Automation of the Reverse Engineering of Unknown Binary Network Protocols

Dissertation Defense

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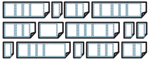
Institute of Distributed Systems

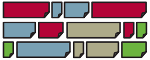
April 26, 2024

Definition of Protocol Reverse Engineering

PROTOCOL REVERSE ENGINEERING (PRE)
is the process of *inferring* the

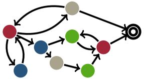
message formats,





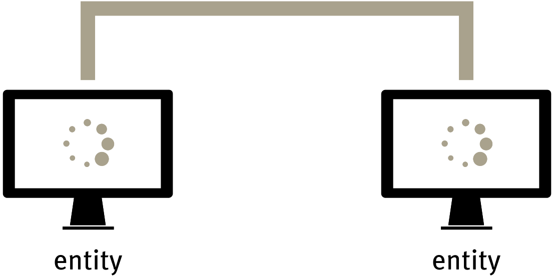
message types, and

grammar



of a network protocol
for which a formal *specification is unknown*.

Motivation for Protocol Reverse Engineering



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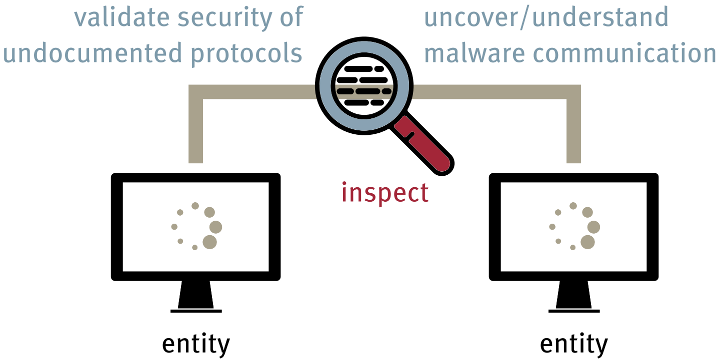
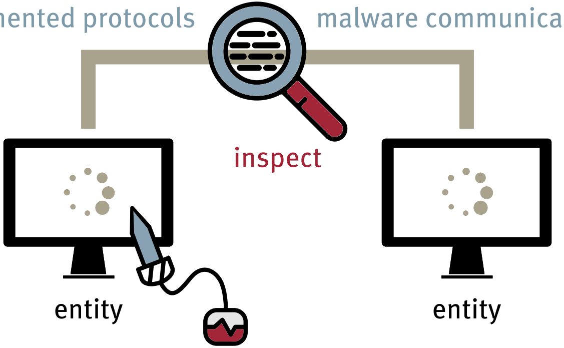


Motivation for Protocol Reverse Engineering

validate security of
undocumented protocols

uncover/understand
malware communication



probe the implementation

Smart Fuzzing to discover vulnerabilities

Motivation for Protocol Reverse Engineering

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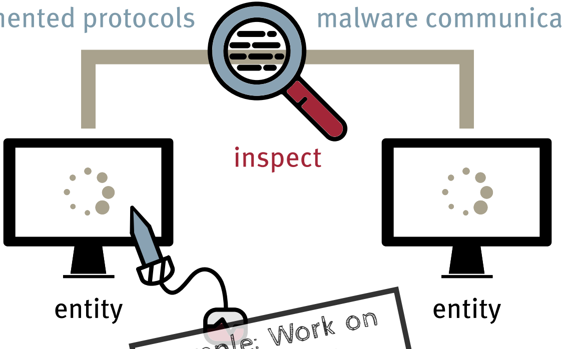
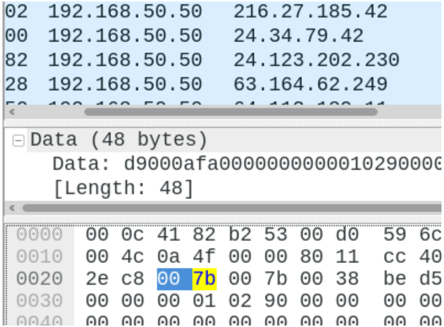


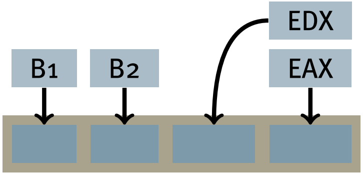
Example: Work on Apple protocols

probe the implementation

Smart Fuzzing to discover vulnerabilities

Methods of Protocol Reverse Engineering





Message TX/RX Buffer

```
MOVSB [0x1000], [0xff00]
MOVSB [0x1001], [0xff01]
MOVSB [0x1002], EDX
MOVSB [0x1003], EAX
```

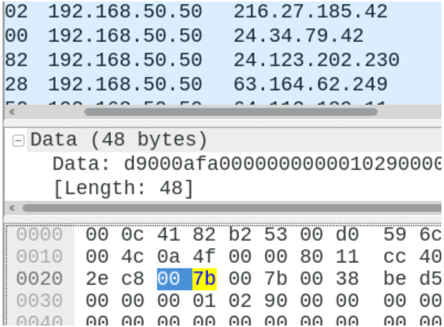
Static Traffic Analysis

Recording observable transmission of data

Dynamic Entity Analysis

Source code or binary program of entities

Methods of Protocol Reverse Engineering



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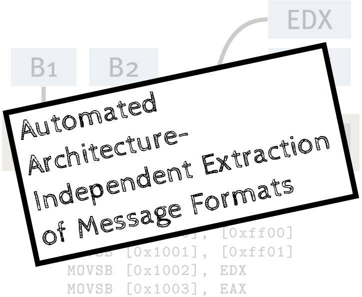

Dynamic Entity Analysis

Source code or binary program of entities

Types of Protocols

Field Boundaries of...

... textual protocols (e. g., SMTP):

RCPT | | TO: | | <twanda@blue6.ex> |

... binary protocols (e. g., DHCP):

63 82 53 63 | 35 01 | 05 36 04 ac 14 03 01 | 33 04 00 00 0e 10

Keyword

Separator

Value

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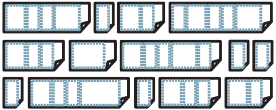
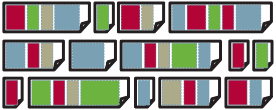
STATIC TRAFFIC ANALYSIS OF
UNKNOWN BINARY NETWORK PROTOCOLS

Targets of Protocol Reverse Engineering

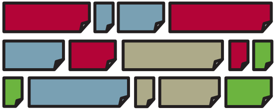
Protocol Specification



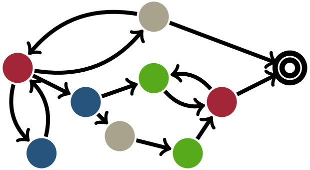
Message Formats | Fields



Field Data Types | Semantic



Message Types | Vocabulary



Behavior Model | Grammar

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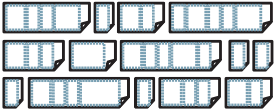

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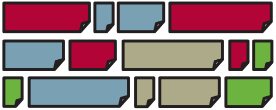

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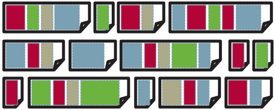

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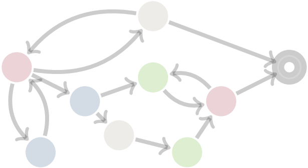

Behavior Model | Grammar

Static Traffic Analysis: Related Work Survey

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Weidong Cui et al., USENIX Security 2007.

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Static Traffic Analysis: Overcoming Limitations of Related Work[1]

Common limitations of related work: many specific assumptions about protocols

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Static Traffic Analysis: Overcoming Limitations of Related Work[1]

Common limitations of related work: many specific assumptions about protocols

In contrast, make few assumptions: generically applicable approach

- No specific message format or protocol structure
- No preceding classification of messages into types or flows
- No meta-data/encapsulation required

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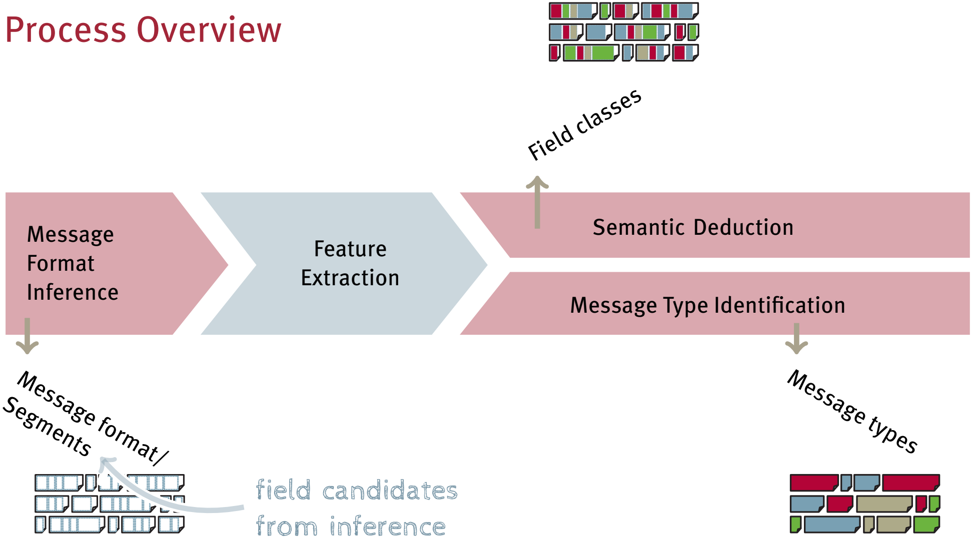
Process Overview



Process Overview[1]

Preparation

Data Collection and Preprocessing

Message Format Inference

Feature Extraction

Semantic Deduction

Message Type Identification

Behavior Model Reconstruction

Processing of Results

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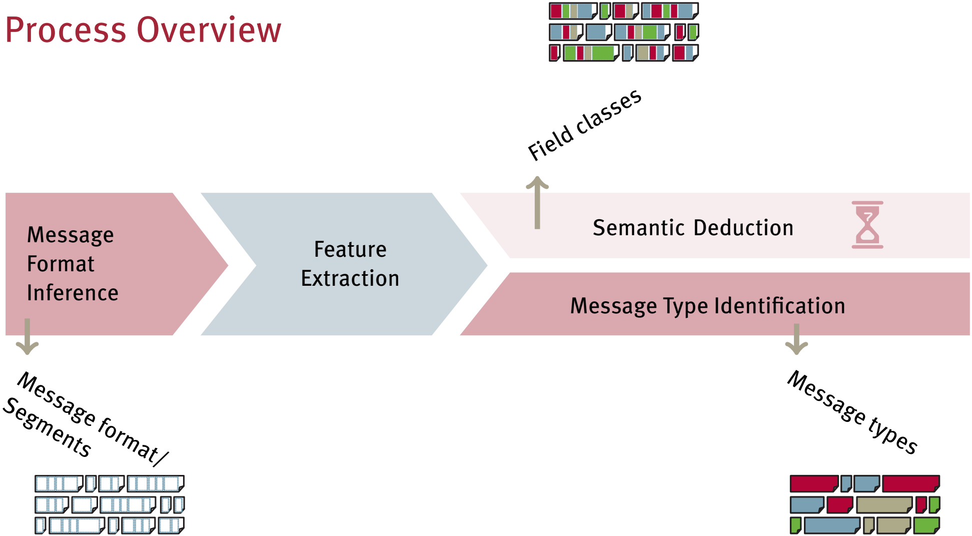
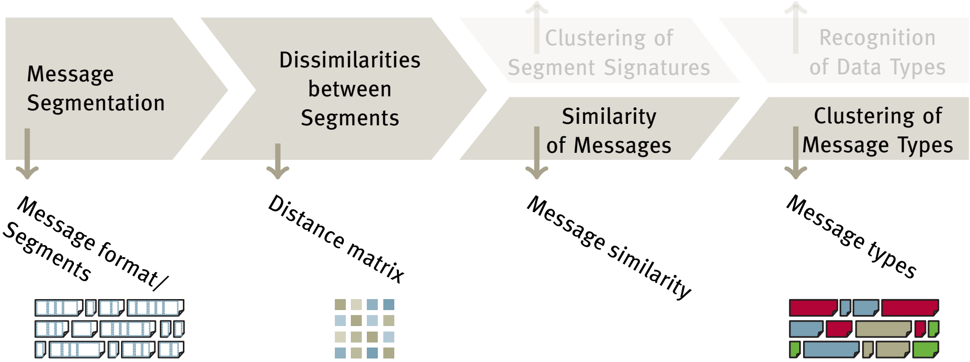


NemeRE:
NEtwork MEssage
Reverse Engineering



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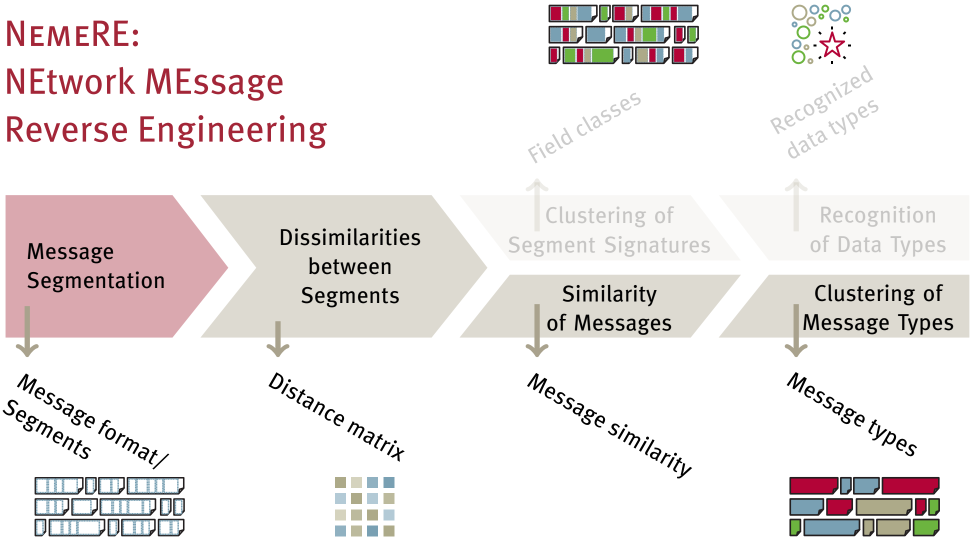
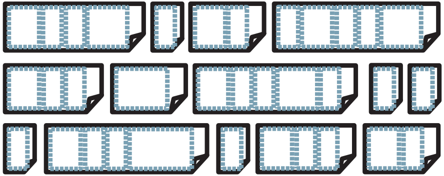


NEtwork MEssage SYntax analysiS

NEMESYS[1]: heuristic message segmentation

- Analyze each and every message individually
- Efficient heuristic for characteristics of substructures
- Intrinsic message structure
- Find probable field boundaries



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NEMESYS: Deltas of Bit Congruence

Bit Congruence: Comparison of bit-wise match of two subsequent bytes

Deltas of Bit Congruence:
Difference in the congruence of two pairs of subsequent byte values

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Difference in the congruence of two pairs of subsequent byte values

```
19 04 0a ec 00 00 02 7b 00 00 12 85 0a 64 00 c8 d2 3d 06 a2 53 5e d7 1e d2
```

Message of 25 bytes in hexadecimals

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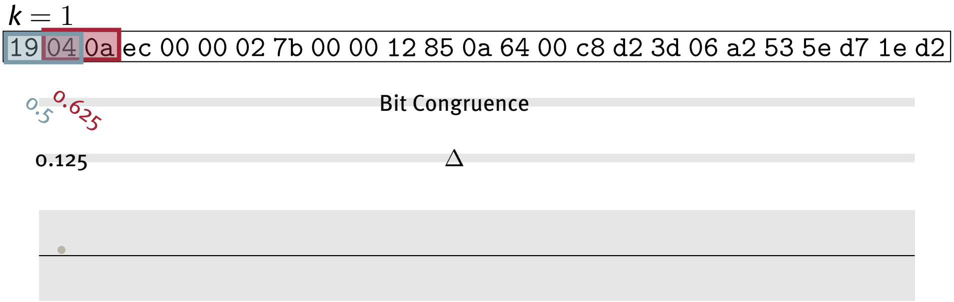

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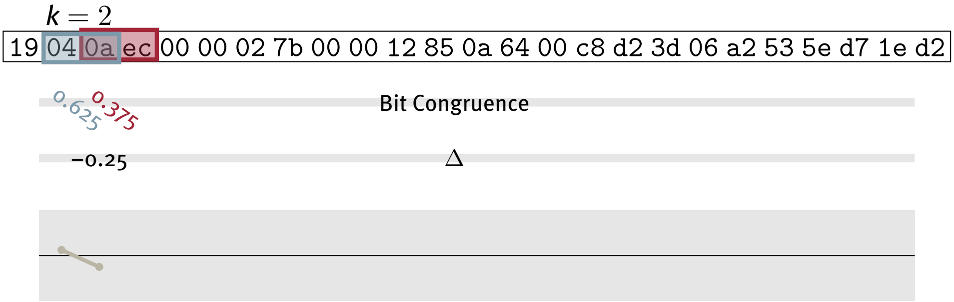

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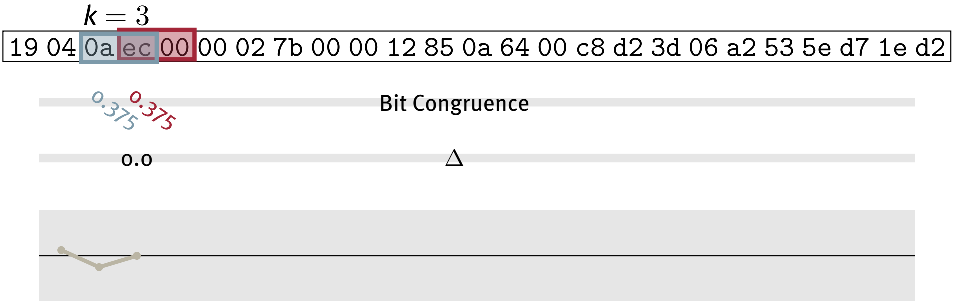

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$k = 4$

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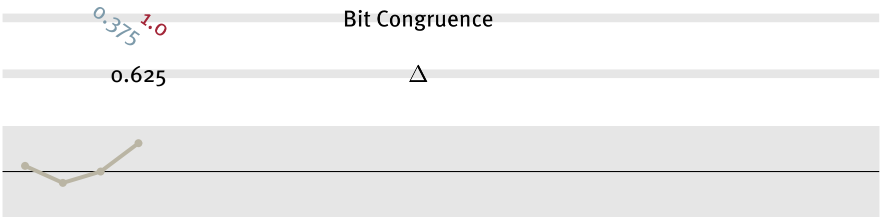

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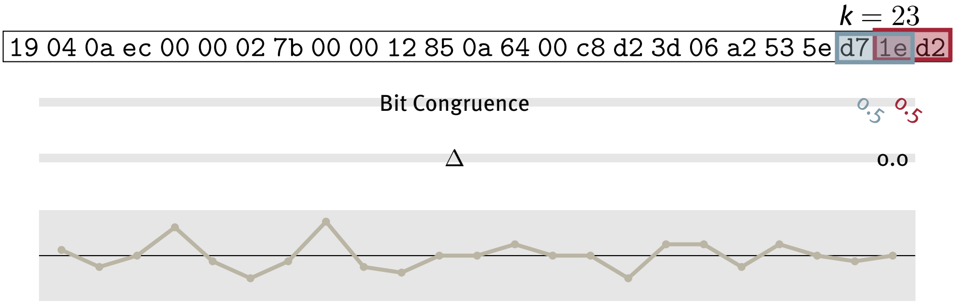

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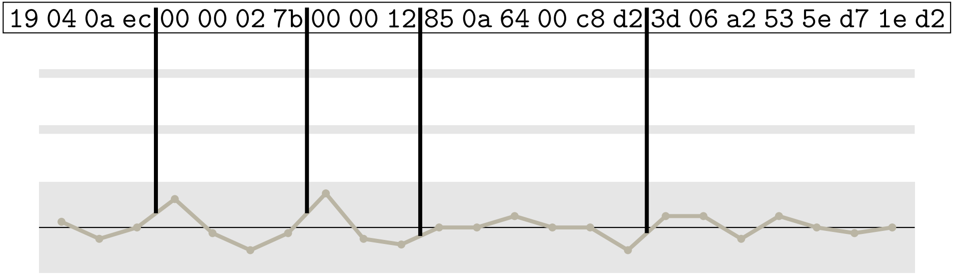


Refinement by Principal Component Analysis (PCA)[1]

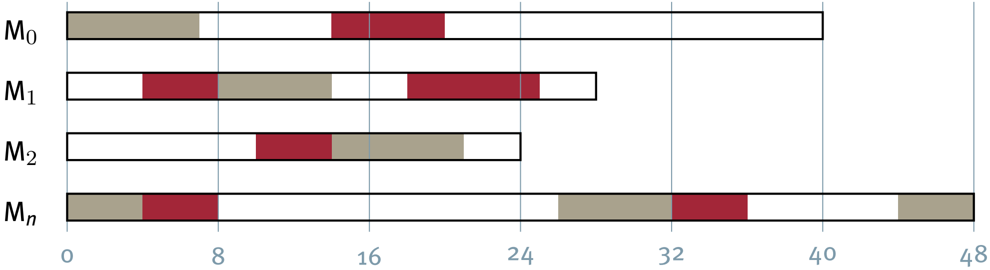
NEMESYS suffers from frequent off-by-one errors in field boundaries

Correct NEMESYS errors using Principal Component Analysis:

- Variance-locked bytes typically comprise one field
- Principal Component Analysis quantifies multivariate variance
- Basis: covariance matrix $\mathbf{C}$ of the data matrix $\mathbf{X}$

[1] Stephan Kleber and Frank Kargl. „Refining Network Message Segmentation with Principal Component Analysis“. In: *Proceedings of the tenth annual IEEE Conference on Communications and Network Security*. CNS. IEEE, 2022.

Recursive Clustering: Collecting Similar Segments



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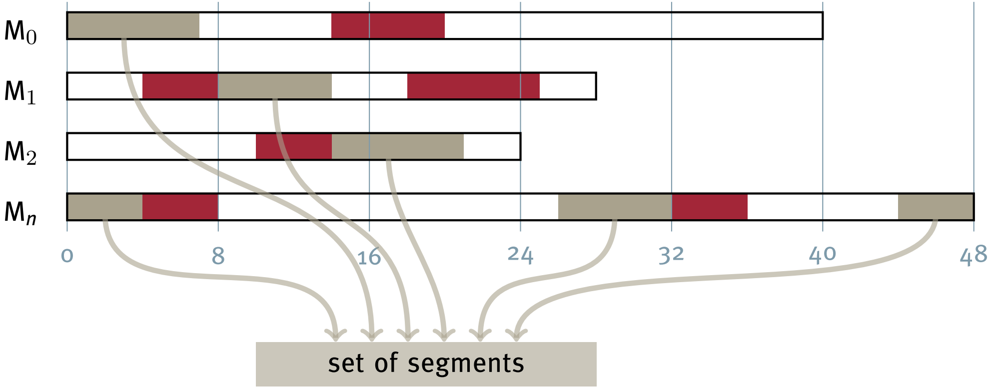

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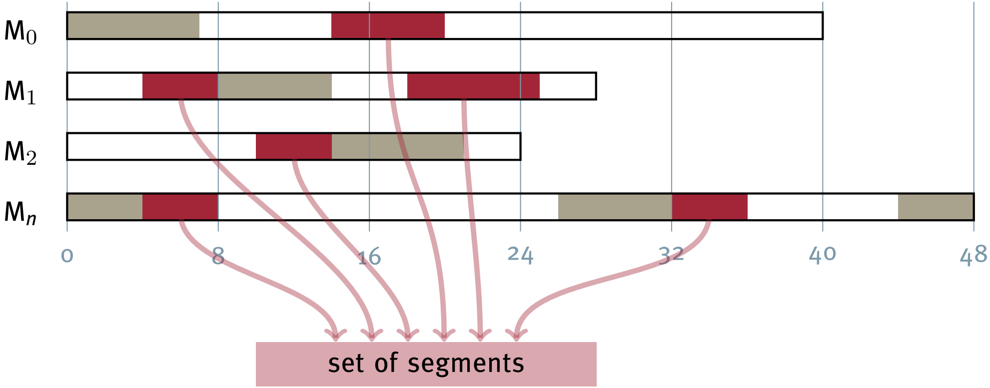

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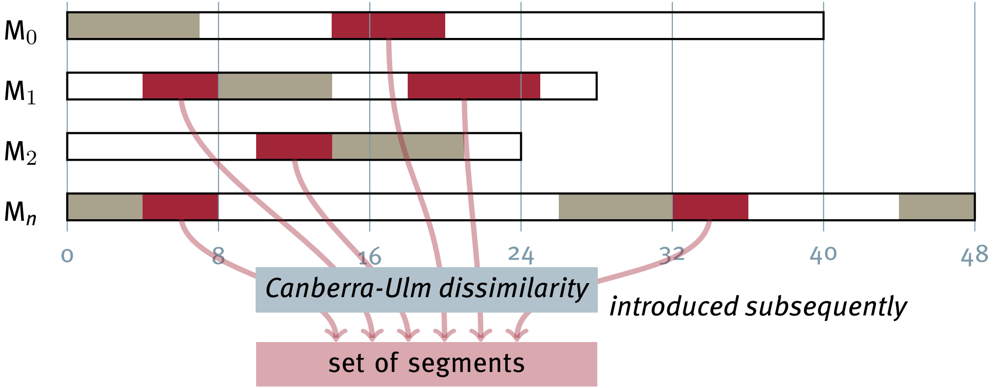

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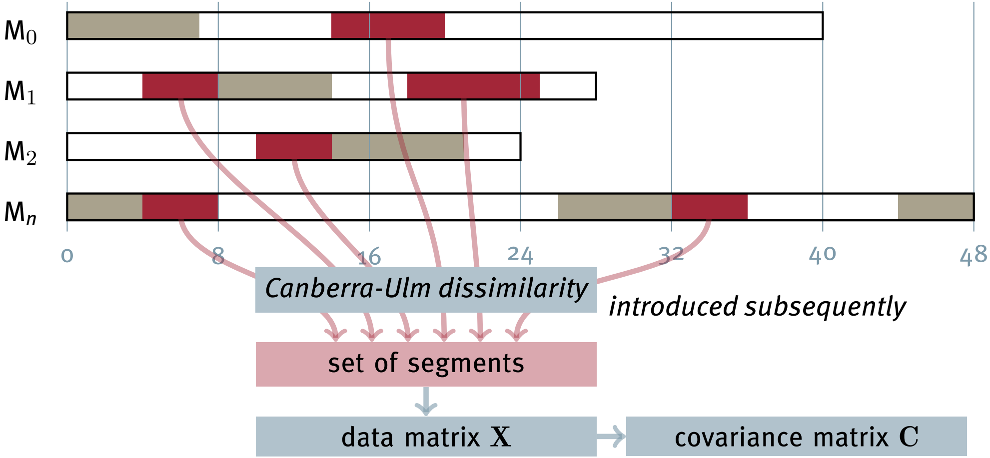
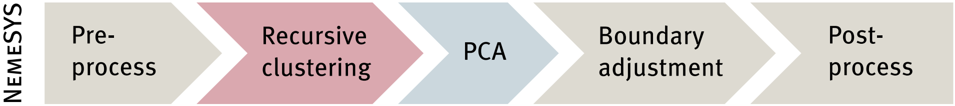


Refinement of NEMESYS: Byte-wise Segment Variance Analysis



Recursive clustering:

- Ensures application of PCA to a set of related segments

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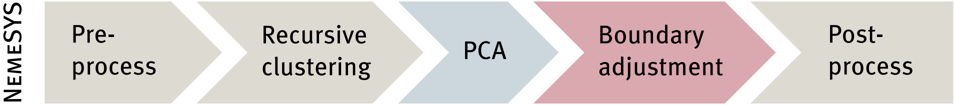

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- Heuristic rules for field boundary adjustments, e. g., sharp variance drops

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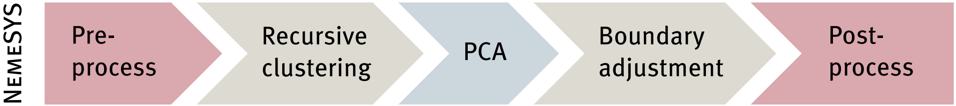

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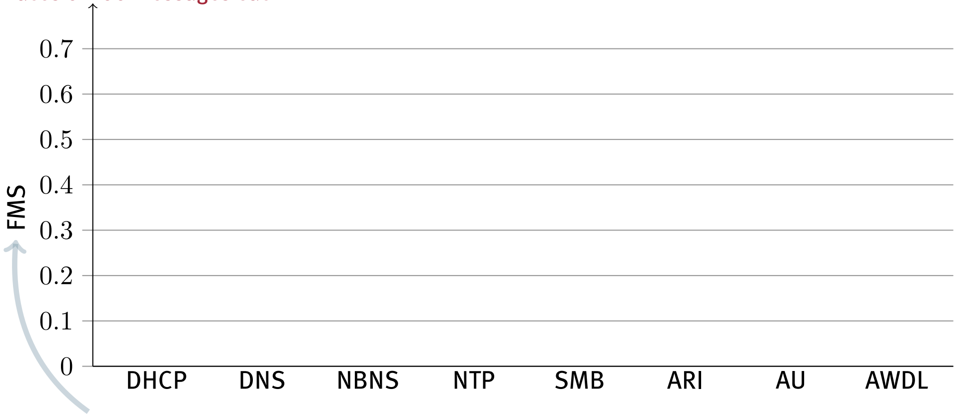
Static-rule pre- and post-processing:

- Merging of segments with similar local entropy
- Accommodate embedded text by character segment refinement

Evaluation of NEMESYS Segmentation

Traces of 100 messages each



Format Match Score (FMS)[1]: Conformance of inference to message format specification

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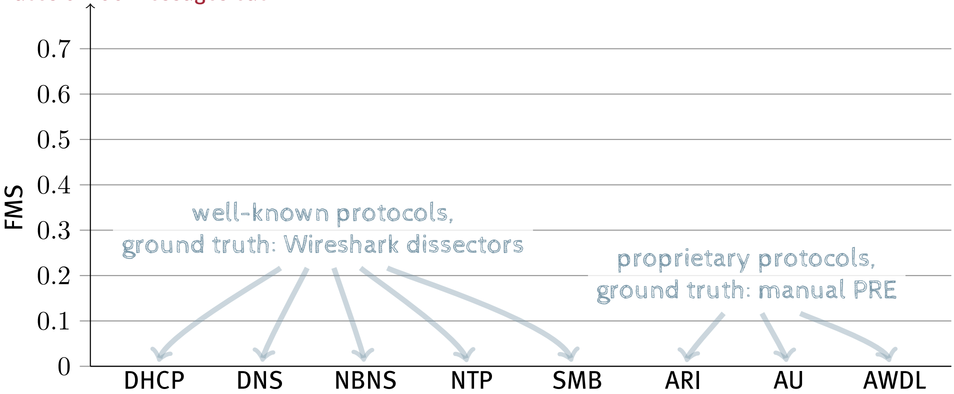

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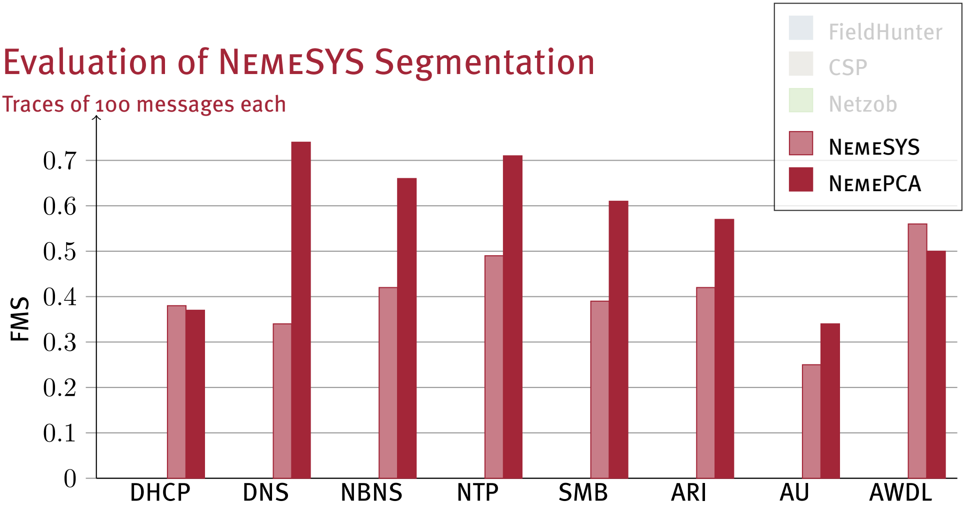

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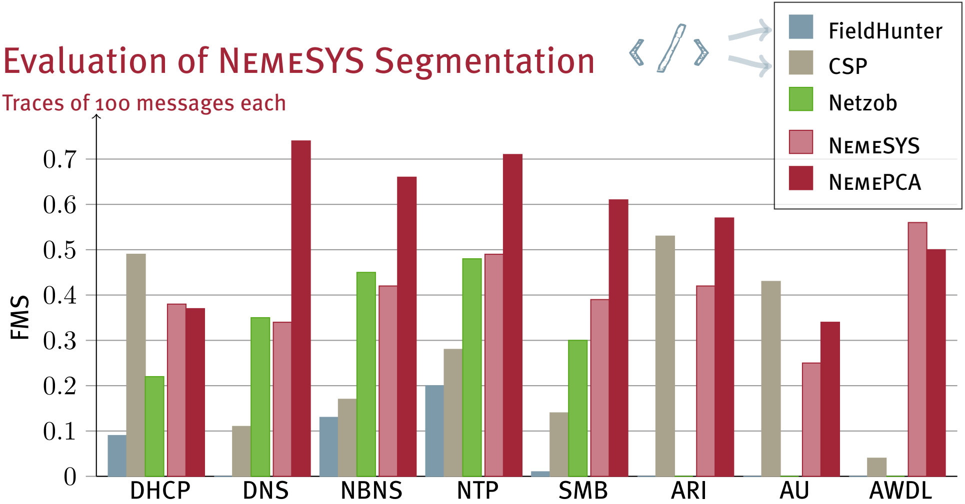

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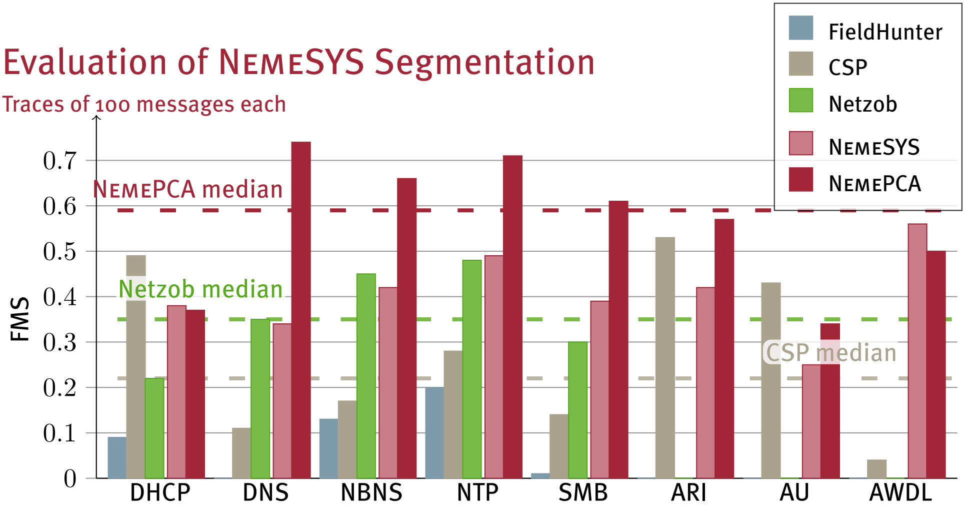

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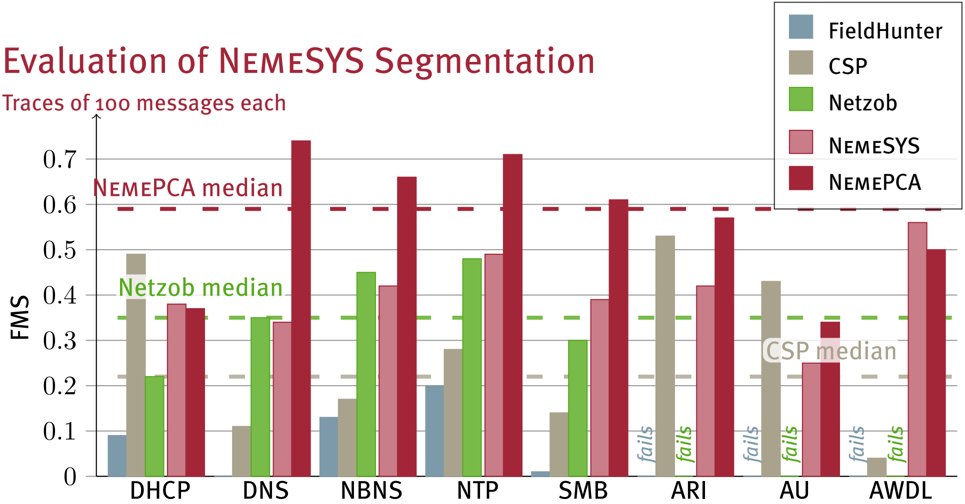

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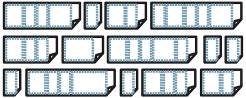
Result of Message Format Inference

Segmentation into Field Candidates



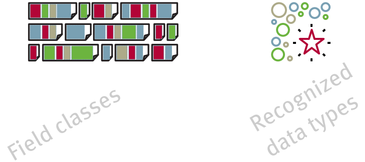
NEMESYS: NEtwork MEssage SYntax analysIS (WOOT2018)[1]

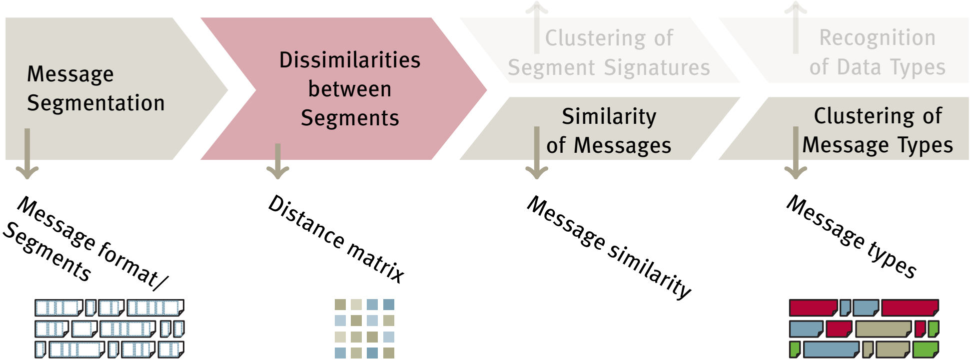
NEMEPCA: NEMESYS with PCA Refinement (CNS2022)[2]

[1] Stephan Kleber et al. „NEMESYS: Network Message Syntax Reverse Engineering by Analysis of the Intrinsic Structure of Individual Messages“. In: *Proceedings of the 12th USENIX Workshop on Offensive Technologies*. WOOT. USENIX Association, 2018.

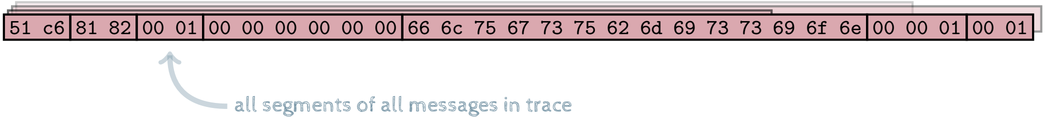
[2] Stephan Kleber and Frank Kargl. „Refining Network Message Segmentation with Principal Component Analysis“. In: *Proceedings of the tenth annual IEEE Conference on Communications and Network Security*. CNS. IEEE, 2022.

NEMERE:
NEtwork MEssage
Reverse Engineering





Calculate Segment Dissimilarities



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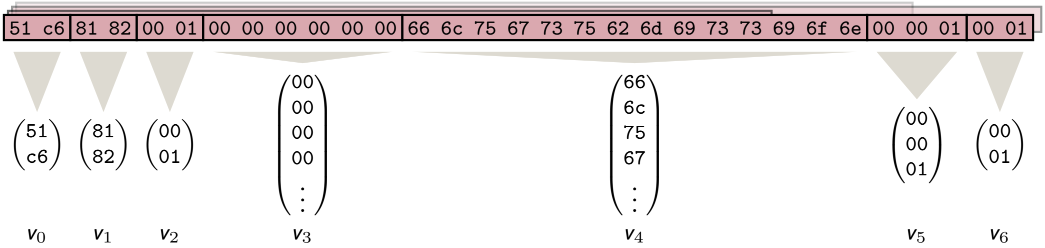

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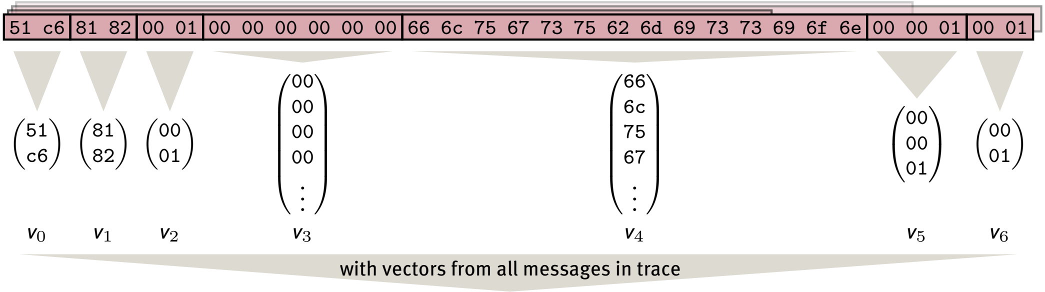
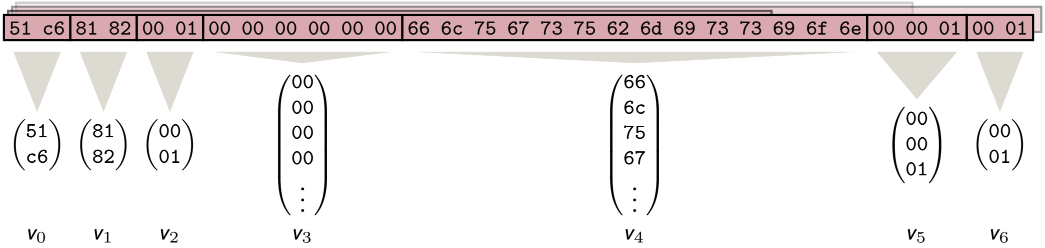


Dissimilarity matrix **D**

	v_0	v_1	v_2	v_3	v_5	$\cdots$	v_n
v_0	0.0	0.2	1.0	1.0	0.7		1.0
v_1	0.2	0.0	1.0	1.0	0.6		1.0
v_2	1.0	1.0	0.0	0.7	1.0		0.0
v_3	1.0	1.0	0.7	0.0	1.0		0.7
v_5	0.7	0.6	1.0	1.0	0.0		1.0
$\vdots$						$\ddots$	0.3
v_n	1.0	1.0	0.0	0.7	1.0	0.3	0.0

Calculate Segment Dissimilarities



with vectors from all messages in trace

Dissimilarity matrix **D**

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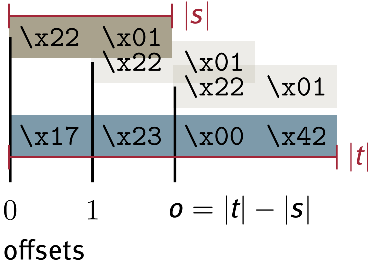
$\vdots$						$\ddots$	0.3
v_n	1.0	1.0	0.0	0.7	1.0	0.3	0.0

pairwise,
gradual dissimilarity
instead of boolean match

Linear Subspaces from Sliding Window



$$d_C\left(\begin{pmatrix}0x17\\0x23\end{pmatrix},\begin{pmatrix}0x22\\0x01\end{pmatrix}\right)$$

$$d_C\left(\begin{pmatrix}0x23\\0x00\end{pmatrix},\begin{pmatrix}0x22\\0x01\end{pmatrix}\right)$$

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Canberra distance d_C

weighted L_1 or Manhattan distance

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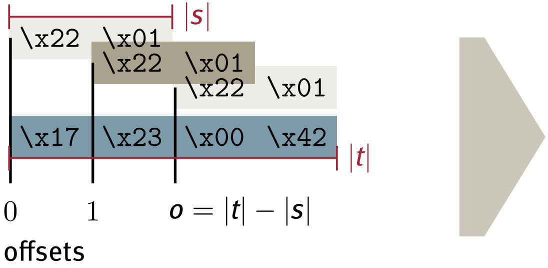

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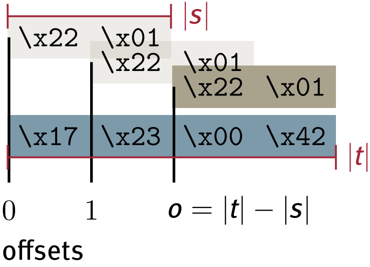

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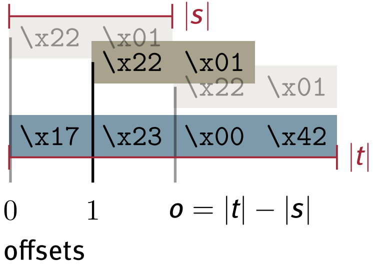

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Minimum Canberra distance

$$d_\beta(T, \mathrm{s}) = \frac{\min_T(\{d_C(\mathbf{t}_{[o,o+|s|]})\})}{|s|} \tag{1}$$

Canberra-Ulm Dissimilarity[1]

$$d_m(\mathrm{s}, \mathrm{t}) = \qquad + \qquad + \tag{2}$$

[1] Stephan Kleber et al. „Message Type Identification of Binary Network Protocols using Continuous Segment Similarity“. In: *Proceedings of the Conference on Computer Communications*. INFOCOM. IEEE, 2020.

Canberra-Ulm Dissimilarity[1]

$$d_m(\mathrm{s}, \mathrm{t}) = \underbrace{\frac{|s|}{|t|} d_\beta(\mathrm{s}, \mathrm{t})}_{\text{subterm 1}} + \qquad + \tag{2}$$

normalize d_β

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Canberra-Ulm Dissimilarity[1]

$$d_m(\mathrm{s},\mathrm{t}) = \underbrace{\frac{|s|}{|t|} d_\beta(\mathrm{s},\mathrm{t})}_{\text{subterm 1}} + \underbrace{r}_{\text{subterm 2}} + \quad (2)$$

with the relative segment length difference

$$r = \frac{|t| - |s|}{|t|}$$

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Canberra-Ulm Dissimilarity[1]

$$d_m(\mathrm{s},\mathrm{t}) = \underbrace{\frac{|s|}{|t|} d_\beta(\mathrm{s},\mathrm{t})}_{\text{subterm 1}} + \underbrace{r}_{\text{subterm 2}} + \underbrace{(1 - d_\beta(\mathrm{s},\mathrm{t}))r(\frac{|s|}{|t|^2} - p_f)}_{\text{subterm 3}} \quad (2)$$

penalize absolute dimensionality differences

with the relative segment length difference

$$r = \frac{|t| - |s|}{|t|}$$

„2 out of 4 bytes is less information than 4 out of 8 bytes“ despite both $r = \frac{1}{2}$

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Canberra-Ulm Dissimilarity[1]

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Result of Feature Extraction

Canberra-Ulm Dissimilarity of Segments

Basis for Field Data Type Classification
and Message Type Identification

NEMERE:
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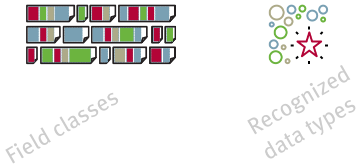
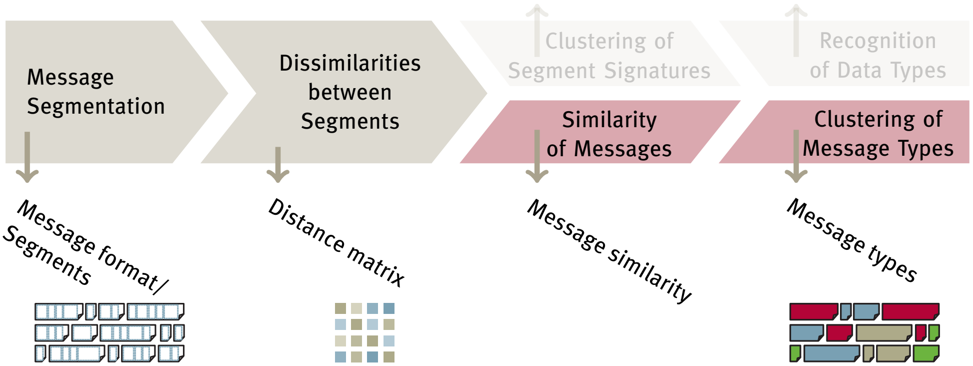
Reverse Engineering





Similarity of Messages

$m_0 =$	0208	0008	07	*GAP*
$m_1 =$	07	2700	0008	2317
$\vdots$				
$m_n =$	$\cdots$			

Segment dissimilarity
in conjunction with
Needleman-Wunsch (NW)
Sequence Alignment

Similarity of Messages

$m_0 =$	0208	0008	07	*GAP*
$m_1 =$	07	2700	0008	2317
$\vdots$				
$m_n =$	$\cdots$			

Segment dissimilarity in conjunction with Needleman-Wunsch (NW) Sequence Alignment

NW-scores message similarity:

	m_0	m_1	$\cdots$	m_n
m_0	4	0.76		
m_1	0.76	3		
$\vdots$			$\ddots$	
m_n				

DBSCAN Clustering

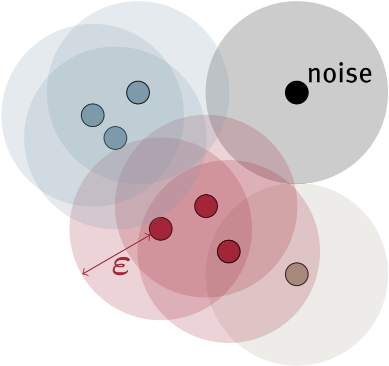
Density-Based Spatial Clustering of Applications with Noise

Main Parameter ε

Range around a density core of samples that should constitute a cluster

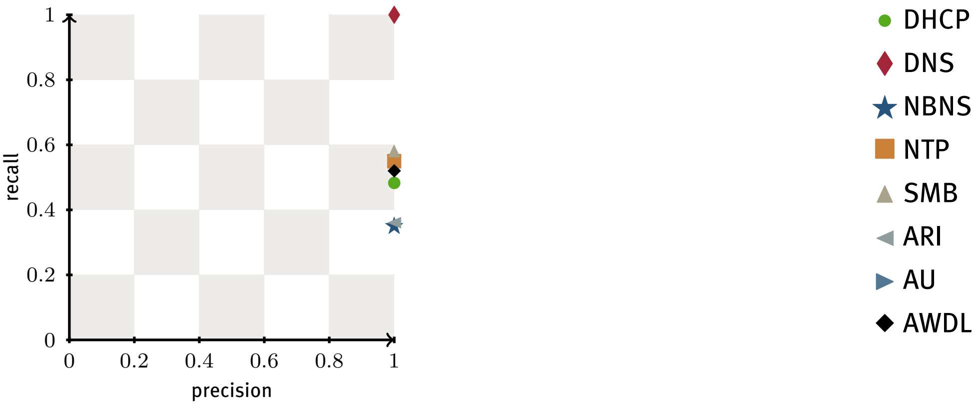
Auto-Configuration of ε

Greatest change in message similarity distribution



Evaluation Results: Message Type Quality...

... with segments from **Wireshark**



Evaluation Results: Message Type Quality...

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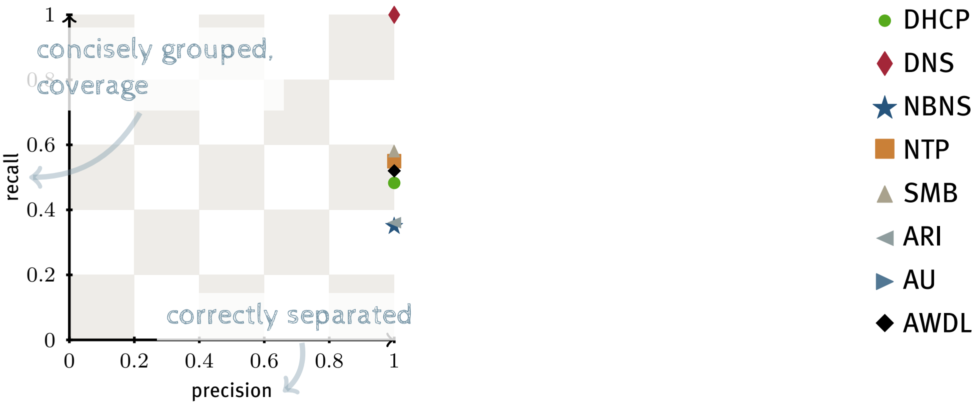
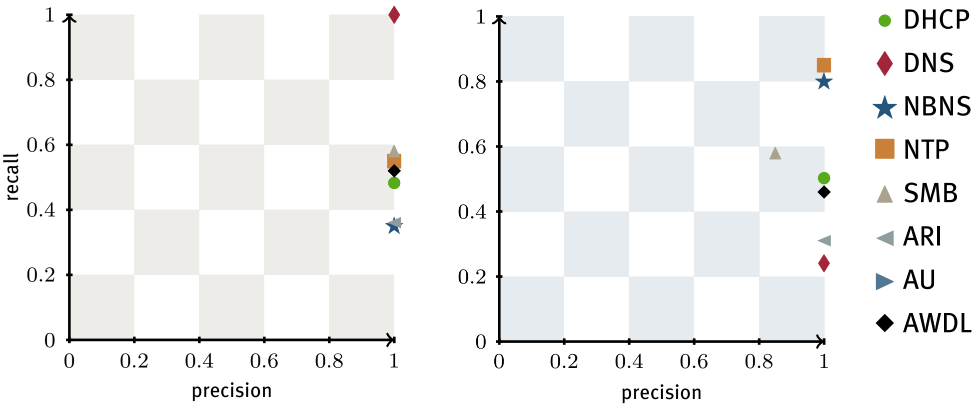


Evaluation Results: Message Type Quality...

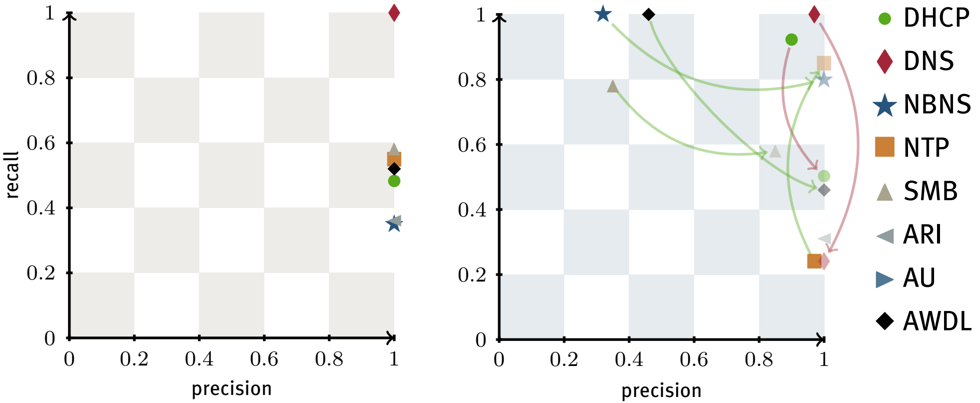
... with segments from **Wireshark** ... with segments from **NEMEPCA**



Evaluation Results: Message Type Quality...

... with segments from **Wireshark**

... with segments from **NEMEPCA**
... when clustering with **Netzob**



Evaluation Interpretation

Prioritize Precision over Recall

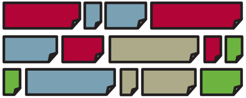
Wireshark Canberra-Ulm Dissimilarity works as expected, differences in message structure reveal message types.

Netzob Netzob's recall outperforms NEMESYS in few cases, Netzob's precision is unreliable.

NEMEPCA Close-to-perfect precision with heuristic segments, Segmentation quality has tremendous effect.

Result of Message Type Identification

Clusters of Messages resembling Message Types



NemeTYL: NEtwork MEssage TYpe identification by aLignment (INFOCOM2020)[1]

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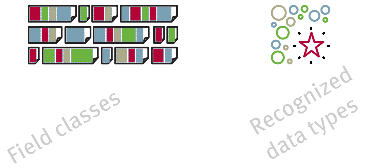

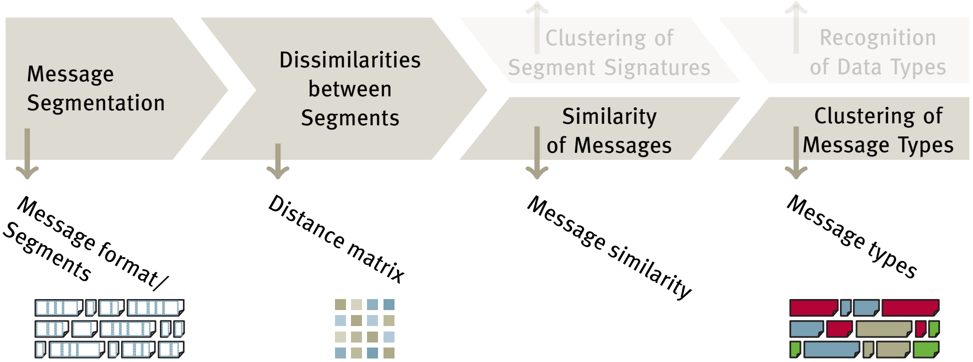

Limitations and Future Work

Limitations

- Encryption, compression, and obfuscation
- Empirical parameters. Robustness thoroughly tested but not provable

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- Encryption, compression, and obfuscation
- Empirical parameters. Robustness thoroughly tested but not provable

Future Work

- Alternatives to sequence alignment, e.g., LDA, LSTM
- Supervised learning of cluster properties for recognition by a ML model

Foundational Advances for Static Traffic Analysis

Related Work

Message Format Inference

Message Type Identification

Semantic Deduction

Foundational Advances for Static Traffic Analysis

Related Work

Contributions: Static Traffic Analysis process formalization

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Contributions: Canberra-Ulm Dissimilarity of segments + DBSCAN clustering autoconf.

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Foundational Advances for Static Traffic Analysis

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Semantic Deduction

Contribution: First generic semantic interpretation of field data types from traces

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Contribution: First generic semantic interpretation of field data types from traces

Peer-Reviewed Publications

dissertation-related

Stephan Kleber, Henning Kopp and Frank Kargl. „NEMESYS: Network Message Syntax Reverse Engineering by Analysis of the Intrinsic Structure of Individual Messages“. In: *Proceedings of the 12th USENIX Workshop on Offensive Technologies*. WOOT. USENIX Association, 2018.

Stephan Kleber and Frank Kargl. „Poster: Network Message Field Type Recognition“. In: *Proceedings of the 26th Conference on Computer and Communications Security*. CCS. 2019.

Stephan Kleber, Lisa Maile and Frank Kargl. „Survey of Protocol Reverse Engineering Algorithms: Decomposition of Tools for Static Traffic Analysis“. In: *IEEE Communications Surveys and Tutorials* 21.1 (Feb. 2019). Firstquarter.

Stephan Kleber, Rens Wouter van der Heijden and Frank Kargl. „Message Type Identification of Binary Network Protocols using Continuous Segment Similarity“. In: *Proceedings of the Conference on Computer Communications*. INFOCOM. IEEE, 2020.

Stephan Kleber and Frank Kargl. „Refining Network Message Segmentation with Principal Component Analysis“. In: *Proceedings of the tenth annual IEEE Conference on Communications and Network Security*. CNS. IEEE, 2022.

Stephan Kleber, Milan Stute, Matthias Hollick and Frank Kargl. „Network Message Field Type Classification and Recognition for Unknown Binary Protocols“. In: *Proceedings of the DSN Workshop on Data-Centric Dependability and Security*. DCDS. IEEE/IFIP, 2022.

further

Stephan Kleber, Rens W. van der Heijden, Henning Kopp and Frank Kargl. „Terrorist Fraud Resistance of Distance Bounding Protocols Employing Physical Unclonable Functions“. In: *Proceedings of the International Conference and Workshops on Networked Systems*. NetSys. IEEE, 2015.

Florian Unterstein, Stephan Kleber, Matthias Matousek, Frank Kargl, Frank Slomka and Matthias Hiller. „Design of the Secure Execution PUF-based Processor (SEPP)“. In: *Proceedings of the Workshop on Trustworthy Manufacturing and Utilization of Secure Devices, TRUDEVICE 2015*. Universität Ulm, 2015.

Stephan Kleber, Henrik Ferdinand Nölscher and Frank Kargl. „Automated PCB Reverse Engineering“. In: *Proceedings of the 11th USENIX Workshop on Offensive Technologies*. WOOT. USENIX Association, 2017.

Stephan Kleber, Florian Unterstein, Matthias Hiller, Frank Slomka, Matthias Matousek, Frank Kargl and Christoph Boesch. „Secure Code Execution: A Generic PUF-Driven System Architecture“. In: *Proceedings of the 21st Information Security (ISC 2018)*. Universität Ulm, 2018.

Thomas Lukaseder, Kevin Stölzle, Stephan Kleber, Benjamin Erb and Frank Kargl. „An SDN-based Approach For Defending Against Reflective DDoS Attacks“. In: *Proceedings of the Conference on Local Computer Networks (LCN)*. IEEE, 2018.

Tobias Kröll, Stephan Kleber, Frank Kargl, Matthias Hollick and Jiska Classen. „ARIstoteles - Dissecting Apple's Baseband Interface“. In: *Proceedings of the European Symposium on Research in Computer Security*. ESORICS. 2021.

Patrick Wachter and Stephan Kleber. „Analysis of the DoIP Protocol for Security Vulnerabilities“. In: *Proceedings of the Computer Science in Cars Symposium*. CSCS. ACM, 2022.

Stephan Kleber and Patrick Wachter. „A Strategy to Evaluate Test Time Evasion Attack Feasibility“. In: *Datenschutz und Datensicherheit - DuD* 47.8 (Aug. 2023), S. 478–482.

Overview of Contributions

Preparation

Data Collection and Preprocessing

Message Format Inference

Feature Extraction

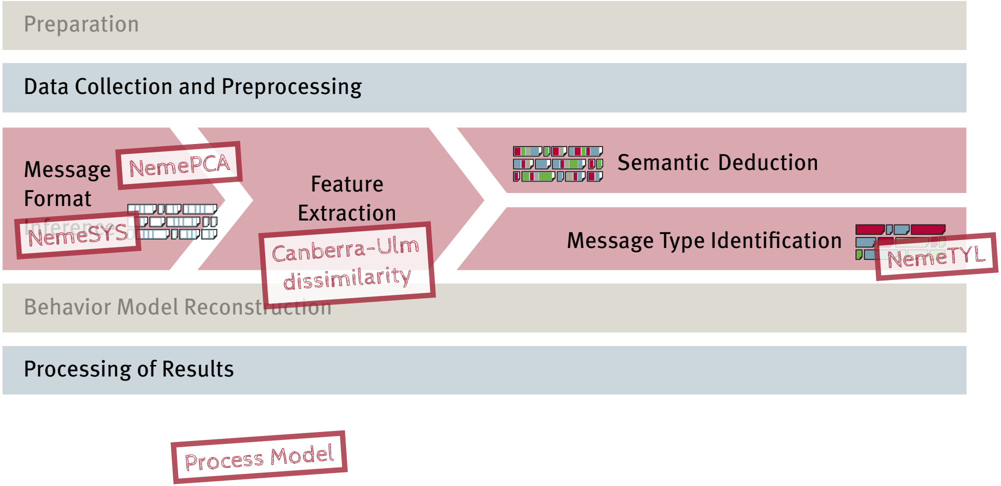
Semantic Deduction

Message Type Identification

Behavior Model Reconstruction

Processing of Results

Overview of Contributions



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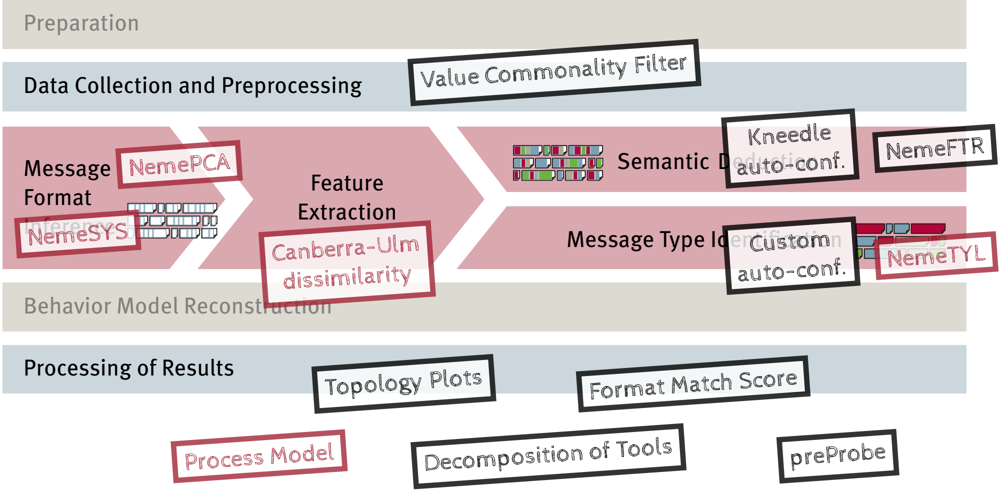

THANK YOU!

Questions?

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LinkedIn stephan-kleber

Institute of Distributed Systems, Ulm University

web uulm.de/in/vs
mail frank.kargl@uni-ulm.de
github github.com/vs-uulm

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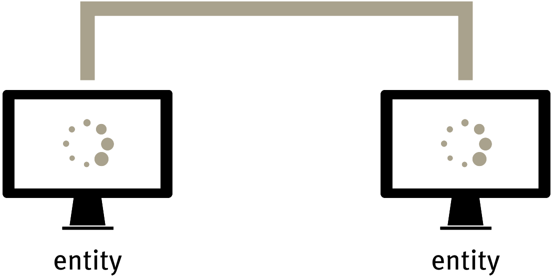
Icon Sources

Pictograms from Stephan Kleber, based on icon set by Lisa Maile

From the Noun Project, modified by Stephan Kleber:

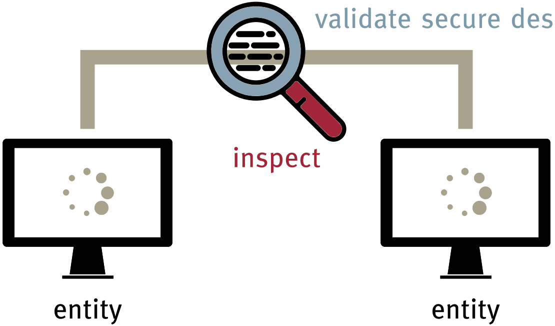
- *Searching* Created by Ziyad Al junaidi
- *Communication* Created by SlideGenius
- *Sensor* Created by Adnen Kadri
- *Specification* Created by ProSymbols
- *Paper* Created by Ilham Fitrotul Hayat
- *Hourglass* Created by Aswell Studio

Motivation for Protocol Reverse Engineering



Motivation for Protocol Reverse Engineering

uncover/understand malware communication,
validate secure design



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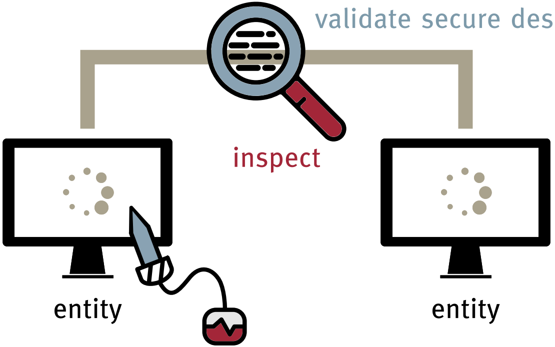

probe the implementation

Smart Fuzzing to discover vulnerabilities

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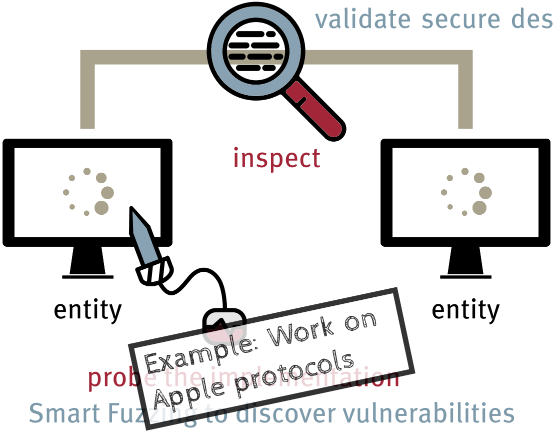

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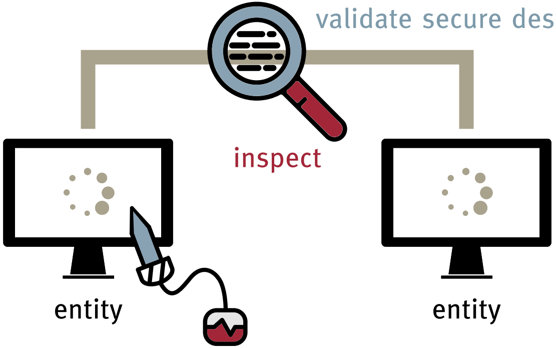

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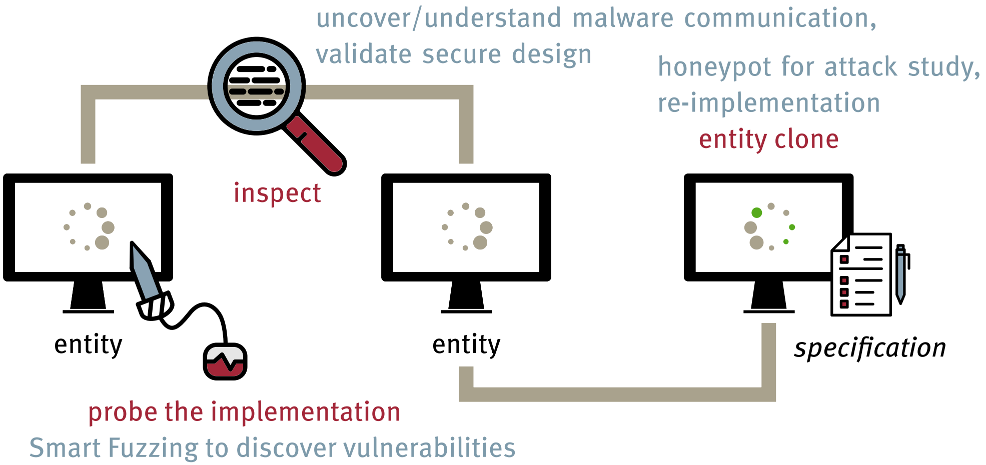

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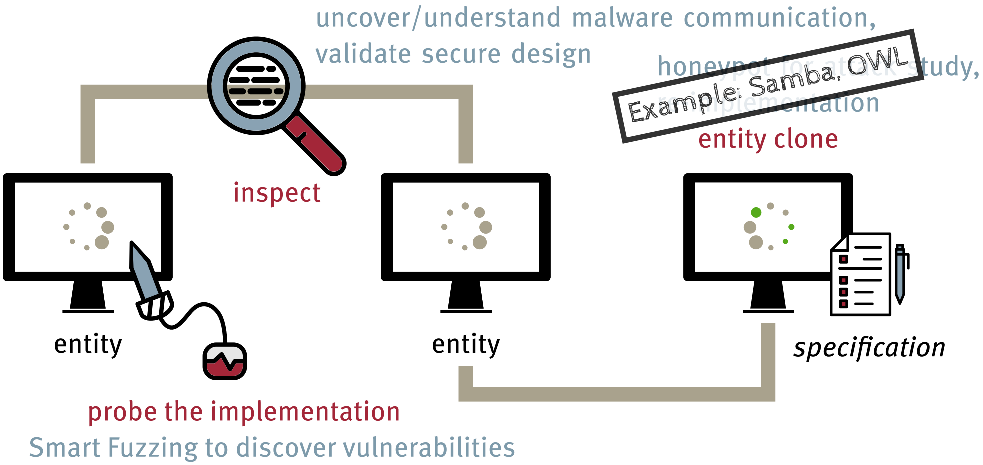

References for Use Cases

- Validating the correct and secure implementation of network services

  - Rouf, Ishtiaq, et al. „Security and Privacy Vulnerabilities of In-Car Wireless Networks: A Tire Pressure Monitoring System Case Study“. In Proceedings of the 19th USENIX Security Symposium, 323–38. USENIX Association, 2010.
  - Halperin, Daniel, et al. „Pacemakers and Implantable Cardiac Defibrillators: Software Radio Attacks and Zero-Power Defenses“. In IEEE Symposium on Security and Privacy. SP. Washington, DC, USA: IEEE, 2008.
  - Fereidooni, Hossein, et al. „Breaking Fitness Records Without Moving: Reverse Engineering and Spoofing Fitbit“. In 20th International Symposium Research in Attacks, Intrusions, and Defenses. RAID. Atlanta, GA, USA: Springer, 2017.
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  - Wen, Shameng, et al. „Protocol Vulnerability Detection Based on **Network Traffic Analysis** and Binary Reverse Engineering“. PLOS ONE 12, Nr. 10 (19. Oktober 2017).
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  - Stute, Milan, David Kreitschmann, and Matthias Hollick. „One Billion Apples’ Secret Sauce: Recipe for the Apple Wireless Direct Link Ad Hoc Protocol“. Proceedings of the 24th Annual International Conference on Mobile Computing and Networking - MobiCom ’18, 2018.
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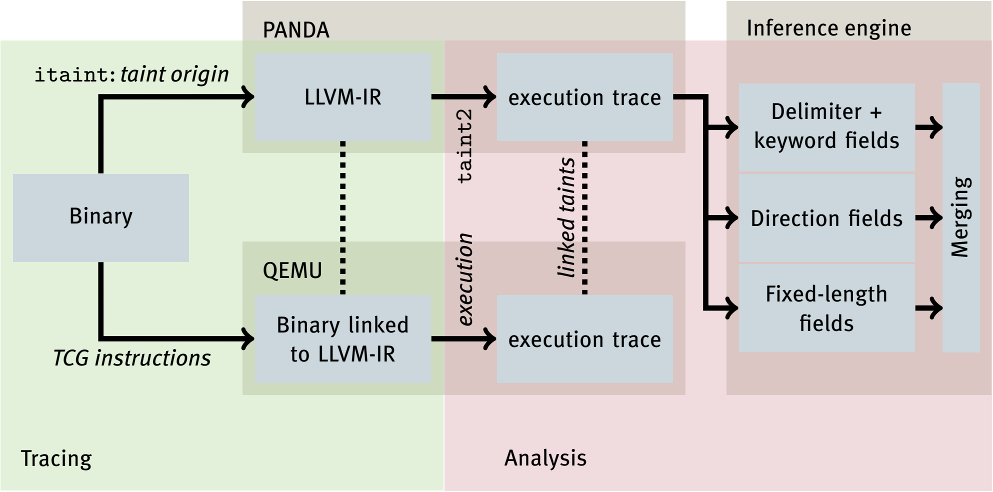
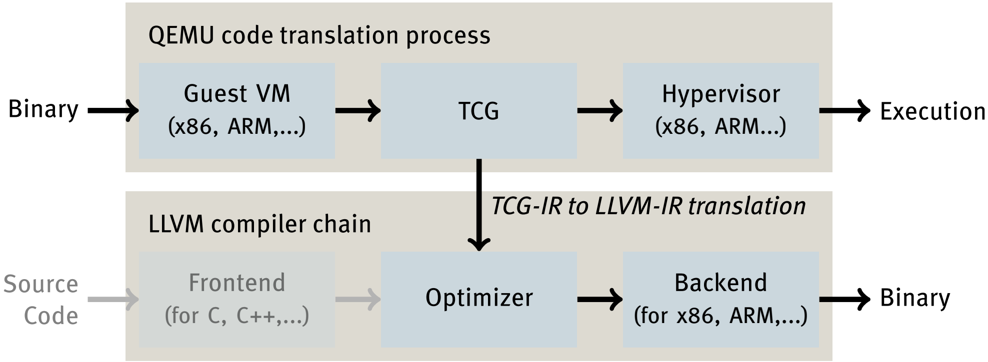
Automated Architecture-Ind. Extraction of Message Formats



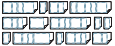
Overview of PANDA's translation process



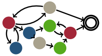
Static Traffic Analysis Process: Survey[1]

D. Message Format Inference

E. Message Type Identification

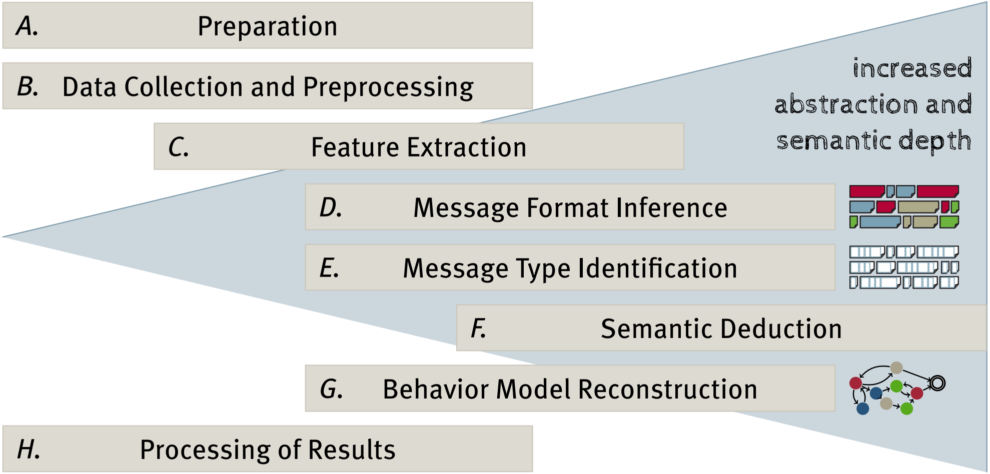


G. Behavior Model Reconstruction



[1] Stephan Kleber et al. „Survey of Protocol Reverse Engineering Algorithms: Decomposition of Tools for Static Traffic Analysis". In: *IEEE Communications Surveys and Tutorials* 21.1 (Feb. 2019). Firstquarter.

Static Traffic Analysis Process: Survey[1]



[1] Stephan Kleber et al. „Survey of Protocol Reverse Engineering Algorithms: Decomposition of Tools for Static Traffic Analysis“. In: *IEEE Communications Surveys and Tutorials* 21.1 (Feb. 2019). Firstquarter.

Static Traffic Analysis Process: Survey[1]

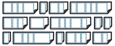
A. Preparation

B. Data Collection and Preprocessing

C. Feature Extraction

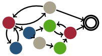
D. Message Format Inference

E. Message Type Identification



F. Semantic Deduction

G. Behavior Model Reconstruction



H. Processing of Results

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[1] Stephan Kleber et al. „Survey of Protocol Reverse Engineering Algorithms: Decomposition of Tools for Static Traffic Analysis“. In: *IEEE Communications Surveys and Tutorials* 21.1 (Feb. 2019). Firstquarter.

Static Traffic Analysis: Related Work Survey

Discoverer[1]: Message Types by Segmentation of textual message parts.

PRISMA[2]: Message Types and Behavior using Markov Models.

Netzob[3]: Message Types and Formats by aligning identical bytes in messages.

FieldHunter[4]: Identify few specific field types within messages.

Contiguous Sequential Pattern[5]: Recursive inference by frequency analysis.

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[1] Weidong Cui et al., „Discoverer: Automatic Protocol Reverse Engineering from Network Traces“, USENIX Security 2007.

[2] Tammo Krueger et al., „Learning Stateful Models for Network Honeypots“, AISec 2012.

[3] Georges Bossert et al., „Towards Automated Protocol Reverse Engineering Using Semantic Information“, CCS 2014.

[4] Ignacio Bermudez et al., „Towards Automatic Protocol Field Inference“, COMCOM 84 (2016).

[5] Y.-H. Goo et al., „Protocol Specification Extraction Based on Contiguous Sequential Pattern Algorithm“, IEEE Access, vol 7 (2019).

Static Traffic Analysis: Limitations of Related Work

- Fixed message length and similar syntaxes — Discoverer, PRISMA, FieldHunter
- Few, specific heuristics with low coverage — Discoverer, FieldHunter
- Inefficient application of sequence alignment — Netzob
- Insufficient coarse-grained similarity measures for binary data — Netzob
- Requires environment/context information like flow associations — FieldHunter

Research Questions

1. Which methods are currently used for application in PRE, and which of these are candidates to improve automation?
2. What is the generic process for STA, and which steps offer room for improved automation?
3. Which methods and algorithms are suitable for improving automation and result quality, and how must they be applied to reliably infer arbitrary communication?
4. How can the correctness of the specification inference be measured?
5. Has traffic analysis with active probing the potential to surpass STA’s correctness and to automatically discover insights not contained in the traces?

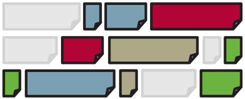
Research Questions - Sub-Questions of RQ3

3 Which methods and algorithms are suitable for improving automation and result quality, and how must they be applied to reliably infer arbitrary communication?

- 3.A How can messages be efficiently split into segments that approximate fields?
- 3.B How can segments be related to generically characterize the message contents and deduce field properties?
- 3.C How can the format and content of messages reliably and correctly be inferred, as well as, message types and field data of an arbitrary communication robustly be classified?

Preprocess

Filtering trace for messages of target protocol



Sub-sample message number:
reduce memory complexity/limit runtime

Preprocess: Input Trace Optimization

- Reduce redundancy and increase value variance
- Value Commonality Filter:
  - Determine value frequency of NEMESYS segments
  - Calculate the median of the value frequencies throughout the message
  - Select unique messages with the least medians
- Truncate message number for comparing the evaluations of multiple traces

NEMESYS: Deltas of Bit Congruence

Bit Congruence:

based on similarity measure for bit strings
by Sokal and Michener (1958)

NEMESYS: Deltas of Bit Congruence

Bit Congruence:

$$\mathrm{BC}(b, \overline{b}) = \frac{c_{\mathrm{agree}}(b, \overline{b})}{8}$$

$c_{\mathrm{agree}}(b, \overline{b})$: number of congruent bits for bytes b and $\overline{b}$

NEMESYS: Deltas of Bit Congruence

$$\Delta\mathrm{BC} = \big(\mathrm{BC}(m_k, m_{k+1}) - \mathrm{BC}(m_{k-1}, m_k)\big)_{0<k<n}$$

with

$$\mathrm{BC}(b, \overline{b}) = \frac{c_{\mathrm{agree}}(b, \overline{b})}{8}$$

m_k: Message m's byte at position k, m has length $n+1$

$c_{\mathrm{agree}}(b, \overline{b})$: number of congruent bits for bytes b and $\overline{b}$

NemeSYS: Deltas of Bit Congruence

Illustration of a message   byte values color-coded: `0x00` = black to `0xff` = white

$$\Delta \mathrm{BC} = \big(\mathrm{BC}(m_k, m_{k+1}) - \mathrm{BC}(m_{k-1}, m_k)\big)_{0<k<n}$$

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NemeSYS: Deltas of Bit Congruence

$k = 1$

Illustration of a message   byte values color-coded: 0x00 = black to 0xff = white

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$c_{\text{agree}}(b, \overline{b})$: number of congruent bits for bytes b and $\overline{b}$

NEMESYS: Deltas of Bit Congruence

$k = 3$

Illustration of a message   byte values color-coded: `0x00` = black to `0xff` = white

$$\Delta \mathrm{BC} = \left(\mathrm{BC}(m_k, m_{k+1}) - \mathrm{BC}(m_{k-1}, m_k)\right)_{0<k<n}$$

with

$$\mathrm{BC}(b, \overline{b}) = \frac{c_{\text{agree}}(b, \overline{b})}{8}$$

m_k: Message m's byte at position k, m has length $n+1$

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NEMESYS: Deltas of Bit Congruence

Illustration of a message byte values color-coded: 0x00 = black to 0xff = white

$$\Delta \mathrm{BC} = \left(\mathrm{BC}(m_k, m_{k+1}) - \mathrm{BC}(m_{k-1}, m_k)\right)_{0<k<n}$$

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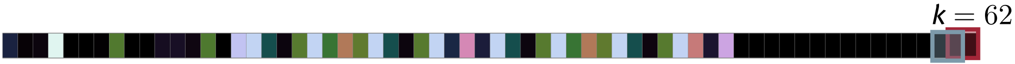
NEMESYS: Deltas of Bit Congruence



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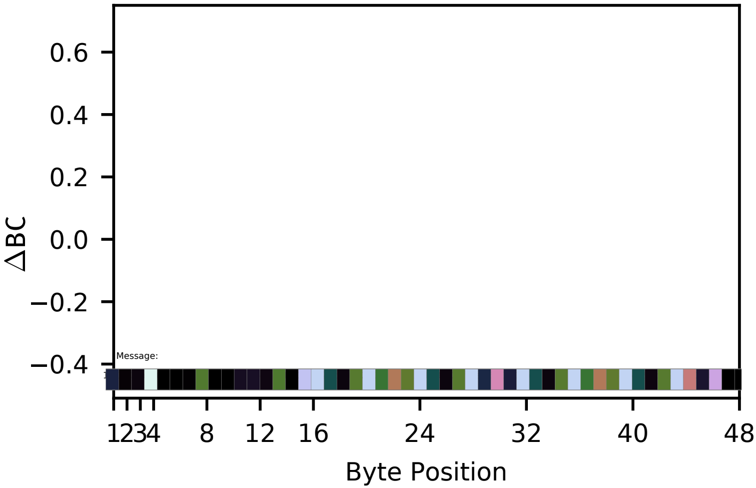
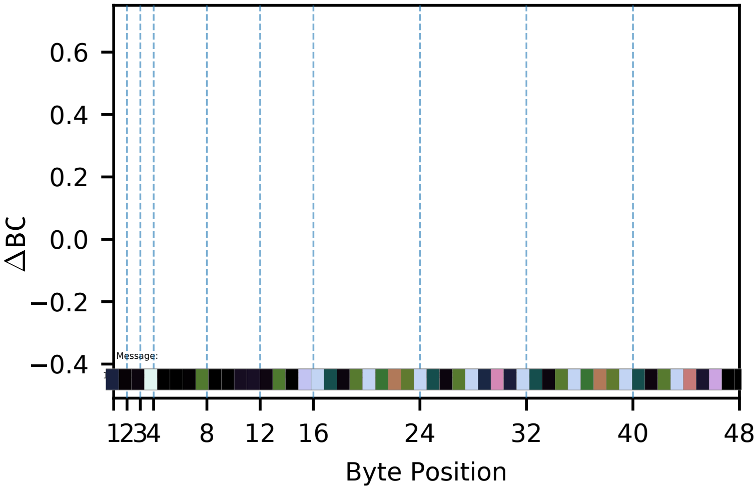
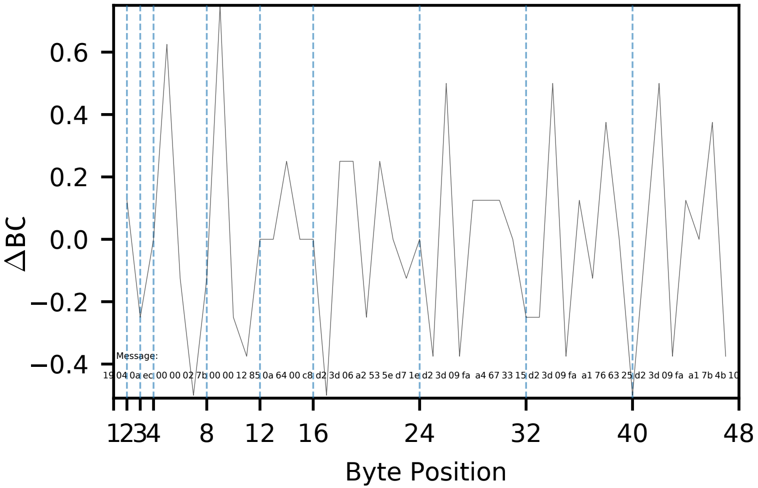
NEMESYS: Value Pattern Example NTP



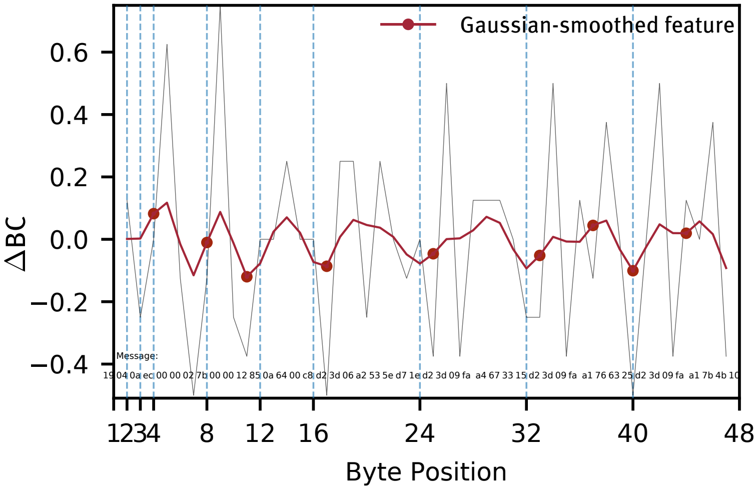
NEMESYS: Value Pattern Example NTP



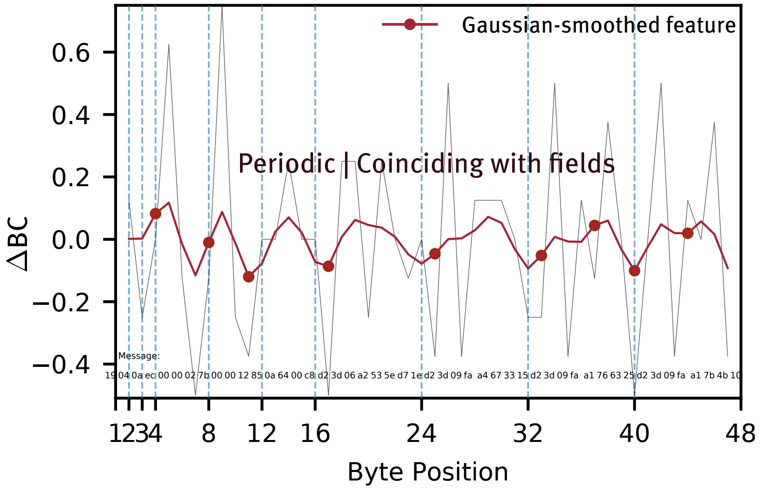
NEMESYS: Value Pattern Example NTP



NEMESYS: Value Pattern Example NTP



NEMESYS: Value Pattern Example NTP



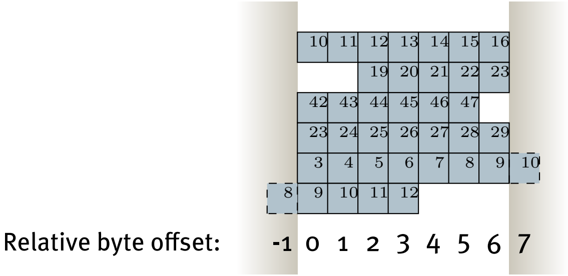
NemeSYS: Heuristic Position of Field Boundaries

Feature $\triangle$BC:
distinctive distribution for binary numbers:

- At field transition: low $\triangle$BC
- Towards field end: high $\triangle$BC
- Gaussian filter $g_\sigma(\cdot)$ to reduce noise

Inflection points of rising edges of $g_\sigma(\triangle\mathrm{BC})$

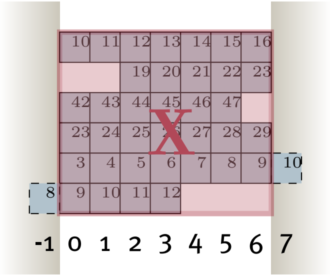
Overlaying Segment Vectors



- Superimpose segments at most useful offsets: meaningfully comparable
- Quantified by Canberra dissimilarity: *Kleber et al., INFOCOM 2020*
  extension of Canberra distance to vectors of differing dimensions
- Relative byte offsets of all segments at lowest dissimilarity

Overlaying Segment Vectors

Relative byte offset:



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  extension of Canberra distance to vectors of differing dimensions
- Relative byte offsets of all segments at lowest dissimilarity

Covariance

Byte values of similar segments:

	Relative byte offset 0	1	2	3	4
Segment 1	00	08	50	00	02
Segment 2	01	08	90	00	04
Segment 3	01	08	90	00	07
Segment 4	01	08	b0	00	02
Segment 5	02	90	40	01	02
Segment 6	02	90	40	01	02
Segment 7	01	08	80	00	04
Segment 8	01	08	80	00	04

Covariance

Byte values of similar segments:

$$\mathbf{X} = \begin{pmatrix} 00 & 08 & 50 & 00 & 02 \\ 01 & 08 & 90 & 00 & 04 \\ 01 & 08 & 90 & 00 & 07 \\ 01 & 08 & \text{b0} & 00 & 02 \\ 02 & 90 & 40 & 01 & 02 \\ 02 & 90 & 40 & 01 & 02 \\ 01 & 08 & 80 & 00 & 04 \\ 01 & 08 & 80 & 00 & 04 \end{pmatrix}$$

Covariance

Byte values of similar segments:

$$\mathbf{C} = \begin{pmatrix} 0.41 & 34 & -9.71 & 0.25 & -0.19 \\ 34 & 3963 & -2020 & 29.14 & -53.42 \\ -9.71 & -2020 & 1737 & -14.85 & 34.85 \\ 0.25 & 29.14 & -14.85 & 0.21 & -0.39 \\ -0.19 & -53.42 & 34.85 & -0.39 & 3.12 \end{pmatrix}$$

$$\mathbf{X} = \begin{pmatrix} \texttt{00} & \texttt{08} & \texttt{50} & \texttt{00} & \texttt{02} \\ \texttt{01} & \texttt{08} & \texttt{90} & \texttt{00} & \texttt{04} \\ \texttt{01} & \texttt{08} & \texttt{90} & \texttt{00} & \texttt{07} \\ \texttt{01} & \texttt{08} & \texttt{b0} & \texttt{00} & \texttt{02} \\ \texttt{02} & \texttt{90} & \texttt{40} & \texttt{01} & \texttt{02} \\ \texttt{02} & \texttt{90} & \texttt{40} & \texttt{01} & \texttt{02} \\ \texttt{01} & \texttt{08} & \texttt{80} & \texttt{00} & \texttt{04} \\ \texttt{01} & \texttt{08} & \texttt{80} & \texttt{00} & \texttt{04} \end{pmatrix}$$

Covariance

Byte values of similar segments:

$$\mathbf{X} = \begin{pmatrix} \texttt{00} & \texttt{08} & \texttt{50} & \texttt{00} & \texttt{02} \\ \texttt{01} & \texttt{08} & \texttt{90} & \texttt{00} & \texttt{04} \\ \texttt{01} & \texttt{08} & \texttt{90} & \texttt{00} & \texttt{07} \\ \texttt{01} & \texttt{08} & \texttt{b0} & \texttt{00} & \texttt{02} \\ \texttt{02} & \texttt{90} & \texttt{40} & \texttt{01} & \texttt{02} \\ \texttt{02} & \texttt{90} & \texttt{40} & \texttt{01} & \texttt{02} \\ \texttt{01} & \texttt{08} & \texttt{80} & \texttt{00} & \texttt{04} \\ \texttt{01} & \texttt{08} & \texttt{80} & \texttt{00} & \texttt{04} \end{pmatrix}$$

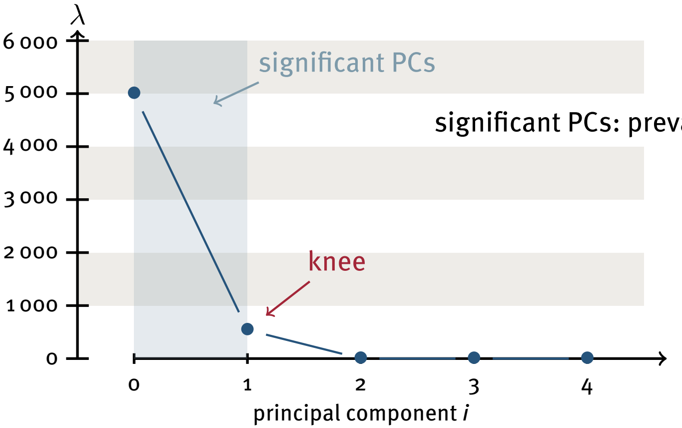
$$\mathbf{C} = \begin{pmatrix} 0.41 & 34 & -9.71 & 0.25 & -0.19 \\ 34 & 3963 & -2020 & 29.14 & -53.42 \\ -9.71 & -2020 & 1737 & -14.85 & 34.85 \\ 0.25 & 29.14 & -14.85 & 0.21 & -0.39 \\ -0.19 & -53.42 & 34.85 & -0.39 & 3.12 \end{pmatrix}$$

$\mathbf{C}$'s eigenvalues λ: scores, factors

$$\begin{aligned} \lambda_0 &= 5158 \\ \lambda_1 &= 543 \\ \lambda_2 &= 2.3 \\ \lambda_3 &= 0.023 \\ \lambda_4 &= -4.5 \cdot 10^{-16} \end{aligned}$$

Determining Significant Variance

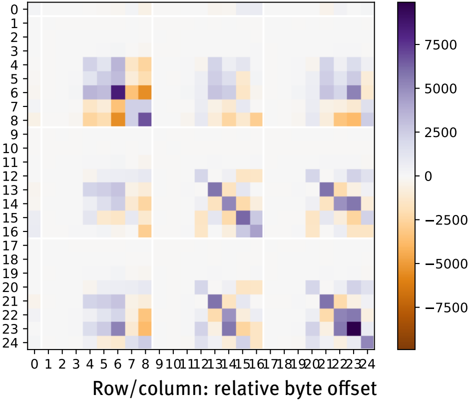
Scree graph of principal components (PCs) sorted by their scores λ_i



significant PCs: prevalent variance in data

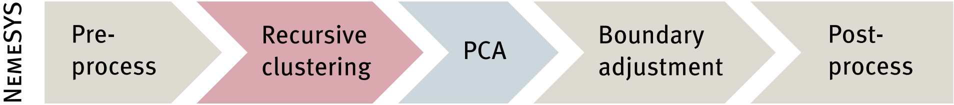
Covariance Matrix for Principal Component Analysis

Covariance matrix $\mathbf{C}$ as heat map



PCA: strengths of linearly dependent variance at all byte offsets in a set

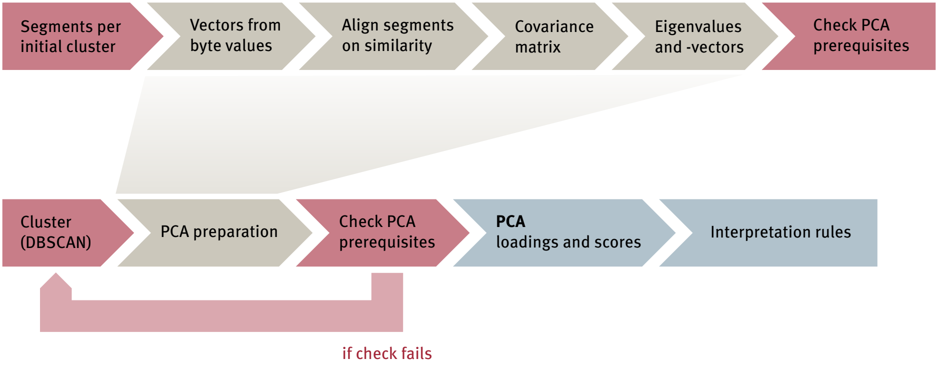
Refinement of NEMESYS: Byte-wise Segment Variance Analysis



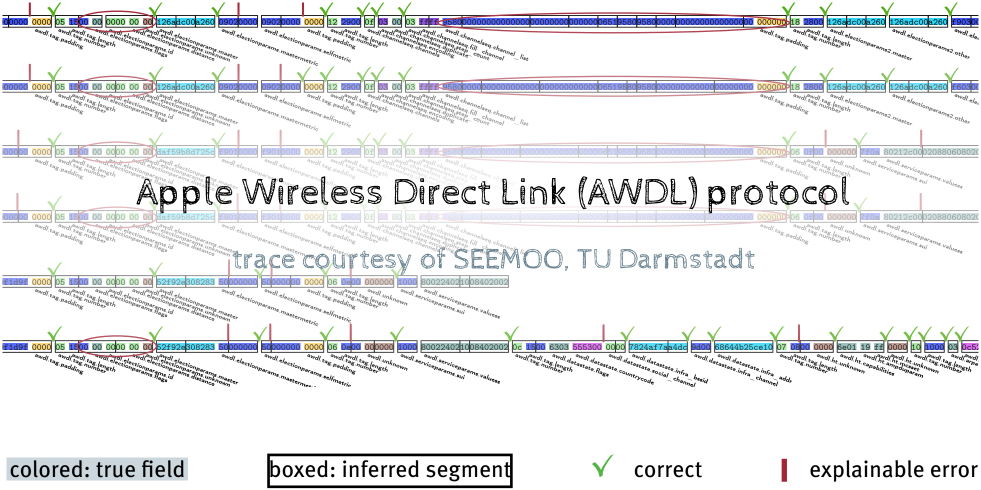
Recursive clustering:

- Ensures application of PCA to a set of related segments

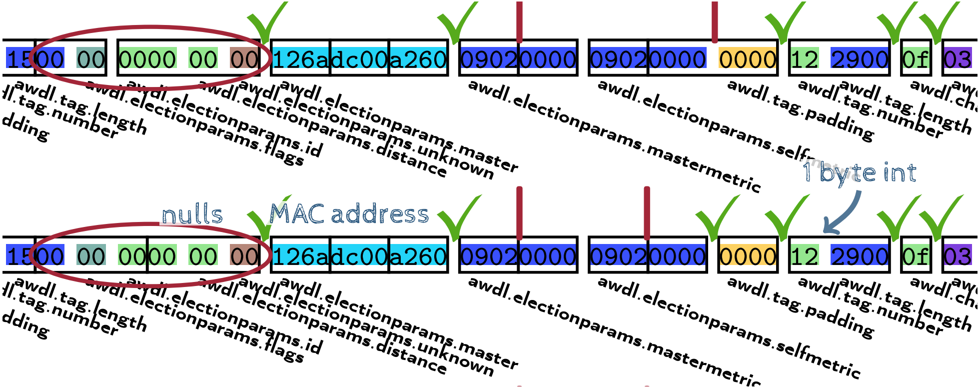
Recursive Clustering



True Fields and NEMESYS-Inferred Segments Interleaved



True Fields and NEMESYS-Inferred Segments Interleaved



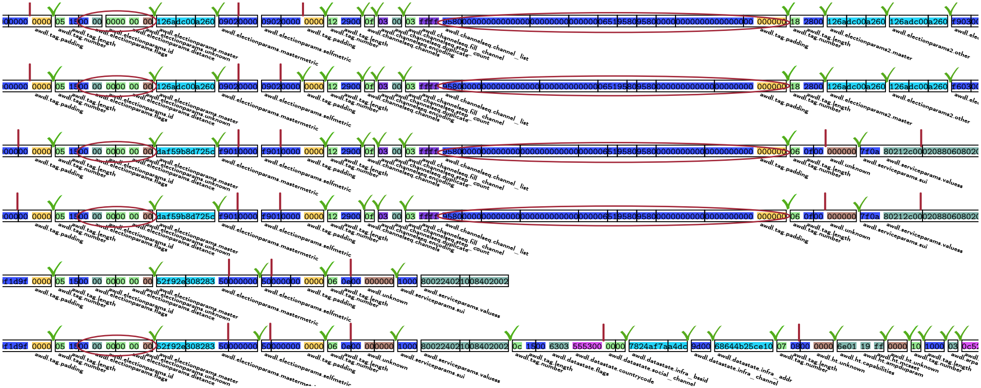
colored: true field

boxed: inferred segment

✓ correct

| explainable error

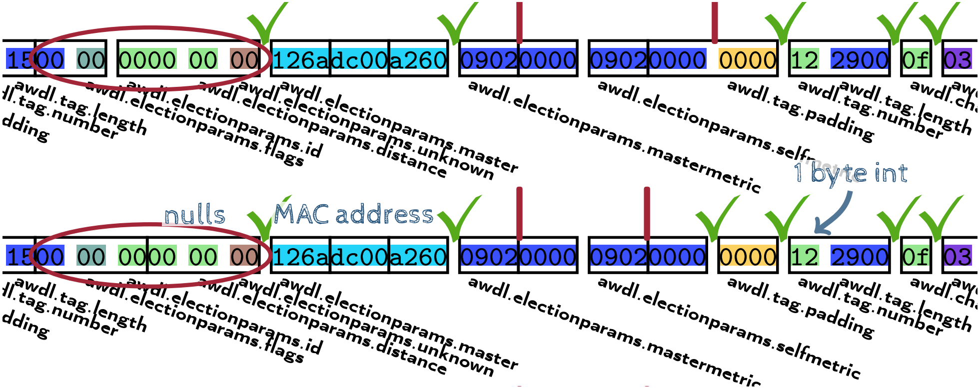
AWDL: Interleave True Fields and Inferred Segments



✓ correct

| explicable error

AWDL: Interleave True Fields and Inferred Segments



✓ correct

| explicable error

AWDL: Interleave True Fields and Inferred Segments

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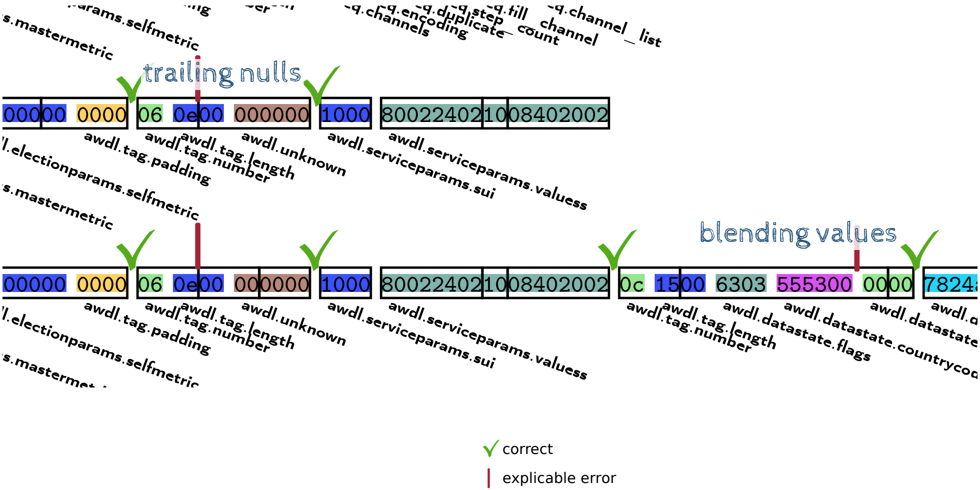
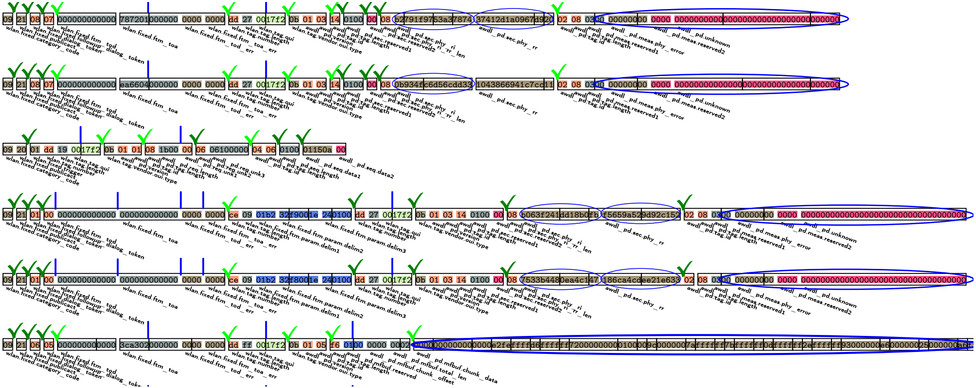


AU-WiFi: Interleave True Fields and Inferred Segments



✓ larger structures correct ✓ small structures correct

| difficult/impossible to know otherwise

AU-WiFi: Interleave True Fields and Inferred Segments

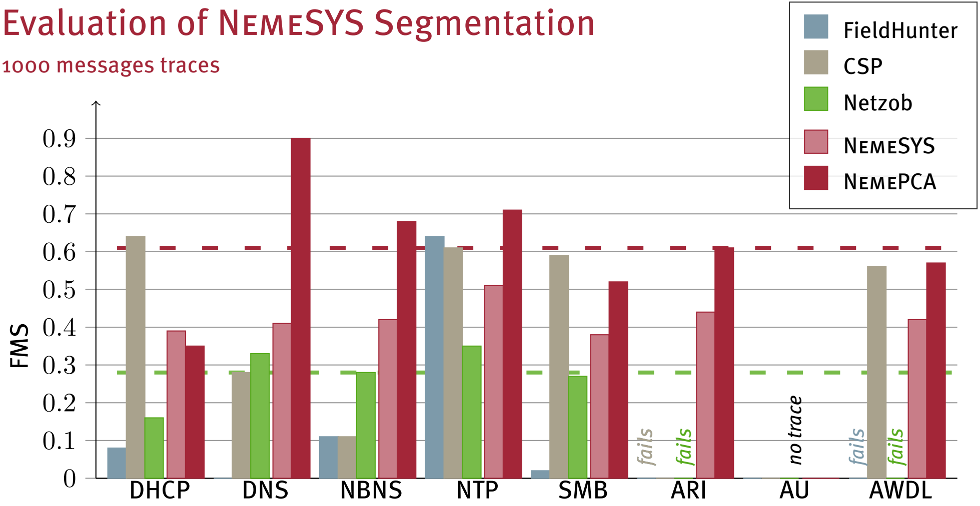
larger structures correct

small structures correct

| difficult/impossible to know otherwise

Evaluation of NEMESYS Segmentation

1000 messages traces



Minimum Canberra Distance d_β vs. Canberra Dissimilarity d_m

$\mathbf{t}$	0208	0008	0208	5706906e
$\mathbf{t}_{[o,\lvert s \rvert]}$	0208	00	08	5706
$\mathbf{s}$	0008	00	07	2700
d_β	0.5	0.000	0.067	0.690

Minimum Canberra Distance d_β vs. Canberra Dissimilarity d_m

$\mathbf{t}$	0208	0008	0208	5706906e
$\mathbf{t}_{[o,\lvert s \rvert]}$	0208	00	08	5706
$\mathbf{s}$	0008	00	07	2700
d_β	0.5	0.000	0.067	0.690
d_m	0.5	0.460	0.496	0.814

Previous Approaches for Comparing Binary Protocol Messages

…	Field 02	Field 03	Field 04	Field 05	Field 06	Field 07	Field 08	Field 09	Field 10	…
	0000000a	0000	80	00	00	00	0000	c0a801	65	
	4f214e45	0000	80	00	00	00	0000	c0a801	66	
	8940fa36	0000	80	00	00	00	0000	c0a801	67	
	a55cb819	0000		00		00	c0a80166	c0a801	66	
	0a4da00f	0000		00		00	c0a80169	c0a801	69	
	8940fa36	0000		00		00		c0a801	6700000000	

- Align on **values** in messages (Netzob, Discoverer)
- Search for tokens to correlate message **values** (PRISMA)

Unsupervised Clustering Algorithm Criteria

1. **Number** of message types/clusters is unknown
2. Stable **auto-**configuration: no **parameter**/threshold to specify by the analyst
3. Performance **efficient** enough to deal with large traces

	1	2	3
Hierarchical Agglomerative, Affinity Propagation		⊖	⊖
Spectral	⊖	⊖	
Single Linkage, Support Vector Machine (SVM)		⊖	
k-means, Partitioning around Medoid (PAM)	⊖		
Density-Based Spatial Clustering of Applications with Noise (DBSCAN)		○	
Hierarchical DBSCAN (HDBSCAN), OPTICS		⊖	

Message Type Discriminators

Cluster refinement by discriminator fields:

- Split underspecific clusters
- Merge overspecific clusters

Examples

AWDL:

MIF and PSF + `awdl.datastate.extflags`

AU-WiFi:

series of `awdl_pd.tag.id` (values: `0x01` to `0x05`) and
`wlan.fixed.ftm.param.status_indication` (values: `0x0`, `0x1`)
which is subfield of `wlan.fixed.ftm.param.delim1`

Introducing Topology Plots[1]

Goal Visualize distances of the clustered segments

Problem Mixed dimensionality (> 3) of feature vectors,
only pairwise pseudo-distances in dissimilarity matrix

[1] Stephan Kleber and Frank Kargl. „Poster: Network Message Field Type Recognition“. In: *Proceedings of the 26th Conference on Computer and Communications Security*. CCS. 2019.

Introducing Topology Plots[1]

Goal Visualize distances of the clustered segments

Problem Mixed dimensionality (> 3) of feature vectors,
only pairwise pseudo-distances in dissimilarity matrix

Multidimensional scaling (MDS)

Place segments as points in an n-dimensional space
according to their relative distances.

Here: $n = 2$ to plot a diagram („Topology of Distances“)

---

[1] Stephan Kleber and Frank Kargl. „Poster: Network Message Field Type Recognition“. In: *Proceedings of the 26th Conference on Computer and Communications Security*. CCS. 2019.

Introducing Topology Plots[1]

no coherent feature vector space

no message coordinates for plot

pairwise dissimilarities ≈ relative distances

absolute positions meaningless

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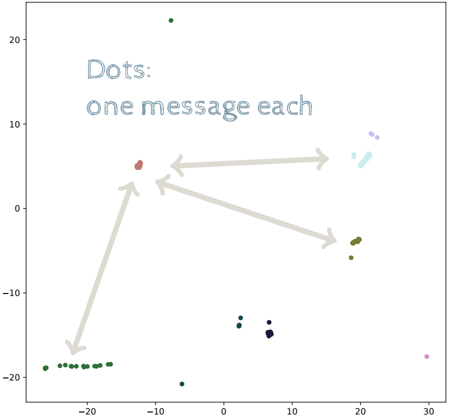
Introducing Topology Plots[1]



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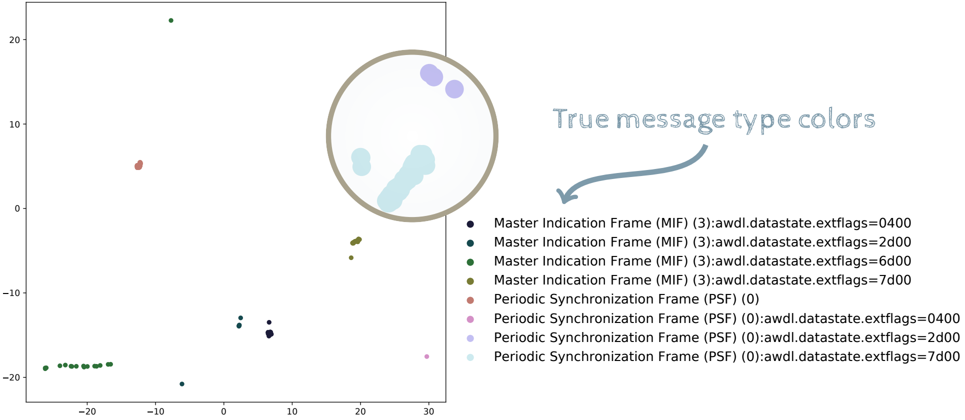

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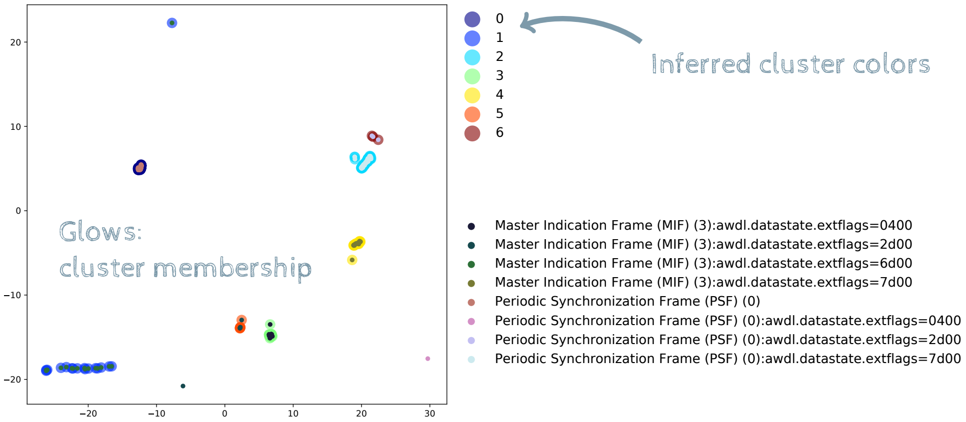

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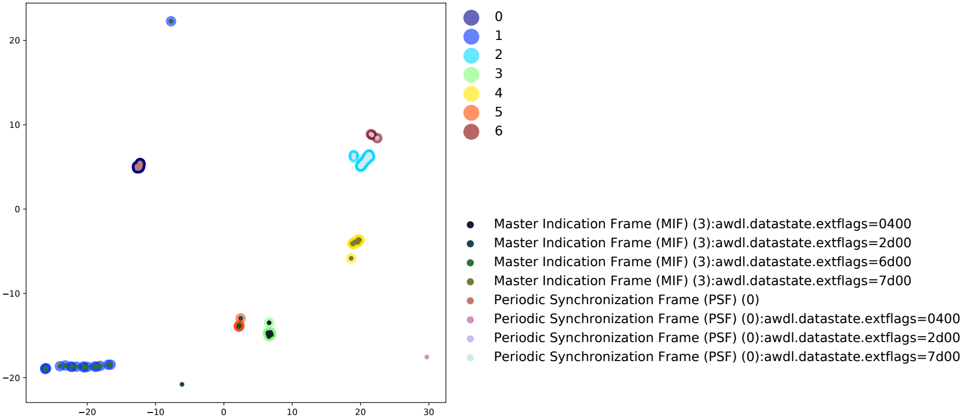
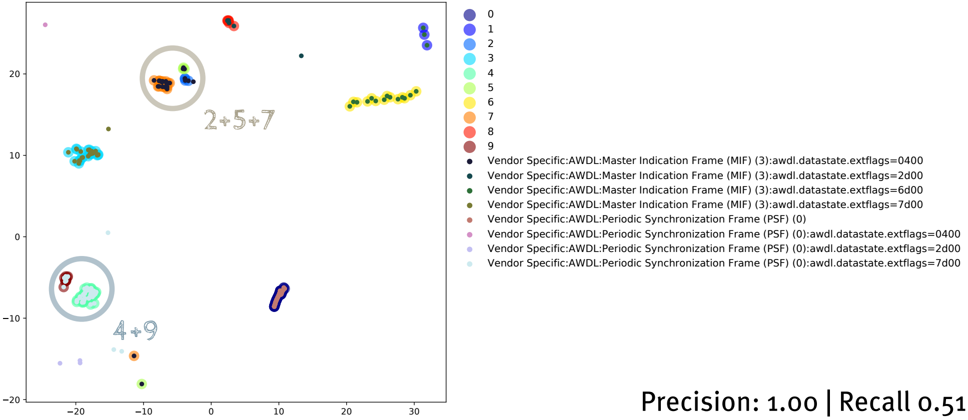
AWDL: Topology Plot of Messages using Groundtruth from Wireshark

Apple Wireless Direct Link protocol



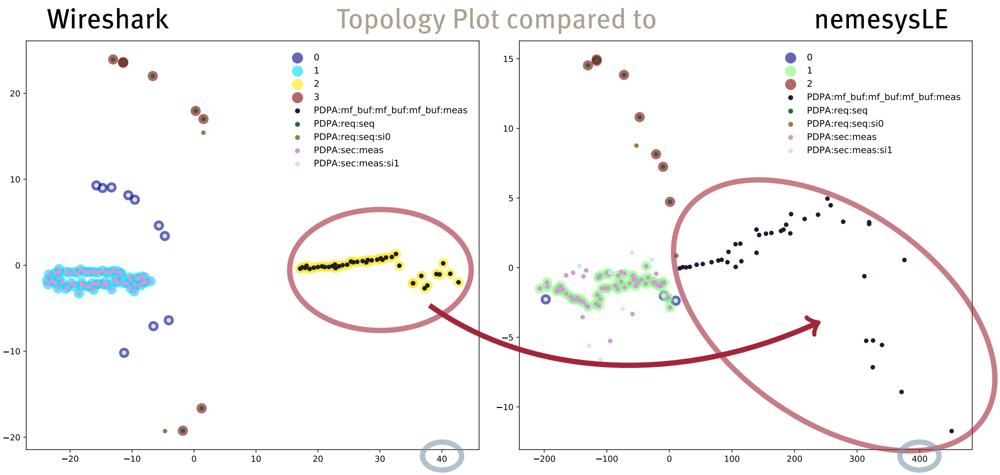
AWDL: Topology Plot of Messages using Segmenter NEMESYS

Apple Wireless Direct Link protocol

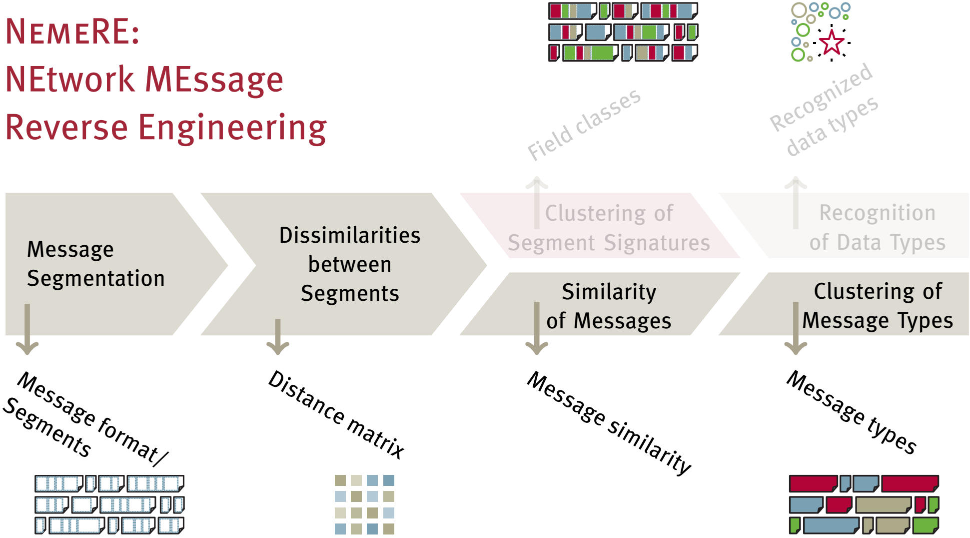


Precision: 1.00 | Recall 0.51

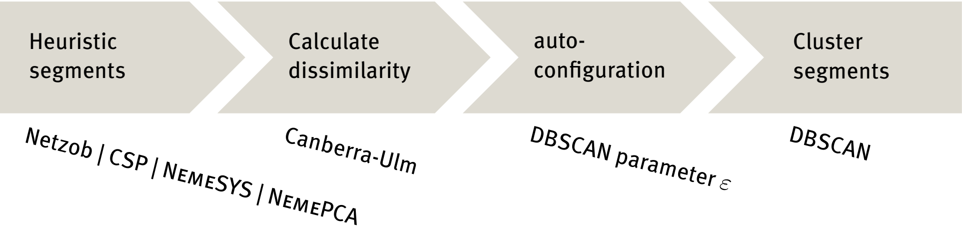
AU-WiFi: NEMETYL- Segmenter: NEMESYS



NemeRE:
NEtwork MEssage
Reverse Engineering



Field Type Classification[1,2]

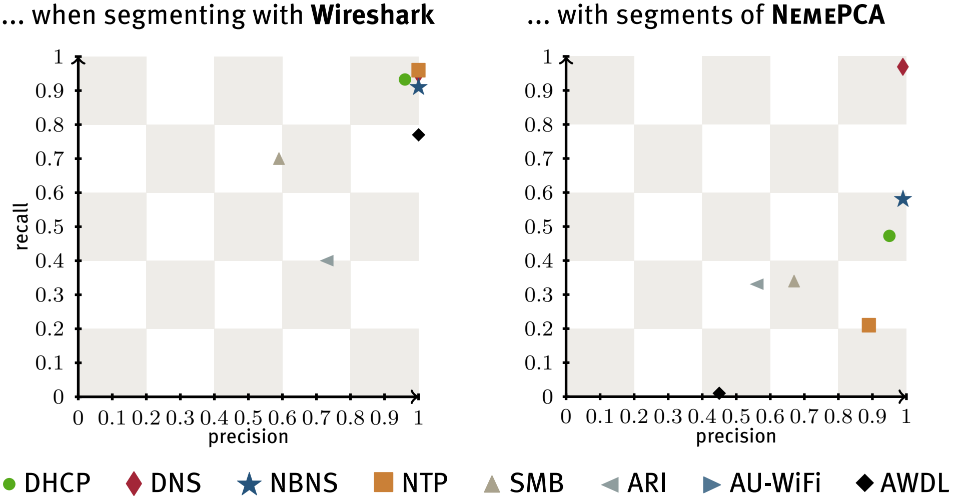


Ground truth: Field data type (e. g., int, timestamp, address) from Wireshark

[1] Stephan Kleber and Frank Kargl. „Poster: Network Message Field Type Recognition“. In: *Proceedings of the 26th Conference on Computer and Communications Security*. CCS. 2019.

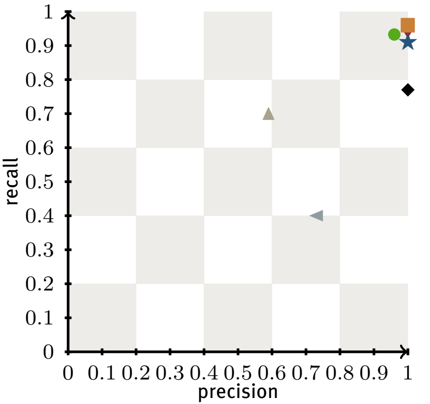
[2] Stephan Kleber et al. „Network Message Field Type Classification and Recognition for Unknown Binary Protocols“. In: *Proceedings of the DSN Workshop on Data-Centric Dependability and Security*. DCDS. IEEE/IFIP, 2022.

Field Type Classification - Clustering Results...

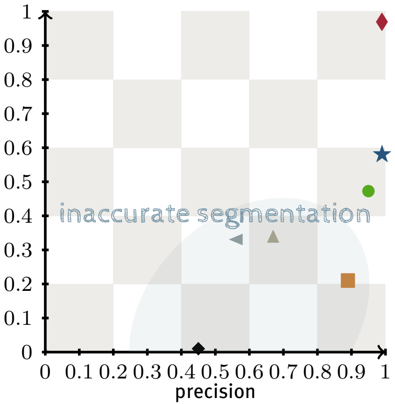


Field Type Classification - Clustering Results...

... when segmenting with **Wireshark**



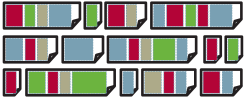
... with segments of **NemePCA**



● DHCP ♦ DNS ★ NBNS ■ NTP ▲ SMB ◀ ARI ▶ AU-WiFi ◆ AWDL

Result of Field Type Classification

Clusters of Segments resembling Field Data Types



NemeFTR: NEtwork MEssage Field Type Classification

(poster at CCS2019[1]; paper at DCDS2022[2])

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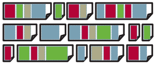
NEMERE:
NEtwork MEssage Reverse Engineering

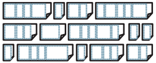


Field classes

Recognized data types

Message Segmentation → Dissimilarities between Segments → Similarity of Messages / Clustering of Segment Signatures → Clustering of Message Types / Recognition of Data Types

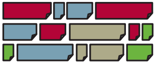
Message format/ Segments



Distance matrix

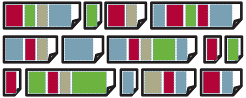
Message similarity

Message types



Result of Field Type Recognition

Recognition of Learned Data Types



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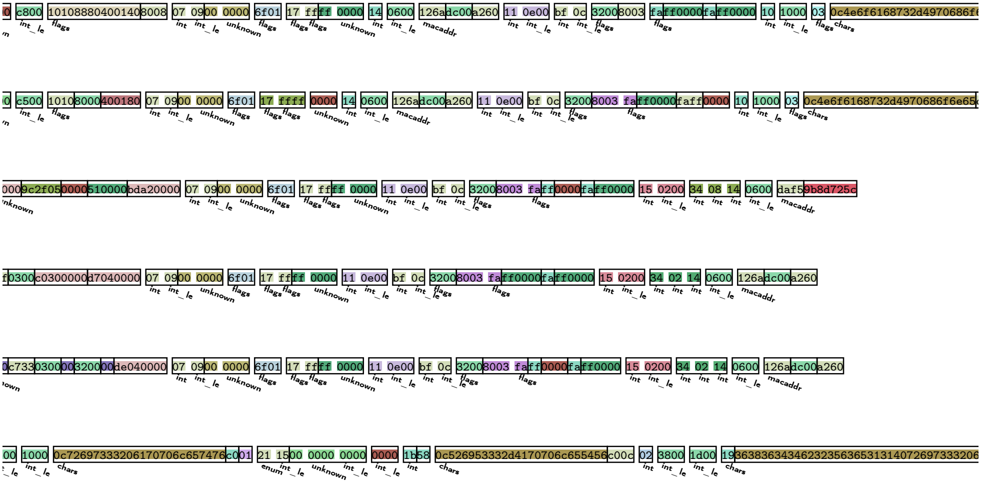
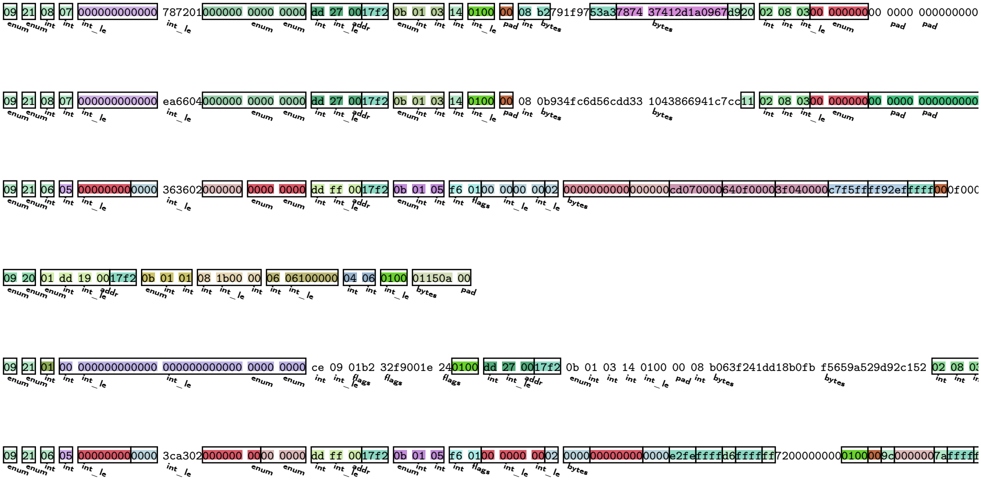
AWDL: Clustered Data Types Marked in Messages

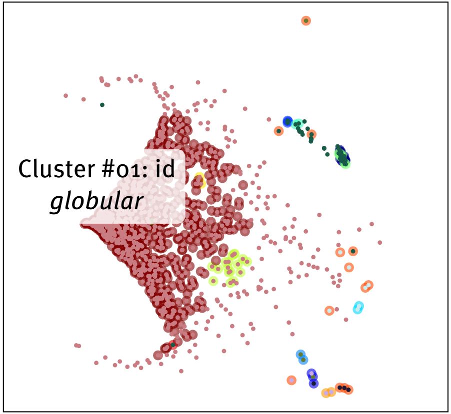


AU-WiFi: Clustered Data Types Marked in Messages



Field Type Classification - Groundtruth: Wireshark

DNS



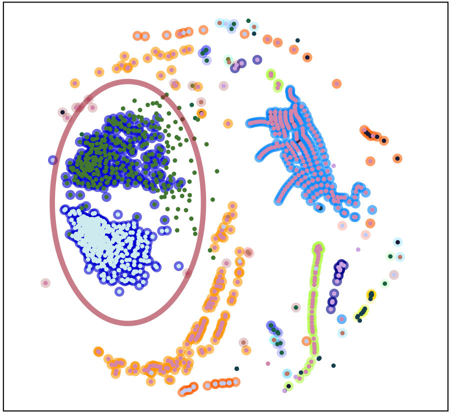
DNS

true data types

- chars
- flags
- id
- int
- ipv4

Field Type Classification - Groundtruth: Wireshark

SMB



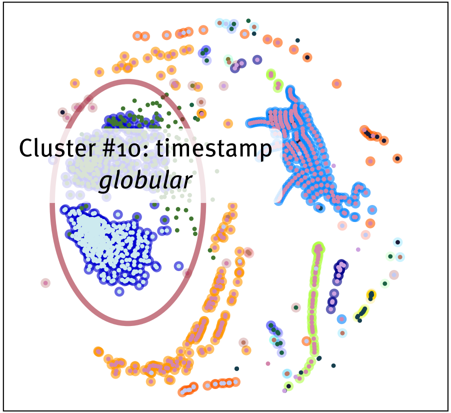
SMB

true data types

- bytes
- chars
- crypto
- enum
- flags
- id
- int
- int-le
- timestamp

Field Type Classification - Groundtruth: Wireshark

SMB



SMB

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Field Type Classification - Groundtruth: Wireshark

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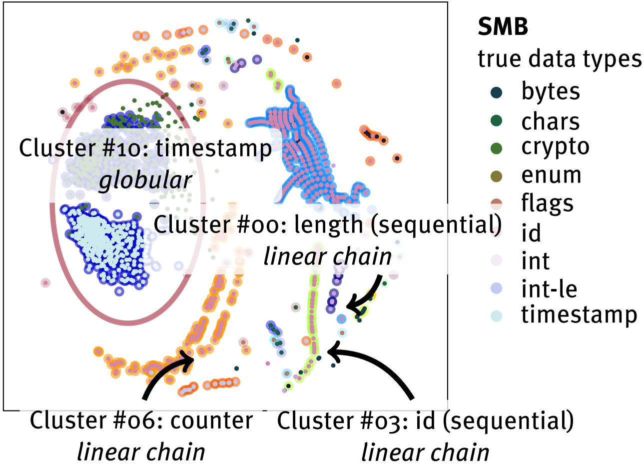

Field Type Classification - Groundtruth: Wireshark

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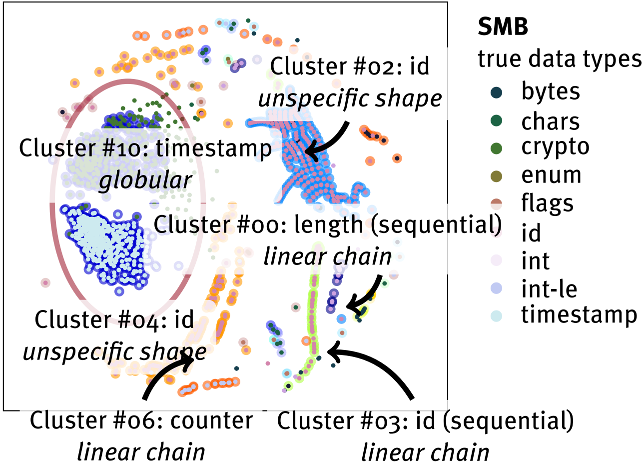
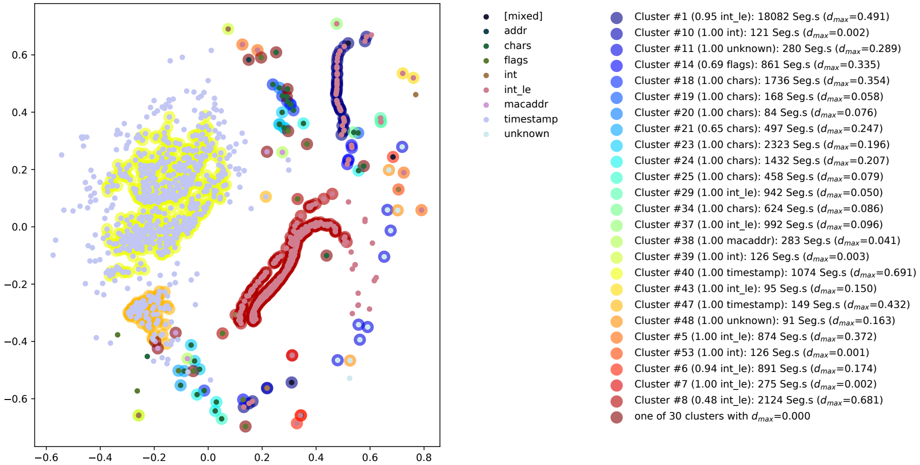


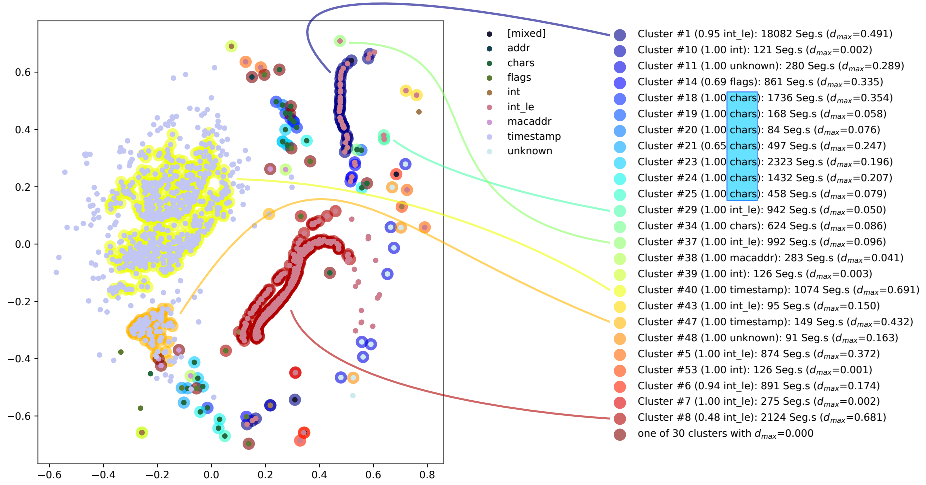
Field Type Classification - Groundtruth: Wireshark

Apple Wireless Direct Link protocol

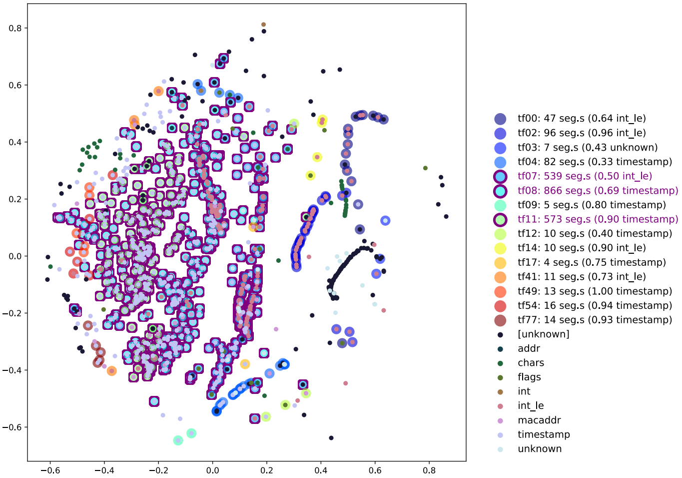


Field Type Classification - Groundtruth: Wireshark

Apple Wireless Direct Link protocol



NEMEFTR with NEMESYS Segments

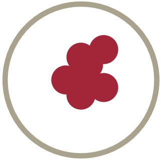


Data-Type-Specific Patterns

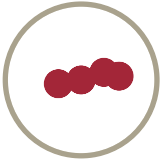
Signatures of Variance: Characteristic feature patterns for data types

- int (BE/LE) — 00 00 15 7b — variance increases towards most significant byte
- chars — 69 44 53 00 — typical ASCII value domain, null-terminated
- id/flags — frequent distinct values
- enumerations

- timestamps

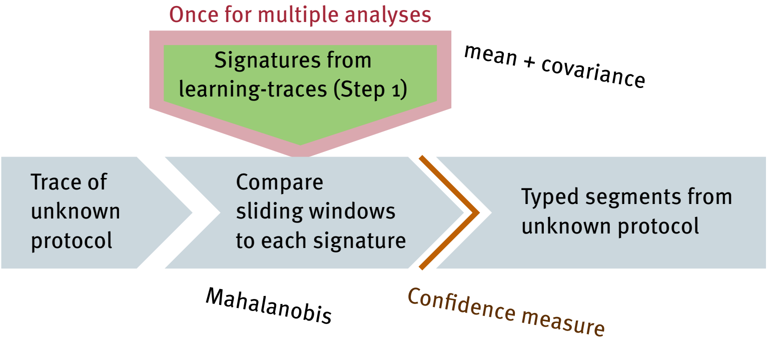


- addresses



Field Type Recognition Process[1]

- Recognize specific field data types in unseen traces
- Learned from field patterns of a mix of sample protocols



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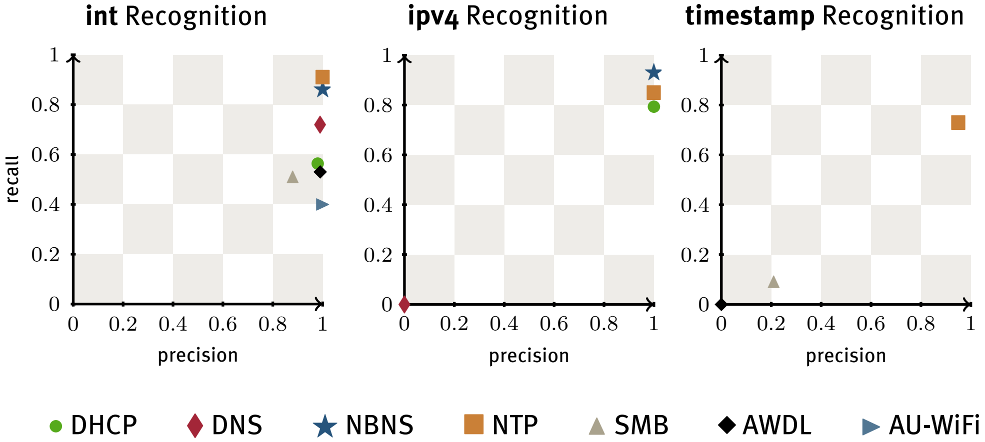
Field Type Recognition Quality



Byproducts

- Preprocessing for STA: Diversification by value commonality filter and discrimination of textual from binary protocols and parts of mixed protocols
- Data representation in support of PRE
- Character string detection heuristic supporting Unicode
- Enhanced PCAP importer
- JSON parser for tshark dissectors
- Scapy, Wireshark, and Sulley exporters for message formats
- tikz visualization of message formats

- Dynamic Binary Analysis by Automated Architecture-Independent Extraction of Message Formats

Limitations

- Encryption, compression, and obfuscation
- Gracefully deals with embedded text parts, but does not analyze
- Encoding and language (non-western) may prevent text detection
- Heuristic method limits optimum
- Mostly empirical determination of parameters. Robustness thoroughly tested but not provably optimal
- Misinterpretation of structurally similar message and field types
- Memory requirement for dissimilarity matrix
- STA depends on trace contents: Limited by missing and implicit information
- Typically only positive samples observed
- Human involvement for interpretation (message types and data)

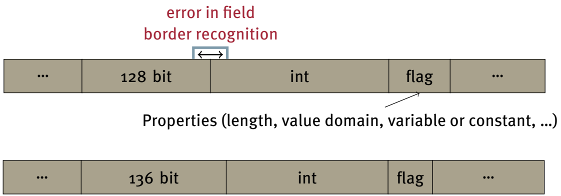
Future Work

- Filter traces for increased variance while retaining valid chronologically sorted message sequences
- Optimizations for NEMESYS: Alternative features like Value Delta, Slit Pivot Bit Congruence
- Performance optimizations: reduce memory consumption of dissimilarity measure
- More sophisticated rule sets for deducing boundaries from relations between principal components
- Alternatives to sequence alignment, e.g., LDA, LSTM
- More fine-grained, robust, and diverse recognition rules for data types
- Supervised learning of cluster properties for unattended recognition by a machine-learning model
- User studies with visual message inspection

Detailed List of Contributions

1. Static Traffic Analysis process model
2. Decomposition of Static Traffic Analysis tools
3. Traffic trace input optimization
4. Clustering topology plots
5. Efficient segmentation: Delta of bit congruence and NEMESYS
6. Canberra-Ulm dissimilarity for comparing sequential binary data
7. Kneedle auto-configuration for DBSCAN
8. Custom auto-configuration for DBSCAN
9. Segmentation refinement by NEMEPCA
10. Message type identification by NEMETYL
11. Field data type clustering
12. Field data type recognition
13. Format Match Score evaluation measure
14. Dynamic Traffic Analysis by PREPROBE

Format Metrics



Quantify Format Inference Quality

Validate format inference method:

Measure correctness by benchmarking with a known protocol

Format Match Score

$$\mathrm{FMS} = \underbrace{\exp\left(-\left(\frac{|R| - |I|}{|R|}\right)^2\right)}_{\text{Specificity penalty}} \cdot \underbrace{\frac{1}{|R|}\sum_{r \in R} \exp\left(-\left(\frac{\delta_r}{\gamma}\right)^2\right)}_{\text{Match gain}}$$

Format Match Score

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Quality aspects:

$|R|$ Number of real field boundaries

$|I|$ Number of inferred field boundaries

Format Match Score

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Quality aspects:

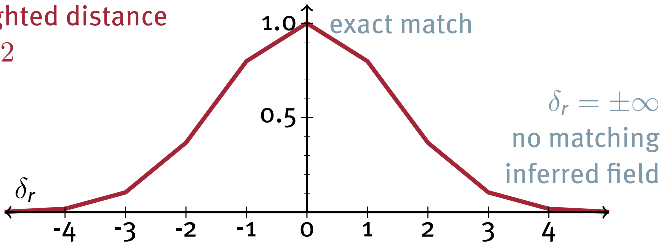
- $|R|$ Number of real field boundaries
- $|I|$ Number of inferred field boundaries
- δ_r Distance of real boundary r from next inferred one
- γ Required accuracy

Format Match Score

$$\mathrm{FMS} = \underbrace{\exp\left(-\left(\frac{|R|-|I|}{|R|}\right)^2\right)}_{\text{Specificity penalty}} \cdot \underbrace{\frac{1}{|R|}\sum_{r\in R}\exp\left(-\left(\frac{\delta_r}{\gamma}\right)^2\right)}_{\text{Match gain}}$$

Weighted distance

$\gamma = 2$



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Quantify format correctness

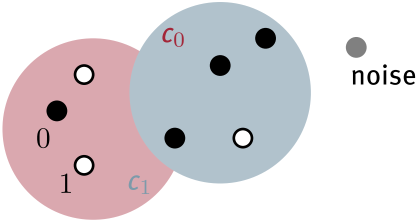
Combinatorial Cluster Quality Measure

Test runs with **known** protocols: Compare to **ground truth**

true message types

message classification

	l	$\bar{l}$
c_l	TP	FP
$c_{\bar{l}}$	FN	TN



$$P = \frac{\text{TP}}{\text{TP} + \text{FP}} \quad \text{and} \quad R = \frac{\text{TP}}{\text{TP} + \text{FN}}$$

Combinatorial Cluster Quality Measure

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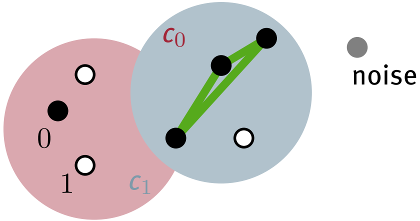

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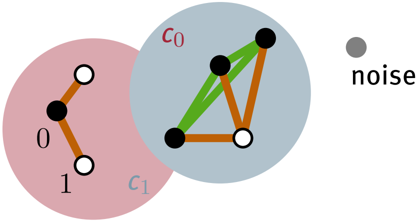

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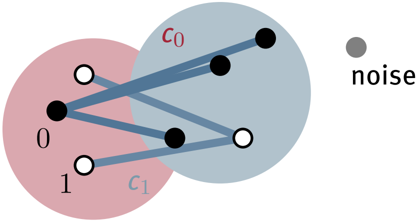
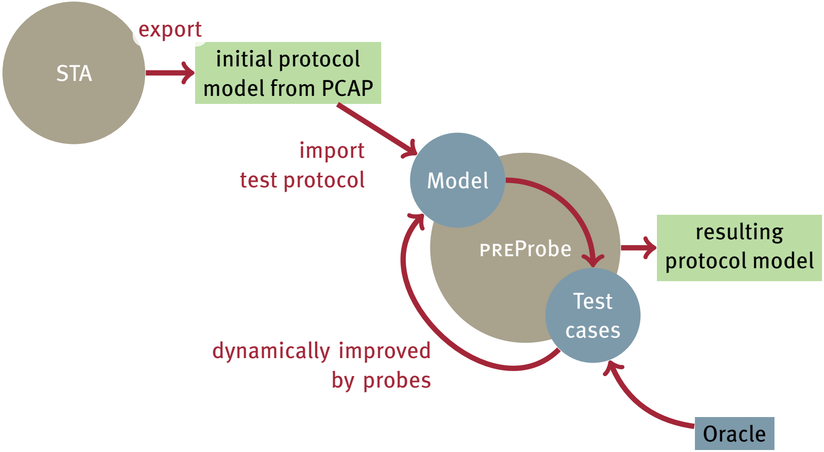


$$P = \frac{\text{TP}}{\text{TP} + \text{FP}} \quad \text{and} \quad R = \frac{\text{TP}}{\text{TP} + \text{FN}}$$

Dynamic Traffic Analysis



Dynamic Traffic Analysis: PREPROBE