

**Writing a Thesis:
Guidelines for Writing a Master's Thesis
in Computer Science**

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Writing a Thesis: Guidelines for Writing a Master's Thesis in Computer Science

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Abstract

Writing a thesis is a vast, overwhelming endeavour. There are many obstacles and false dawns along the way. This thesis takes a fresh look at the process and addresses new ways of accomplishing this daunting goal.

The abstract should concisely describe what the thesis is about and what its contributions to the field are (what is new). Market your contributions to your readership. Also make sure you mention all relevant keywords in the abstract, since many readers read *only* the abstract and many search engines index *only* title and abstract.

This thesis explores the issues concerning the clear structuring and the academic criteria for a thesis and presents numerous novel insights. Special attention is paid to the use of clear and simple English for an international audience, and advice is given as to the use of technical aids to thesis production. Two appendices provide specific local guidance.

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Keith Andrews

Graz, Austria, 10 Nov 2021

Credits

I would like to thank the following individuals and organisations for permission to use their material:

- The thesis was written using Keith Andrews' skeleton thesis [Andrews 2021].

Chapter 1

Introduction

1.1 Motivation

Virtual Private Networks (VPNs) are used to allow secure communication over an insecure channel. They function by creating a secure encrypted tunnel through which users can send their data. Example use cases include additional privacy from prying eyes such as Internet Service Providers, access to region-locked online content and secure remote access to company networks. The importance of VPN software has increased dramatically since the beginning of the COVID-19 pandemic due to the influx of people working from home [Abhijith and Senthilvadivu 2020]. This makes finding vulnerabilities in VPN software more critical than ever. IPsec is a popular VPN protocol and most commonly uses the Internet Key Exchange (IKE) protocol to share authenticated keying material between involved parties. Therefore, IKE and IPsec are sometimes used interchangeably. We will stick to the official nomenclature of using IPsec for the full protocol and IKE for the key exchange only. IKE has two versions, IKEv1 and IKEv2, with IKEv2 being the newer and recommended version [Barker et al. no date]. However, despite IKEv2 supposedly replacing its predecessor, IKEv1, sometimes also called Cisco IPsec, is still in widespread use today. This is reflected by the company AVM to this day only offering IKEv1 support for their popular FRITZ!Box routers [GmbH 2022]. Additionally, IKEv1 is also used for the L2TP/IPsec, one of the most popular VPN protocols according to NordVPN [Ferguson and Schneier 2021]. The widespread usage of IPsec-IKEv1, combined with its relative age and many options makes it an interesting target for security testing.

1.2 Research Problems and Goals

State machines of protocol implementations are useful tools in state-of-the-art software testing. They have, e.g., been used to detect specific software implementations, or to generate test cases automatically [Pferscher and Aichernig 2021; Pferscher and Aichernig 2022]. Mealy machines are a type of state machine that can be used to describe the behavior a system when faced with external input. Often we are interested in testing software without knowing its exact inner workings. We call these systems black-box systems. However, despite lacking information on the inner structure of a black-box system, the state machine of the system can still be extracted. One method of generating the state machine of such a system is to use active automata learning. A notable example of an active automata learning algorithm is the L^* algorithm by Angluin [Angluin 1987a]. In L^* , a learner queries the System under Learning (SUL) and constructs an automaton describing the behavior of the SUL through its responses. This automaton is then compared with the SUL, adapting it if they show different behaviors. The resulting automaton then fully describes the behavior of the SUL.

By combining automata learning with fuzzing or similar software testing techniques, network protocols can be extensively and automatically tested without requiring access to their source code. Guo et al. Guo et al. [2019] tested IPsec-IKEv2 using automata learning and model checking, however so far, no studies

have focused on IKEv1 in the context of automata learning. Therefore our goal was to black-box test the IPsec-IKEv1 protocol using automata learning in combination with automata-based fuzzing. We used the active automata learning framework AALPY Muškardin et al. [2022] with a custom mapper to learn the state machines of various IPsec-IKEv1 server implementations. We then further utilized the learned models for fuzzing and fingerprinting.

1.3 Structure

This thesis is structured as follows. Chapter 2 gives an overview of related and relevant literature. Chapter 3 introduces necessary background knowledge, covering the IPsec-IKEv1 protocol, Mealy machines, automata learning and fuzzing. Our learning setup, custom mapper and fuzzing methodology are presented in chapter 4. In chapter 5 we present and analyze the learned models and the results of the fuzzing tests. Finally we summarize the thesis in chapter 6 and discuss future work.

Chapter 2

Related

The aim of this chapter is to give a brief overview of related work, focusing mainly on automata learning and testing of secure communication protocols. The concept of learning through the means of membership and equivalence queries was introduced in 1987 by Angluin [Angluin 1987a]. Angluin presented an algorithm for learning regular languages from queries and counterexamples, called L^* . In it, a student questions a teacher and constructs a hypothesis based on its responses. The hypothesis is then tested through equivalence queries which check if the hypothesis correctly matches the regular language being learned. While the L^* algorithm was originally designed to learn deterministic finite automata (dfa), it can be simply extended to work for Mealy machines by making use of the similarities between dfa and Mealy machines, as shown by Steffen et al. [Steffen et al. 2011]. Over time, many related and improved algorithms were published, such as the one proposed by Rivest and Schapire in 1993 in which homing sequences were used to infer finite automata [Rivest and Schapire 1993]. Another, more recent algorithm came in the form of a redundancy-free active automata learning approach titled TTT by Isberner et al [Isberner et al. 2014]. In this algorithm, essential data is stored in three tree data structures, stripping away unessential information.

Model learning network protocols for the purpose of testing is a more recent development, with models of protocols like SSH Fiterău-Broștean et al. 2017, or TCP Fiterău-Broștean et al. [2016] being learned and used for model checking. Both Novickis et al. Novickis et al. [2016] and Daniel et al. Daniel et al. [2018] learned models of the related OpenVPN protocol and used the learned models to perform protocol fuzzing. In a work by Pferscher and Aichernig Pferscher and Aichernig [2021], learned models were used to fingerprint Bluetooth Low Energy devices (BLE), showing yet another possible use case of automata learning. Guo et al. Guo et al. 2019 used automata learning to learn and test the IPsec-IKEv2 protocol. They used the LearnLib ¹ library for automata learning and performed model checking of the protocol, using the learned state machine. In contrast, our work focuses on the IPsec-IKEv1 protocol, the predecessor of IPsec-IKEv2, which, to the best of our knowledge, has not yet been tested with methods utilizing automata learning. The protocols differ greatly on a packet level, with IKEv1 needing more than twice the amount of packets to establish a connection than IKEv2. Additionally we used the AALPY ² library for automata learning and focused on fuzzing and fingerprinting as opposed to model checking.

¹<https://learnlib.de/>

²<https://github.com/DES-Lab/AALpy>

Chapter 3

Preliminaries

3.1 Mealy Machines

Mealy machines are finite state machines where each output transition is defined by the current state and an input. More formally, a Mealy machine is defined as a 6-tuple $M = \{S, S_0, \Sigma, \Lambda, T, G\}$, where S is a finite set of states, $S_0 \in S$ is the initial state, Σ is a finite set called the input alphabet, Λ is a finite set called the output alphabet, T is the transition function $G : S \times \Sigma \rightarrow \Lambda$ which maps a state and an element of the input alphabet to another state in S and G is the output function $T : S \times \Sigma \rightarrow S$ which maps a state-input alphabet pair to an element of the output alphabet Λ . We use Mealy machines to model the state of learned IPsec implementations.

3.2 Automata Learning

Automata learning refers to methods of learning the state model, or automaton, of a system through an algorithm or process. We differentiate between active and passive automata learning. In passive automata learning (PAL), models are learned based on a given data set describing the behavior of the SUL, e.g. log files. In contrast, in active automata learning (AAL) the SUL is queried directly. In this paper, we will focus on AAL and will, moving on, be referring to it as automata learning or AAL interchangeably.

AAL began in 1987 with a paper by Dana Angluin, titled “Learning regular sets from queries and counterexamples” [Angluin 1987b]. In this seminal paper, Angluin introduced the L^* algorithm, variants of which are still used for learning deterministic automata to this day, for example by the AAL python library AALPY [Muškardin et al. 2022]. While the original L^* algorithm was designed to learn deterministic finite automata, the algorithm can be extended to learn Mealy machines [Niese 2003]. While many modern implementations, including AALPY use improved versions of L^* , fundamentally they still resemble the original algorithm by Angluin. The base L^* algorithm is briefly explained below.

L^* works using a Minimally Adequate Teacher (MAT) model in which a learner queries a teacher about a SUL. The teacher must be able to answer equivalence and membership queries posed by the learner regarding the SUL. Equivalence queries are used to check if a learned model accurately matches the SUL. Membership queries are used to check whether a word is included/accepted. The learner, using the responses to its queries, then updates its model of the SUL. Learned models are commonly represented as Mealy machines, finite-state machines with outputs depending on the current state as well as inputs.

3.3 Fuzzing

3.4 IPsec

Virtual Private Networks (VPN) are used to extend and or connect private networks across an insecure channel (usually the public internet). They can be used e.g. to gain additional privacy from prying eyes such as Internet Server Providers, access to region-locked online content or secure remote access to company networks. Many different VPN protocols exist, including PPTP, OpenVPN and Wireguard. IPsec or IP Security, is a VPN layer 3 protocol used to securely communicate over an insecure channel. It is based on three sub-protocols, the Internet Key Exchange (IKE) protocol, the Authentication Header (AH) protocol and the Encapsulating Security Payload (ESP) protocol. IKE is mainly used to handle authentication and to securely exchange as well as manage keys. Following a successful IKE round, either AH or ESP is used to send packets securely between parties. The main difference between AH and ESP is that AH only ensures the integrity and authenticity of messages while ESP also ensures their confidentiality through encryption.

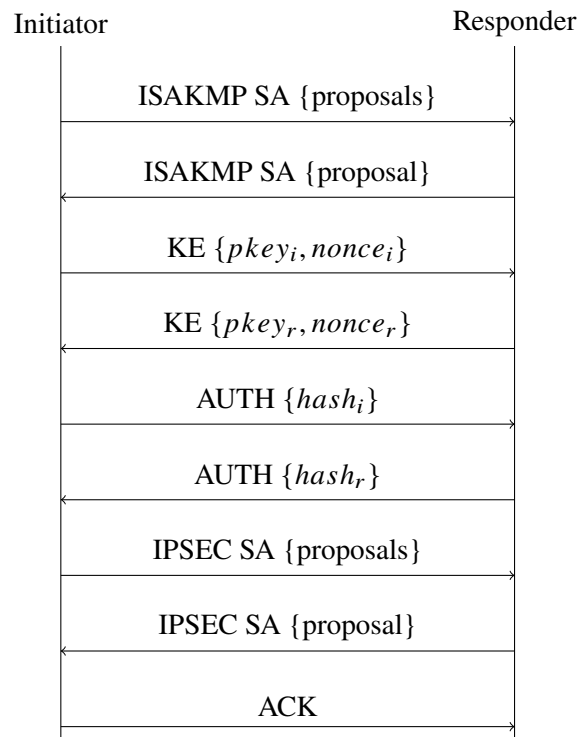


Figure 3.1: IKEv1 between two parties

The IKEv1 protocol works in two main phases, both relying on the Internet Security Association and Key Management Protocol (ISAKMP). Additionally, phase one can be configured to proceed in either Main Mode or Aggressive Mode. A typical exchange between two parties, an initiator and a responder, using Main Mode for phase 1, can be seen in Figure 3.1. In phase one (Main Mode), the initiator begins by sending a Security Association (SA) to the responder. A SA essentially details important security attributes required for a connection such as the encryption algorithm and key-size to use, as well as the authentication method and the used hashing algorithm. These options are bundled in containers called proposals, with each proposal describing a possible security configuration. While the initiator can send multiple proposals to give the responder more options to choose from, the responder must answer with only one proposal, provided both parties can agree upon one of the suggested proposals. This initial

communication is denoted as *ISAKMP SA* in Figure 3.1. Subsequently, the two parties perform a Diffie-Hellman key exchange, denoted as *KE*, and send each other nonces used to generate a shared secret key *SKEYID* as detailed in Listing 3.1. PSK refers to the pre-shared key, Ni/Nr to the initiator/responder nonce and CKY-I/CKY-R to the initiator/responder identifier cookie. Note that IKEv1 allows using various different authentication modes aside from PSK, including public key encryption and digital signatures. *SKEYID* is used as a seed key for all further session keys *SKEYID_d*, *SKEYID_a*, *SKEYID_e*, with g^{xy} referring to the previously calculated shared Diffie-Hellman secret and prf to a pseudo-random function (in our case, HMAC). Following a successful key exchange, all further messages of phase one and two are encrypted using a key derived from *SKEYID_e* and *SKEYID_a* for authentication. Finally, in the last section of phase one *AUTH*, both parties exchange and verify hashes to confirm the key generation was successful. Once verification succeeds, a secure channel is created and used for phase two communication. If phase one uses Aggressive Mode, then only three packets are needed to reach phase two. While quicker, the downside of Aggressive Mode is that the communication of the hashed authentication material happens without encryption. This means, that using short pre-shared keys in combination with Aggressive Mode is inherently insecure, as the unencrypted hashes are vulnerable to brute-force attacks provided a short key-size¹. The shorter phase two (Quick Mode) begins with another SA exchange, labeled with *IPSEC SA* in Figure 3.1. This time, however, the SA describes the security parameters of the ensuing ESP/AH communication and the data is sent authenticated and encrypted using the cryptographic material calculated in phase one. This is followed by a single acknowledge message, *ACK*, from the initiator to confirm the agreed upon proposal. After the acknowledgment, all further communication is done via ESP/AH packets, using *SKEYID_d* as keying material.

```

1  # For pre-shared keys:
2  SKEYID = prf(PSK, Ni_b | Nr_b)
3
4  # to encrypt non-ISAKMP messages (ESP)
5  SKEYID_d = prf(SKEYID, g^xy | CKY-I | CKY-R | 0)
6
7  # to authenticate ISAKMP messages
8  SKEYID_a = prf(SKEYID, SKEYID_d | g^xy | CKY-I | CKY-R | 1)
9
10 # for further encryption of ISAKMP messages in phase 2
11 SKEYID_e = prf(SKEYID, SKEYID_a | g^xy | CKY-I | CKY-R | 2)

```

Listing 3.1: IKE Keying

In addition to the packets shown in Figure 3.1, IKEv1 also specifies and uses so called ISAKMP Informational Exchanges. Informational exchanges in IKEv1 are used to send ISAKMP Notify or ISAKMP Delete payloads. Following the key exchange in phase one, all Informational Exchanges are sent encrypted and authenticated. Prior, they are sent in plain. ISAKMP Notify payloads are used to transmit various error and success codes, as well as for keep-alive messages. ISAKMP Delete is used to inform the other communication partner, that a SA has been deleted locally and request that they do the same, effectively closing a connection.

Compared to other protocols, IPsec offers a high degree of customizability, allowing it to be fitted for many use cases. However, in a cryptographic evaluation of the protocol, Ferguson and Schneier Ferguson and Schneier [1999] criticize the complexity arising from the high degree of customizability as the biggest

¹<https://nvd.nist.gov/vuln/detail/CVE-2018-5389>

weakness of IPsec. To address its main criticism, IPsec-IKEv2 was introduced in RFC 7296 to replace IKEv1 [Kaufman et al. 2014]. Nevertheless, IPsec-IKEv1 is still in wide-spread use to this day, with the largest router producer in Germany, AVM, still only supporting IKEv1 in their routers [GmbH 2022]. We use IPsec-IKEv1 with Main Mode and ESP in this paper and focus on the IKE protocol as it is the most interesting from an AAL and security standpoint.

Chapter 4

Learning

test

Chapter 5

Evaluation

test

Chapter 6

Conclusion

test

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