# Learning Fragments of the TCP Network Protocol

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**Abstract.** We apply automata learning techniques to learn fragments of the TCP network protocol by observing its external behaviour. We show that different implementations of TCP in Windows 8 and Ubuntu induce different automata models, thus allowing for fingerprinting of these implementations. In order to infer our models we use the notion of a mapper component introduced by Aarts, Jonsson and Uijen, which abstracts the large number of possible TCP packets into a limited number of abstract actions that can be handled by the regular inference tool LearnLib. Inspection of the learned models reveals that both Windows 8 and Ubuntu 13.10 violate RFC 793.

## 1 Introduction

Our society has become reliant on the security and application of protocols, which are used for various operations. Standards describing these protocols typically fail to specify what an agent should do in case another agent does not follow the rules of the protocol, which can result in exploits by hackers. Moreover, implementations of these standards can differ, and may deviate slightly from the official standard, resulting in security vulnerabilities. Automata learning techniques can help expose and/or mitigate such problems through tools that help generate state models for these systems.

Learning techniques enable the inference of state models for systems available as black boxes. Inferring such models is important not only for understanding these systems, but also for model checking and model based testing. To this end, several learning algorithms and tools have been developed, such as those presented in [4, 19, 17, 2, 20, 12].

Whereas learning algorithms such as L* [4], work for systems with limited numbers of abstract inputs and outputs, many protocols make use of messages with parameters, for instance sequence numbers or flags. Moreover, network protocols may have variables. As an example, the TCP protocol maintains several variables for connection initialization and synchronization. Efforts have been

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made to develop techniques to learn these more complex systems. In particular, building on the extension of the L* algorithm used to learn Mealy machines (Niese [11]), F. Aarts et al. describe in [3] a methodology for learning systems via abstraction. This method entails introducing a *mapper* component in-between the protocol and the learner. The *mapper* reduces the parameters and state variables implied by the protocol to a small number of abstract values, on which learning algorithms can then be applied. By using this technique, they were able to infer state models of simulated versions of the Transmission Control Protocol (TCP) and the Session Initiation Protocol (SIP).

In this work we use abstraction to learn implementations of the TCP-protocol for different operating systems. We then highlight a situation where these implementation do not adhere to the standard. We use the abstraction based on the approach described in [22], but extend it to include the increment operator which is needed to learn the TCP protocol. While the learning setup used specifically targets TCP, it can be adapted to learn other protocols.

*Related work.* In recent years there have been many applications of automata learning to protocol analysis. We mention here only a few selected references and refer to these works for a more extensive overview of the literature. In [21], automata learning was used to establish that implementations of SSH violate the standard. In [6], automata learning techniques was used to reproduce a widely publicized mistake in a protocol for electronic banking. The methodology described by Aarts et al. [3] was also used to infer state diagrams of banking cards in [1]. Dawn Song et al. [7] developed techniques to learn the state diagram of a network protocol used to control botnets. Learning techniques were also used to automatically infer HTTP interaction models for web applications, as part of the SPaCIoS Project [5].

*Organization.* The paper is structured as follows: Section 2 gives a brief description of the TCP network protocol, Section 3 sets the context of regular inference with abstraction. Section 4 presents the framework we implemented to learn the TCP network protocol. Section 5 explains how the setup implements abstraction. Section 6 explains difficulties encountered and how we managed them. Section 7 presents experiments carried out to learn TCP. Section 8 outlines conclusions and future work.

## 2 The TCP Network Protocol

The transmission control protocol [16], or TCP, is a connection-based network protocol that allows two application programs to transfer data bidirectionally in a reliable and orderly manner. The programs can run on the same or on separate machines. TCP supports data transfer through the *connection* abstraction where a *connection* comprises two endpoints associated with each of the two programs. A connection progresses from one state to the next following events. Possible events are user actions, receipt of TCP *segments*, which are network packets containing flags and register data, and timeouts. Connection progression is depicted in Figure 1.

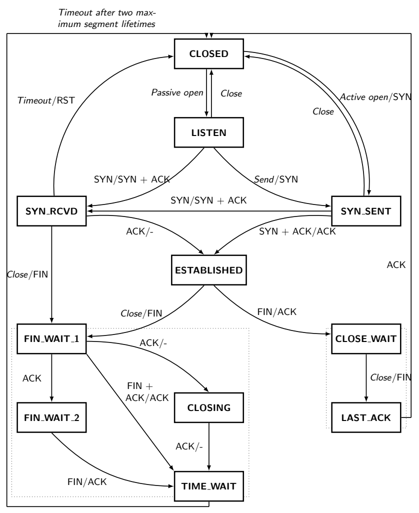


**Fig. 1.** A state diagram describing TCP [1]

We give a brief example of how the protocol functions from connection initiation to termination. For brevity, we use FLAGS-segment as shorthands for segments having the mentioned control flags activated.

The two systems communicating through TCP have different roles: one system acts as a *server* and the other as a *client*. Connection between *server* and *client* is established through the three-way handshake. Assuming the *server* is in the LISTEN-state, waiting for a *client* to connect to it, the *client* sends a SYN-segment on an ACTIVE OPEN-action and transitions to the SYN_SENT-state. On receiving this segment, the *server* responds with a SYN+ACK-segment, transitioning to the SYN_RCVD-state. The *client* then acknowledges the *server*'s segment with an ACK-segment and transitions to the ESTABLISHED-state. On receiving this segment, the *server* also transitions to the ESTABLISHED-state, connection is established and data can be transferred, thus concluding the three-way handshake.

When either side has finished sending data, that side sends a segment with a FIN-flag on an ACTIVE CLOSE-action, signaling that it has no more data left to send. This can be acknowledged with a FIN+ACK-segment if the other device also wants to close the connection, or with a ACK-segment if that device still wants to send data. Once the device has sent all data, it sends a FIN-message, closing the connection.

Notice that the state diagram in Figure 1 does not fully specify the behaviour of the TCP-implementation. More specifically, the model does not reveal what response is given in case either side receives a segment for which no transition

[1] Retrieved from `http://www.texample.net/tikz/examples/tcp-state-machine/`. Copyright 2009 Ivan Griffin. Reprinted under the LaTeX Project Public License, version 1.3.

is defined (for instance, if a RST-segment is received in the SYN_RCVD-state). Moreover, the model abstracts away from register data such as the sequence and acknowledgment numbers found in TCP packets. Many of these details can be inferred from the protocol standard. There are, however, some details which are implementation specific, with each operating system providing its own TCP implementation. Moreover, such implementations do not always adhere to the prescribed standards. Such was the case for HTTP, as shown in [15]. Hence, inferring models of these TCP implementations represents a valuable asset in analyzing their concrete behavior.

## 3 Regular Inference Using Abstraction

In this section, we recall the definition of a Mealy machine, the basic ideas of regular inference in Angluin-style, and the notion of a mapper which allows us to learn "large" models with data parameters.

### 3.1 Learning Mealy Machines

We will use Mealy machines to model TCP protocol entities. A Mealy machine $\mathcal{M}$ is the tuple $\mathcal{M} = \langle I, O, Q, q_0, \rightarrow \rangle$, where

– $I$, $O$, and $Q$ are nonempty sets of *input symbols*, *output symbols*, and *states*, respectively,
– $q_0 \in Q$ is the *initial state*, and
– $\rightarrow \subseteq Q \times I \times O \times Q$ is the *transition relation*.

Transitions are tuples of the form $(q, i, o, q') \in \rightarrow$. A transition implies that, on receiving an input $i \in I$, when in the state $q \in Q$, the machine jumps to the state $q' \in Q$, producing the output $o \in O$. Mealy machines are deterministic if for every state and input, there is exactly one transition. A Mealy machine is finite if $I$ and $Q$ are finite sets.

Angluin described L* in [4], an algorithm to learn deterministic finite automata. Niese [11] adapted this algorithm to learning deterministic Mealy machines. Improved versions of the L* algorithm were implemented in the LearnLib tool [17, 13]. A graphical model of the basic learning setup is given in Figure 2.

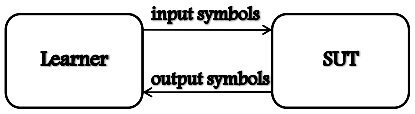


**Fig. 2.** Overview of the learner and the SUT

We assume an implementation, or System Under Test (*SUT*), and postulate that its behaviour can be described by a deterministic Mealy Machine $\mathcal{M}$.

The *learner*, connected to the *SUT*, sends *inputs* (or queries) to the *SUT* and observes resulting *outputs*. After each observation, the *learner* sends a special *reset* message, prompting the reset of the implementation. Based on the observation of the outputs, it builds a hypothesis $\mathcal{H}$. The hypothesis is then tested against the implementation. Testing involves running a number of test sequences which determine whether the hypothesis conforms to the *SUT*. The hypothesis is returned if all test sequences show conformation, otherwise it is further refined on the basis of the new counterexample. This process is repeated until all equivalence queries are passed.

### 3.2 Inference using Abstraction

Existing implementations of inference algorithms only proved effective when applied to machines with small alphabets (sets of input and output symbols). Practical systems like the TCP protocol, however, typically have large alphabets, e.g. inputs and outputs with data parameters of type integer or string.

A solution to this problem was proposed by Aarts et al in [3]. In this work, the concrete values of every parameter are mapped to a small domain of abstract values in a history-dependent manner. A *mapper component* is placed in-between the *learner* and the *SUT*. The *learner* sends abstract inputs comprising abstract parameter values to this component. The mapper component then turns the abstract values into concrete values (by taking the inverse of the abstraction function), forming concrete inputs, and sends them to the *SUT*. The concrete outputs received from the *SUT* are subsequently transformed back to abstract outputs and are returned to the *learner*. Reset messages sent by the *learner* to the *SUT* also reset the mapper component. A graphical overview of the *learner* and mapper component is given in Figure 3.

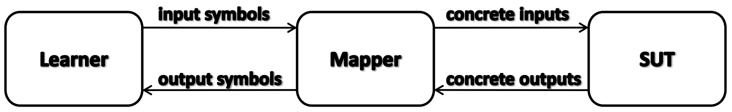


**Fig. 3.** Overview of the learner, the mapper and the SUT

Formally, the behaviour of the intermediate component is fully determined by the notion of a *mapper* $\mathcal{A}$, which essentially is just a deterministic Mealy machine. A mapper encompasses both concrete and abstract sets of input and output symbols, a set of states, an initial state, a transition function that tells us how the occurrence of a concrete symbol affects the state, and an abstraction function which, depending on the state, maps concrete to abstract symbols. Each mapper $\mathcal{A}$ induces an abstraction operator $\alpha_{\mathcal{A}}$, which transforms a concrete Mealy machine with concrete inputs $I$ and outputs $O$ into an abstract Mealy machine with abstract inputs $X$ and outputs $Y$. If the behaviour of the *SUT* is described by a Mealy machine $\mathcal{M}$ then the *SUT* and the mapper component together are described by the Mealy machine $\alpha_{\mathcal{A}}(\mathcal{M})$. Dually, each mapper also induces a concretization operator $\gamma_{\mathcal{A}}$, which transforms an abstract hypothesis Mealy machine $\mathcal{H}$ with inputs $X$ and outputs $Y$ into a concrete Mealy machine with inputs $I$ and outputs $O$. A key result proved by Aarts et al [3] is that $\alpha_{\mathcal{A}}(\mathcal{M}) \leq \mathcal{H}$ implies $\mathcal{M} \leq \gamma_{\mathcal{A}}(\mathcal{H})$, where $\leq$ denotes behavioural inclusion of Mealy machines. This result allows us to transform an abstract model $\mathcal{H}$, inferred through interaction with a mapper component, into a concrete model that over-approximates the behaviour of the *SUT*.

## 4 Learning Setup

In the case of TCP, the *SUT* is the *server* in the TCP communication. On the other side, the *learner* and *mapper* simulate the *client*. On the client side we also introduce the *adapter*, a component that performs a 1 to 1 translation of messages to segments that are to be sent over the network. More specifically, it builds request segments from concrete inputs, sends them to the *server*, retrieves the response segments and infers the respective concrete outputs, which it delivers to the *learner*-*mapper* assembly. The *adapter* is also responsible for detecting system timeouts. It is important to make distinction between the *mapper* and *adapter*. Whereas the *mapper* implements mapping between abstract and concrete messages, the *adapter* transforms these concrete messages to a format that is readable by the *SUT*.

With that said, we present in Figure 4 the framework implemented to learn fragments of the TCP implementation. On the learner side, we use *LearnLib* [17] and *Tomte* [22], two Java based learning tools. LearnLib provides the Java implementation of the L* based learning algorithm, while we use some of Tomte's libraries to connect the *learner* to a Java based *mapper* via direct method calls. A Python adapter based on *Scapy* [18] is used to craft, send request packets and retrieve response packets. Communication between the *mapper* and *adapter* is done over sockets.

We conducted our experiments on both a single and on two separate machines. The *client* and *server* reside in separate operating systems. The model which is inferred via learning describes the TCP implementation for the operating system on which the *server* resides. Each operating system enables the user to configure parameters involved in TCP. These parameters can also have an influence over the resulting model. We used *Wireshark* to monitor communication between *client* and *server*.

The experiments were carried out with the *server* deployed on Windows 8 and Ubuntu 13.10 respectively. The *server* passively listens for incoming connections on a port while the *learner*, acting as a "fake client", sends messages to the *server* through its own port. The source code of the learning setup, along with some documentation on usage, is available at [10]. With virtualization, the experiments can be run on a personal PC.

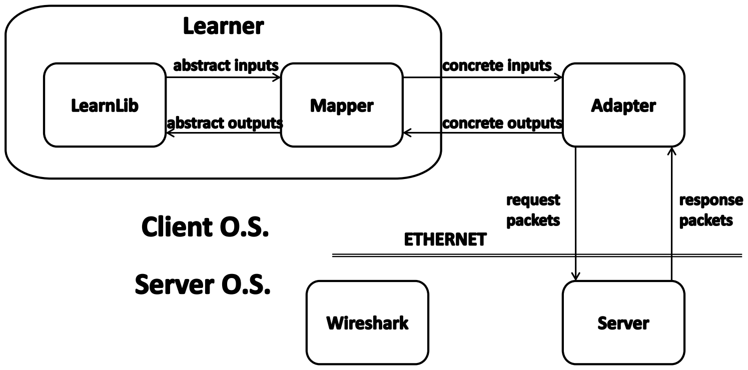


**Fig. 4.** Overview of the experimental setup

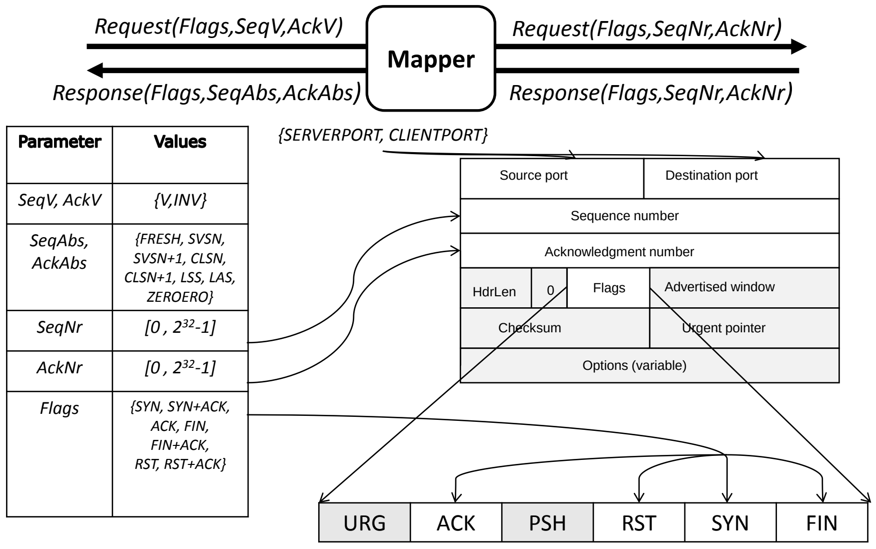
## 5 Messages and Abstraction

### 5.1 Mapper description

As mentioned previously, the *mapper* component translates abstract input messages into concrete input messages, and concrete output messages into abstract output messages. More specifically, parameters contained in messages are mapped from a concrete to an abstract domain, and vice versa. Figure 5 shows the concrete and abstract parameters used in learning. Also shown is how the concrete parameters are then associated with fields within TCP segments by the *adapter*. Our message selection is based on the work of Aarts et al. in [3]. Like in their work, both inputs and outputs are generated based on the sequence number, acknowledgement number and flags found in each TCP segment.

Both the concrete and the abstract alphabets comprise *Request* inputs and *Response* outputs. Each of these inputs and outputs takes 3 parameters corresponding to the sequence number, acknowledgment number and the TCP flags. The concrete parameters *SeqNr* and *AckNr* are defined as 32 bit unsigned integers, while their corresponding abstract parameters *SeqV* and *AckV* are either *valid* or *invalid*. The *Flags* parameter can have the values ACK, SYN, FIN, RST, or any valid combination as listed in Figure 5. These flags correspond to bitfields of the control register in the TCP-frame, in which flags are either set or unset. In other words, each element of *flags* defines which flags have been set: all flags mentioned are set, all other flags are not.

We abstract away from the sequence and acknowledgement numbers sent to the *server* by way of validity. We define validity based on whether the sequence and acknowledgement numbers comply to the standard TCP flow. Here the sequence number sent is equal to the last acknowledgement number received while the acknowledgement number sent is equal to the last sequence number received (the server sequence number) plus the length of the data that the *client* expects to receive (which in our case is 0, no data is transferred) plus 1 in case the segment carries a SYN or a FIN flag. ACK flags do not lead to any increase.



| **Parameter** | **Values** |
|---|---|
| *SeqV, AckV* | *{V,INV}* |
| *SeqAbs, AckAbs* | *{FRESH, SVSN, SVSN+1, CLSN, CLSN+1, LSS, LAS, ZEROERO}* |
| *SeqNr* | *[0 , $2^{32}$-1]* |
| *AckNr* | *[0 , $2^{32}$-1]* |
| *Flags* | *{SYN, SYN+ACK, ACK, FIN, FIN+ACK, RST, RST+ACK}* |

**Fig. 5.** Message scheme

Numbers that comply to this standard are *valid*, those that do not are *invalid*. We except from this rule whenever the *server* is in the LISTENING-state with no connection set up. In this case, new sequence numbers are generated via ISN (Initial Sequence Number), a number generation algorithm. We abstract away from this algorithm by deeming all generated numbers *valid* and none *invalid* at this stage. Consequently, we ignore any messages containing *invalid* parameters that the *learner* generates at this point. (we do not create and send segments for these inputs)

We abstract away from the sequence and acknoweldgement numbers received from the *server* by comparing them with values encountered in the communication up to that point. These values are stored in state variables which are maintained by the *mapper*. We also define the abstract output *timeout* for the case when no response segment is received.

In order to map between abstract and concrete the *mapper* maintains the following state variables:

– {*lastFlagSent*,*lastAckSent*,*lastSeqSent*} store the last flag, acknowledgement and sequence numbers sent by the client
– {*lastAbsSeq*,*lastAbsAck*} store the last sequence and acknowledgement abstractions sent by the client
– *valClientSeq* stores the last *valid* sequence number sent by the client
– *InitServSeq* stores the server's initial sequence number
– *INIT* records whether the server is in its initial state.

Variables *lastSeqSent*, *lastAckSent*, *lastFlagSent*, *lastAbsSeq*, *lastAbsAck* and *InitServSeq* store the first or most recent occurrence of certain message parameters. Variable *valClientSeq* stores the last valid sequence number: its definition is based on knowledge of the protocol. Variable *INIT* records whether the server is in the initial state.

On the basis of these variables, we define below the functions for *Request* transmission, *Response* receipt, and *Timeout*. For symmetry, we use *SeqAbs* and *AckAbs* as notations for both abstract input and abstract output parameters.

```
function REQUEST($Flags$, $SeqNr$, $AckNr$)
    $lastFlagSent \leftarrow Flags$
    if $INIT \vee SeqNr == valClientSeq$ then
        $SeqAbs \leftarrow valid$
        $valClientSeq \leftarrow SeqNr$
    else
        $SeqAbs \leftarrow invalid$
    end if
    $lastSeqSent \leftarrow SeqNr$
    $lastAbsSeq \leftarrow SeqAbs$
    if $INIT \vee AckNr == InitServSeq + 1$ then
        $AckAbs \leftarrow valid$
    else
        $AckAbs \leftarrow invalid$
    end if
    $lastAckSent \leftarrow AckNr$
    $lastAbsAck \leftarrow AckAbs$
     return $Request(Flags, SeqAbs, AckAbs)$
end function
```

In the context of *Response* outputs, we compare values found in server responses to a set of reference values. Note the similarity between the conditions we chose and the conditions used in nmap [14] to perform OS fingerprinting. Also note that we assume no collision between different reference values. It is indeed possible that the client sequence number is equal to the server sequence number. However, the likelihood is very low due to the extended range these numbers can take values in.

```
function RESPONSE($Flags$, $SeqNr$, $AckNr$)
    if $INIT$ then
        $SeqAbs \leftarrow$ FRESH
        $InitServSeq \leftarrow SeqNr$
    else
        $SeqAbs \leftarrow$ ABSTRACT($SeqNr$)
    end if
    $AckAbs \leftarrow$ ABSTRACT($AckNr$)
    if $AckAbs ==$ CLSN + 1 then
        $InitServSeq \leftarrow SeqNr$
    end if
    $INIT \leftarrow IsInitial()$
     return $Response(Flags, SeqAbs, AckAbs)$
```

```
end function
function ABSTRACT($concVal$)
    if $concVal == valClientSeq + 1$ then
        $absVal \leftarrow \mathbf{CLSN+1}$
    else if $concVal == valClientSeq$ then
        $absVal \leftarrow \mathbf{CLSN}$
    else if $concVal == InitServSeq$ then
        $absVal == \mathbf{SVSN}$
    else if $concVal == InitServSeq + 1$ then
        $absVal \leftarrow \mathbf{SVSN+1}$
    else if $concVal == lastSeqSent$ then
        $absVal \leftarrow \mathbf{LSS}$
    else if $concVal == lastAckSent$ then
        $absVal \leftarrow \mathbf{LAS}$
    else if $concVal == 0$ then
        $absVal \leftarrow \mathbf{ZERO}$
    else
        $absVal \leftarrow \mathbf{INV}$
    end if
     return $absVal$
end function
function TIMEOUT
    $INIT \leftarrow IsInitial()$
end function
```

## 5.2 Initial state detection

One important aspect is the detection of the initial state (ie. the LISTENING-state in the TCP protocol, *INIT* in the mapper definition). This is necessary in order to follow the TCP flow, wherein transitions from this state imply that new sequence numbers are generated for both *client* and *server*. The server and client sequence number variables (*clientSN* and *serverSN*) must be updated accordingly. For this purpose, we defined an oracle which tells whether the system is in the initial state. We found that such an oracle for Windows 8 can be implemented by a function over the state variables stored in the mapper and the output parameters. For Ubuntu 13.10, definition of such a function was made difficult by the fact that, depending on the system's current state, the abstract input *Request*(ACK+RST, *valid*, *invalid*) either resets the system or is ignored. If the oracle is defined via a function, definition of this function depends on the operating system for which TCP is learned. We show the definition of *INIT* for Windows 8 below.

```
function ISINITIAL
    if $IsResponse$ then
        $INIT \leftarrow RST \in Flags \wedge SeqAbs = valid \wedge SYN \in lastFlagSent$
    else if $IsTimeout$ then
```

```
        $INIT \leftarrow INIT \vee (lastAbsSeq = valid \wedge RST \in lastFlagSent)$
    end if
end function
```

Obviously, such a function would have to be inferred manually for every implementation of TCP that is learned. To circumvent this, we implemented a mechanism that automatically checks whether a trace (sequence of inputs) triggers a return to the initial state. This verification relies on distinguishing inputs to signal whether the LISTENING-state is reached and consequently, whether fresh values can be accepted by the mapper. For TCP, we assume, based on the protocol specification, that a SYN-segment with fresh register values is a distinguishing input for the initial state, as only in the LISTENING-state state does a SYN-segment yield a SYN+ACK-segment which acknowledges the sequence number sent. A valid implementation of TCP should always adhere to this condition, otherwise connections could easily be interrupted by spurious SYN-segments. Addition of this automatic mechanism enables us to learn TCP implementations without changing the *mapper* to fit the operating system.

This mechanism is embedded into the learning process as follows: for each input sent, we check if the trace leading up to and including that input, is a resetting trace, that is, it prompts the transition to the initial state. This information is then fed to the $IsInitial()$ function, for proper update of the mapper. After each check, the $SUT$ must return to the state it had previously to the check being done. In the case of TCP, this can only be done by re-running the whole trace. Information accumulated on the resetting property of traces is stored after each check, so next time the same trace is checked, we have a direct result and do not have to reapply the whole trace. There is of course, considerable overhead since a trace of $n$ inputs now entails feeding $\frac{(n+1)*(n+2)}{2}$ inputs. This number grows if we consider the additional RST-segments we have to send. But such overhead is acceptable in a setting where a small maximum trace length is still adequate for learning.

## 6 Complications encountered

To learn the system, several issues had to be addressed. Firstly, we had to implement resetting mechanisms that would prompt the TCP connection to return to the start state. We implemented two approaches, one by opening a new connection to the *server* on a different port each time we started a new query, the other by resetting the connection via a valid RST-segment. In the first case, we were hit by thresholds on the number of connections allowed. For Ubuntu, each connection is associated with a file descriptor. Not closing the file descriptor on the *server* side as not to interfere with learning means that the default limit, 1024, can be reached using relatively few inputs. This limit can be increased to 4096 for Ubuntu 13.10 32-bit version using *ulimit*, which is still not sufficient for learning using a alphabet. The solution was using garbage collection to clear out these unused descriptors. In Java, this is done automatically. For Windows, we found that once the *server* reaches a certain number of connections left in the

CLOSE_WAIT-state, the *server* proceeds to send FIN+ACK-segment to close all connections. The second approach implies sending a RST-segment with a *valid* sequence number, which was possible with the mapper previously described. In our learning experiments we combined the two approaches, that is, we switched ports on every run and each run was ended with a valid RST-segment, leaving no idle connection behind.

We also had to manage the handling of SYN+ACK retransmits. When the *server* is in the SYN_RCVD-state, it expects a corresponding ACK-segment to the SYN+ACK-segment it sent, thus ending the 3 way handshake. In this situation, the TCP protocol specifies that, if the *server* does not receive the expected acknowledgement within a time frame (defined by the initial retransmission timeout or *initialRTO* ), it re-sends the SYN+ACK-segment a number of times after which it closes the connection. This behaviour is not accounted for because it would require timer adjustments to fit with the *initialRTO* . All traces must therefore be run within *initialRTO* time. We disabled SYN+ACK retransmission for Ubuntu by setting the *tcp_synack_retries* to 0. Unfortunately, Ubuntu does not allow the user to modify the *initialRTO* since its value is hard coded to around one second(see TCP_INIT_TIMEOUT at [23]). The time window provided by the *initialRTO* forced us to lower the maximum trace length as to fit within this time frame. For Windows 8, *initialRTO* is initially set to 3 seconds (and can be configured, see [24]), which provides sufficient time to execute sequences of long inputs. An alternative approach would have been to ignore the retransmissions of similar SYN+ACK-segments.

We also encountered difficulties with packet receipt. By analyzing packet communication we found that Scapy sometimes misses fast *server* responses, that is, responses sent after a short time span from their corresponding requests. We believe this could be caused by Scapy's slow performance in intercepting responses quick enough. To circumvent this problem, we crafted a network tracking tool based on Impacket [8] and Pcapy [9] which augments Scapy's receipt capabilities. In case Scapy does not receive any responses back, the tracking tool either confirms that no response was intercepted or returns the response that Scapy missed.

Our experiments were also affected by the operating system on which the *learner* setup was deployed. The Ubuntu operating systems the *learner* was run on are unaware of what network packets are sent by Scapy, and therefore cannot recognize the response packets sent by the *server*. More specifically, as a TCP-connection is set up by the *learner*, the operating system notices a connection that it has not set up itself. Consequently, it responds with a RST-segment to shut down that connection. The problem was solved by dropping all RST-segments sent by the operating system via a firewall rule. This can be done in Ubuntu using the *iptables* command. Windows required no such tweak.

For Ubuntu 13.10 we also found that, whenever in the ESTABLISHED or CLOSE_WAIT states, the *server* behaved apparently non-deterministically when receiving ACK and FIN+ACK segments with *valid* sequence numbers and *invalid* acknowledgement numbers. On receiving these packets, the *server* either retransmitted an ACK-segment or it gave no answer. This behaviour is partly, but not completely, explained by a fragment in the source code in which invalid acknowledgements are dropped. In order to handle this situation, we split the *invalid* range of numbers for these inputs into three subranges, each exhibiting specific behaviour. These ranges are $[2^{31}, -WIN-1], [-WIN, -1], [1, 2^{31}-1]$ where $WIN$ is the window size, which correspond to $B, W$ and $A$ in the inferred Ubuntu model. The ranges are given relative to what a *valid* server sequence number would be.

## 7 Experimental Results

We learned models for Windows 8 and Ubuntu 13.10 LTS. As mentioned previously, the *client* and *server* reside in different operating systems. Because the *adapter* can only function under Linux, we ran the learner setup (or *client*) on Ubuntu systems.

For Windows 8, the *client* was deployed on a guest virtual machine using the Ubuntu 12.04 LTS operating system, while the *server* resided on the Windows 8 host. We also experimented with the *client* residing on a separate computer running Ubuntu 13.10 that communicated with the same Windows 8 server and obtained identical results. Similarly for Ubuntu 13.10, the *server* and *client* were deployed both on one computer, each in its own Ubuntu virtual machine within the same Windows 8 host, and on separate machines.

In order to reduce the size of the diagram, we eliminate all self loops that have *timeout* outputs. Moreover, we use the initial flag letters as shorthands: *s* for *syn*, *a* for *ack*, *f* for *fin* and *r* for *rst*. We condense $Request/Response(flags, seq, ack)$ to $flags(seq, ack)$ and we group inputs that have the same abstract output and resulting state. *valid* and *invalid* abstract parameters are shorthanded to $v$ and *inv* respectively. Finally, inputs having the same effect regardless of the *valid* or *invalid* value of a parameter are merged and the parameter is replaced with _.

Figures 6 and 7 show the state models learned for the two operating systems. Both models depict 4 states of the reference model. We can identify handshake and termination on the two diagrams by following the sequence of inputs: S($v$,$v$), A($v$,$v$), AF($v$,$v$). We see that for each input in the sequence the same output is generated. There are, however, notable differences, like for example the verbosity of the listening state in case of Ubuntu 13.10. RST-segment responses also differ. Whereas in Ubuntu 13.10, a RST-segment response always carries a 0 acknowledgement number, for Windows 8, similar to its joining sequence number, it takes the value of the last acknowledgement number sent resulting in RST(*las*,*las*) outputs.

Checking the models against the specification reveals potential non-conformance with the rfc standard [16]. The standard specifies on page 36 (see quotation below) that, when in synchronized states, receiving unacceptable segments should trigger specific ACK-segment sent back. Later, an exception is made for RST-segment, which should be dropped. Our learned models, as well as manual tests show that implementations do not follow this specification.

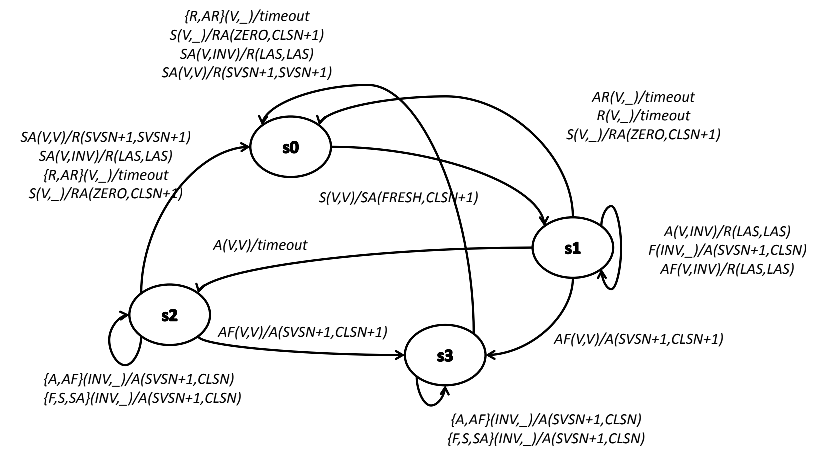


**Fig. 6.** Learned model for Windows 8 TCP

> If the connection is in a synchronized state (ESTABLISHED,FIN-WAIT-1, FIN-WAIT-2, CLOSE-WAIT, CLOSING, LAST-ACK, TIME-WAIT), any unacceptable segment (out of window sequence number or unacceptible acknowledgment number) must elicit only an empty acknowledgment segment containing the current send-sequence number and an acknowledgment indicating the next sequence number expected to be received, and the connection remains in the same state.

## 8 Concluding Remarks and Future Work

We defined and implemented a learning setup for the inference using abstraction of the TCP network protocol. We then used this setup to learn fragments of different implementations of the TCP protocol, more specifically, the Windows 8 and Ubuntu 13.10 implementations. We learned these implementations on the basis of flags, acknowledgement and sequence numbers.

For our experiments, we built initial state predicting mappers tailored to the operating system's TCP implementation. These mappers reduced the number of concrete inputs and outputs to a small set of abstract inputs and outputs. We ran our setup for each mapper and respective operating system and, in each case, covered 4 states of the TCP protocol.

Comparing the models obtained for each protocol, we found a slight variation between the Windows and Ubuntu implementations of the TCP protocol. While in normal scenarios behaviour turned out to be similar, some abnormal scenarios revealed differences in the values of sequence and acknowledgement numbers, as well as the flags found in response packets. This variation results in differing transitions between the state machines inferred for each OS. The difference in behaviour is already leveraged by tools such as nmap(see [14]), as a

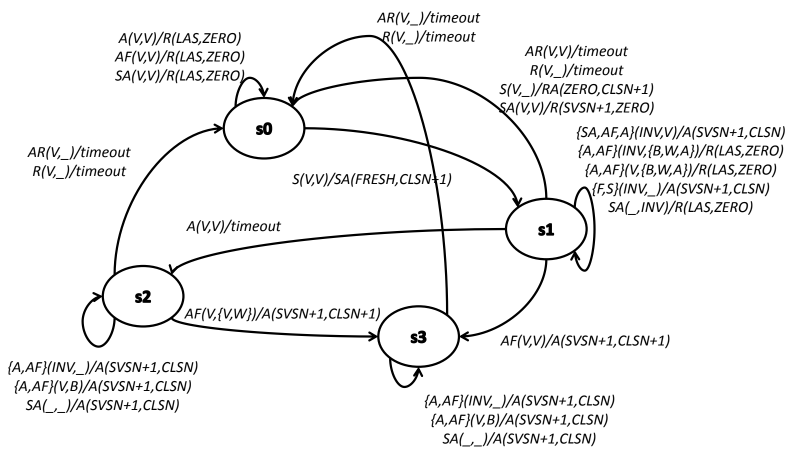


**Fig. 7.** Learned model for Ubuntu 13.10 TCP

means of operating system fingerprinting. We also identified a case where both implementations deviated from the RFC 793 standard [16].

In the future we want to extend the TCP alphabet so that we also account for data transfer and for the sliding window. We also aim to learn fragments of protocols built over TCP, for instance FTP or HTTP. A long term goal is automating the learning process which would considerably facilitate future experiments. We believe the mapper can be constructed automatically using tools that automatically infer invariants over sets of values. These tools can then be harnessed by algorithms that automatically construct the mapper. Such algorithms already exist, the only invariant they support however is equality. We believe we can extend this constraint to simple linear invariants. This would enable the automatic inference of mappers for more complex systems, such as the TCP protocol.

Our work and related efforts such as [6, 21] show that automata learning is rapidly becoming a very effective technqe for studying (non)compliance of implementations to protocol standards.

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