as a phone call or in-person communication. If both users decide the words match, they accept or decline respectively.

The unique aspect of TrustWords is its mapping of a single word to 16-bits. If compared to alternative literature, this is the highest number of bits-per-word seen. Full mappings (no duplication of words) would, therefore, require 2^{16} words in the dictionary. This number of words is arguably higher than most users' vocabulary. This deviation from the norm has not been currently backed up by research.

```
[...]  
52127 ZYGOTE  
52128 ZYGOTIC  
52129 ZYMURGY  
52130 AACHEN  
52131 AARDVARK  
52132 AAREN  
[...]
```

Figure 2.3: Re-mapping position in Trust-word dictionary

Alongside the abnormally high number of words, the design choice to exclude slang and profanities from the English Trustword dictionary requires dual-mapping of a section of words. Approximately 13633/65536 (20.8%) of words are re-mapped in the dictionary, leaving 51903 unique words. The re-mapping looped with the dictionary remaining alphabetical. Figure 2.3 shows the position in the dictionary where this occurs.

Moreover, the primary RFC documentation remains in a draft stage and states: *“It is for further study, what minimal number of words (or entropy) should be required.”*. These aspects highlight a substantial gap in the current literature.

Topic conclusion

In conclusion to this topic, the current research has primarily focused on the research and creation of visual representations. Research for textual fingerprints is fragmented and incomplete with work Juola and Zimmermann [17] and M. Goodrich *et al.* [18] providing meaningful research to build upon in terms of word and sentence based encodings. The fragmentation of this research leaves room for further work into this topic area. Alongside this, findings from the previous section's research show that human language based encodings provided the best usability and, therefore, should be a target for further research looking

to improve upon their security and usability.

2.3.3 Attacks on encoding schemes

This area of research studies ways to physically execute attacks on fingerprint encoding schemes. This topic differs from previously examined work due to papers discussing the performance and fallibility of encoding schemes simulated the attack without consideration for how the attack execution. Research in this area is scant, with lots of research attention on security of Man-in-the-Middle (MITM) attacks and not the encoding schemes themselves.

Research in 2002 by **Konrad Rieck**[20] is one the first formalisation of attacks on fingerprint representations. The paper titled *“Fuzzy Fingerprints Attacking Vulnerabilities in the Human Brain”* aimed to look into ways users check hexadecimal encoded OpenSSH fingerprint representations. The author created an elegant way to ‘weight’ essential chunks of the digest. The bytes furthest to the right and left of the digests provided the highest weight. This technique provides a way to score digests and determine the best partial collisions found. For example, with the target fingerprint: 9F23 and partial match 9313 is given a score of 45% even though only two characters are matching.

The paper contains an implementation with a “1.2GHz CPU” being able to obtain 130,000 H/s (With MD5). In comparison to this, a mid-range Intel i5-3320M CPU can today obtain 111,700,000 MD5 H/s. This imbalance shows that the results obtained from the paper are significantly outdated. However, even with the low hash rate, the author was able to obtain some promising results. Figure 2.4 contains the best example used.

```
TARGET: d6:b7:df:31:aa:55:d2:56:9b:32:71:61:24:08:44:87
MATCH:  d6:b7:8f:a6:fa:21:0c:0d:7d:0a:fb:9d:30:90:4a:87
```

Figure 2.4: Best match obtained after a few minutes of hashing

Overall the paper shows an interesting way to create partial fingerprint matches but is not quantified by any empirical evidence gathered on real-world users.

The only other relevant research on this topic is the work by **M Shirvanian et al.**[21] and their paper: *“Wiretapping via Mimicry: Short Voice Imitation Man-in-the-Middle Attacks on Crypto Phones”*. Further research in the area of “human voice impersonation” has received lots of

2 Background

attention [22][23][24]. This paper was chosen over other alternatives due to its specific use of encoding schemes in its evaluation.

In this paper, the authors develop a way to impersonate users when authenticating Short-authentication-Strings (SAS) in the pairing of Cryptophones. To achieve this impersonating they propose two methods: “Short voice re-ordering attack” where an arbitrary SAS string is recreated by re-ordering snippets obtained from eavesdropping a previous connection and “Short voice morphing attacks” whereby the use of previously eavesdropped audio snippets the attacker can morph their voice to match that of the victim. With these methods, they aimed to attack encodings of Numbers, PGP word list (previously discussed work by Juola and Zimmermann [17]) and MadLib (M. Goodrich *et al.* [18] work also previously discussed). The effectiveness of these attacks was evaluated with a study involving 30 participants.

Results from the paper show the effectiveness of these methods. Compared to the baseline of the attacker’s voice replacing the victim, performed with an $\sim 18\%$ success rate. Morphing gained an overall success rate of 50.58% and re-ordering a very impressive 78.23% success rate and showing that these attacks provide an improvement on top of the naive implementation.

One of the most significant limitations addressed by the authors was the reduction in success rates as the size of the authentication string grew. The morphing and re-ordering attacks become increasingly ineffective as the user had more time to detect imperfections. This aspect is not quantified by the author and the extent of this degradation is never empirically discussed. Therefore, the results from this study are only effective and applicable in a SAS context.

Topic Conclusion

Overall the literature for this subtopic remains sparse and incomplete. Further suggested work could look into the feasibility of generating partial collisions for all textual representations alongside quantified effectiveness on users. With the possibility to concentrate on a few selected implementations. The work would aim to focus on the various physical methods used and their feasibility. This is one area the previous literature has failed to cover and has only theoretically quantified attacker strength without consideration for the actual real-world cost of these attacks.

2.4 Overall Summary

In summary of the literature gaps areas discovered; encoding scheme performance requires further work in the performance of all graphical schemes to back up the results made by other work. Furthermore, there is a gap with the assessment of encoding schemes in the context of "remote-vs-proximity" first proposed by M. Shirvanian et al. as it would arguably provide a better simulation of real-world scenarios.

In the context of human demographics and the way they alter the performance of the schemes; further research is required into how the fluency of languages affects authentication ceremony. This further work would be a continuation of the initial work by Hsiao et al. and could allow the creation of schemes that are better suited to specific languages. Alongside this, there is a research gap in the investigation of how mental impairments affect the performance. This aspect is useful due to the number of potential users being affected due to systems not being designed with them in mind. For example, 7% of the population have been identified as having dyslexic tendencies[25]. This fact means that with a UK population of around 63,000,000¹¹ 4,410,000 people could benefit from encoding schemes designed to work well with dyslexia. Dyslexia, however, is only one of many impairments that could affect a scheme's performance, thus further contributing to the substantial effect further work could have on this area.

Other possible large areas for consideration is the lacks of direct consideration for attack strength when assessing the vulnerability of encoding schemes. Issues included the previously discussed wide range of attack strength (2^{28} - 2^{242}) alongside the lack of consideration at all from the majority of papers. Moreover, the complete lack of computation and storage complexity considerations means this is a prime area for further research as it would improve the applicability of results.

The final significant research gap identified is the lack of justification for the newly created Trustwords. Abnormal design choices (16-bit per word) and its recent creation alongside the shown effectiveness of language-based encodings, such as words makes this a promising area for further research.

¹¹From the 2011 Census collated by the Office for National Statistics

3 Project Aims

This chapter defines the selected gaps and the subsequent research questions extracted.

The chosen project aims to assess the security of $p \equiv p$'s minimum recommendation of four Trustwords (As stated in Figure 3.1). As discussed in the previous chapter, Trustwords aims to sacrifice security for increased usability. The encoding scheme has been designed to assist this by having the user compare a reduced set of words. Moreover, issues with the dictionary's design, such as the presence of homophones and dual-mapping of words show the potential for possible vulnerabilities.

As discussed in the previous chapter, the identified research gap regarding the minimal consideration of attack complexity would be a suitable addition for this project. This choice is due to it providing the ability to assess actual performance and, thus, the actual real-world strength of Trustwords while providing research to a scant area. Therefore, the security assessment is supplemented with complexity considerations alongside an actual implementation of the attack proposed.

"Short Trustword Mapping (S-TWM) requires a number of Trustwords that MUST retain at least 64 bits of entropy. Thus, S-TWM results into at least four Trustwords to be compared by the user."

Figure 3.1: Most recent RFC security recommendation

By sampling the $p \equiv p$ documentation they have defined the use case of the Trustword handshake: *"A handshake is done by comparing the Trustwords between two users through a separate communication channel (e.g. in person or by phone)"*.¹ It can be assumed due to the increased globalization that is the time and of the planet that the most common handshake occurrence is over the phone, and, therefore, not in person. This is the assumed context of the handshake. This means, to create near-matches, the similarity of words is quantified phonetically instead of visually.

¹https://www.pep.security/docs/general_information.html#handshake

3.1 Research Questions

With the previously discussed points in mind, the following research questions have been proposed.

1. What are the different ways phonetic similarity can be quantified?
2. Out of a chosen set of metrics, which are the most effective?
3. What are the time and computation complexity required to generate a 'similar' keys for a targeted key pair?
4. What kind of hardware is required to compute a matching key?
5. What percentage of attacks successfully deceive a user?
6. Is the recommended minimum number of four Trustwords enough to provide a basic level of security?

4 Design

This chapter discusses an overview of the proposed designs for elements required to answer the research questions. Alternative solutions are explained when relevant alongside a justification of design choices.

4.1 Overall attack design

The attack on Trustwords involves generating "near-collision" keys. This attempts to provide the base to answer Research Questions 6, 3 and 4.

Near-collision keys are keys that are deemed a match by the phonetic similarity metric (More on this aspect in the following sections). A similarity metric is an algorithm designed to determine if two words are phonetically a match. For example, the words "THEIR" and "THERE" is a match, whereas the words "DARK" and "PRINCIPLE" are not phonetically matching.

As each combined key in Trustwords is an exclusive-or of both sides' public-key (Figure 4.1 shows this process) the attack is designed to target a single pair of users and requires recomputation for every attack target. This aspect is considered when discussing the attack feasibility. Each pair is split into an "Uncontrolled" or "Controlled" key. Uncontrolled is the receiver of the communication, and, thus, the key cannot be altered. The Controlled key is the one we are attempting to impersonate. It is assumed that there is the ability to replace the Controlled key with the malicious option. These descriptions are the terminology used throughout the paper. However, the uncontrolled and controlled keys can be swapped around with the ability to compute both directions. Thus, resulting in the possibility to intercept both directions of communication. This, however, requires performing the attack separately for both directions.

$$KeyFingerprint_1 \oplus KeyFingerprint_2 = TrustwordsFingerprint$$

Figure 4.1: Creation of the combined Trustword fingerprint

When attacking a similarity metric is used to compute a list of possibilities for each position in the target fingerprint.

Figure 4.2 shows the process of generating a subsection of the combinations. A list of each words' matches is generated and combined to create the comprehensive list of near-collision keys.

```
CHOKE BLUSHING FRIGHTENING HAND
COKE
SMOKE

CHOKE
COKE BLUSHING FRIGHTENING HAND
SMOKE

CHOKE
COKE
SMOKE BLUSHING FRIGHTENING HAND
```

Figure 4.2: Visualisation of the generation of near matches

Completing these steps produces a list of fingerprints that can be inserted into a tool designed to hash a large number of keys and search for matches. This aspect of using a extensive list to search for keys massively reduces the complexity of the search.

In summary, the attack steps are:

1. Compute all possible matches using a similarity metric on all words in a dictionary (Only needs performing once).
2. Select a target and allocate "Uncontrolled" and "Controlled" key identification.
3. Calculate all permutations of near-collisions for the key pair and produce a list of similar key fingerprints.
4. Use a list of similar keys in the mass computation of keys to find near-collision keys.

4.2 Similarity metrics

One of the first requirements for the attack is quantifying "phonetic similarity." This section is looking to provide an answer for Research Question 1. There are many algorithms currently available to provide this functionality. This section describes the algorithms alongside the reasons they were selected for assessment later in the project.

4.2.1 Soundex

One of the earliest examples of a phonetic algorithm is known as Soundex. It is one of the most famous algorithms due in part to its implementation into major database clients like MySQL[26], Oracle[27] and PostgreSQL[28]. Initially designed for indexing names by phonetics alongside spelling mistakes due to transpositions in letters. Therefore, due to it being based on the phonetic features, it is highly suitable for this project's use-case.

Soundex produces a four-digit code for each word assessed. The first letter of the word is retained alongside the removal of all of a, e, i, o, u, y, h and w. The remaining letters are then mapped to numbers. These mappings are displayed in Figure 4.3.

b, f, p, v	1
c, g, j, k, q, s, x, z	2
d, t	3
l	4
m, n	5
r	6

Figure 4.3: Soundex mappings of letters to numbers

Soundex Issues

Due to the fixed length and limited digit set the initial concerns from this design is the limited number of combinations. There are a total of 5616 codes due to 26 initial letters and three digits of 6 values ($26 * 6^3$). The limited combinations result in matches of limited quality.

Further issues posed in [29] are discussed below and show the further deficiencies of Soundex in a dictionary word matching context.

1. **Dependency on the first letter:** Soundex cannot match words together if their first letters are different, meaning, for example, the words "KORBIN" and "CORBIN" are considered non-matching.
2. **Silent consonants.** Soundex does not have logic embedded to deal with silent consonants.
3. **Poor precision.** Due to the previously discussed point of a limited code space. [29] re-iterates this point, but in the context of name matching where Soundex's poor performance was demonstrated. Soundex only gained an overall accuracy of 36.37% when matching names within a provided database.

However, even with Soundex's issues, its algorithmic simplicity and popularity allows it to remain relevant in this application.

4.2.2 NYSIIS

The New York State Identification and Intelligence System (NYSIIS) phonetic code was created for use matching the phonetics of American names. The motivation for its inception was mostly due to the presence of Hispanic names in the American based databases (this was an aspect Soundex was known to have low accuracy with). However, due to it having embedded rules to handle word phonetics, it would again be applicable in this application.

It also allows for variable-length codes and, thus, allows the applicability of the application to increase due to it not confronting the limited code issue of Soundex. It was in use right up until the end of 1998 within various US Government departments. Due to NYSIIS's aforementioned use in a professional setting alongside its high occurrence in literature, it was deemed suitable as one of the selected similarity metrics.

4.2.3 Metaphone

Metaphone was invented by Lawrence Philips in 1990[30] in response to the deficiencies in Soundex. It improves on Soundex by including information around inconsistency and variation in English spelling in an attempt to create a more accurate phonetic representation. Metaphone is arguably on the same level of ubiquity as that of Soundex with it finding itself implemented in languages such as PHP[31]. Metaphone was chosen due to similar reasons to that of Soundex and NYSIIS.

Further work would involve the implementation of newer versions of Metaphone. Double Metaphone (2000) and Metaphone 3 (2009) that claim to improve over the original version due to further research performed by Philips.

4.2.4 Levenshtein Distance

Levenshtein distance is a string metric designed to measure the 'distance' between two strings. It is merely the number of single-character edits (insertions, deletions or substitutions) required to reach the other string. Edit distance is not technically designed as a phonetic algorithm, but due to similar-sounding words often being spelt in similar ways[32]. Alongside this, Levenshtein is also the most algorithmically simplistic of

all the considered options. These aspects contributed to Levenshtein's inclusion.

An example distance between `trace` and `place` would be the substitutions of the first to letters, from `tr` to `pl`, meaning the two strings have a Levenshtein distance of 2.

4.2.5 Phonetic Vectors

Phonetic Vectors is a unique addition to the chosen set. Created by Allison Parrish in 2017[33], Phonetic vectors is as the name suggests the vectorisation of the phonetics of a word.

Phonetic features are used in this work as a way to compare the similarity of phonemes. Phonemes are the phonetic elements that construct a word. For example, the word "RING" translated into the phonemes /R IH NG/.

Extensive prior work has gone into producing models of features that map to phonemes [34][35][36]. Features, therefore, are an attempt at mapping the varying and inconsistent rules around the pronunciation of the English language. The vectors were created using lists phonemes from the CMU Pronouncing Dictionary and mapping them to possible features.

Phone	Features	Phone	Features	Phone	Features
AA	bck, low, unr, vwl	F	frc, lbd, vls	P	blb, stp, vls
AE	fnt, low, unr, vwl	G	stp, vcd, vel	R	alv, apr
AH	cnt, mid, unr, vwl	HH	apr, glt	S	alv, frc, vls
AO	bck, lmd, rnd, vwl	IH	fnt, smh, unr, vwl	SH	frc, pla, vls
AW	bck, cnt, low, rnd, smh, unr, vwl	IY	fnt, hgh, unr, vwl	T	alv, stp, vls
AY	cnt, fnt, low, smh, unr, vwl	JH	alv, frc, stp, vcd	TH	dnt, frc, vls
B	blb, stp, vcd	K	stp, vel, vls	UH	bck, rnd, smh, vwl
CH	alv, frc, stp, vls	L	alv, lat	UW	bck, hgh, rnd, vwl
D	alv, stp, vcd	M	blb, nas	V	frc, lbd, vcd
DH	dnt, frc, vcd	N	alv, nas	W	apr, lbv
EH	fnt, lmd, unr, vwl	NG	nas, vel	Y	apr, pal
ER	cnt, rzd, umd, vwl	OW	bck, rnd, smh, umd, vwl	Z	alv, frc, vcd
EY	fnt, lmd, smh, unr, vwl	OY	bck, fnt, lmd, rnd, smh, unr, vwl	ZH	frc, pla, vcd

Table 4.1: Phonemes to feature mapping table

Table 4.1 contains the mappings used in [33] to create the phonetic feature lists. Using this with all 133,852 entries in version 0.7b of the CMU Pronouncing Dictionary, 949 unique properties were produced overall. The author then performed principal components analysis¹ on the unique properties to reduce them down to 50.

This metric allows for a unique set of actions to be performed on the phonetic output. Not only does this metric allow the user to measure

¹Details regarding this process is outside the scope of the project. Please, however, if interested please refer to this resource for more information: <http://setosa.io/ev/principal-component-analysis/>

dissimilarity (as opposed to the similar-or-not method of the alternatives) the continuous nature of the value allows mathematical operations to be performed on the output. An example shown in [33] was the addition of word vectors.

No	Operation	Result
1	$Vec(sub) + Vec(marine)$	submarine
2	$Vec(miss) + Vec(sieve)$	missive
3	$Vec(fizz) + Vec(theology)$	physiology

Table 4.2: Examples of vector addition

For example, the addition of vectors can be seen in Table 4.2. This works for any mathematical operation with examples like multiplication allowing the ‘tinting’ words with a theme.

The ability to perform operations and measure dissimilarity allows for a plethora of applications. One possible application of note would be the creation of a wordlist where the phonetic difference (vector distance) is maximised. This application, if the vector mappings are an accurate representation, could allow the creation of a phonetically distinctive wordlist. These unique aspects contribute to the inclusion of this metric in the set.

4.3 Alternative Similarity Metrics

4.3.1 Match Rating Approach

Matching Rating Approach (MRA) is another algorithm designed to match names within a database; therefore, its operation can be grouped with that of NYSIIS and Soundex. MRA was discarded as an option. This removal of this metric is due to the lack of known utilisation in any substantial real-world use-cases alongside its similarity to more established algorithms like Soundex and NYSIIS.

Further work could compare this algorithm to similar alternatives in phonetically matching of words to quantify performance. This further work is discussed in the evaluative sections of the report.

4.3.2 Caverphone

Another notable alternative solution is that of Caverphone that was designed in New Zealand. Caverphone, as is the case with the vast majority of phonetic algorithms, was designed for use with name matching.

Caverphone was not chosen to similar reasons to that of MRA alongside its optimisation for the New Zealand dialect. Therefore, the low level of utilisation alongside the unique design features contributed to its exclusion. However, this has not been assessed empirically and thus would be a candidate for further work.

Metric	Output
Soundex	T614
NYSIIS	TRAVAL
Metaphone	TRFL
Caverphone	TRF111
MRA	TRVL

Table 4.3: The various phonetic encodings of the word "Travel"

4.4 Design of GreenOnion

In order to answer Research Questions 3 and 4 fully, it is necessary to implement an actual tool to generate actual keys.

The inspiration for the design of this tool was taken from a tool called Scallion². Scallion was designed by Richard Klafter and Eric Swanson and was used to demonstrate that 32-bit PGP key IDs were insufficient. To keep with the onion-based theme, the proposed tool is known as GreenOnion and is a re-write of Scallion in C++. This language was chosen due to the well-understood efficiency benefits. The proposed tool differs from Scallion, most notably in its ability to concurrently search for a large number of keys, GreenOnion improves on this substantially. More implementation and experimental details are discussed in later chapters.

The tool should take two keys as parameters (Uncontrolled/Controlled) and a chosen similarity metric and produce a list of target keys fingerprints. This list is then used as a search criterion when searching for keys. To utilise the parallel nature of the GPU to compute the hash of a large number of keys, the tool utilises a GPGPU (General-purpose computing on graphics processing units) framework. The chosen framework was OpenCL due to its support for the chosen language (C++) and platform (Linux). OpenCL allows the creation of code chunks referred to as "kernels" to be executed concurrently, this provides a massive speed increase compared to the sequential nature of the CPU. Technical details are explained further in Chapter 5.

²<https://github.com/lachesis/scallion>

4.5 Experiment Design

To answer some of the research questions, empirical evidence is required and, thus, experiments are required. In this section, the designs and considerations of the chosen experiments are discussed.

4.5.1 Metric performance

This section answers Research Question 2. To reduce the number of metrics to assess in the later rounds, the performance of similarity metrics required comparison. The thinning out of metrics is required due to limited resources. Therefore, possible further work could involve repeating this work with a much more varied selection of metrics. As explained in a previous section (See Section 4.2) the chosen metrics up for assessment are Soundex, Metaphone, NYSIIS, Levenshtein and Phonetic vectors.

The design for the experiment involves assessing the quality of the metrics matches by having participants rate them on a scale of 1 to 5.

Matches

A match for each code based metric (Soundex, Metaphone and NYSIIS) occurs when the codes are identical. However, for the other cases where the difference is variable other ways of defining a match are required.

In the case of Levenshtein values of similarity are discrete due to it being the number of single-character edits. Therefore, this requires less deliberation. Match size was used as a way to decide on a cut-off point.

Metric	Matches
Soundex	1,527,554
Metaphone	412,916
NYSIIS	188,474
Levenshtein (Distance 1) [L1]	97,730
Levenshtein (Distance 2) [L2]	1,070,656

Table 4.4: Levenshtein number of matches comparison

As it can be seen from Table 4.4, the number of matches for L2 is more significant than all metrics excluding Soundex. As the issues with Soundex have been discussed in previous sections (See Section 4.2.1) it can be excluded as an abnormality in this context. Therefore, due to the

excessively high value for a L2, L1 was chosen as the Levenshtein cap for defining a match.

Match size was also used to define the cap for the phonetic vectors. The decision is less apparent than that of Levenshtein due to the continuous nature of the distance between two vectors. However, the complexity was reduced by limiting it to increments of 0.5.

Metric	Matches
Soundex	1,527,554
Metaphone	412,916
NYSIIS	188,474
Levenshtein	97,730
Phonetic Vector (Distance 3.0)	14,550
Phonetic Vector (Distance 4.0)	73,962
Phonetic Vector (Distance 4.5)	216,156
Phonetic Vector (Distance 5.0)	685,516

Table 4.5: Phonetic vector number of matches comparison

Table 4.5 contains the match size comparison for Phonetic vectors distance. Distance 4.5 was chosen as a suitable size due to the total matches fitting well within the other metrics. Distance 4.0 was the other alternative; this was discarded due to its small size. Any metric with a number of matches below 100,000 results in an inadequate number of possible near-collision keys later in the process, a lower number of matches may imply better quality, but a balance is required between computational cost and attack quality. This is discussed in more detail in later chapters.

***TODO:** Link the less than 100,000 point to experiment data*

Comparisons

Each participant is asked to rate the similarity of a match on a scale of 1 to 5. Figure 4.4 shows an example match and the connected scale. Users are provided with five of these comparisons per metric.

The experiment randomises the order of these comparisons per session alongside a complete refreshing of matches once per submission. This design makes sure selections from the samples are fair and consistent as each user has a different selection of matches.

RANGE-RANCE						
	1	2	3	4	5	
Very different sound	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Very similar sound

Figure 4.4: Example experiment question

Quality control

As the study was being outsourced to Amazon's Mechanical Turk, the requirement to check the quality of results is essential. Therefore, a couple of additions were provided to check a result's validity.

The first was the addition of five "Random matches" questions. These are matches consisting of two random words selected from the dictionary. Therefore, the expected average rating of these words should be close to one. This design allows for a simple check for valid results. If their average is too high, their results are discarded.

UNIVERSITY-UNIVERSITY						
	1	2	3	4	5	
Very different sound	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Very similar sound

Figure 4.5: Exact experiment attention question

Alongside this, was the addition of two questions comparing precisely the same word. As both words are the same, the result should always be a full 5/5 rating, any results without a full rating are discarded. Figure 4.5 contains one example of the attention questions used to filter inaccurate results.

The final check to ensure the validity of results is a check for native English fluency. Having non-native English speakers complete the experiment can introduce inconsistencies into the data and, therefore, needs to remain controlled. To achieve this, a preliminary MTurk study has been created to ask users for their perceived English fluency on a scale of 1 (Basic Understanding) to 5 (Native). Workers with an answer of 5

are provided with a Qualification³ that tags them as defining themselves as native speakers. This qualification is then added as a prerequisite when running the experiment. This prerequisite ensures only fully native speakers are being assessed. The possibility of the worker falsely stating their level of fluency has also been considered. However, as the worker does not know the purpose of this initial study, thereby providing inaccurate results has no real valid motive for the worker.

Considerations

The first consideration is the way the words are compared. Due to the channel of authentication being phone-based, the comparison of words is a mixture of auditory and textual. This mixture is because a user needs to match a words sound to the one displayed on their device. This experiment asks users to compare the sound of two words that are visually displayed to them. This visual aspect is the first point of contact between the participant and the question, followed by a mental comparison of the phonetics of the word. Therefore, this initial visual contact has the potential to bias the results of the study. Levenshtein has the potential to be most affected by this due to the matches never being more than one character different, therefore, resulting in very similar-looking words. The alternative method of running this experiment is to get users to compare audio samples of words; this forces the user to compare just the phonetics of the words and not be influenced by the visual aspects of the pair. However, this adds a substantial cost to the operation of the study. Due to the aforementioned lack of resources, the chosen design was decided as most feasible as it is a balance between cost and accuracy. Further work, therefore, could improve by producing more conclusive results on the performance of the metrics by implementing the more accurate but costly alternative.

Another consideration is the demographics of people accessible on Mechanical Turk. A comprehensive and still active survey run by D Difallah *et al.* [37] shows that MTurk workers are younger and have a more substantial household income than that of the US population. This deviation has to be taken into consideration when interpreting the results because it has the potential to introduce a bias.

4.5.2 Trustword Attacks

TODO: Include explanation into how audio is generated

³<https://blog.mturk.com/tutorial-understanding-requirements-and-qualifications-99a26069fba2>

4 Design

The final experiment required to answer Research Question 5 requires the simulation attacks on participants. The user is presented with the same design as the p≡p Android application (See Section 2.3.2).

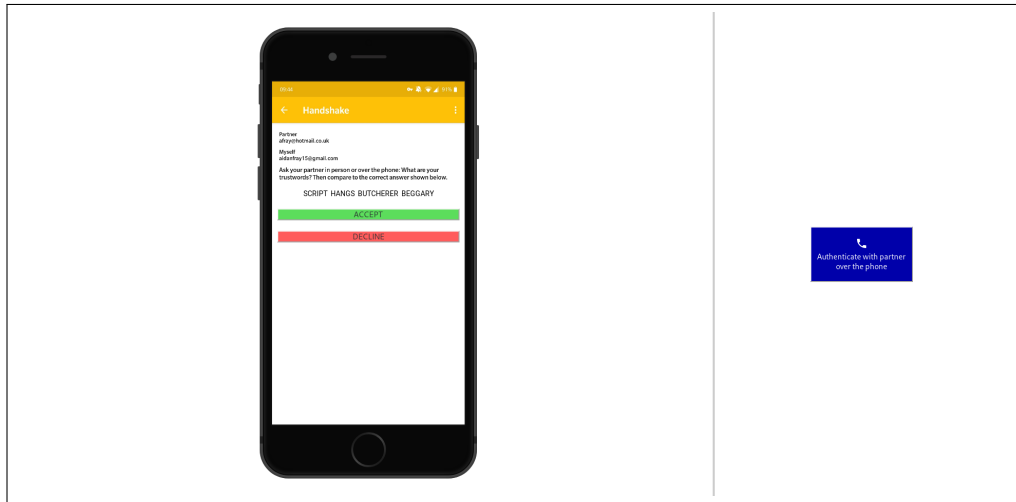


Figure 4.6: Experiment UI

Figure 4.6 shows the design of the experiments front end. As can be seen by comparing it to Figure 2.2, it has been designed to be as close as possible to the actual application. The blue button is clicked to simulate the authentication ceremony over the phone. A text-to-speech system then read a set of words and the user should accept if they match and decline if they don't.

Design

Due to the scarcity of attacks in a real-world setting, users are often complacent about their occurrence. Therefore, in this experiment, attacks only occur 30% of the time. This occurrence is a much higher value than in a real-world setting, but it is a balance between resources and realistic design. Alongside, this the first 5 trials of a new experiment is always benign. This inclusion is to ensure users are lulled into a level of complacency regarding the possibility of an attack.

Certain keys have higher levels of near-collision possibilities than others due to how certain words are deemed similar by the chosen metric. Therefore, this presents the possibility to have keys with a very low number of similar matches. The distribution of these keys is explained further in Chapter 6. Therefore, if random sets of words are chosen with no restraints, there are attacks presented to the user that in a real setting would be infeasible as they are close to a 2^{64} attack

(4 Words * 16-bits). Therefore, the experiment is designed to sample from a list of "vulnerable" keys. These are keys that have a number of combinations that allow an attack in a specified timeframe.

Furthermore, certain levels of attacks are also simulated. Below is the list of possible attacks:

- **Zero static words** - All words in the set can vary.
- **One static word** - All but the first word can vary.
- **Two static words** - All but the first and last word can vary.

The start and ends were chosen as the highest priority words to keep static. This design choice is due to research highlighting on the common habit of users only to check the start and end of a checksum. [38] shows this by measuring user eye movement and displaying it as a heat map.

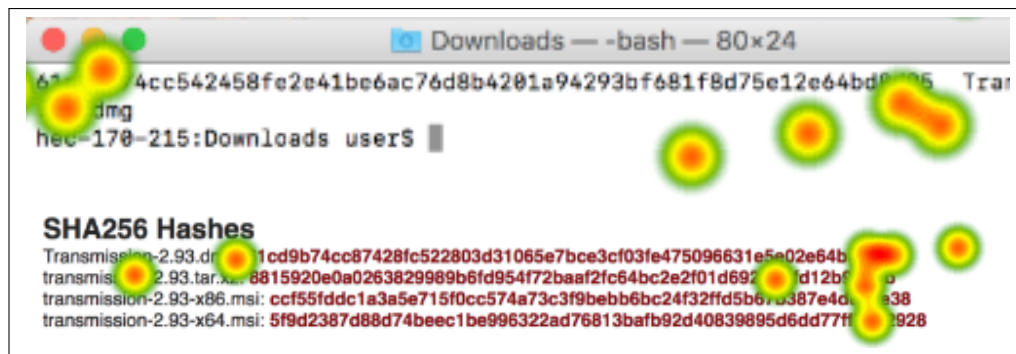


Figure 4.7: Failed verification of an incorrect checksum[38]

Figure 4.7 shows the results of an eye-tracking experiment where the user failed to detect a mismatching digest. As it can be seen, the users never compared the centre of the digest.

However, this may not be applicable in this context due to the user being linearly fed an audio stream that they cannot skip to the start or end. We believe, however, that attention also plays a part in defining the most important areas of comparison. The hypothesis is that the users' attention is lower in the middle sections of comparison, where it peaks at the start and end. All of these aspects require empirical evidence to conclude. Therefore, this requires consideration when assessing the results of the experiment.

These attacks are ascending in complexity. The timeframe for finding a match was decided as 7-days with attack strengths of 1 GPU/day, 10 GPU/days and 100 GPU/days on a mid-range GPU (AMD RX 480 was the example in experiments). Due to the long lifetime of PGP keys, 7 days was chosen as a reasonable length of the attack. The tool

requires no user interaction once started, therefore, it can be left for an extended period to compute potential keys. This timeframe is also a maximum time, these attacks also include keys that have a shorter average computation time.

GPU/days	No of combinations required	Attack Type
1	15250	Zero static
10	1525	One static
100	152	Two static

Table 4.6: Summary of attack requirements

Table 4.6 contains a summary of the different level of attacks and their respective restrictions. More combinations make the attack search quicker. Any key that exceeds this criterion is deemed as vulnerable. A list of these vulnerable keys is sampled from when an attack is simulated. The percentage of vulnerable keys is explored in Chapter 6.

Quality control

Like the previous experiment, participants are sourced from MTurk. Therefore, again, quality control is an aspect that requires consideration. As with the previous study, initially screened native speakers are used, alongside the utilisation of the same process to recruit suitable workers. Two metrics are used to detect invalid results: audio-button-clicks and the overall-time.

Audio-buttons-clicks is the number of times the blue "*Authenticate with partner over the phone*" button in Figure 4.6 is clicked. If there are rounds without button clicks, this is a sign of non-attentiveness. The design choice was made to keep this as a result filter, as preventing non-clicks would be a trivial task. This design provides a way to detect and discard click-throughs⁴.

Overall-time is as the name suggest a recording of the time taken to complete the entire experiment. If users complete the experiment in an abnormally small amount of time, it can be used as another detection for invalid responses. Anything below a certain threshold is discarded.

Considerations

As with the previous experiment, sampling from a MTurk demographics results in a collection of participants that are not reflective of the general

⁴Workers that aim to complete the task as fast as possible, with no regard for the quality of responses

4 *Design*

population. Due to the attack context of this experiment is can be assumed that the youth of the participants contributes to less successful attacks. Therefore, the results generated by this experiment can be loosely assumed as a best-case scenario for the scheme. We predict a high attack success rate if assessed over the general population.

5 Implementation

This chapter discusses the implementation details of the project. Instead of explaining all the technical achievements in detail, the most interesting ones are discussed alongside the respective challenges encountered.

5.1 GreenOnion

General design

This section briefly discusses the overall technical implementation of GreenOnion alongside a more in-depth discussion into the unique aspect of the tool.

GreenOnion is written in C++. This language was chosen due to its efficiency bonuses over other alternative languages. The tool begins by generating a 2048-bit RSA key through GPG¹. This key is then used to create a hash of all but the final 512-bit block of the key. The final block of the key is left un-hashed due to the presence of the exponent (e). This exponent is then incremented to create a new unique key. This technique allows the accelerated generation of new keys due to the reduction in expensive large prime generation. Entropy starvation is an example of a common issue encountered when generating a large number of RSA keys. This process produces valid keys, but with abnormally large exponents, this was deemed suitable due to the short term use-case for these keys. Three bytes are used to represent the exponent giving the potential to create $2^{24} - 1$ extra keys for a single expensive key generation.

All keys including the intermediate hash are loaded on the GPU via an OpenCL kernel. This kernel is designed to hash the final block, obtain the final fingerprint and check if the fingerprint is present in the provided list.

¹GNU Privacy Guard

Bloom filter

Mass checking of fingerprints is the tool's central ability as it allows for millions of keys to be checked with a minimal amount of overhead. This functionality is achieved through the use of a bloom filter. A bloom filter is a probabilistic data structure that allows efficient checking for the presence of an element in a set. It is effectively a vast array of booleans that state whether an element is present. A pre-defined hashing algorithm decides the index in the array. This process is repeated several times with a set number of hashing algorithms (k) to populate the array of length (m). To check the presence of an element in the set means hashing the target value and checking the indices returned. This data structure, therefore, has a complexity of $O(k)$ regardless of the number of elements in the set. This is the only data structure that provides this characteristic. This benefit comes at a cost. Due to the use of hashing algorithms, there is the possibility for collisions and, thus, the possibility of false-positives. The data structure, however, does not produce any false-negatives.

These qualities, therefore, makes it fully suited to this use-case as any fingerprints tagged as “possibly” being present in the bloom filter can be followed up with a more expensive hash-table check to determine their actual presence. Therefore, if the levels of false-positives are controlled (by altering k and m), the tool can search through a vast number of potential keys without any decrease in speed.

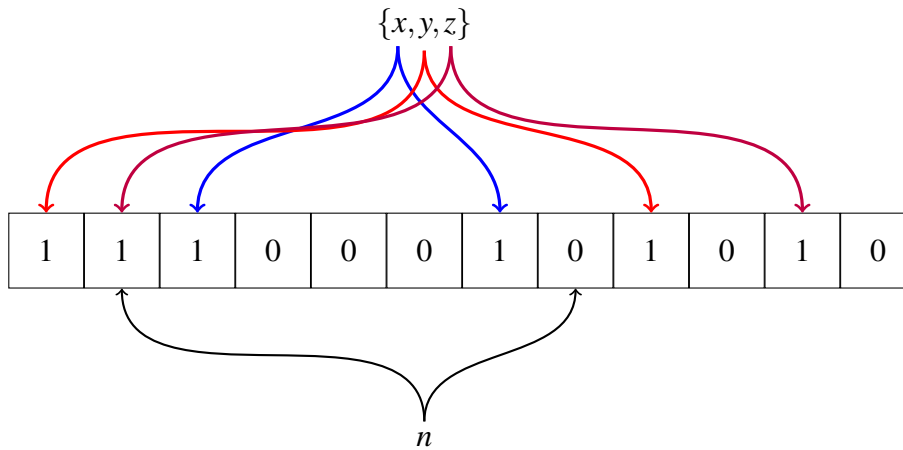


Figure 5.1: Bloom filter example

Figure 5.1 shows the operation of a simple bloom filter. As can be seen, the element n does not exist in the set due to both array indices not being set. The performance boost when comparing large numbers of keys is substantial when compared to a similar tool Scallion (See Section 4.4.) The results from the comparison are quantified in Chapter 6.

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OpenCL

In order to process a substantial number of keys in a concurrent fashion, OpenCL was required. Figure 5.2 contains the main sections of the code uploaded to the GPU.

```
1  __kernel void key_hash(__global uint* finalBlock,
2                          __global uint* currentDigest,
3                          __global bool* bitVector,
4                          __global long* bitVectorSize,
5                          __global uint* outResult)
6  {
7      uint W[16];
8      uint H[5];
9
10     W = finalBlock;
11     H = currentDigest;
12
13     // <EXPONENT_INCREMENTING_CODE>
14
15     // Hashes the final block
16     sha1_block(W, H)
17
18     // Checks against the bloom filter
19     bool match = true;
20     for(int n = 0; n < 2; n++)
21     {
22         uint l = MurmurHash3_x86_32(H[0], n) %
23             bitVectorSize[0];
24
25         uint r = MurmurHash3_x86_32(H[1], n) %
26             bitVectorSize[0];
27
28         if(!bitVector[l] || !bitVector[r])
29         {
30             match = false;
31             break;
32         }
33     }
34
35     // Returns parts needed to recreate the key
36     if(match)
37     {
38         outResult[0] = 0x12345678;
39         outResult[1] = newExponent;
40     }
41 }
```

Figure 5.2: OpenCL Kernel

The <EXPONENT_INCREMENTING_CODE> is explained in the next section. After the exponent is incremented, the code produces the final digest by calling `sha1_block(W, H)`. The 32-bit left and right sections of the digest are hashed using the MurmurHash algorithm. MurmurHash does not exhibit features suitable for secure hashing as it can be trivially reversed. Its use-cases include hash-based lookups due to its speed and its distributive properties, making it suitable to work well with a bloom

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filter. The hashed values are then checked against the bloom filter array. If there is a possible match, the identification value (0x12345678) is placed in the first byte of the `outResult` alongside the exponent used to produce the possibly matching PGP key. The minimal amount of data returned to the CPU via the `outResult` variable is due to efficiency reasons. Use of this memory is computationally expensive; therefore, at every opportunity, writing or reading this memory has been avoided.

```
1 //The exponent is split across two words
2 // i.e
3 //
4 // W[3] = XX EE EE EE
5 // W[4] = EE XX XX XX
6 //
7 int newExponent = get_global_id(0) + \
8                     ORIGINAL_EXPONENT_VALUE;
9
10 // Moves the value to the right i.e. 0x01ffff -> 0x0001ff
11 // Dividing by "0x100" moves the hex value 3 digits
12 // to the right
13 int exponentMaskLeft = ((int)(ORIGINAL_EXPONENT_VALUE / 0
14                             x100)) ^ ((int)(newExponent / 0x100));
15
16 W[3] = W[3] ^ exponentMaskLeft;
17
18 // Grabs the last byte of each exponent to apply to
19 // the next word
20 int lastByte = (int)(ORIGINAL_EXPONENT_VALUE / 0x100) *
21                 0x100 ^ ORIGINAL_EXPONENT_VALUE;
22
23 int lastByteNew = (int)(newExponent / 0x100) * 0x100 ^
24                   newExponent;
25
26 // Moves it into position as the MSB of a 32-bit integer
27 // i.e 0xff -> 0xff000000
28 int exponenetMaskRight = (lastByte * 0x1000000) ^
29                           (lastByteNew * 0x1000000);
30
31 W[4] = W[4] ^ exponenetMaskRight;
```

Figure 5.3: Exponent incrementation code

Figure 5.3 contains the code used to increment the exponent. Due to the exponent being split across two words alongside the limited functionality of OpenCL, bitwise operations to increment the exponent. The code utilises the fact that anything XORed with itself becomes zero alongside the fact that XORing a value a with zero provides the result equal to a . The code manipulates the position of values by multiplication or division of base-16 values; these shift the hex value either left or

right, respectively. Once it is in position the "Mask" is created by XORing with the original value and the new intended value, this stores the changes required to reach the required values, this then applied to each of the words. The `get_global_id` command takes the ID from the currently running thread; this allows a different value to be used for each exponent concurrently

5.2 First Experiment

In order to assess and collect data from users for the first experiment (See Section 4.5.1), Google Forms² was used to host and design the questionnaire. It provided the functionality to present questions easily and record responses. However, as the design requirement of refreshing questions after each submission was not part of the main applications functionality, an extra solution was required. This problem was solved by Google's App Script³ service that allows a user to interact with the Form programmatically. This addition allowed the re-sampling of matches each time a user submitted a response.

Figure 5.4 contains an interesting snippet from the script used in the experiment. Each time a user submitted their response, the `updateForm()` endpoint was called, that subsequently updated the questions for the next user. This technique aimed to keep the samplings fair as they are equally likely to appear when attacking the system.

²<https://www.google.com/forms>

³<https://developers.google.com/apps-script/>

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```
1 var ALGOS = ["Soundex", "Metaphone", ...];
2 var ALGO_SIZES = [763777, 412916, ...];
3
4 function updateForm(ss, form) {
5
6     // Obtains a list of the items present on the form
7     formItems = form.getItems();
8
9     // Updates the new values
10    var algo_index = 0;
11    var scale_index = 0;
12    for (var i = 0; i < formItems.length; i++)
13    {
14        if (formItems[i].getType() == "SCALE")
15        {
16            var rnd_index = Math.floor(Math.random() *
17                ALGO_SIZES[algo_index]) + 1;
18
19            // Obtains the Google Sheets object
20            var sheetname = ALGOS[algo_index];
21            var sheet = ss.getSheetByName(sheetname);
22            var range = sheet.getRange(rnd_index, 1)
23            var values = range.getValues();
24
25            // Re-samples from the connected Google Sheets
26            _updateScaleTitle(formItems[i], values[0]);
27
28            scale_index++;
29
30            // Moves on to the next metric when a group size
31            // has been completed
32            if (scale_index != 0)
33            {
34                if (scale_index % QUESTION_PER_ALGO == 0) {
35                    algo_index++;
36                }
37            }
38        }
39    }
40 }
```

Figure 5.4: Section of code from the First Experiment’s Google App Script

5.3 MainExperiment

In order to assess users in a similar scenario to ones experienced when utilizing p \equiv p in the real-world, a custom application was required. The front-end is developed in Javascript with a Python-Flask backend that

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acts as the functionality of the webpage. Several endpoints are exposed like `get_audio` or `get_words` that are requested and displayed on the front-end.

One of the main problems encountered was the handling of each user's session. Initially, during testing, it was noted that changes in one endpoint if timed correctly would overwrite the progress of another, this is commonly known as a "Lost update". This issue was due to the user session being stored in the `session` cookie. When sending off a request the session cookie is included in the header, the code then utilises the data within the cookie to make decisions and alter state, the updated state is then returned as a cookie in the response. If, however, another request is executed before the first has completed, the second request is using the context of the first request and, thus, any alterations made by the first is completely lost.

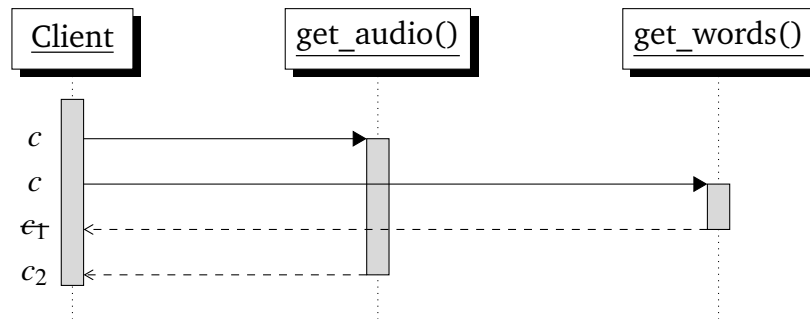


Figure 5.5: Sequence diagram for the 'Lost Update' problem

Figure 5.5 shows this problem visually. As it can be seen the response cookie `c2` is based on the old data of `c`. When `c2` is eventually returned, it removes the progress of `c1`. The restriction of the UI solved this problem. When a button is clicked, all other operations are disabled until a response is received. This technique stopped the possibility of sending off another request while another is still processing. This solution was chosen to keep the complexity of the backend low.

In order to collate data for results later in the process, the state had to be retained. One potential solution would be to format the data and save it as a `.csv` file. However, this is a static way of data persistence and would require alteration every time the data schema was modified. The chosen solution utilised a python object serialisation library known as 'Pickle'⁴. This library saves the instance of a class as a file. This file then can be used to load the instance of the class back into the program. This inclusion allows changes to the object to filter down through the program and keeps the design of the application fluid. For example, after initial feedback gathered about the application, it was decided that

⁴<https://docs.python.org/2/library/pickle.html>

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the inclusion of ‘Round times’ would be a useful addition. Edits were made to the `experiment` class and the changes propagated through the application; no changes were needed on the save functionality. To distinguish between old and new save formats, a version number was used.

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6.1 Scallion vs GreenOnion

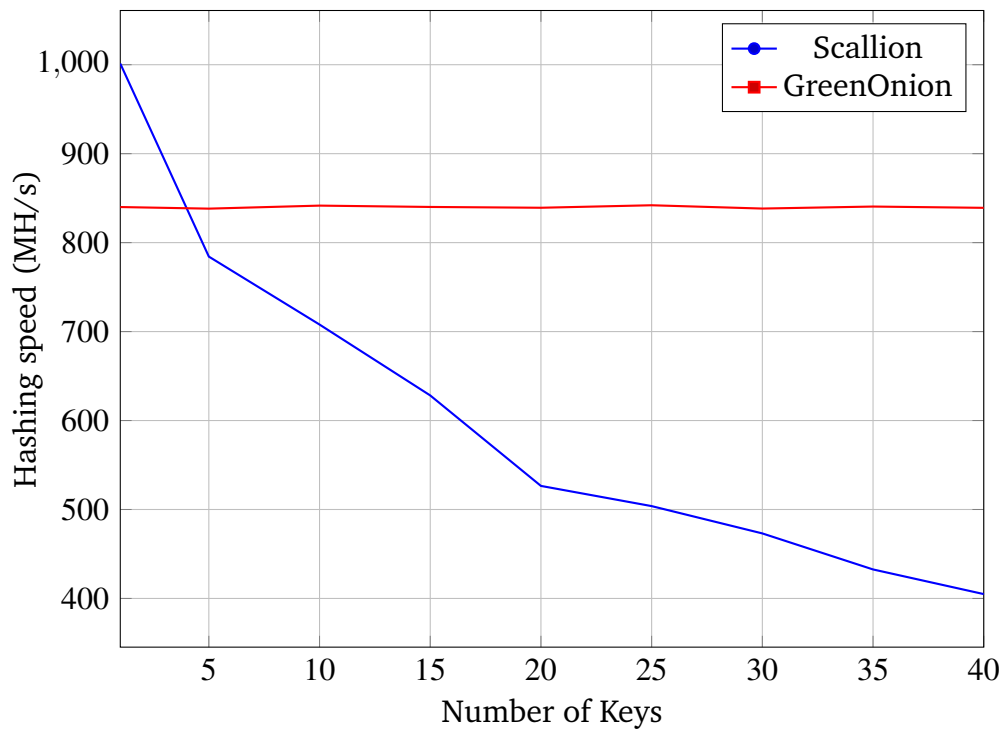


Figure 6.1: Speed comparison between Scallion and GreenOnion

This section compares Scallion and the newly designed GreenOnion ability to search for a large number of potential keys.

Figure 6.1 shows the speed decline as the number of keys increases for Scallion. Any number of keys over 40 resulted in a crash for Scallion. GreenOnion’s speed is almost perfectly consistent. It is slower up until around 5 keys. This consistency is

Scallion	
OS	Windows 10 (May 2019)
Version	Scallion-2.0 ¹
GreenOnion	
OS	Linux Mint (Version: TODO)
Hardware	
GPU	GTX 750 Ti
CPU	AMD FX-6300

Table 6.1: Testing environment

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due to the overhead of the bloom filter; however, as the number of keys increase, the bloom filter's benefits become apparent. In this test, the bloom filter size was kept consistent at exactly 5,000 elements.

GreenOnion has been tested to handle more than 1.5 million keys with a slight reduction in performance. This improvement over Scallion is, therefore, substantial.

6.2 Experiment 1 - Metric performance

As discussed in Section 4.5.1, the goal of the experiment was the cull the number of metrics to be assessed in the following experiment. This section will discuss the demographics of participants alongside the subsequent results.

Gender	Male:	44.44%
	Female:	55.56%
Age:	18-24:	10.10%
	25-29:	20.20%
	30-39:	31.31%
	40-49:	21.21%
	50-59:	12.12%
	60-69:	4.04%
	70-79:	1.01%
Highest Education:	GCSE:	13.13%
	A-Level/O-Level:	19.19%
	Bachelor's degree:	52.53%
	Master's degree:	13.13%
	PhD:	2.02%

Table 6.2: Participant demographics

Overall, 104 participants were assessed in this study. Five results were discarded from the set due to either failing the attention questions (See in Section 4.5.1) or having too low of a fluency rating. This dismissal was a necessary process to improve the health of the results.

Table 6.2 contains the demographical breakdown of the reduced set of participants. The average ages of the participants were 37.3 years ($\sigma = 11.67$) with a split of 44.44% of Males to 55.56% of Females. As can be seen, over 60% of participants can be considered highly educated (Bachelor's and up). This level of education is not sufficiently reflective of the general population and therefore, has to be considered when interpreting the results. All participants were sourced from the US; this again requires consideration due to the broad range of dialects present

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that may bias the results. Further work could investigate the effect of location and dialect on similar results.

Figure 6.3 shows the average results for the metrics. It can be seen that Levenshtein came out substantially above the rest. The breakdown of the ratings in Figure 6.7 also shows Levenshtein's dominance. Levenshtein has a much more significant proportion of 4 and 5 ratings than the alternatives. This performance may, however, be due to the visual way the comparisons are being performed. (Discussed in detail in Section 4.5.1).

Metric	Average Rating	σ
Leven	3.66	1.15
NYSIIS	2.92	1.31
Metaphone	2.56	1.32
Phonetic Vec	2.50	1.35
Soundex	2.08	1.12
Random	1.16	0.46

Table 6.3: Average metric performance

Due to the averages of Metaphone and Phonetic Vectors being so close standard deviation was used as the final decider. As can be seen, Megaphone has a slightly lower σ value of that of Phonetic vectors, thus, contributing to the decision to select Metaphone.

Considerations

As discussed in Section 4.5.1, compromises were made to fulfil all requirement with a minimized cost. Levenshtein's abnormal performance further backs up concerns around the visual aspect biasing the performance of the metric. This aspect requires consideration when interpreting the results.

Even with the discussed issues, the experiment was designed to reduce the number of metrics promptly. This experiment, therefore, has achieved that goal of providing three metrics for the subsequent experiment while balancing between accuracy and expenditure. The results are also an improvement over informal ad-hoc methods. Further work could aim to reproduce this study with the proposed audio-based design (See Section 4.5.1).

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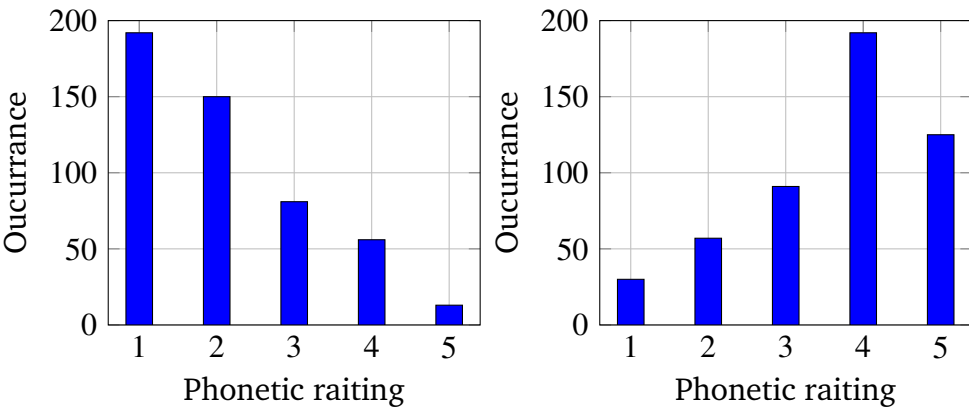


Figure 6.2: Soundex

Figure 6.3: Levenshtein

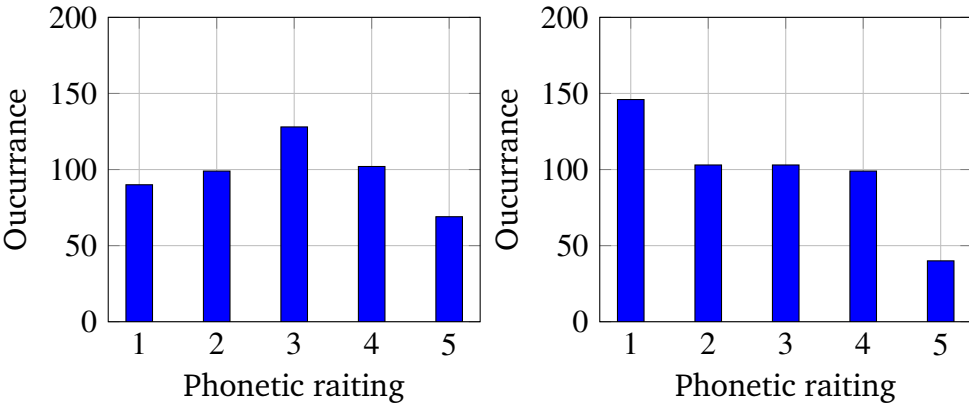


Figure 6.4: NYSIIS

Figure 6.5: Metaphone

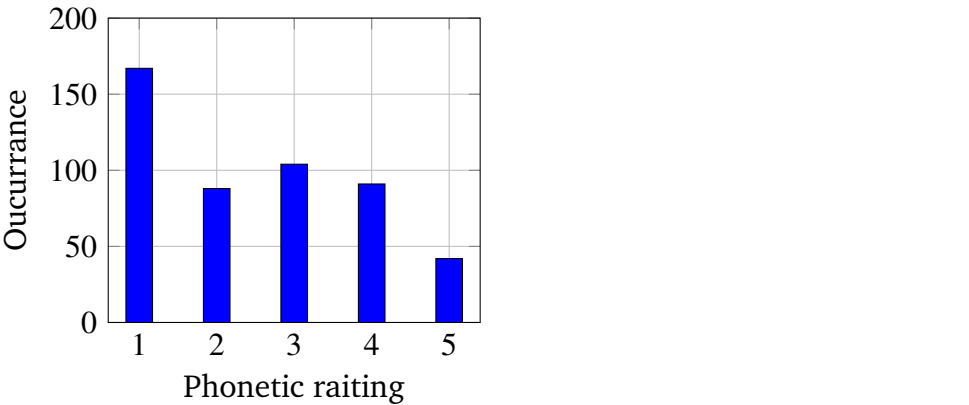


Figure 6.6: Phonetic vector

Figure 6.7: Individual breakdown of results for each metric

6.3 Experiment 2 - Trustword attacks

This experiment aims to quantify the success rate of the proposed attack. Design details for this experiment can be seen in Section 4.5.2. This section presents and discusses the results of the experiment alongside a comparison to relevant literature.

Demographics

Overall, 435 paid participants recruited via Amazon’s MTurk were assessed in this experiment. We excluded 66 results; 7 due to being non-native speakers and 59 were discarded for failing the attention metrics (Discussed in Section 4.5.2).

Gender	Male:	50.41%
	Female:	49.59%
Age:	18-24:	12.74%
	25-29:	18.16%
	30-39:	37.4%
	40-49:	17.89%
	50-59:	8.67%
	60-69:	4.34%
	70-79:	0.81%
Highest Education:	GCSE:	13.82%
	A-Level/O-Level:	24.12%
	Bachelor’s degree:	51.49%
	Master’s degree:	8.4%
	PhD:	2.17%

Table 6.4: Participant demographics

The reduced set of 369 participants had an average age of 36.63 ($\sigma = 11.35$) and consisted of an almost equal split of Male (50.41%) to Female (49.59%). Around 62% of participants had completed a single stage of university (Bachelor and up). This aspect makes this set of participants more educated than the general population. All participants were also sourced from the USA and have rated themselves as fully native English speakers.

As user-agent strings were collected for each participant collations of OS and internet browser versions was made possible. Tables 6.5 and 6.6 contain the browser and OS breakdowns, respectively. Chrome and Windows 10 seem to dominate the proportion of their respective domains alongside the surprisingly large proportion of workers utilizing older versions of Windows such as 7 or 8 (15.81%).

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Browser	Percentage
Chrome	85.09%
Firefox	12.20%
Safari	1.90%
Other	0.81%

Table 6.5: Internet Browser breakdown

Operating System	Percentage
Windows (All)	74.26%
<i>Windows 7</i>	12.74%
<i>Windows 8</i>	4.07%
<i>Windows 10</i>	57.45%
MacOS X	13.82%
ChromeOS	3.79%
Android	4.34%
iPhone	1.08%
iPad	0.54%
Linux	2.17%

Table 6.6: Operating System breakdown

Results

Table 6.7 contains the break down of results for the experiment. It can be seen that the best metric out of the set was Levenshtein with an overall success of 19.80%. The best performer, when regarding attack strength, as expected, is the 2 static words. Levenshtein’s 2 static attack performed the best overall with a success rate of 32.05%. The worst performer was Metaphone, with an average of 16.88% over its three levels of attacks. When comparing the performance of the metrics to the previous experiment the ordering remains the same with Levenshtein, NYSIIS and Metaphone all ranking in the same order.

Considerations

As previously mentioned, the set of recruited participants are more highly educated than the general population. This, combined with the lower average age, contributes to an inevitable bias being introduced into the data. An assumption can be made that higher education leads to more skilful interaction with computer-based systems, this, therefore, with the previous assumption in mind means the results of this experiment can be considered a ‘best case’ scenario. The attacks, therefore, would be expected to be more successful on less technical users. This consideration, however, requires further research and possible empirical

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Metric	Successful Attacks	Total Attacks	Success Rate
Levenshtein	218	1101	19.80%
0 static	34	358	9.50%
1 static	59	353	16.71%
2 static	125	390	32.05%
Metaphone	181	1072	16.88%
0 static	38	345	11.01%
1 static	57	375	15.20%
2 static	86	352	24.43%
NYSIIS	209	1114	18.76%
0 static	36	385	9.35%
1 static	72	375	19.20%
2 static	101	354	28.53%
Overall	608	3287	18.50%

Table 6.7: Success rates for simulated attacks

data to determine the validity of the assumption.

During this study, the main task was to perform the authentication ceremony a set number of times. In the real-world, the ceremony is a secondary task due to it not strictly being required. This aspect, alongside the potential for users to downplay the possibility of attack, leads to the conclusion that the success rates could be much higher in a real-world setting. The assumption is that these results display the success rate for extremely attentive users where they make sure to double-check with their authentication partner multiple times. It is, therefore, assumed that the majority of users aim to complete the task as quickly as possible, if at all.

Comparison to alternative literature

This section compares the results of the experiment to similar literature.

Work by Kaında *et al.* [7] (previously discussed in Chapter 2) is the most comparable to this experiment. They were the only study to use exactly 4 words but differed on the size of the dictionary (1024 words) and how a near-match were calculated. Near-matches were a difference in a single word, but without the consideration for similarity, this is the unique aspect considered with this experiment.

However, with those aspects in mind attacks on words encoding received an overall success rating of 3.3%, considerably lower than that of this study. In the worst-case, our simulated attacks achieved almost 3

times as many successes compared to this study.

Other relevant work by Dechand *et al.* [5] also discussed in Chapter 2 assess the success rate of attacks on words. Their experiment is less similar as 14 words per attack were assessed with each participant, where the comparison was performed visually. However, the success was 8.78%. As 10/14 words were kept static, this result is more comparable to the highest attack strength “2 static”. This, therefore, leads to another 3 fold improvement in the success rates of our simulated attacks.

The final relevant paper to compare is that of Tan *et al.* [6]. This paper had the highest number of words assessed with 16 overall. With it assessing the same wordlist and attack strength as the work by Dechand *et al.*, the attack success was 14% overall. This success rate compared to the highest attack assessed in the experiment results in another sizeable difference.

In conclusion, all related literature had much lower attack success rates than the results presented in this experiment. With all papers using similarly designed wordlists, it highly suggests that the deficiencies in Trustwords are the cause for the substantial increase in attack success. Alongside this, the consideration for similarity when calculating near-collisions could have also resulted in the higher attack success rates. This aspect is also a unique consideration compared to the available literature.

6.4 Average number of near-collision keys for each metric

In order to predict the effectiveness of the attack over a wide variety of keys the number of average near-matches requires computation. Table 6.8 shows the average keys for each metric. The “Compute Time” is the computation time required for a single mid range (2000MH/s) GPU.

As it can be seen metrics like Levenshtein have a low overall average and would require much more attacker resources to become feasible. On the other hand, Metaphone has attacks that could be computed on average in under 2 days. The success rate for this attack type in the second experiment was 11.01% on average. This means on commodity hardware commonly found in the home, an attacker could compute a key in less than two days that could succeed more than 10% of the time. This is substantial and highlights on weaknesses in the Trustword system.

6 Experiments

Metric		Mean matches	σ	Compute Time
NYSIIS				
	0 static	1963.07	24769.48	27.19 days
	1 static	448.37	4316.57	119.14 days
	2 static	98.07	550.44	1.49 years
Metaphone				
	0 static	27138.78	529229.35	1.97 days
	1 static	2822.74	23932.39	18.91 days
	2 static	339.84	1730.97	157.45 days
Levenshtein				
	0 static	293.92	2158.24	182.17 days
	1 static	102.75	719.28	1.43 years
	2 static	35.53	120.71	4.18 years

Table 6.8: Each metric’s average near-collision keys

6.5 Distribution of vulnerable keys

As discussed in the design of the second experiment (See Section 6.3) the attacks sampled from a list of ‘vulnerable keys’. These vulnerable keys were created using real keys extracted from PGP key servers. These keys were then randomly sampled and used to create the combined key as discussed in Section 2.3.2. 100,000 random key pairs were created and used as the sample. Any vulnerable keys in this set were recorded and used in the experiment.

TODO: Reference David’s work

Attack Type	Metric	Vulnerable %
2 static (152)	Levenshtein	4.295%
	Metaphone	24.095%
	NYSIIS	10.441%
1 static (1525)	Levenshtein	0.827%
	Metaphone	15.569%
	NYSIIS	4.341%
0 static (15250)	Levenshtein	0.157%
	Metaphone	10.202%
	NYSIIS	1.824%

Table 6.9: Number of vulnerable keys per metric

Table 6.9 contains the breakdown of the number of vulnerable keys.

The takeaways from this table is the extremely low values for Levenshtein in the higher attacks. This is due to the low number of overall matches produced by Levenshtein. This means Levenshtein will not be effective in the vast majority of cases. However, the standout metric is Metaphone with a good proportion of vulnerable keys, it was the worst performer when assessed against real users but only by as little as 2%. If you take into consideration the number of vulnerable keys detected in the set alongside the average amount near-collision matches in Table 6.8 Metaphone appears to be the most usable metric overall.

6.6 Generation of keys

To demonstrate that the the generation of the near collision keys is not only theoretical actual generation of keys was performed using GreenOnion. A random metric was selected from the three carried forward from the first experiment. Alongside this a random uncontrolled key was generated as the simulated attack target (See Appendix A for the armor public key). Then for each attack level (0 static, 1 static, 2 static) a key was computed. NYSIIS was chosen as the selected metric. To expedite the process an initial search was performed for controlled keys that had the highest number of near-collisions, this was due to the demonstrative purpose of this experiment. Producing near-matching keys from key pairs with a very small number of potential matches, adds very little to this demonstration.

Tables 6.10, 6.11 and 6.12 contain the parameters and results on the computation. Due to varying availability of resources each computation has a varying hashing speed. This, however, has been normalized by the introduction of the "GPU Day" metric. This is simply the computation time required to reach the same conclusion on a single 2000 MH/s GPU.

As it can be seen most notably from Table 6.12 the generation of the actual Trustwords differs in only 3 characters making it arguably very similar. When linking this generated key to results of the second experiment (See Section 6.3) computation of 2.53 days on a single mid-range GPU is able to achieve around a 28% success rate when assessed against actual users. Even with the least restricted attack type presented in Table 6.10 the computation of half a day can provide almost a 10% success rate when attacking users. This means any user with a single commodity GPU could compute enough keys in less than a week to have a very high probability of fooling an actual user.

6 Experiments

Potential near-collision keys	142,296
Hashing speed	4000 MH/s
Estimated computation time	9 hours
Actual computation	6.41 hours
GPU Days	0.52
Original Trustwords	BELL GRIND ALGERIA ANNULI
Actual Trustwords	BOIL GRAND ALGER ANNUL

Table 6.10: NYSIIS - 0 static

Potential near-collision keys	133,200
Hashing speed	8000 MH/s
Estimated computation time	4.2 hours
Actual computation	5.12 hours
GPU Days	0.853
Original Trustwords	ASSUMING SONOMA DENS KEENER
Actual Trustwords	ASSUMING SUMMON DENNI CONNOR

Table 6.11: NYSIIS - 1 static

Potential near-collision keys	16,464
Hashing speed	6000 MH/s
Estimated computation time	2.16 days
Actual computation	23.44 hours
GPU Days	2.93
Original Trustwords	VOCATION BORE TANN ANTE
Actual Trustwords	VOCATION BARE TONE ANTE

Table 6.12: NYSIIS - 2 static

7 Evaluation

This chapter will collate the findings of the paper, evaluate the paper’s success against the research questions and discuss potential further work.

7.1 Research Question 1

Research Question 1 asks: “*What are the different ways phonetic similarity can be quantified?*”. This paper has discussed a number of metrics used to quantify phonetic similarity (See Section 4.2). Most metrics were chosen due to their high utilization and occurrence in literature. The only exception to this is the presence of Phonetic Vectors that were chosen due to their unique qualities. This project has succeeded in presenting a comparison of ways to compare similarity metrics. A more in-depth comparison of all possible metrics is a substantial task and would require a project with this sole dedication.

7.2 Research Question 2

Research Question 2 asks: “*Out of a chosen set of metrics, which are the most effective?*”. The paper has presented the performance of a suite of algorithms that are mostly present in alternative literature. Performance of these metrics were quantified in a direct study that selected the top three from a set of five. These newly selected metrics were then assessed in an attack context with their performance being indirectly quantified. From the historical set of metrics Levenshtein was the best performer with participants rating its matches as substantially better. Levenshtein was also the best performer in the attack context with it having the best average attack success rate. This, therefore, seems to corroborate work showing that words with similar spelling tend to share phonetic similarity [32]. This area, however, will require further work to provide more conclusive results on the most effective ways to quantify phonetic similarity.

7.3 Research Question 3

Research Question 3: “*What are the time and computation complexity required to generate a ‘similar’ keys for a targeted key pair?*” has been discussed by the project, the actual generation of keys was shown in Section 6.6 where actual keys were generated. Further more the distribution of key permutations on a set of real-world keys were discussed in Section 6.4 and 6.5. To achieve this the tool GreenOnion was developed where inspiration was gathered from a currently available tool known as Scallion. Experimentation results were gathered and displayed in Section 6.1 that showed the significant increase in the number of near-collision keys GreenOnion can test for with GreenOnion being able to handle in excess of 1.5 million keys. This is in comparison to maximum of 40 keys Scallion can compare.

7.4 Research Question 4

Research Question 4 states: “*What kind of hardware is required to compute a matching key?*”. Through the computation of actual keys presented in Section 6.6 and the theoretical calculation into key computation in some cases it has been shown that a single mid-range GPU¹ can be used to compute actual keys.

7.5 Research Question 5

Research Question 5 “*What percentage of attacks successfully deceive a user?*” was shown by the results presented in Section 6.3. The weakest attack strength and ones that can be computed by a single mid-range GPU for a single week achieved success rate ranging from 9.35% - 11.01%. The middle attack involving the use of 10 mid-range GPUs for a week had success rates of 15.20% - 19.20%. Finally, the highest attack strength that theoretically involved the use of 100 mid-range GPUs computing for a week has success rates: 24.43% - 32.05%. Therefore, showing the number attacks would deceive a set assessed users.

¹AMD RX-480

7.6 Research Question 6

Research Question 6 states “*Is the recommended minimum number of four Trustwords enough to provide a basic level of security?*”. The paper has investigated this through the creation of an attack and quantification of its success on actual participants. Findings have shown that an attack computed in half a day can have a success rate of about 9.35%. A user, therefore, could initiate this attack on-mass with hardware present inside the average gaming computer. On the other hand, the best level of attack success was shown to be 32.05%.

Further more, comparison of these results to similar literature show a huge increase in success rates for the attack present in this paper. All alternative literature used a small dictionary of around 1024 words. This, therefore, is highly suggestive that the issue lies with the design of Trustwords. Therefore, we believe that 4 Trustwords as a minimum has not provided a basic level of security towards users.

7.7 Further work

Trustword improvements

The first area of proposed work could be recommendations into how to improve Trustwords backed by empirical evidence. We feel the most promising avenue would be the utilization of Phonetic Vectors unique qualities to identify words of low quality by measuring very low vector distances. For example, present in the dictionary are the words `THERE` and `THEIR`, these could be massively improved upon and could result in a better quality word list. Moreover, utilizing the quantification of dissimilarity could be used to create a dictionary of maximized phonetic distance that could then be assessed in a similar way to detect the feasibility of the attack with the alterations and its success rate against users.

Similar metrics performance

Another area of further work is the comprehensive assessment of algorithms used to assess phonetic similarity. The algorithms assessed in this work are a very small proportion of potential options. Thus, further work could assess the performance of metrics against each other to determine the one that works best with human models of phonetics. This could be achieved by repeating the improved experiment discussed

in Section 4.5.1. This could be repeated with a very large number of metrics. Other elements for consideration could be age, location and dialect as variables that affect the metrics performance.

GreenOnion optimizations

Very little work and time was invested into improving the performance of GreenOnion as low-level optimizations are a very time consuming process. A project, therefore, could aim to improve on the performance already recorded in this paper. This could, therefore, improve on the performance of the attack and allow for more successful attacks to be computed in less time.

8 Conclusion

Overall, the project has demonstrated a potential attack on p≡p's implementation of Trustwords. An attack was proposed that utilized phonetic similarity algorithms to exploit the weaknesses in the Trustword dictionary to generate near-collision keys. To achieve this a tool was created to compute a massive number of keys in a concurrent fashion. It was based of a known tool but improves on its key searching performance substantially. The performance of similarity metrics were compared alongside an experiment assessing participants fallibility to the proposed attack. Results showed as much as a 32.05% success rate for the best attack. The main project aim was to show that the recommend minimum number of four Trustwords was insufficient to provide a basic level of security. We believe we have demonstrated that four Trustwords is too low to provide enough security for general use-case and the minimum provided words should, therefore, be increased.

TODO: Recommendation for metric - Metaphone because best balance of number of possibilities and success rate

A Randomly generated uncontrolled key

```
1 -----BEGIN PGP PUBLIC KEY BLOCK-----
2
3 mQENBF0vHaYBCACxOy7RacHIprgaUo66vGmIB2VIaSwToliuaEBxOAlOD+wTB/T9
4 TOKgAMLWMgK2z3/tOZj2l5k9ATUr0nZ9iBgew5Ih3ykOp+OkE9dh4NTD3EJz5UWo
5 Mlr6scPhby92zMBqKi0iPF1Pcvk+eg+SPusxIp+Vn16ALoB2pwGQvG+qoFEJfdVP
6 nwSAWJo1mcd+TCxgIMqe11FXDzxp4BEpMXsHOB8NH/TUiI57sxqT8A2HnnyWo2i
7 5vs93VAP8rTTIRfGelW2c3oqhV9XhXbvVpJPmVkTxM/SshV1L5HhYr1TUAkAQw6w
8 RUZqooysgZEDqQw581FQ7C9p1CHOpXIEhbE7ABEBAAG0HEpvaG4gSm9obnNvbIA8
9 am9obkB3b3JrLmNvbT6JAVQEEwEIAD4WIQRQZ0ukmi5QUEz7KB3FwHKSVKqpwgUC
10 XS8dpgIbAwUJA8JnAAULCQgHAgYVCgkICwIEFgIDAQIeAQIXgAAKCRDFwHKSVKqp
11 wg4YB/9knveazSM4yN3EJY7HRZe5PVA5r0GGD1EDMte+surPKLsV/T39SNl8qTH+
12 DXnOyC4rt1kykTJP+ULcKqGkVRnH2XYZP/W6E9wwBPjoKHaWyn8MP0ix5kgkq6Ld
13 ZWEQ2pUwCsAhWv8K/ybjQ+Li484JKbrz/GRALp8qU3hZgCo/Fw3sD2KcTPU1v8qU
14 av9G2N5sul0W7G0F1ozszFit+r2iinoZtGSddBPG+pIUETzoBn4V2FRRS01UY/TU
15 jGf2BLsk+ZkNJdx5x6IEU9CQ+ivPuKtupVu9ySKqE2Qfmn5lh9iAjYDN3XxUQfCf
16 braGoC9JLnL5QmT1JaQXfxxkIHilyuQENBF0vHaYBCADDP/u8D/TG5d5HmabmgbBF
17 3R2d3J00vt7VQQ5sIRMLyP0cx6qy2bTIy9mgfU3/WcrhRp728gBo+NnUfxyiTb5R
18 u7AbntlkerF3dh0JLm5eIossPW37QXn3Ce4Tv4ixGRLbsGKTu6h01P41FM5VcqV9
19 9NE1iml3WynngnsFdKeUYqPW4QY+ydyjpsyblbQTMptIKG2llCmsd9k+hb8nnGx/d
20 GvyGKaZ270iVGY2im/9VP2VwzqXlFxxx6Dux4egJMMAY5xkzBKf+SzmmlpMJkt2
21 4sBrwmLnuUobgsAkq8K+MqEpWeFi6aWsh7RnY8T0SEb/3QUwG12V77ePhrarBwmf
22 ABEBAAGJATwEGAEIACYWIQRQZ0ukmi5QUEz7KB3FwHKSVKqpwgUCXS8dpgIbDAUJ
23 A8JnAAAKCRDFwHKSVKqpwoW3CACeKICQFuVv2vpUHq/4ATH0atPYqR1NbJTegE+v
24 XZyrNHtmRF4V+kdx/1KX9jsIY2TjyxbhTsrtMFkMZMfAVjXVoS4y8OkwX5IJWgHC
25 0JQIHQrvaIGfIlyuVrNvWYyPXFxNtbntrgTd8JKYGKYaTqXNZ2r1ozbZElp7fQtr
26 rWNUGJYYo+aHHLm+Aot5k+Z3YqHifuPSnCEYt/GxnMhYq1IL3LSZ96hsgwqeFoLP
27 +v4RsvY52Yb5tiOzxZwikAL0JdM2aAumxq8RlnYHiswWxotw2WkKFlB7gfLpbMWs
28 Y+o4J7QKSqpVTrUYBTPF1F4kBWOMY10kpeCDbZ1YwJOZJf8P
29 =aHBu
30 -----END PGP PUBLIC KEY BLOCK-----
```

B Computed Attack Keys

B.1 NYSIIS - 0 Static

B.1.1 Controlled Key

```
1 -----BEGIN PGP PUBLIC KEY BLOCK-----
2
3 mI0EXS8lIAEEAMWEJ+NGB/ukiUi jzdT+DvzVwouWV/j4Rw78X9YdgJP0ExT4ncHG
4 TJbOKjEMEI9bb/oYMLF/434ufScYNci+rL/3RVY8Cc jEv5l0UGX+udZ78c7Z/vf1
5 zFr2MQAglr9M8599JwUY25LiNkzDYc87B16hqRV8hRaXHfAFFHBxRsgBABEBAAAG0
6 HUF1dG9nZW5lcmF0ZWQgS2V5IDxlc2VyQENWRUQ+iNQEEwEKAD4WlQSlBU278MbT
7 iVM5h6GNohojnp5YQgUCXS8lIAIbLwUJAeJfkAULCQgHAgYVCgkICwIEFgIDAQIe
8 AQIXgAAKCRCNohojnp5YQvxSA/0bjL+4me3hLjrM+8IckKABCRdRYYRG7svbln9q
9 ULUngsXMpbIMoHFg1ePpT2lniiHtQhDC88ZW1J5yeVZN1cfJhRsByyKlkzG3Dcy7
10 5wKonbVz1LSYpIDq/DNNP0eINzuVNclrxqRXPGAh6NHnmZN5MqxLNyu0DSX9oJHm
11 KbbtLQ==
12 =FQCu
13 -----END PGP PUBLIC KEY BLOCK-----
```

B.1.2 Computed key

```
1 -----BEGIN PGP PUBLIC KEY BLOCK-----
2
3 mQE0BF0zhx4BCAD0iC55GShgArPzKZdn6we2mrkxS8o8fI7HdWXnLoRAta1Q1j9z
4 U+mYU9tGYb0yjqIARjjUK2qnq0CsGZJpB65AhbrOsDLv6dmI68tuit4xjmcM6+6
5 6M/EY5E5hYpZeurDJ8rSYrfu/v9P0bV78VnM17uU14PTyEBmbJsE9ksqz4MXd5yz
6 G+ibBPBvnBWSlRQzyCFMgTL8gQH36XJUj7jgxTKoJWzli/QtNcMOjwSQtEZxFWVK
7 +qsJjYUC1pg9KkowlLqJmEc1Tj98EipypDtdwnQhn4wHQVgu7SliANNmrR8MpP9o
8 gL9hhfafx5FsE7v4zHhzu+ubR+c7KnUlwJyfABkBhI5atQAeSm9obiBEb2UgPGNo
9 YW5nZV9tZUBlbWFpbC5jb20+
10 =
11 -----END PGP PUBLIC KEY BLOCK-----
```

B.2 NYSIIS - 1 Static

B.2.1 Controlled Key

```
1 -----BEGIN PGP PUBLIC KEY BLOCK-----
2
3 mI0EXS8o2AEEAKQmxot2Z5XFrNjg4zXBfvLsTzo03vZeEI9l8+U2X8aq5KVQJpPU
4 BRSfqQuMZvA1zh3vH3w4I/vR4nXCnw/hPCi0B/DckUe6IJPZJfMiQfTlXt16ZEms
5 W53CBiNqnt5xrUo4wKwoKGuHEltPcD4K/iBIFt6n3UTi+R8xU4WMc+PjABEBAAG0
6 HUFldG9nZW5lcmF0ZWQgS2V5IDxlc2VyQENWRUQ+iNQEEwEKAD4WIQTFXc8VXOqe
7 13ib8ldcbeH3Z8A13wUCXS8o2AIbLwUJAeJb2AULCQgHAgYVCgkICwIEFgIDAQIe
8 AQIXgAAKCRBcbeH3Z8A13wItA/kBbfc6kxtLumDQiGpcIzgWmM9UhCn0V8ny9iB2
9 gt4V8bImpC3qicj6+KywsEsvFIgsJO0UcNeoREKAnpXxPf6T7tvBUTLQjPJFedsn
10 J57996JiZ9COQ4lEg2AvfAKy1a1KrMs0Xy4hWrHY9cJWsla7KpbrsioHd4vDRgMS
11 2yRn/w==
12 =krrv
13 -----END PGP PUBLIC KEY BLOCK-----
```

B.2.2 Computed key

```
1 -----BEGIN PGP PUBLIC KEY BLOCK-----
2
3 mQEOBF0yA4QBCAC78Lk2k9BdUEufpql14D60iAuYVrxVs3lpjwP2hpszBFFw8vY4
4 26uWlC7MPo9l40teks5626hWAAgI1/YHFwWpBDdTWYEnVGrjv5v0Juz5IZc7kiwp
5 Ui2XWJ7I3VpE5nljFyzaQMGaS5Cvmtco5cjin1Tx486jieGBt0loQQdtiJ3gEAFT
6 XlUvwIQSdYWY2F8xWKg5aJoDFEZN74KfwQqB7hx/53VHyzoJGygnvvpMcJaX3c8E
7 V3t7n90WvXJWND7bn6HIJrnFKyRJsKHneL2n0wGd/N0NLCuLTvNK+uQ7sXGNZox1
8 Qa4a1guiSdaq9NO5mX+tOYox3/onzpshJgVDABkBVckntQAeSm9obiBEb2UgPGNo
9 YW5nZV9tZUBlbWFpbC5jb20+
10 =
11 -----END PGP PUBLIC KEY BLOCK-----
```

B.3 NYSIIS - 2 Static

B.3.1 Controlled Key

```
1 -----BEGIN PGP PUBLIC KEY BLOCK-----
2
3 mI0EXS8s+gEEANkph53UuQkNVFhYimrzH0bXBp/Y3InV9p5MP09TZxtTOF44JBPP
4 MCFMvgFJpVK3D5PQ2h7fW1lNb41THkiGC7Jk+F7gd+beqH5kaaKmc+RNAF0aZ5av
5 2a15JvtHT0Z8/1r8bxfp33WLMQXK0/9EwL4HvERRGh7wZ5WemvCrvZPXABEBAAG0
6 HUF1dG9nZW51cmF0ZWQgS2V5IDx1c2VyQENWRUQ+iNQEEwEKAD4WISjUV9vx1LP
7 LPE78Z2TulybLqhYHAUCXS8s+gIbLwUJAeJXtgULCQgHAgYVCgkICwIEFgIDAQIe
8 AQIXgAAKCRCTulybLqhYHONrBAC8uh/K2Adq/o/Qe/EVM5JpT6ETE1WlAj2iUMWB
9 MAmdjgiQlRyBCTd4Lt9xFsbnvQG9pj4GVHosXjVpuA/1NxyS+DE4EkBDzXA3NuR8
10 0djhyD27VSsn2q1j8bB1wx07sLbjo30SIBG2wUaft5DVJiBGG69kh4pt+aKKOcjb
11 LLPldw==
12 =dCl/
13 -----END PGP PUBLIC KEY BLOCK-----
```

B.3.2 Computed key

```
1 -----BEGIN PGP PUBLIC KEY BLOCK-----
2
3 mQEOBF0wxGEBACsqQN92G3IizweQHw42OhUM5ZySKT vzPqVhAeCb2ETSBDZFbGN
4 lHYPa6dytXwLbU6kdlt8kgxbk75iPJScSPLAUzKv1Vd2rkTu5xtKPFqDTRvbjoJf
5 Ik8zJimXJGZNYVrMUqkfPR2FtVC4VUJXtML8voj/1lcLxTWRcYjuNQUSRNhJQtUP
6 ViZMTj97IO8941Vg+ciZXEZkzHzlriqeLqwTupQxvzqjmObmeH1NCPSfGcTSNIBu
7 cNG/DrXTXsVpZPUilIRsXTtc2FM9iY49Zjv01KdZsJlV97JVyghYFFCEe1xq7Twp
8 U9TOzypXD4NdTKivFZUNT4jdG2HoJE4IcZ3NABkBh0qYtB5Kb2huIERvZSA8Y2hh
9 bmdlX21lQGvtYWlsLmNvbT4=
10 =0nU6
11 -----END PGP PUBLIC KEY BLOCK-----
```

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