Prospex: Protocol Specification Extraction

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Motivation

- Stateful protocol specifications can be used for
  - Black-box vulnerability analysis
  - Automated fuzz testing
  - Deep packet inspection
  - Intrusion detection
  - Show differences between implementations of protocols
    - Fingerprinting
    - Testing

Motivation

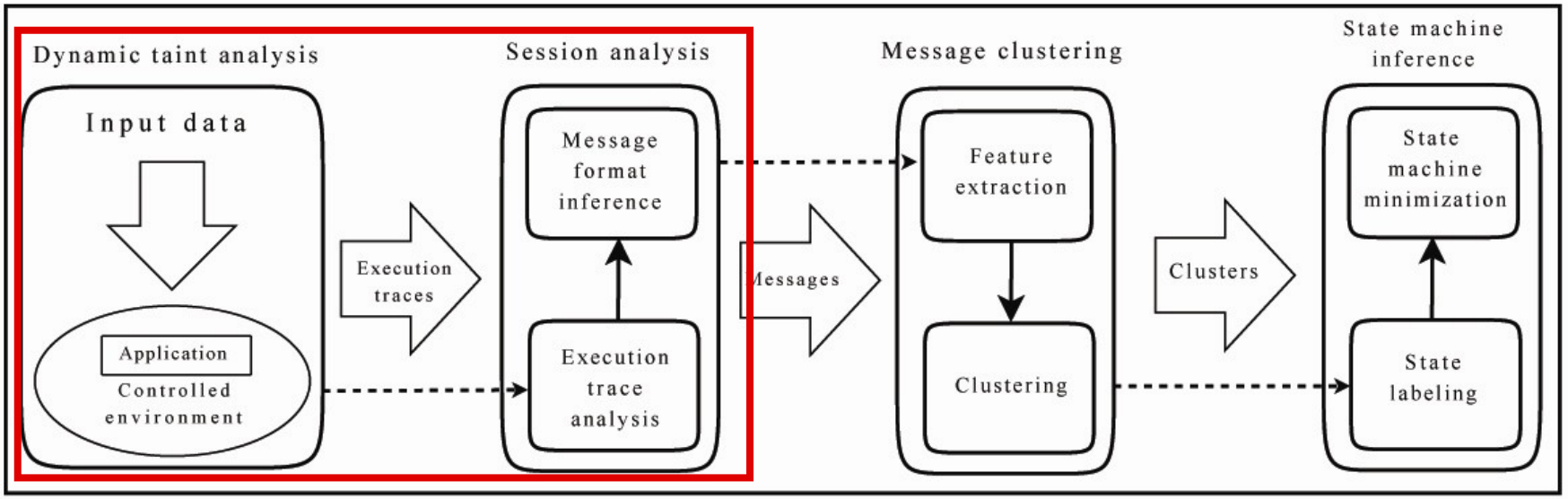
- Manual network protocol reverse engineering is a time-consuming and tedious task
- Goal: Automatic extraction of application- level protocol specifications
- Several systems exist that can automatically extract precise message formats for *individual* messages, however they do not aim at extracting a protocol state machine
- Prospex aims at producing detailed specifications for *stateful* protocols

Our Contributions

- We present
  - a technique for automatically determining message types
  - a novel way for inferring a minimal automaton that is consistent with a set of application sessions (state machine)
- Our system is the first to automatically infer specifications for stateful protocols
- Specifications for fuzz testing are automatically generated from the recovered specifications

System Overview

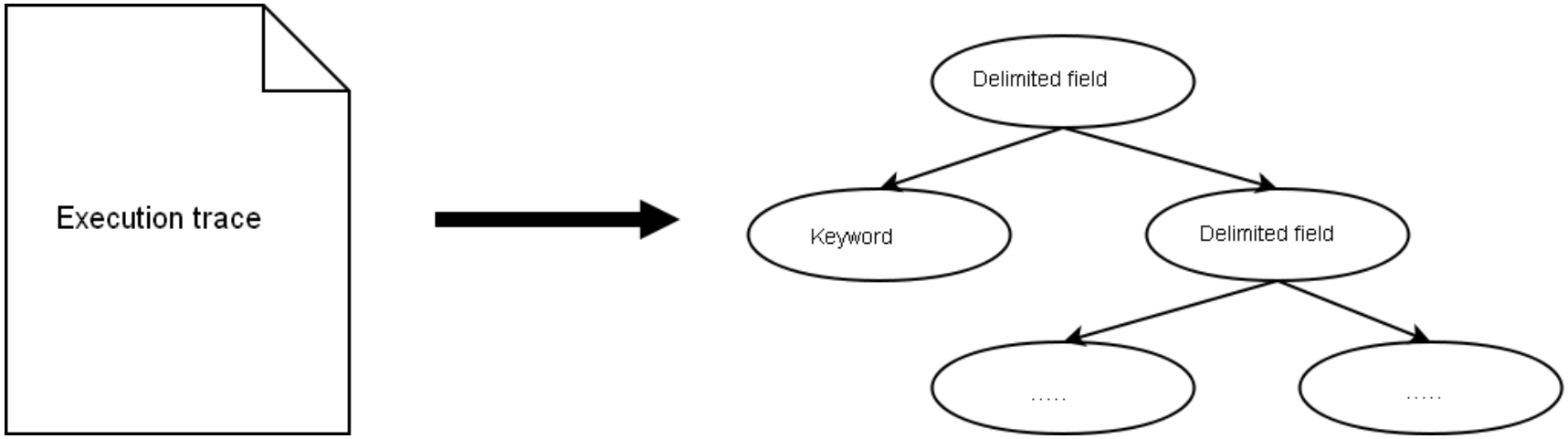
- Our system operates in four phases
- Each phase produces input for the following phase



Session Analysis Phase

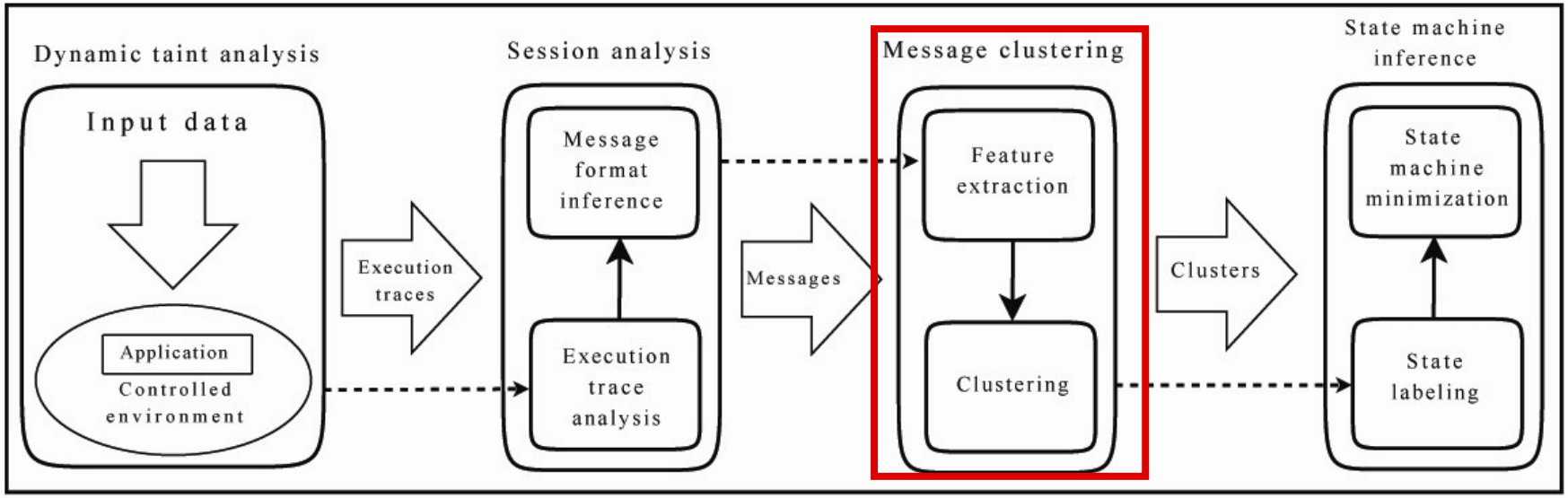
- How is the server processing messages?
  - Behavior based approach
- Record an execution trace
  - Run the application (server) in a dynamic data tainting environment
  - Assign a label to each input byte, track its propagation during the execution
  - Do this while engaging the server in a series of application sessions (using a client)
  - For example, observe `sendmail` (SMTP daemon) while using a mail client to send mail
  - Yields an *execution trace* for a session, containing all executed instruction and taint labels of all instruction operands

Message Format Inference



- Apply a set of techniques and heuristics to the execution trace
- Described in previous work (Automatic Network Protocol Analysis, NDSS 2008)
- Allows us to recover message formats for individual messages
- Each message format is represented as a tree of nested fields

Message Clustering Phase



Message Clustering

- After the session analysis phase, we have format specifications for *individual* messages
- We want to automatically determine the different message *types* that appear in the observed application sessions
- Assume a similar “reaction“ of the server to similar messages (e.g. if they have the same type)
- First step: Find a metric of similarity between messages

Message Similarity

- We define several similarity features and distance functions
- These features can be divided into three groups:
  - Input similarity features (“message format“)
  - Execution similarity features (“code execution“)
  - Impact similarity features (“behavior“)
- For each group, we compute a similarity score

Input Similarity Feature

- Assumption: Messages of the same type have a similar field structure
- To compute an input similarity score, we use a modified sequence alignment algorithm (hierarchical Needleman – Wunsch)
- The sequences of fields for all message formats are compared
- Similar parts get aligned, exposing differences or missing parts (matches, mismatches, gaps)

Execution Similarity Features

- Assumption: Similar messages are handled by similar code
- For each pair of messages, the sets of
  - system calls
  - process activity (clone, kill,…)
  - invoked functions
  - invoked library functions
  - executed addresses

  are recorded
- Then, the Jaccard indices (measure of set similarity) are computed:

$$J(a,b) = \frac{|a \cap b|}{|a \cup b|}$$

Impact Similarity Features

- Assumption: Similar messages trigger similar behavior in the server application
- Output similarity feature
  - Captures the output behavior of the server, based on destination and taint status
  - Four possible destinations considered:
    - Client‘s socket, other socket, files, terminal
  - Taint status
    - Previously tainted (e.g. echoed) or not
  - For each message, as a sequence of tuples <sink, taint> is considered (consecutive duplicates removed)
  - Needleman Wunsch is used to compute the output similarity score

Impact Similarity Features

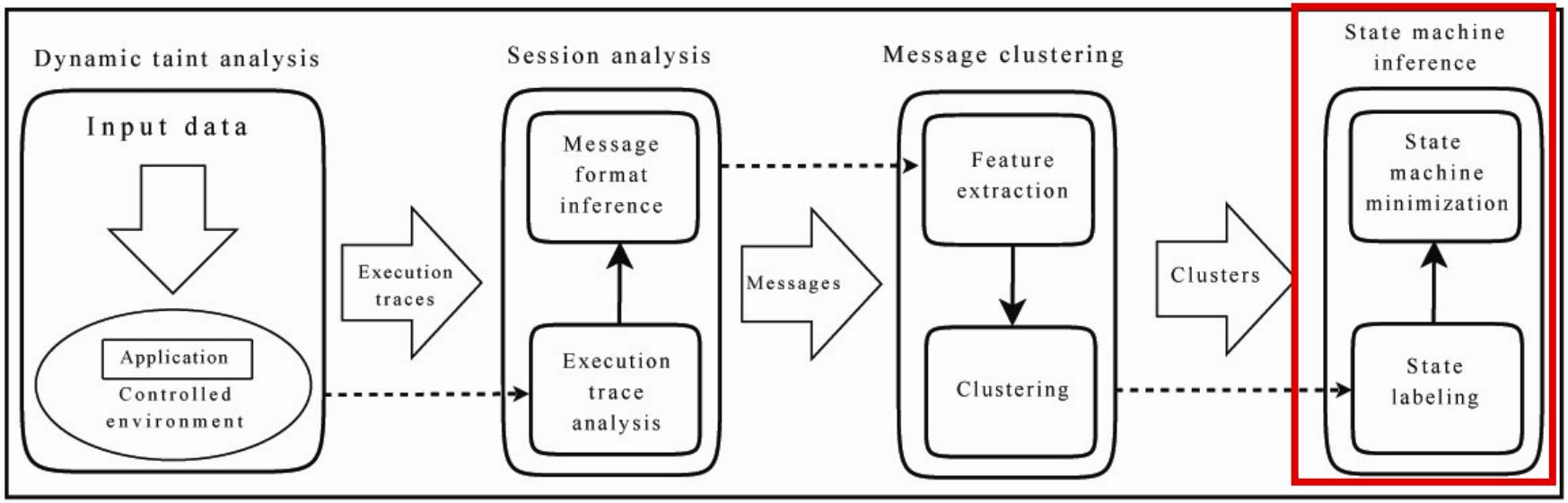
- File system feature
  - Captures the server file system activity
    - We consider system calls that perform FS actions like opening a file, getting info on a directory, etc.
  - Sets of <operation, path> tuples are assigned to each message
  - “path“ needs to be generalized
  - For each part of the path, we check if it is
    - Hardcoded in the binary
    - Tainted (“TAINT”)
    - Contained in an (optionally provided) config file (“CONFIG”)
    - Neither tainted nor in config file (“VARIABLE”)
  - Examples: <open, “/CONFIG/TAINT“>, <write, “/var/log/samba/VARIABLE>
  - The similarity distance is then computed using the Jaccard index

Clustering

- The similarity features are used to compute a distance matrix

  $d(a,b) = 1 - \sum_i \omega_i s_i(a,b)$
- We apply the partitioning around medoids (PAM) algorithm for clustering
- PAM needs the desired number of clusters k as a parameter
- We determine k by employing a generalization of the Dunn index
  - Dunn index is a standard intrinsic measure of clustering quality (cluster separation / cluster compactness)
- Result: Clusters of messages that are similar (e.g. same type)
- For each cluster, a generalized message format is generated

State Machine Inference

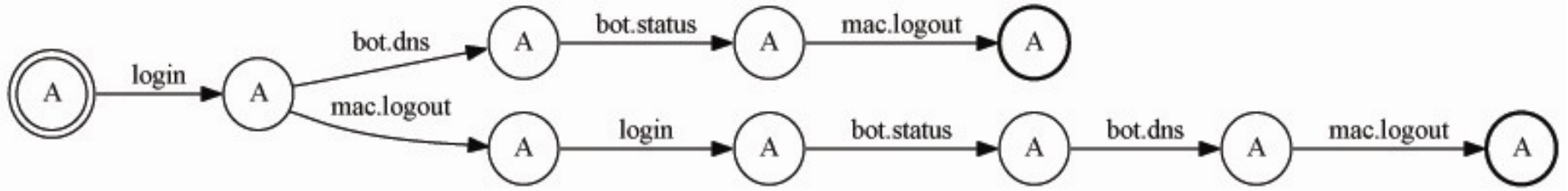


State Machine Inference

- Goal: Use the information on message types and the application sessions that we observed to infer a minimal state machine
- Find the minimal automaton that is consistent with our training set, without being overly general
- We start by constructing an Augmented Prefix Tree Acceptor (APTA)
- APTA = Incompletely specified DFA with a state transition graph that is a tree
- Each branch of the tree represents the sequence of message types within an observed application session

Augmented Prefix Tree Acceptor (APTA)

- Agobot (malware) example with 2 application sessions in the training set:



- We want to generalize the APTA by merging some states
- We only want to merge states that correspond to similar states in the server application (otherwise overly general)

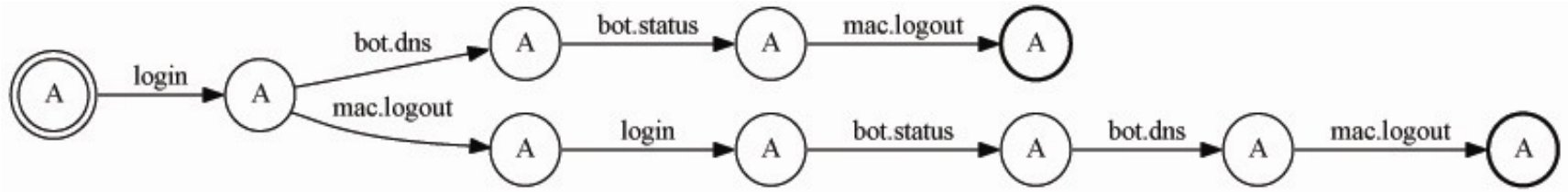
Minimization

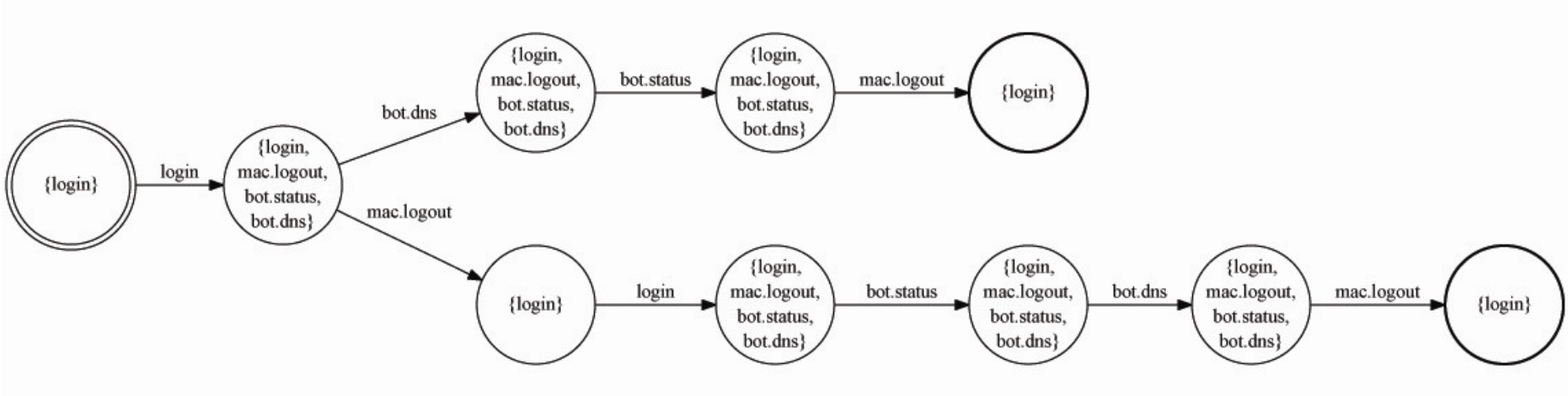
- Goal: Identify and merge similar states
- Commonly, in application level protocols, specific messages have to be sent before the server can perform certain actions
  - For example, often a *login* is necessary before other commands can be executed
  - Other commands may lead the server away from these states
- Identify states where the application can process similar commands based on the sequence of messages that it previously received

State Labeling

- To capture this intuition, we use prerequisites
- A prerequisite is a sequence of messages that the server has received that leads it to a specific state
- For the server to be in a state where it can meaningfully process a message of type *m*, it first has to receive a message of type *r* (always), optionally followed only by messages of certain types
- Algorithm to find all prerequisites presented in paper
- Once all prerequisites are computed, each state is labeled with the set of message types that are *allowed* as input in that state
- *m* is allowed in a state if the sequence of message types leading to this state matches all prerequisites for *m*

Labeled Example



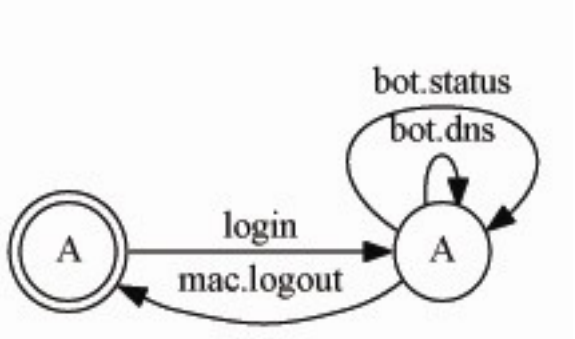


State Machine Minimization

- Compute the minimal consistent DFA from the labeled APTA to get the state machine:
  - End-state detection
    - Simple heuristic: Mark end-states by finding messages that only appear last in sessions
  - Apply a known algorithm:
    - Exbar is the state-of-the-art exact algorithm for minimal consistent DFA inference
    - Prospex runs Exbar on the *labeled* state tree
  - Result is the protocol state machine

Agobot Example

- Example state machine (generated from 2 observed application sessions):



- Captures the notion that “login“ is necessary for the command, and “logout“ returns to the initial state

Evaluation

- We created state machines for 4 widely deployed real-world protocols
- Agobot
  - Malware example
  - Text-based protocol (close to IRC), bots often use custom C&C protocols
  - We mimicked a bot herder and performed a few commands on our own IRC server
- SMTP
  - Applied our system to `sendmail` daemon
  - Used 16 application sessions (sending email) as training set

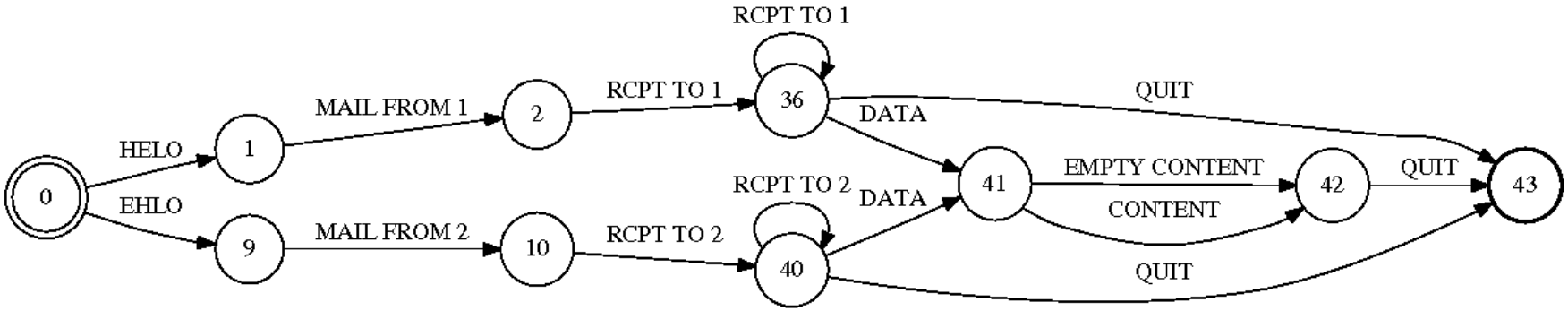
Evaluation

- Server Message Block (SMB)
  - Complex, stateful, binary protocol
  - We observed the `smbd` daemon
  - Used `smbclient` for creating the training set
  - Recorded 31 training sessions, performing file operations

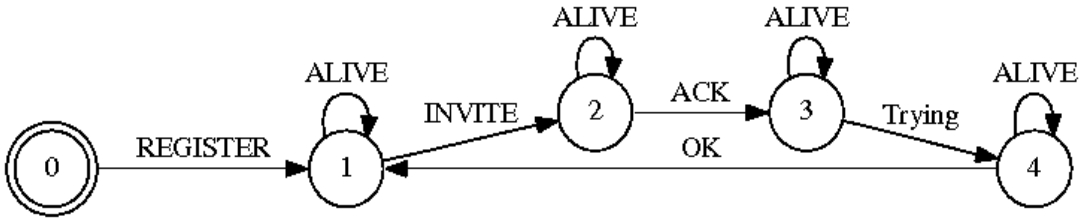
- Session Initiation Protocol (SIP)
  - Text-based protocol
  - Often used in VOIP infrastructure
  - `Asterisk` server
  - Connected using 2 client soft-phones, made phone calls, using voice boxes etc.
  - Training set represents the use cases of calling someone

Example State Machines

SMTP

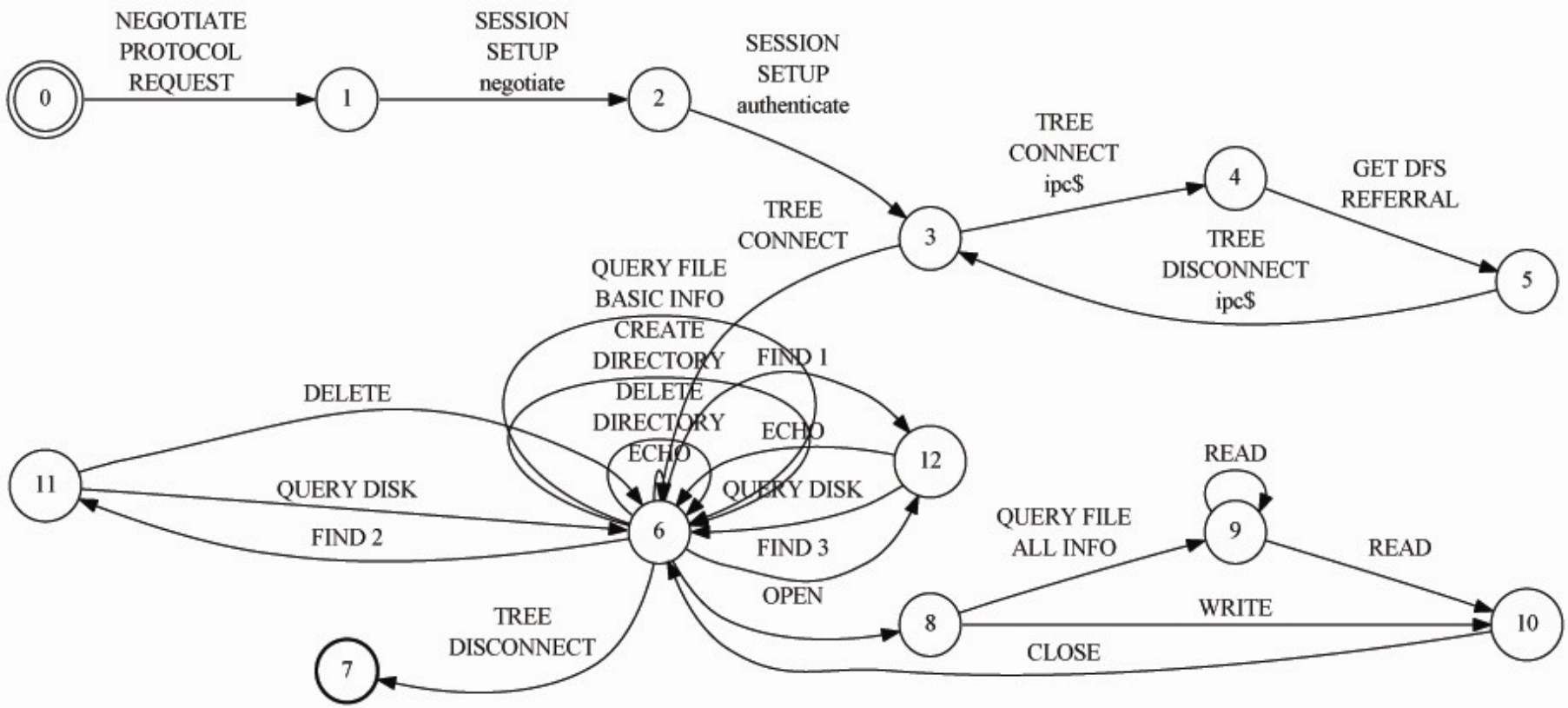


SIP



Example State Machines

SMB



Quality of Specifications

- How good are these results?
  - Specifications should parse valid sessions without being too general
- Parsing success
  - “Complete“ means not overly restrictive, e.g. the inferred state machine parses valid sessions
  - To this end, we parsed real-world network traces with the extracted specifications

Protocol	#Sessions	Parsing success
SMTP	31,903	93,5%
SIP	80	100%
SMB	80	90%

  - SMTP: remaining 6.5% used TLS encryption (limitation)
  - SMB: Fails were previously unknown error conditions (files not found etc.)

Quality of Specifications

- State machine comparison:
  - We built reference state machines for the tested protocols
  - Performed 50,000 random walks over inferred state machines, and checked if the message sequences are valid in the reference state machines
  - Precision: Ratio of sequences generated by random walks over the inferred state machine that are accepted by the reference state machine
  - Recall: Ratio for sequences from random walks over the reference state machine that are accepted by the inferred state machine

Protocol	Precision	Recall
Agobot	1	1
SMTP	1	1
SMB	1	.58
SIP	1	1

Comparative Evaluation

- Compare our state machine inference with known algorithms for inductive inference (based on Minimum Message Length)
  - Sk-strings, beams
- Known algorithms did not provide acceptable performance on our training data

	Agobot		SMTP		SMB		SIP	
	P	R	P	R	P	R	P	R
Prospex	1	1	1	1	1	.58	1	1
beams	.56	1	.89		1	.50	1	1
sk-strings(and)	.79	.20	1	.	1	.30	1	.01
sk-strings(or)	.11	.92	.11		.12	.62	1	1

1
88
1

Application: Fuzz testing

- Prospex can create fuzzing specifications from the extracted message formats and the state machine
- We contributed to the open source Peach Fuzzing Platform (statefulness) and applied the system to two applications

- SMB
  - 2,100 lines of Peach XML created
  - Found a file traversal vulnerability in `smbd` that allows downloading of `/etc/passwd` (filename semantic)
- SIP
  - Found a bug that segfaults Asterisk when a return value is set to “0“

- Vulnerabilities were unfortunately already known
- Non-stateful fuzzing would not get to these vulnerabilities

Limitations

- We limit ourselves to the analysis of the communication in a single direction, but both communication partners could be monitored simultaneously, combining the state machines and message formats
- We cannot handle encrypted network traffic
- Quality of specifications is limited by quality and variety of training data, e.g. observed sessions

Conclusion

- Prospex can automatically infer protocol specifications for stateful protocols
- Automatically identify message types
- Infer the protocol state machine
- Generate protocol specifications for a stateful fuzzer

Thanks for your attention!