UNITED STATES PATENT AND TRADEMARK OFFICE

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BEFORE THE PATENT TRIAL AND APPEAL BOARD

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CROWDSTRIKE, INC.
Petitioner

v.

WEBROOT INC.
Patent Owner

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Case No. IPR2023-01053
Patent No. 11,409,869

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DECLARATION OF JUNE ANN MUNFORD

1. My name is June Ann Munford. I am over the age of 18, have personal knowledge of the facts set forth herein, and am competent to testify to the same.

2. I earned a Master of Library and Information Science (MLIS) from the University of Wisconsin-Milwaukee in 2009. I have over ten years of experience in the library/information science field. Beginning in 2004, I have served in various positions in the public library sector including Assistant Librarian, Youth Services Librarian and Library Director. I have attached my Curriculum Vitae as Appendix CV.

3. During my career in the library profession, I have been responsible for materials acquisition for multiple libraries. In that position, I have cataloged, purchased and processed incoming library works. That includes purchasing materials directly from vendors, recording publishing data from the material in question, creating detailed material records for library catalogs and physically preparing that material for circulation. In addition to my experience in acquisitions, I was also responsible for analyzing large collections of library materials, tailoring library records for optimal catalog

search performance and creating lending agreements between libraries during my time as a Library Director.

4. I am fully familiar with the catalog record creation process in the library sector. In preparing a material for public availability, a library catalog record describing that material would be created. These records are typically written in Machine Readable Catalog (herein referred to as "MARC") code and contain information such as a physical description of the material, metadata from the material's publisher, and date of library acquisition. In particular, the 008 field of the MARC record is reserved for denoting the date of creation of the library record itself. As this typically occurs during the process of preparing materials for public access, it is my experience that an item's MARC record indicates the date of an item's public availability.

5. Typically, in creating a MARC record, a librarian would gather various bits of metadata such as book title, publisher and subject headings among others and assign each value to a relevant numerical field. For example, a book's physical description is tracked in field 300 while title/attribution is tracked in field 245. The 008 field of the MARC record is reserved for denoting the creation of the library record itself. As this is the only date reflecting the inclusion of said materials within the library's collection, it is my experience

that an item's 008 field accurately indicates the date of an item's public availability.

6. I have reviewed Exhibit 1005, "Mal-ID: Automatic Malware Detection Using Common Segment Analysis and Meta-Features" by Gil Tahan, Lior Rokach and Yuval Shahar as published in *Journal of Machine Learning Research*, 2012.

7. Attached hereto as Appendix TAHAN01 is a true and correct copy of the MARC record for *Journal of Machine Learning Research* as held by the Central Michigan University library. I secured this record myself from the library's public catalog. The MARC record contained within Appendix TAHAN01 accurately describes the title, author, publisher, and ISSN number of *Journal of Machine Learning Research.* The 'Full Text Availability' field of this record visible on page 2 indicates this collection includes the 2012 edition of *Journal of Machine Learning Research* containing "Mal-ID: Automatic Malware Detection Using Common Segment Analysis and Meta-Features".

8. Attached hereto as Appendix TAHAN02 is a true and correct copy of "Mal-ID: Automatic Malware Detection Using Common Segment Analysis and

Meta-Features" as published in *Journal of Machine Learning Research* as held by the Central Michigan University library. I secured these scans myself from the library's collection. In comparing Exhibit 1005 to Appendix TAHAN02, it is my determination that Exhibit 1005 is a true and correct copy of "Mal-ID: Automatic Malware Detection Using Common Segment Analysis and Meta-Features" by Gil Tahan, Lior Rokach and Yuval Shahar as published in *Journal of Machine Learning Research* 2012.

9. The 008 field of the MARC record in Appendix TAHAN01 indicates the date of record creation. The 008 field of Appendix TAHAN01 indicates the Central Michigan University library first acquired this journal as of February 12, 2001 and holds the journal in perpetuity. Considering this information, it is my determination that *Journal of Machine Learning Research* 2012 and therefore "Mal-ID: Automatic Malware Detection Using Common Segment Analysis and Meta-Features" was made available to the public shortly after its initial release in 2012.

10. The 515 field of the MARC record in Appendix TAHAN02 indicates any usual publishing patterns associated with the journal, in this case the field reads: "Articles are published immediately after acceptance and submission of the final manuscript to the publisher rather than when an issue is

completed." Page 1 of Appendix TAHAN01 indicates "Mal-ID: Automatic Malware Detection Using Common Segment Analysis and Meta-Features" was published as of April 2012. Considering this information, it is also my determination that "Mal-ID: Automatic Malware Detection Using Common Segment Analysis and Meta-Features" was made available to the public soon after publication in April 2012.

11. I have been retained on behalf of the Petitioner to provide assistance in the above-illustrated matter in establishing the authenticity and public availability of the documents discussed in this declaration. I am being compensated for my services in this matter at the rate of $100.00 per hour plus reasonable expenses. My statements are objective, and my compensation does not depend on the outcome of this matter.

12. I declare under penalty of perjury that the foregoing is true and correct. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

Dated: 7/3/2023

June Ann Munford

June A. Munford
Curriculum Vitae

Education

University of Wisconsin-Milwaukee - MS, Library & Information Science, 2009
Milwaukee, WI

- Coursework included cataloging, metadata, data analysis, library systems, management strategies and collection development.
- Specialized in library advocacy, cataloging and public administration.

Grand Valley State University - BA, English Language & Literature, 2008
Allendale, MI

- Coursework included linguistics, documentation and literary analysis.
- Minor in political science with a focus in local-level economics and government.

Professional Experience

Researcher / Expert Witness, October 2017 – present
Freelance ● Pittsburgh, Pennsylvania & Grand Rapids, Michigan

- Material authentication and public accessibility determination. Declarations of authenticity and/or public accessibility provided upon research completion. Experienced with appeals and deposition process.

- Research provided on topics of public library operations, material publication history, digital database services and legacy web resources.

- Past clients include Alston & Bird, Arnold & Porter, Baker Botts, Fish & Richardson, Erise IP, Irell & Manella, O'Melveny & Myers, Perkins-Coie, Pillsbury Winthrop Shaw Pittman and Slayden Grubert Beard.

Library Director, February 2013 - March 2015
Dowagiac District Library ● Dowagiac, Michigan

- Executive administrator of the Dowagiac District Library. Located in

Southwest Michigan, this library has a service area of 13,000, an annual operating budget of over $400,000 and total assets of approximately $1,300,000.

● Developed careful budgeting guidelines to produce a 15% surplus during the 2013-2014 & 2014-2015 fiscal years while being audited.

● Using this budget surplus, oversaw significant library investments including the purchase of property for a future building site, demolition of existing buildings and building renovation projects on the current facility.

● Led the organization and digitization of the library's archival records.

● Served as the public representative for the library, developing business relationships with local school, museum and tribal government entities.

● Developed an objective-based analysis system for measuring library services - including a full collection analysis of the library's 50,000+ circulating items and their records.

November 2010 - January 2013
Librarian & Branch Manager, Anchorage Public Library ● Anchorage, Alaska

● Headed the 2013 Anchorage Reads community reading campaign including event planning, staging public performances and creating marketing materials for mass distribution.

● Co-led the social media department of the library's marketing team, drafting social media guidelines, creating original content and instituting long-term planning via content calendars.

● Developed business relationships with The Boys & Girls Club, Anchorage School District and the US Army to establish summer reading programs for children.

June 2004 - September 2005, September 2006 - October 2013
Library Assistant, Hart Area Public Library
Hart, MI

● Responsible for verifying imported MARC records and original MARC

cataloging for the local-level collection as well as the Michigan Electronic Library.

● Handled OCLC Worldcat interlibrary loan requests & fulfillment via ongoing communication with lending libraries.

Professional Involvement

Alaska Library Association - Anchorage Chapter
● Treasurer, 2012

Library Of Michigan
● Level VII Certification, 2008
● Level II Certification, 2013

Michigan Library Association Annual Conference 2014
● New Directors Conference Panel Member

Southwest Michigan Library Cooperative
● Represented the Dowagiac District Library, 2013-2015

Professional Development

Library Of Michigan Beginning Workshop, May 2008
Petoskey, MI
● Received training in cataloging, local history, collection management, children's literacy and reference service.

Public Library Association Intensive Library Management Training, October 2011
Nashville, TN
● Attended a five-day workshop focused on strategic planning, staff management, statistical analysis, collections and cataloging theory.

Alaska Library Association Annual Conference 2012 - Fairbanks, February 2012
Fairbanks, AK
● Attended seminars on EBSCO advanced search methods, budgeting, cataloging, database usage and marketing.

Depositions

2019 ● Fish & Richardson

Apple v. Qualcomm (IPR2018-001281, 39521-00421IP, IPR2018-01282 and 39521-00421IP2)

2019 ● Erise IP

Implicit, LLC v. Netscout Systems, Inc (Civil Action No. 2:18-cv-53-JRG)

2019 ● Perkins-Coie

Adobe Inc. v. RAH Color Technologies LLC (Cases IPR2019-00627, IPR2019-00628, IPR2019-00629 and IPR2019-00646)

2020 ● O'Melveny & Myers

Maxell, Ltd. v. Apple Inc. (Case No. 5:19-cv-00036-RWS)

2021 ● Pillsbury Winthrop Shaw Pittman LLP

Intel v. SRC (IPR2020-1449)

2022 ● Perkins-Coie

Realtek v. Future Link (IPR2021-01182)

2023 ● Fish & Richardson

Neuroderm Ltd. v. Abbvie, Inc (Case No. PGR2022-00040)

2023 ● Fish & Richardson

Nearmap US Inc. v. Pictometry International Corp. (IPR2022-00735)

Limited Case History & Potential Conflicts

Alston & Bird

- Ericsson

  v. Collision Communications (IPR2022-01233)

- Nokia

  v. Neptune Subsea, Xtera (Case No. 1:17-cv-01876)

Arnold & Porter

- Ivantis

  v. Glaukos (Case No. 8:18-cv-00620)

- Samsung

  v. Jawbone (Case No. 2:21-cv-00186)

Benesch Friedlander Coplan & Aronoff

- Voyis

  v. Cathx (Case No. 5:21-cv-00077-RWS)

Erise I.P.

- Apple

  v. Ericsson Inc. (IPR2022-00715)

  v. Future Link Systems (IPRs 6317804, 6622108, 6807505, and 7917680)

  v. INVT (Case No. 20-1881)

  v. Navblazer LLC (IPR2020-01253)

  v. Qualcomm (IPR2018-001281, 39521-00421IP, IPR2018-01282, 39521-00421IP2)

  v. Quest Nettech Corp (Case No. 2:19-cv-00118-JRG)

  v. Telefonaktiebolaget LM Ericsson (IPR2022-00275)

- Fanduel
    - v. CGT (Case No. 19-1393)
- Garmin
    - v. Phillips North America LLC (Case No. 2:19-cv-6301-AB-KS)
- Netscout
    - v. Longhorn HD LLC (Case No. 2:20-cv-00349)
    - v. Implicit, LLC (Civil Action No. 2:18-cv-53-JRG)
- Sony Interactive Entertainment LLC
    - v. Bot M8 LLC (IPR2020-01288)
    - v. Infernal Technology LLC (Case No. 2:19-CV-00248-JRG)
- Unified Patents
    - v. GE Video Compression (Civil Action No. 2:19-cv-248)

Fish & Richardson

- Apple
    - v. AliveCor (3:21-cv-03958)
    - v. LBS Innovations (Case No. 2:19-cv-00119-JRG-RSP)
    - v. Koss Corporation (IPR2021-00305)
    - v. Masimo (IPR 50095-0012IP1, 50095-0012IP2, 50095-0013IP1, 50095-0013IP2, 50095-0006IP1)
    - v. Neonode (Case No. 21-cv-08872-EMC)
    - v. Qualcomm (IPR2018-001281, 39521-00421IP, IPR2018-01282, 39521-00421IP2)
- Dell
    - v. Neo Wireless (IPR2022-00616)

- Dish Network
    - v. Realtime Adaptive Streaming (Case No. 1:17-CV-02097-RBJ)
    - v. TQ Delta LLC (Case No. 18-1798)
- Evapco Dry Cooling
    - v. SPG Dry Cooling (IPR2021-00688)
- Genetec
    - v. Sensormatic Electronics (Case No. 1:20-CV-00760)
- Huawei
    - v. Bell Northern Research LLC (IPR2019-01174)
- Kianxis
    - v. Blue Yonder (Case No. 3:20-cv-03636)
- LG Electronics
    - v. Bell Northern Research LLC (Case No. 3:18-cv-2864-CAB-BLM)
- Metaswitch
    - v. Sonus Networks (IPR2018-01719)
- Microsoft
    - v. Throughputer Inc (IPR2022-00757)
- MLC Intellectual Property
    - v. MicronTech (Case No. 3:14-cv-03657-SI)
- Nearmap Inc
    - v. EagleView Technologies (IPR2022-01009)
- Neuroderm Ltd.
    - v. Abbvie, Inc (Case No. PGR2022-00040)
- Realtek Semiconductor
    - v. Future Link (IPR2021-01182)

- Quectel
    - v. Koninklijke Philips (Case No. 1:20-cv-01710)
- Samsung
    - v. Aire Technology (IPR2022-00877)
    - v. Bell Northern Research (Case No. 2:19-cv-00286-JRG)
    - v. Communication Technologies Inc (IPR2022-01221)
    - v. Jawbone Innovations (IPR2022-00865)
    - v. MemoryWeb LLC (IPR2022-00885)
    - v. Telefonaktiebolaget LM Ericsson (IPR2021-00615)
- Texas Instruments
    - v. Vantage Micro LLC (IPR2020-01261)
- Xilinx
    - v. Sentient Sensors LCC (Case No. 1:22-cv-00173)

Irell & Manella

- Curium

O'Melveny & Myers

- Apple
    - v. Maxell (Case No. 5:19-cv-00036-RWS)

Perkins-Coie

- Heru Industries
    - v. The UAB Research Foundation (IPR2022-01148)
- Realtek Semiconductor
    - v. Future Link (IPR2021-01182)

- Twitter Inc

  v. VOIP-Pal.com (Case No. 3:20-cv-02397-JD)

- TCL Industries

  v. Koninklijke Philips NV (IPR2021-00495, IPR2021-00496 and IPR2021-00497)

Pillsbury Winthrop Shaw Pittman

- Intel

  v. FG SRC LLC (Case No. 6:20-cv-00315)

- Gravel Rating Systems

  v. Costco (Case No. 4:21-cv-149)
  v. Lowe's Home Centers (Case No. 4:21-cv-150)
  v. T-Mobile USA (Case No. 4:21-cv-152)
  v. Kohl's Inc. (Case No. 4:21-cv-258)
  v. Under Armor (Case No. 4:21-cv-356)

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Mal-ID: Automatic Malware Detection Using Common Segment Analysis and Meta-Features

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Abstract

This paper proposes several novel methods, based on machine learning, to detect malware in executable files without any need for preprocessing, such as unpacking or disassembling. The basic method (Mal-ID) is a new static (form-based) analysis methodology that uses common segment analysis in order to detect malware files. By using common segment analysis, Mal-ID is able to discard malware parts that originate from benign code. In addition, Mal-ID uses a new kind of feature, termed meta-feature, to better capture the properties of the analyzed segments. Rather than using the entire file, as is usually the case with machine learning based techniques, the new approach detects malware on the segment level. This study also introduces two Mal-ID extensions that improve the Mal-ID basic method in various aspects. We rigorously evaluated Mal-ID and its two extensions with more than ten performance measures, and compared them to the highly rated boosted decision tree method under identical settings. The evaluation demonstrated that Mal-ID and the two Mal-ID extensions outperformed the boosted decision tree method in almost all respects. In addition, the results indicated that by extracting meaningful features, it is sufficient to employ one simple detection rule for classifying executable files.

Keywords: computer security, malware detection, common segment analysis, supervised learning

1. Introduction

Nowadays the use of the Internet has become an integral part of modern life and Internet browsers are downloading to users a wide variety of content, including new computer software. One consequence of this widespread use is that many computer systems are vulnerable to and infected with malware—malicious software. Malware can be categorized into several groups:

1. Viruses—computer programs that are able to replicate themselves and infect files including the operating systems (OS);

2. Worms—self-replicating computer software that is able to send itself to other computers on a network or the Internet;

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3. Trojans—a software that appears to perform the desired functionally but is actually implementing other hidden operations such as facilitating unauthorized access to a computer system;

4. Spyware—a software installed on a computer system without the user's knowledge to collect information about the user.

The rate of malware attacks and infections is not yet leveling. In fact, according to O'Farrell (2011) and Symantec Global Internet Security Threat Report Trends for 2010 (Symantec, 2010), attacks against Web browsers and malicious code variants installed by means of these attacks have increased.

There are many ways to mitigate malware infection and spread. Tools such as anti-virus and anti-spyware are able to identify and block or identify malware based on its behavior (Franc and Sonnenburg, 2009) or static features (see Table 1 below). A static feature may be a rule or a signature that uniquely identifies a malware or malware group. While the tools mitigating malware may vary, at their core there must be some classification method to distinguish malware files from benign files.

Warrender et al. (1999) laid the groundwork for using machine learning for intrusions detection. In particular, machine learning methods have been used to analyze binary executables. For example, Wartell el al. (2011) introduce a machine learning-based disassembly algorithm that segments binaries into subsequences of bytes and then classifies each subsequence as code or data. In this paper, the term segment refers to a sequence of bytes of certain size that was extracted from an executable file. While it sequentially scans an executable, it sets a breaking point at each potential code-to-code and code-to-data/data-to-code transition. In addition, in recent years many researchers have been using machine learning (ML) techniques to produce a binary classifier that is able to distinguish malware from benign files.

The techniques use three distinct stages:

1. Feature Extraction for file representation—The result of the feature extraction phase is a vector containing the features extracted. An executable content is reduced or transformed into a more manageable form such as:

   (a) Strings—a file is scanned sequentially and all plain-text data is selected.

   (b) Portable Executable File Format Fields—information embedded in Win32 and Win64-bit executables. The information is necessary for the Windows OS loader and application itself. Features extracted from PE executables may include all or part of the following pieces of information: attribute certificate—similar to checksum but more difficult to forge; date/time stamp; file pointer—a position within the file as stored on disk; linker information; CPU type; Portable Executable (PE) logical structure (including section alignment, code size, debug flags); characteristics—flags that indicate attributes of the image file; DLL import section—list of DLLs and functions the executable uses; export section—which functions can be imported by other applications; resource directory—indexed by a multiple-level binary-sorted tree structure (resources may include all kinds of information. For example, strings for dialogs, images, dialog structures; version information, build information, original filename, etc.); relocation table; and many other features.

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(c) n-gram—segments of consecutive bytes from different locations within the executables of length n. Each n-gram extracted is considered a feature (Rokach et al., 2008).

(d) Opcode n-gram—Opcode is a CPU specific operational code that performs specific machine instruction. Opcode n-gram refers to the concatenation of Opcodes into segments.

2. Feature Selection (or feature reduction)—During this phase the vector created in phase 1 is evaluated and redundant and irrelevant features are discarded. Feature selection has many benefits including: improving the performance of learning modules by reducing the number of computations and as a result the learning speed; enhancing generalization capability; improving the interpretability of a model, etc. Feature selection can be done using a wrapper approach or a correlation-based filter approach (Mitchell, 1997). Typically, the filter approach is faster than the wrapper approach and is used when many features exist. The filter approach uses a measure to quantify the correlation of each feature, or a combination of features, to a class. The overall expected contribution to the classification is calculated and selection is done according to the highest value. The feature selection measure can be calculated using many techniques, such as gain ratio (GR); information-gain (IG); Fisher score ranking technique (Golub et al., 1999) and hierarchical feature selection (Henchiri and Japkowicz, 2006).

3. The last phase is creating a classifier using the reduced features vector created in phase 2 and a classification technique. Among the many classification techniques, most of which have been implemented in the Weka platform (Witten and Frank, 2005), the following have been used in the context of benign/malware files classification: artificial neural networks (ANNs) (Bishop, 1995) , decision tree (DT) learners (Quinlan, 1993), nave-Bayes (NB) classifiers (John and Langley, 1995), Bayesian networks (BN) (Pearl, 1987), support vector machines (SVMs) (Joachims, 1999), k-nearest neighbor (KNN) (Aha et al., 1991), voting feature intervals (VFI) (Demiröz and Güvenir, 1997), OneR classifier (Holte, 1993), Adaboost (Freund and Schapire, 1999), random forest (Breiman, 2001), and other ensemble methods (Menahem et al., 2009; Rokach, 2010).

To test the effectiveness of ML techniques, in malware detection, the researchers listed in Table 1 conducted experiments combining various feature extraction methods along with several feature selection and classification algorithms.

Ye et al. (2009) suggested using a mixture of features in the malware-detection process. The features are called Interpretable Strings as they include both programs' strings and strings representing the API execution calls used. The assumption is that the strings capture important semantics and can reflect an attacker's intent and goal. The detection process starts with a feature parser that extract the API function calls and looks for a sequence of consecutive bytes that forms the strings used. Strings must be of the same encoding and character set. The feature-parser uses a corpus of natural language to filter and remove non-interpretable strings. Next, the strings are ranked using the Max-Relevance algorithm. Finally, a classification model is constructed from SVM ensemble with bagging.

Ye et al. (2010) presented a variation of the method, presented above, that uses Hierarchical Associative Classifier (HAC) to detect malware from a large imbalanced list of applications. The malware in the imbalanced list were the minority class. The HAC methodology also uses API calls as features. Again, the associative classifiers were chosen due to their interpretability and their capability to discover interesting relationships among API calls. The HAC uses two stages:

to achieve high recall, in the first stage, high precision rules for benign programs (majority class) and low precision rules for minority class are used, then, in the second stage, the malware files are ranked and precision optimization is performed.

Instead of relying on unpacking methods that may fail, Dai et al. (2009) proposed a malware-detection system, based on a virtual machine, to reveal and capture the needed features. The system constructs classification models using common data mining approaches. First, both malware and benign programs are executed inside the virtual machine and the instruction sequences are collected during runtime. Second, the instruction sequence patterns are abstracted. Each sequence is treated as a feature. Next, a feature selection process in performed. In the last stage a classification model is built. In the evaluation the SVM model performed slightly better then the C4.5 model.

Yu et al. (2011) presented a simple method to detect malware variants. First, a histogram is created by iterating over the suspected file binary code. An additional histogram is created for the base sample (the known malware). Then, measures are calculated to estimate the similarity between the two histograms. Yu et al. (2011) showed that when the similarity is high, there is a high probability that the suspected file is a malware variant.

The experiments definitely proved that is possible to use ML techniques for malware detection. Short n-gram were most commonly used as features and yielded the best results. However, the researchers listed did not use the same file sets and test formats and therefore it is very difficult or impossible to compare the results and to determine what the best method under various conditions is. Table 2 presents predictive performance results from various researches.

When we examined the techniques, several insights emerged:

1. All applications (i.e., software files tested in the studies) that were developed using a higher level development platforms (such as Microsoft Visual Studio, Delphi, Microsoft.Net) contain common code and resources that originate from common code and resource libraries. Since most malware are also made of the same common building blocks, we believe it would be reasonable to discard the parts of a malware that are common to all kinds of software, leaving only the parts that are unique to the malware. Doing so should increase the difference between malware files and benign files and therefore should result in a lower misclassification rate.

2. Long n-gram create huge computational loads due to the number of features. This is known as the curse of dimensionality (Bellman et al., 1966). All surveyed n-gram experiments were conducted with n-gram length of up to 8 bytes (in most cases 3-byte n-gram) despite the fact that short n-gram cannot be unique by themselves. In many cases 3- to 8-byte n-gram cannot represent even one line of code composed with a high level language. In fact, we showed in a previous paper (Tahan et al., 2010) that an n-gram should be at least 64 bytes long to uniquely identify a malware. As a result, current techniques using short n-gram rely on complex conditions and involve many features for detecting malware files.

The goal of this paper is to develop and evaluate a novel methodology and supporting algorithms for detecting malware files by using common segment analysis. In the proposed methodology we initially detect and nullify, by zero patching, benign segments and therefore resolve the deficiency of analyzing files with segments that may not contribute or even hinder classification. Note that, when a segment represents at least one line of code developed using a high level language; it can address the second deficiency of using short features that may be meaningless when considered alone. Additionally, we suggest using meta-features instead of using plain features such as n-gram.

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Study	Feature Representation	Feature Selection	Classifiers
Schultz et al. (2001)	PE, Strings, n-gram	NA	RIPPER, Nave Bayes, and Multi-Nave Bayes
Kolter and Maloof (2004)	n-gram	NA	TFIDF, Nave Bayes, SVM, Decision Trees, Boosted Decision Trees, Boosted Nave Bayes, and Boosted SVM
Abou-Assaleh et al. (2004)	n-gram	NA	K-Nearest Neighbors
Kolter and Maloof (2006)	n-gram	Information-Gain	K-Nearest Neighbors, Nave Bayes, SVM, Decision Trees, Boosted Decision Trees, Boosted Nave Bayes, and Boosted SVM.
Henchiri and Japkowicz (2006)	n-gram	Hierarchical feature selection	Decision Trees, Nave Bayes, and SVM
Zhang et al. (2007)	n-gram	Information-Gain	Probabilistic Neural Network
Elovici et al. (2007)	PE and n-gram	Fisher Score	Bayesian Networks, Artificial Neural Networks, and Decision Trees
Ye et al. (2008)	PE	Max-Relevance	Classification Based on Association (CBA)
Dai et al. (2009)	instruction sequence	Contrast measure	SVM
Ye et al. (2009)	PE (API)	Max-Relevance	SVM ensemble with bagging
Ye et al. (2010)	PE (API)	Max-Relevance	Hierarchical Associative Classifier (HAC)
Yu et al. (2011)	histogram	NA	Nearest Neighbors

Table 1: Recent research in static analysis malware detection in chronological order.

A meta-feature is a feature that captures the essence of plain feature in a more compact form. Using those meta-features, we are able to refer to relatively long sequences (64 bytes), thus avoiding the curse of dimensionality.

2. Methods

As explained in Section 1, our basic insight is that almost all modern computer applications are developed using higher level development platforms such as: Microsoft Visual Studio, Embarcadero Delphi, etc. There are a number of implications associated with using these development platforms:

Method	Study	Features	Feature selection	FPR	TPR	Acc	AUC
Artificial Neural Network	Elovici et al. (2007)	5grams	Fisher Score top 300	0.038	0.89	0.94	0.96
Bayesian Network	Elovici et al. (2007)	5grams	Fisher Score top 300	0.206	0.88	0.81	0.84
Bayesian Network	Elovici et al. (2007)	PE	n/a	0.058	0.93	0.94	0.96
Decision Tree	Elovici et al. (2007)	5grams	Fisher Score top 300	0.039	0.87	0.93	0.93
Decision Tree	Elovici et al. (2007)	PE	n/a	0.035	0.92	0.95	0.96
Classification Based on Association	Ye et al. (2008)	PE	Max-Relevance	0.125	0.97	0.93	−−
Boosted Decision Tree	Kolter and Maloof (2006)	4grams	Gain Ratio	−−	−−	−−	0.99

Table 2: Comparison of several kinds of machine learning methods. FPR, TPR, ACC and AUC refers to False Positive Rate, True Positive Rate, Accuracy and the Area Under Receiver Operating Characteristic (ROC) Curve as defined in Section 3.2.

1. Since application development is fast with these platforms, both legitimate developers and hackers tend to use them. This is certainly true for second-stage malware.

2. Applications share the same libraries and resources that originated from the development platform or from third-party software companies. As a result, malware that has been developed with these tools generally resembles benign applications. Malware also tends, to a certain degree, to use the same specialized libraries to achieve a malicious goal (such as attachment to a different process, hide from sight with root kits, etc). Therefore it may be reasonable to assume that there will be resemblances in various types of malware due to sharing common malware library code or even similar specific method to perform malicious action. Of course such malware commonalities cannot be always guaranteed.

3. The size of most application files that are being produced is relatively large. Since many modern malware files are in fact much larger than 1 MB, analysis of the newer applications is much more complex than previously when the applications themselves were smaller as well as the malware attacking them.

The main idea presented in this paper is to use a new static analysis methodology that uses common segment analysis in order to detect files containing malware. As noted above, many applications and malware are developed using the development platforms that include large program language libraries. The result is that large portions of executable code originate from the program language libraries. For example, a worm malware that distributes itself via email may contain a benign code for sending emails. Consequently, since the email handling code is not malicious and can be found in many legitimate applications, it might be a good idea to identify code portions that originate from a benign source and disregard them when classifying an executable file. In other words, when given an unclassified file, the first step would be to detect the file segments that originated from the development platform or from a benign third party library (termed here the Common Function) and then disregard those segments. Finally, the remaining segments would be compared to determine their degree of resemblance to a collection of known malwares. If the resemblance measure satisfies a predetermined threshold or rule then the file can be classified as malware.

To implement the suggested approach, two kinds of repositories are defined:

1. **CFL—Common Function Library.** The CFL contains data structures constructed from benign files.

2. **TFL—Threat Function Library**. The TFL contains data structures constructed from malware without segments identified as benign (i.e., segments that appears in benign files).

Figure 1 presents the different stages required to build the needed data structures and to classify an application file. As can be seen in this figure, our Mal-ID methodology uses two distinct stages to accomplish the malware detection task: setup and detection. The setup stage builds the CFL. The detection phase classifies a previously unseen application as either malware or benign. Each stage and each sub-stage is explained in detail in the following subsections. The Mal-ID pseudo code is presented in Figure 2.

2.1 The Setup Phase

The setup phase involves collecting two kinds of files: benign and malware files. The benign files can be gathered, for example, from installed programs, such as programs located under Windows XP program files folders. The malware files can, for example, be downloaded from trusted dedicated Internet sites, or by collaborating with an anti-virus company. In this study the malware collection was obtained from trusted sources. In particular, Ben-Gurion University Computational Center provided us malware that were detected by them over time. Each and every file from the collection is first broken into 3-grams (three consecutive bytes) and then an appropriate repository is constructed from the 3-grams. The CFL repository is constructed from benign files and the TFL repository is constructed from malware files. These repositories are later used to derive the meta-features—as described in Section 2.2.

Note that in the proposed algorithm, we are calculating the distribution of 3-grams within each file and across files, to make sure that a 3-gram belongs to the examined segment and thus associate the segment to either benign (CFL) or malware (TFL). Moreover, 3-grams that seem to appear approximately within the same offset in all malware can be used to characterize the malware. Before calculating the 3-grams, the training files are randomly divided into 64 groups.

The CFL and TFL repositories share the same data structure:

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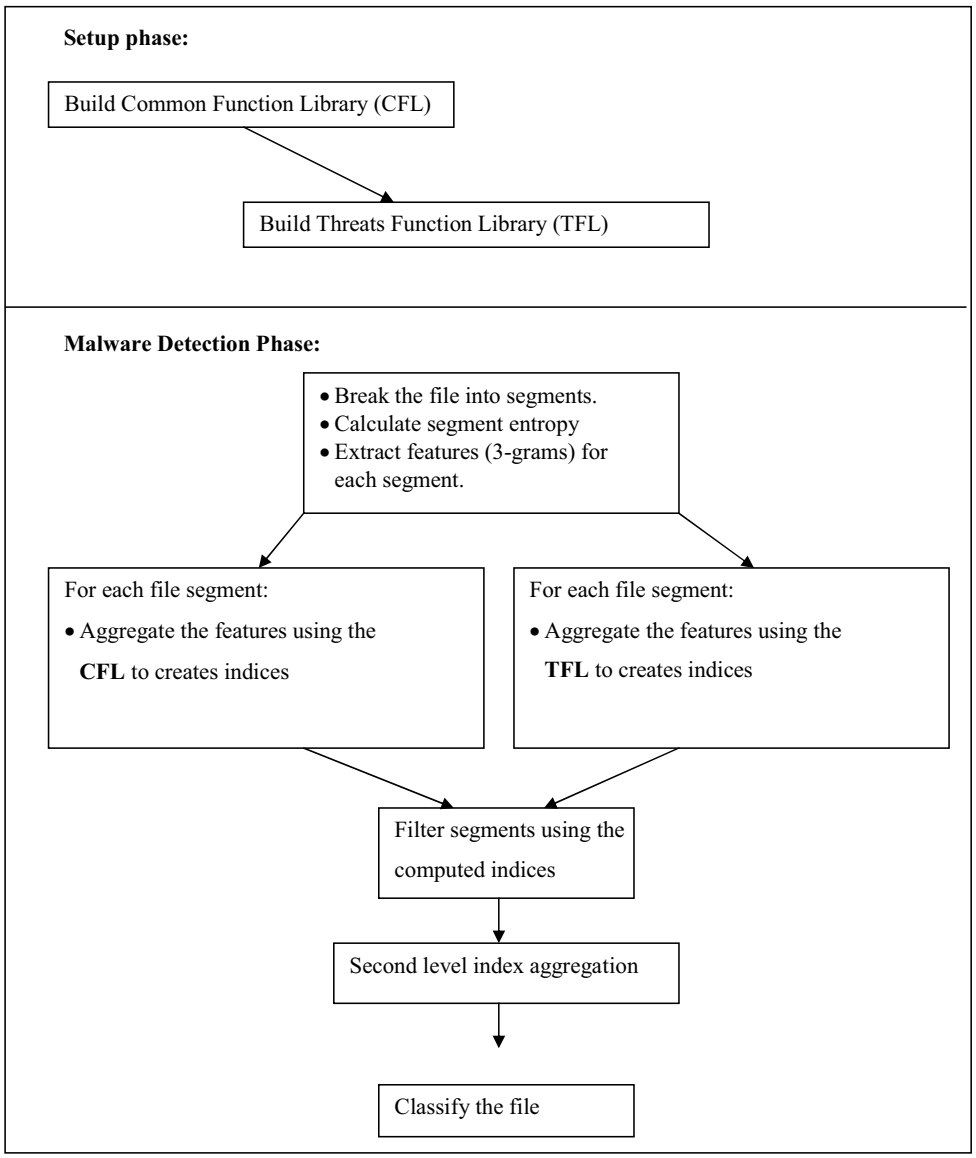

Figure 1: The Mal-ID method for detecting new malware applications.

1. 3-gram-files-association: 2^{24} entries, each of 64 bits. A bit value of 1 in a cell (i, j) indicates the appearance of a specific 3-gram i in the jth group of files. The 64-bit entry size was selected since a previous study showed that this size is the most cost effective in terms of

detection performance vs. storage complexity (Tahan et al., 2010). Other implementations may use larger entries.

1. 3-gram-relative-position-within-file: 2^{24} entries, each of 64 bits. A bit value of 1 in a cell (i, j) indicates the appearance of 3-gram i in the jth internal segment of a file (assuming the file is divided into 64 equal length segments).

The CFL is constructed first and then the TFL:

1. Each file from the malware collection is broken into segments. The Mal-ID implementation has used 64-byte segments.
2. Each segment is broken into 3grams and then tested against the CFL using the algorithm and features described next. Segments that are not in the CFL are added to the TFL.

It is important to note that the end result is the TFL, a repository made of segments found only in malware and not in benign files.

2.2 The Detection Phase

The Mal-ID basic is a feature extraction process followed by a simple static decision rule.

It operates by analyzing short segments extracted from the file examined. Each segment comprises a number of 3-grams depending on the length of the segment (e.g., a segment of length 4 bytes is comprised from two 3-grams that overlap by two bytes). Three features can be derived for each segment: Spread, MFG, and Entropy. The Spread and the MFG features are derived using the data structures prepared in the setup stage described in Section 2.1 above.

The definition and motivation behind the new features are hereby provided:

1. **Spread**: Recall that in the Mal-ID setup phase each file in the training set has been divided into 64 relative-position-areas. The Spread feature represents the spread of the signature's 3-grams along the various areas for all the files in a given repository. The Spread feature can be calculated as follows: for each 3-gram, first retrieve the 3-gram-relative-position-within-file bit-field, and then perform 'And' operations over all the bit-fields and count the resulting number of bits that are equal to 1. In other words, spread approximates the maximum number of occurrences of a segment within different relative locations in train sets. For example, a Spread equal to 1 means that the segment appears (at most) in one relative location in all the files.
2. **MFG:** the maximum total number of file-groups that contain the segment. The MFG is calculated using the 3-gram-files-association bit-field, in the same manner that spread is calculated.
3. **Entropy:** the entropy measure of the bytes within a specific segment candidate. In addition to the new estimators presented above, the entropy feature is also used to enable to identification of compressed areas (such as embedded JPEG images) and long repeating sequences that contain relatively little information.

Note that the features, as described above, are in fact **meta-features** as they are used to represent *features of features* (features of the basic 3-grams). As explained next, using these meta-features,

Mal-ID can refer to relatively long sequences (64 bytes), thus avoiding the data mining problem known as "the curse of dimensionality", and other problems caused when using short n-gram as features. The advantages of using Mal-ID meta-features will be demonstrated in the evaluation results section and in the discussion section.

2.3 The Mal-ID Basic Detection Algorithm

The input for the Mal-ID method is an unclassified executable file of any size. Once the setup phase has constructed the CFL and the TFL, it is possible to classify a file F as benign or as malware using the algorithm presented in Figure 2.

1. Line 1. Divide file F into S segments of length L. All segments are inserted into a collection and any duplicated segments are removed. The end result is a collection of unique segments. The Mal-ID implementation uses 2000 segments that are 64-bytes in length.
2. Line 3. For each segment in the collection:
   (a) Line 5. Calculate the entropy for the bytes within the segment.
   (b) Line 6. The algorithm gets two parameters EntropyLow and EntropyHigh. The entropy thresholds are set to disregard compressed areas (such as embedded JPEG images) and long repeating sequences that contain relatively little information. In this line we check if the entropy is smaller than EntropyLow threshold or entropy is larger than EntropyHigh. Is so then discard the segment and continue segment iteration. Preliminary evaluation has found the values of EntropyLow=0.5 and EntropyHigh=0.675 maximize the number of irrelevant segments that can be removed.
   (c) Line 9. Extract all 3-grams using 1 byte shifts.
   (d) Line 11. Using the CFL, calculate the CFL-MFG index.
   (e) Line 12. If the CFL-MFG index is larger than zero, then discard the segment and continue segment iteration. The segment is disregarded since it may appear in benign files.
   (f) Line 14. Using the TFL, calculate the TFL-MFG index
   (g) Line 15. The algorithm gets the ThreatThreshold parameter which indicates the minimum occurrences a segment should appear in the TFL in order to be qualified as malware indicator. In this line we check if the TFL-MFG index is smaller or equal to the ThreatThreshold. If so then discard the segment and continue with segment iteration. In the Mal-ID implementation only segments that appear two times or more remain in the segment collection. Obviously a segment that does not appear in any malware cannot be used to indicate that the file is a malware.
   (h) Line 17. Using the TFL calculate the TFL-Spread index
   (i) Line 18. The algorithm gets the SR parameter which indicates the Spread Range required. If the TFL-Spread index equals zero or if it is larger than what we term SR threshold, then discard the segment and continue segment iteration. The purpose of these conditions is to make sure that all 3-grams are located in at least 1 segment in at least 1 specific relative location. If a segment is present in more than SR relative locations it is less likely to belong to a distinct library function and thus should be discarded. In our Mal-ID implementation, SR was set to 9.

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(j) Lines 21-25 (optional stage, aimed to reduce false malware detection). A segment that meets all of the above conditions is tested against the malware file groups that contain all 3-gram segments. As a result, only segments that actually reside in the malware are left in the segment collection. Preliminary evaluation showed that there is no significant performance gain performing this stage more than log (SegmentLen) * NumberOfMalwareInTraining iterations.

3. Lines 28-30. Second level index aggregation—Count all segments that are found in malware and not in the CFL.

4. Line 32. Classify—If there are at least X segments found in the malware train set (TFL) and not in the CFL then the file is malware; otherwise consider the file as benign. We have implemented Mal-Id with X set to 1.

Please note that the features used by Mal-ID algorithm described above are in fact meta-features that describe the 3-grams features. The advantages of using Mal-ID meta-features will be described in the following sections.

2.3.1 MAL-ID COMPLEXITY

Proposition 1 *The computational complexity of the algorithm in Figure 2 is* $O(SN + log(SL) \cdot M \cdot MaxMalSize)$ *where SN denotes the number of segments; SL denotes segment length; M denotes the number of malware in the training set; and MaxMalSize denotes the maximum length of a malware.*

Proof The computational complexity of the algorithm in Figure 2 is computed as follows: the GenerateSegmentCollection complexity is $O(SN)$; the complexity of loop number 1 (lines 3-26) is $O(SN + log(SL) \cdot M \cdot MaxMalSize)$; the complexity of loop number 2 (lines 29-30) is $O(SN)$. Thus, the overall complexity is $O(SN + log(SL) \cdot M \cdot MaxMalSize)$. ■

2.4 Combining Mal-ID With ML Generated Models

We attempted to improve the *Mal-ID basic* method by using Mal-ID features with various classifiers, but instead of using the Mal-ID decision model described in Section 2, we let various ML algorithms build the model using the following procedure:

1. We apply the common segment analysis method on the training set and obtain a collection of segments for both the CFL and the TFL as explained in Section 2.

2. For each file's segment, we calculated the CFL-MFG, TFL-MFG and the TFL-spread based on the CFL and TFL. The entropy measure is calculated as well.

3. We discretized the numeric domain of the above features using the supervised procedure of Fayyad and Irani (1993). Thus for each feature we found the most representative sub-domains (bins).

4. For each file we count the number of segments associated with each bin. Each frequency count is represented twice: once as absolute numbers (number of segments) and then as a proportional distribution.

```
SegmentColl=GenerateSegmentCollection(FileContent,SegmentsRequired,SegmentLen);
SegmentCheck=0;
ForEach Segment in SegmentColl do
    {
    Entropy  = Entropy(Segment.string);
    If (Entropy<=EntropyLow) or (Entropy>= EntropyHigh) then
       {SegmentColl.delete(Segment); continue; }

    Segment3Grams:=SegmentTo3Grams(Segment);

    CFL_MFG = CFL.Count_Files_With_All_3gram (Segment3Grams)
    If (CFL_MFG>0) then { SegmentColl.delete(Segment); continue; }

    TFL_MFG = TFL.Count_Files_With_All_3gram (Segment3Grams)
    If (TFL_MFG< ThreatsThreshold) then { SegmentColl.delete(Segment); continue; }

    TFL_spread   = TFL.CalcSpread (Segment3Grams);
    If (TFL_spread =0) or  (TFL_spread >SR)  then
       {SegmentColl.delete(Segment); continue; }

    // optional stage
    SegmentCheck++;
    If (SegmentCheck>log(SegmentLen)*NumberOfMalwareInTraining) then continue;
    InMalwareFile  = TFL.SearchInMalwareFiles(Segment);  //search by bit-fields
    If  not InMalwareFile  then { SegmentColl.delete(Segment); continue; }
    }

SegmentsInMalwareOnly = 0;
ForEach Segment in SegmentColl do
    { SegmentsInMalwareOnly  = SegmentsInMalwareOnly +1; }

Malware_Classfication_Result = SegmentsInMalwareOnly > ThreatSegmentThreshold;
```

Figure 2: Mal-ID pseudo code.

5. An induction algorithm is trained over the training set to generate a classifier.

We compare the following three machine learning induction algorithms:

1. C4.5—Single Decision Tree

2. RF—Rotation Forest (Rodriguez et al., 2006) using J48 decision tree as base classifier. The algorithm was executed with 100 iterations and the PCA method for projecting the data in every iteration.

3. NN—A multilayer perception with one hidden layer trained over 500 epochs using back-propagation.

Finally, using the model is used to detect the malware among the files in the test set.

2.5 Combining Mal-ID With ML Models Post Processing

We have attempted to improve the *Mal-ID basic* method by using the following procedure:

1. First, the *Mal-ID basic* method is used to construct the CFL and TFL. This stage is performed only once before the file classification starts.
2. Next, zero patch each malware in the training set as follows: Iterate over all of the file segments and perform common segment analysis to detect the segments that appear in the CFL. The benign segments (the segments that appear in the CFL) are zero patched in an attempt to reduce the number of n-gram that are clearly not relevant for detecting segments that appear only in malware. The end result is a new file with the same length that has zeros in the benign segments.
3. Finally, construct a classification model using Rotation Forest using J48 decision tree as base classifier. The patched malware collection and the unchanged benign file collection are used for training.

To classify a file we first have to zero-patch the file as explained above then use the classification model created earlier.

3. Experimental Evaluation

In order to evaluate the performance of the proposed methods for detecting malwares, a comparative experiment was conducted on benchmark data sets. The proposed methods were compared with the method presented in the research of Kolter and Maloof (2004). The research of Kolter and Maloof (2006) found that the combination of 500 4-grams with gain ratio feature selection and boosted decision tree provides the best performance over many other evaluated method variations. We will refer to our variation of Kolter and Maloof method as *GR500BDT* as it uses Gain Ratio feature selection, **500** 4-grams, and Boosted Decision Tree classifier. The *GR500BDT* method was specifically selected because it was the best method known to us.

The following terms will be used when referring to the various methods:

1. *GR500BDT*—Our baseline method, which is described above.
2. *Mal-IDP+GR500BDT*—As explained in Section 2.5, we use Mal-ID to zero patch common segments in the test files, and then use *GR500BDT* as usual.
3. *Mal-ID basic*—*Mal-ID basic* method as explained in Section 2.
4. *Mal-IDF+*<induction algorithm>—as detailed in Section 2.4, Mal-ID features will be used by induction algorithm.
   (a) *Mal-IDF+RF*—Mal-ID features with Rotation Forest classification
   (b) *Mal-IDF+C4.5*—Mal-ID features with C4.5
   (c) *Mal-IDF+NN*—Mal-ID features with a multilayer perception.

Specifically, the experimental study had the following goals:

1. To examine whether the proposed basic methods, could detect malware while keeping the false alarm rate as small as possible.
2. Compare the performance of the various *Mal-ID basic* extensions.
3. To analyze the effect of the common library size (benign and malware) on performance.

The following subsections describe the experimental set-up and the results that were obtained.

3.1 Experimental Process

The main aim of this process was to estimate the generalized detection performance (i.e., the probability that a malware was detected correctly). The files repository was randomly partitioned into training and test sets. The process was repeated 10 times and we report the average result. The same train-test partitioning was used for all algorithms.

For evaluating the proposed methodology 2627 benign files were gathered from programs installed under Windows XP program files folders, with lengths ranging from 1Kb to 24MB. An additional 849 malware files were gathered from the Internet with lengths ranging from 6Kb to 4.25MB (200 executables were above 300KB). The detailed list of examined executables can be obtained in the following URL: `http://www.ise.bgu.ac.il/faculty/liorr/List.rar`. The malware and benign file sets were used without any decryption, decompression or any other preprocessing. The malware types and frequencies are presented in Figure 3. The evaluation computer used an Intel Q6850 CPU with 4GB of RAM. The processing time was measured using only 1 CPU core, although the implemented algorithm natively supported multiple cores.

3.2 Evaluation Measures

We used the following performance measures:

- TP = true positive
- FP = false positive
- TN = true negative
- FN = false negative
- FPR = FP / N = FP / (FP + TN) = false positive rate
- TPR = TP / P = TP / (TP + FN) = true positive rate (also known as sensitivity)
- PPV = TP / (TP + FP) = positive predictive value
- NPV = TN / (TN + FN) = negative predictive value
- ACC = (TP + TN) / (P + N) = accuracy
- BER = 0.5(FN/P + FP/N) = balanced error rate

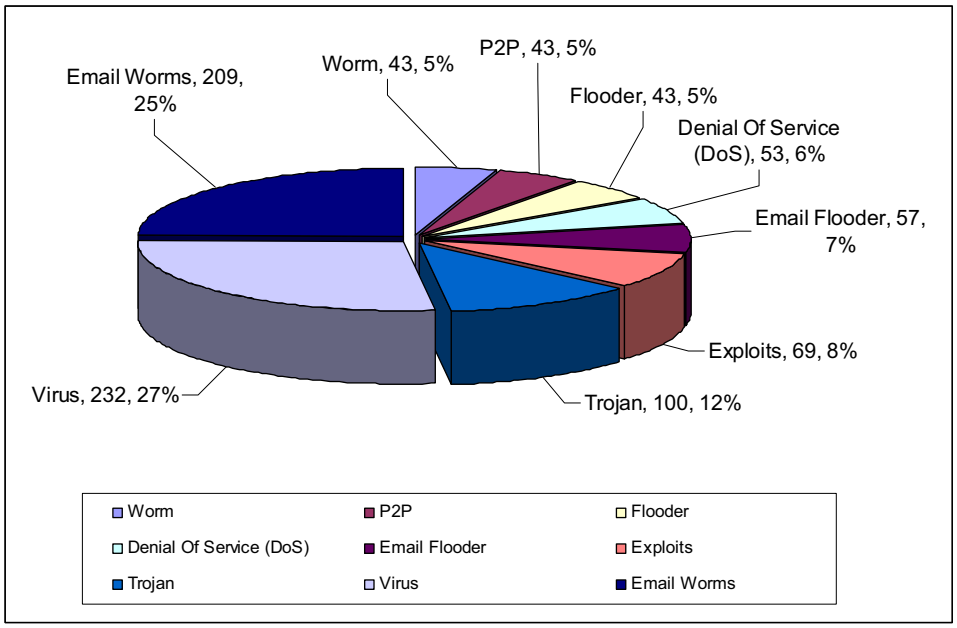

Figure 3: Distribution of malware types in data set.

- BCR = 1- BER = balanced correctness rate
- AUC = area under receiver operating characteristic (ROC) curve

Our measures, such as PPV versus NPV, as well as BER or BCR, try to address the important case of an unbalanced positive/negative instance case mix, which is often ignored in the literature. Given the low rate of malware versus benign code, accuracy might be a misleading measure. For example, a "*Maximal Class Probability*" (MPC) classifier is a classifier that always predicts the most frequent class. Thus, an MPC predicting "BENIGN" for every instance in an environment where 99% of the files are benign would, indeed, be 99% accurate. That would also be its NPV, since there is a 99% probability that the MPC is right when it predicts that the file is benign. However, its PPV would be 0, or rather, undefined, since it never predicts a positive class; in other words, its sensitivity to positive examples is 0.

Furthermore, unlike many studies in the information security literature, we use the cross-entropy as one of our major performance measures. The cross-entropy described by Caruana et al. (2004). It is also referred in the literature by the terms *negative log-likelihood* or *log-loss*. Let $p(x_i)$ represents the posterior probability of the instance x_i to be associated with the malware class according to the classifier. The *average cross-entropy* is defined as the average over all m test instances:

$$Entropy = \frac{1}{m}\sum_{i=1}^{m} I(x_i)$$

where the *cross-entropy* for a certain case is defined as:

$$I(x_i) = \begin{cases} -logP(x_i) & \text{if } x_i \text{ is malware,} \\ -log(1-P(x_i)) & \text{otherwise.} \end{cases}$$

The use of cross-entropy as a measure of knowledge gain allows us to plot the improvement in a learning process, given an increasing number of examples, by noting whether there is a positive information gain (i.e., a reduction in the entropy after learning, compared to the entropy of the previous learning phase). In particular, we would expect an algorithm that really learns something about the classification of both the positive and negative cases to demonstrate a positive monotonic improvement in the cross-entropy measure. It is important to show this positive monotonic improvement since we would prefer an algorithm that generates classifiers in a stable fashion. Such an algorithm can be considered as more trustworthy than an algorithm whose learning curve might be chaotic.

3.3 Results

The following sections describe various Mal-ID evaluation results starting with the *Mal-ID basic* model followed by the results of two enhancements aimed to improve Mal-ID performance.

3.3.1 Results of Mal-ID Basic Model

Table 3 presents the detection performance of the proposed method for 70% of the benign files and 90% of the malware files that are used for training.

TPR	FPR	PPV	NPV	Accuracy	AUC	BCR	BER
0.909	0.006	0.944	0.99	0.986	0.951	0.952	0.048

Table 3: Predictive Performance of *Mal-ID basic*.

Kolter and Maloof (2006) conducted rigorous research to find the best combination of n-gram length, n-gram number, features selection and classification method. They reported that the combination of five hundred 4-grams, gain ratio feature selection and boosted decision tree (AdaBoost.M1 with J48 as a base classifier) produced excellent results where the AUC was over 0.99. As you recall, we reproduced the work of Kolter and Maloof (gain ratio, 500 4-grams with boosted decision tree; referred to as *GR500BDT*) to objectively compare the performance of our methods and theirs under the same conditions such as data set content, data set training size, etc. A preliminary evaluation indicated that Rotation Forest (RF) boosting method (Rodriguez et al., 2006) performed better than AdaBoost.M1 and many other non-boosting methods such as J48, therefore RF was selected for our evaluation. The results of the evaluation are presented in Table 4 below.

Method	Features	Feature selection	FPR	TPR	Acc	AUC
GR500BDT	4grams	Gain Ratio	0.094	0.959	0.948	0.929
Mal-ID	Mal-ID	-	0.006	0.909	0.986	0.951

Table 4: Comparison between Mal-ID and *GR500BDT*.

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3.3.2 RESULTS OF COMBINING MAL-ID WITH ML GENERATED MODELS

As you recall we attempted to improve the *Mal-ID basic* method by using Mal-ID features with various classifiers. The following figures show comparison of various detection performance measures. Many detection performance measures were recorded and reported as presented in the figures below. Please note that "TrainPercentage" refers to the percentage of benign data sets and ranges from 30 to 70 percent. Malware data set percentages range from 40 to 90 percent. The ratio between malware and benign was kept fixed for all cases.

Figure 4 reports the average cross-entropy for a classifier by averaging the entropy of the posteriori probability that it outputs to all test instances. As expected, we see that the cross-entropy decreases as the training set size increases. For the largest training set, Mal-ID basic shows the best decrease in a posteriori cross-entropy.

Figure 5 presents the accuracy of the *Mal-ID basic* model as well that of the *Mal-IDF+NN* and *Mal-IDF+RF* models. As expected, the accuracy increases almost linearly as the training set size increases. For small training set sizes, *Mal-IDF+RF* outperforms the other methods. However, for the largest training set, the *Mal-ID basic* model eventually achieves the best results.

Figure 6 presents the TPR of all methods. *Mal-IDF+C4.5* demonstrates the lowest TPR. The *Mal-IDF+NN* and *Mal-IDF+RF* models perform the best. The *Mal-ID basic* model benefits the most from increasing the training set size. In small training sets, the difference between the *Mal-ID basic* model and either *Mal-IDF+NN* or *Mal-IDF+RF* are statistically significant. However, for larger training sets the differences are no longer significant.

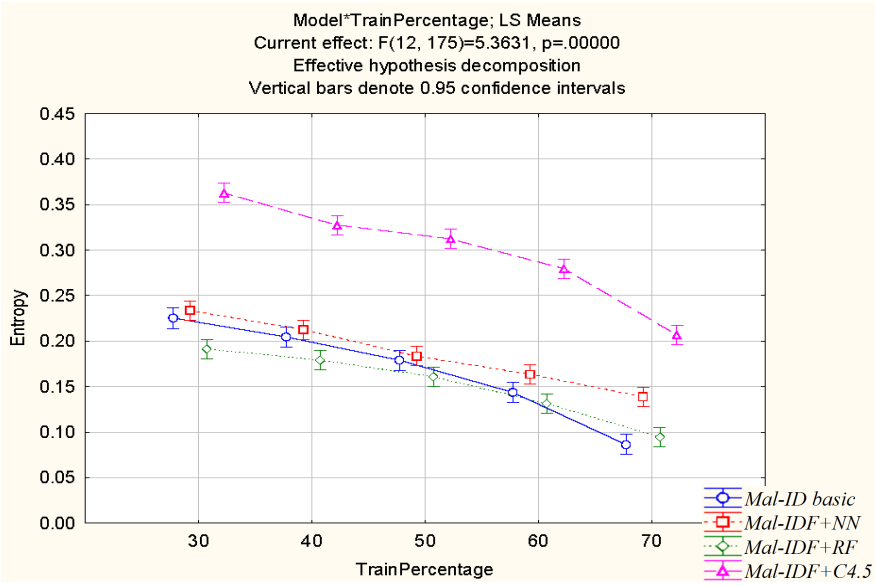

Figure 4: Comparing the a posteriori cross-entropy of various detection modules as a function of training set percentage increase.

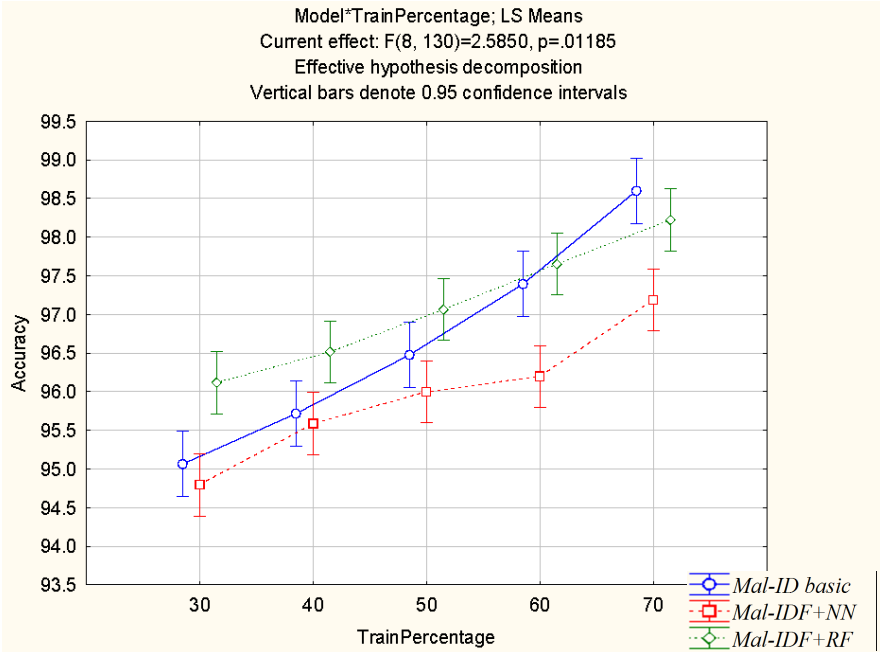

Figure 5: Comparing the accuracy performance of the *Mal-ID basic* model with the machine learning methods on various training set size percentages.

Figure 7 presents the FPR of all methods. The *Mal-ID basic* model demonstrates the best performance. *Mal-IDF+C4.5*, on the other hand, demonstrates the lowest FPR. The performance of *Mal-IDF+NN* does not improve as the training set increases. The *Mal-ID basic* model significantly outperforms *Mal-IDF+C4.5* and *Mal-IDF+NN*. Additionally, a paired t-test indicates the *Mal-ID basic*'s FPR is significantly lower than the FPR of *Mal-IDF+RF* with $p < 0.0001$.

Figure 8 presents the area under the ROC curve for the *Mal-ID basic* model, *Mal-IDF+NN* and *Mal-IDF+RF*. All models improve as the training set increases. The *Mal-ID basic* model shows the lowest AUC but also benefits the most from increasing the training set size. The lower AUC of the *Mal-ID basic* model can be explained by the fact that contrary to the other models, the *Mal-ID basic* model is a *discrete* classifier. Discrete classifiers produce only a single point in ROC space (Fawcett, 2004) and therefore their calculated AUC appears lower.

When we examined the balanced error rate (BER) for *Mal-ID basic*, *Mal-IDF+NN* and *Mal-IDF+RF* Models, we noticed that the BER measure decreases for all models as the training set increases. *Mal-ID basic* demonstrated a significant and sharp decline in the BER as the training set increases. In almost all cases, the *Mal-IDF+RF* achieved the lowest BER. With the largest training set there is no significant difference between the *Mal-ID basic* model and the *Mal-IDF+RF* model.

When we compared the NPV of the *Mal-ID basic* model with the NPV of the *Mal-IDF+NN* and *Mal-IDF+RF*, we noticed, as expected, that the NPV increases almost linearly as the training set

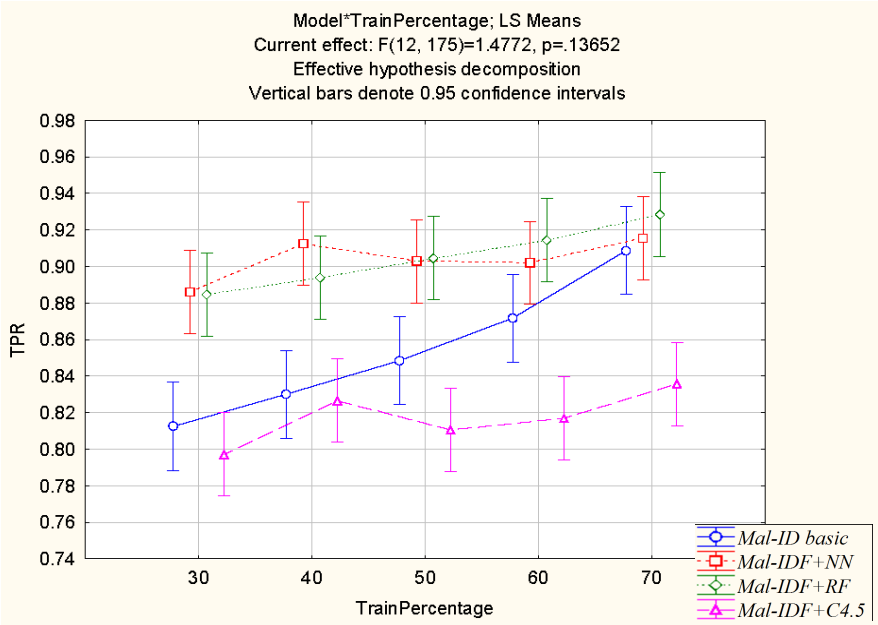

Figure 6: Comparing the true positive rate of the *Mal-ID basic* model with the machine learning methods on various training set size percentages.

size increases. For small training set sizes, *Mal-IDF+RF* and *Mal-IDF+NN* outperform the other methods. Eventually, however, there is no statistically significant difference for the largest training set.

When we compared the PPV of the *Mal-ID basic* model with the PPV of the *Mal-IDF+NN*, *Mal-IDF+C4.5* and *Mal-IDF+RF*, we found out that *Mal-ID basic* has the best PPV for all training set sizes. The *Mal-IDF+RF* performed better than the *Mal-IDF+NN* and the *Mal-IDF+NN* performed better than *Mal-IDF+C4.5*.

To sum up, in many cases Mal-ID basic outperforms the methods that use Mal-ID features combined with a ML classifier and we conclude that a simple decision rule is sufficient.

3.3.3 COMBINING MAL-ID WITH ML MODELS POST PROCESSING

As you recall, we have attempted to improve the *Mal-ID basic* method by using the method to zero-patch the benign common library parts. To measure and compare the effect of the Mal-ID patching prior to classifying, we preformed an evaluation using four methods: *GR500BDT*, *Mal-IDP+GR500BDT*, *Mal-ID basic*, and *Mal-IDF+RF*.

Figure 9 compares the accuracy performance using various training set sizes. The results show that with *Mal-IDP+GR500BDT* we were able to improve performance but only on relatively small training sets. However, compared to the known *GR500BDT*, *Mal-IDP+GR500BDT* show significant and consistent improvements in accuracy by about 2%. All Mal-ID variations were able to

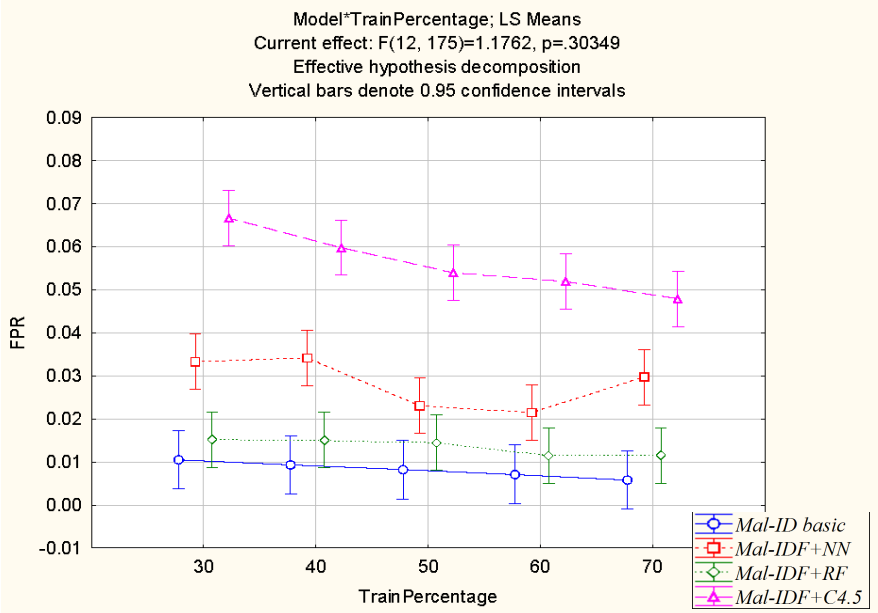

Figure 7: Comparing the false positive rate of the *Mal-ID basic* model with the machine learning methods on various training set size percentages.

outperform *GR500BDT* regardless of training set size. It should be noted that on the one hand we should have expected to an improvement in the predictive performance when the training set size increases. On the other hand because we also increase the imbalance ratio between benign and malware therefore we should have expected to a decrease in the predictive performance. Eventually we observe that accuracy of GR*500BDT* remains almost constant.

Figure 10 compares FPR performance under various training set sizes. The results indicate that there is slight but constant improvement in terms of FPR when first performing a patch with Mal-ID (*Mal-IDP+GR500BDT*) instead of using n-gram without patching (*GR500BDT*). The performance of all n-gram-based methods decreases sharply when the training set consists of more than 50% benign files. The graph shows that in terms of FPR, the *Mal-ID basic* method always performs slightly better than the *Mal-IDF+RF* method and both methods perform significantly better than n-gram based methods. In other words, the graph shows that in terms of FPR, there is a significant difference between methods that use n-gram features and those that use the Mal-ID meta-features.

Table 5 summarizes the detection performance results for the various Mal-ID methods and the *GR500BDT* baseline and can help in choosing the best method when considering detection performance only. Other important considerations will be discussed below. The results demonstrate that *Mal-IDP+GR500BDT* always outperforms *GR500BDT* baseline and *Mal-IDP+GR500BDT* should be used when the highest TPR is desired and a high FPR is acceptable. However *Mal-ID basic* and

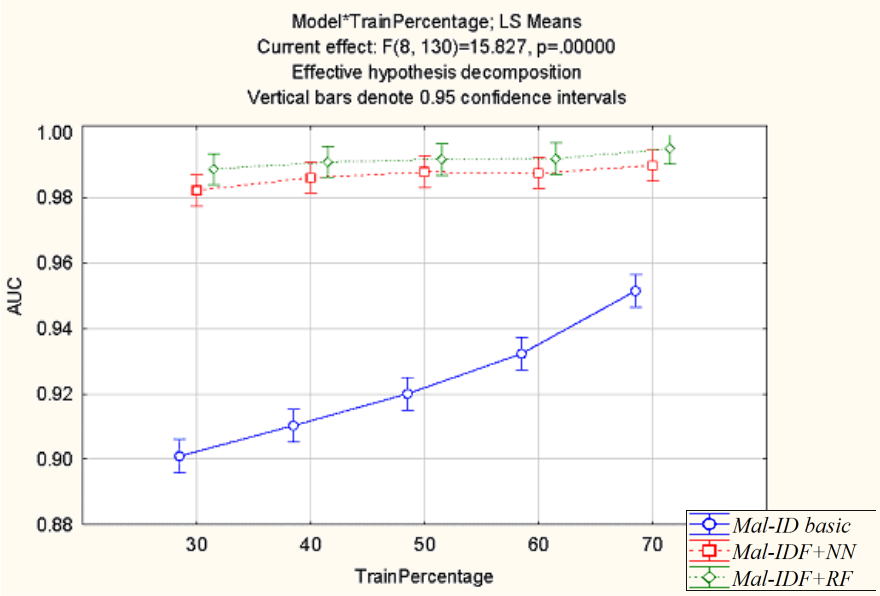

Figure 8: Comparing the AUC of the *Mal-ID basic* model with the machine learning methods on various training set size percentages.

Mal-IDF+RF seems to be the best choice for more balanced performance with extremely low FPR and for achieving the highest accuracy.

Method	**Feature selection**	**FPR**	**TPR**	**Acc**	**AUC**
GR500BDT (un-patched + RF)	Gain Ratio	0.094	0.959	0.948	0.929
Mal-IDP+GR500BDT (patched + RF)	Gain Ratio	0.093	**0.977**	0.963	0.946
Mal-ID basic	Mal-ID	**0.006**	0.909	**0.986**	0.951
Mal-IDF+RF (Mal-ID features + RF)	None	**0.006**	0.916	0.985	**0.995**

Table 5: A comparison of various Mal-ID methods and RF when using maximum training size.

Table 6 presents the training time (in seconds) and detection time (in ms) of all examined methods. The evaluation computer used an Intel Q6850 CPU with 4GB of RAM. All times were measured using only 1 CPU core. The training time of Mal-ID based methods does not include building the CFL and TFL which took around 30 seconds. As expected the training time increases with the training size. In addition, GR500BDT training time does not include the n-gram feature extraction and selection (which took more than ten minutes). The Mal-*ID basic* and Mal-IDF+C4.5 methods demonstrated the best training time performance with less than one second. The detection time

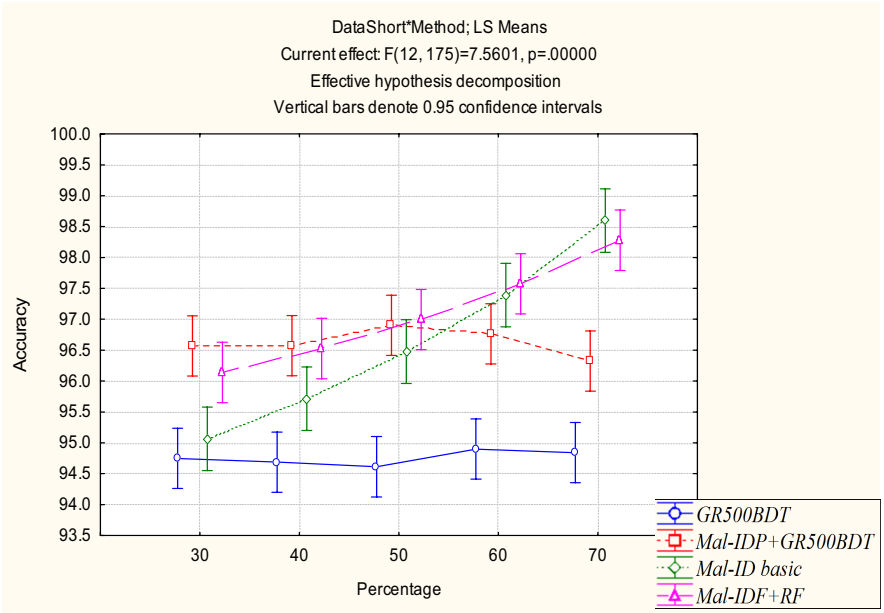

Figure 9: Comparing the accuracy of various Mal-ID-based methods and the n-gram method on various training set size percentages.

seems almost constant regardless of training set size. The only exception is Mal-IDF+RF in which detection time increases almost linearly as the training set increases. Note that the size of the trees (number of nodes) which constitute the rotation forest usually increases with the training set. This can be explained by the fact that the number of leaves in the tree is bounded by the training set size. Larger trees require a longer traversal time and features calculation. Recall that in rotation forest, the features used in the various nodes are linear combination of the original features.

Table 7 reports the mean TPR of *Mal-ID basic* for small malwares (size<=350K) and large malware (size>350K) using the largest training set. Note that the FPR is kept as reported in Table 5 (i.e., FPR=0.006). The results show that the TPR for both small and large group is very similar indicating that MAL ID is not affected by the size of the examined malware.

In order to estimate the effect of obfuscation on detection rate, we have divided the tested malware into two groups—obfuscated and non-obfuscated. Because we were not informed which executable was obfuscated, we have used the following method. We compressed the executables using Zip and sorted them according to the compression ratio. We used a threshold of 50% compression ratio to decide which executable is probably obfuscated. The selection of this threshold was based on experiments of compressing non- obfuscated executables. According to this threshold, about 37.5% of the malware are considered to be obfuscated. Table 8 reports the mean TPR of *Mal-ID basic* for obfuscated and non-obfuscated groups using the largest training set. Note that the FPR is

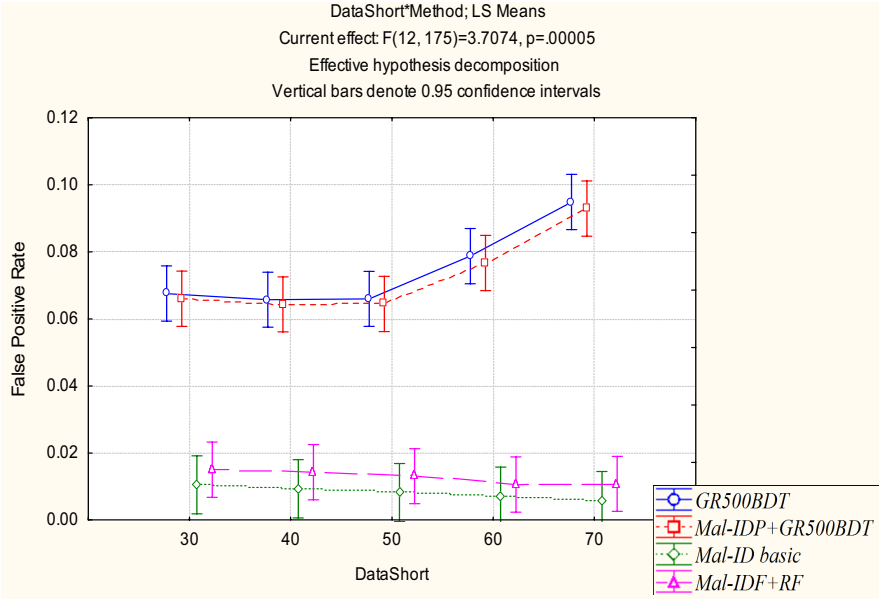

Figure 10: Comparing the FPR of various Mal-ID-based methods and the n-gram method on various training set size percentages.

kept as reported in Table 5 (i.e., FPR=0.006). The results show that the TPR for both obfuscated and non-obfuscated group is very similar with slight advantage to detecting obfuscated malwares.

4. Discussion

This paper proposes a new approach for automatically detecting executable malwares of all kinds and sizes. The results show that using the *Mal-ID basic* and other Mal-ID variants are useful in detecting malware. As can be seen from Table 3, the *Mal-ID basic* method performs very well in respect to all measures. Not only is the accuracy very high (0.986), but the FPR is remarkably low (0.006). In addition, the low Mal-ID BER indicates that the errors are almost uniformly distributed among the malicious and benign files.

As explained in Section 3.3.1, we choose to implement *GR500BDT* as a baseline for comparing the performance of the *Mal-ID basic* method. *GR500BDT* is very similar to the method proposed by Kolter and Maloof (2006). The evaluation shows that *GR500BDT* performed well, but was unable to achieve the AUC of 0.995 that Kolter and Maloof reported. This was probably due to differences in data set content, training size, the benign and malware ratio and possibly other factors. As can be seen from Table 4, under identical conditions the Mal-ID methodology was able to outperform *GR500BDT* in terms of FPR, accuracy and AUC. The FPR of *GR500BDT* method came to almost 10%; Mal-ID FPR was more than 15 times lower.

		Train Percentage				
	Method	**30**	**40**	**50**	**60**	**70**
Training Time (in sec)	MalID-Basic	0.05	0.08	0.11	0.15	0.21
	Mal-IDF+RF	17.19	26.00	36.35	45.78	83.50
	Mal-IDF+C4.5	0.12	0.17	0.22	0.33	0.43
	Mal-IDF+NN	24.33	32.16	40.33	48.37	56.93
	GR500BDT	21.74	34.91	59.86	64.88	75.19
	Mal-IDP+GR500BDT	20.93	31.42	42.96	55.65	63.43
Detection Time per file (in ms)	MalID-Basic	27.86	27.86	27.86	27.86	27.86
	Mal-IDF+RF	49.17	54.69	63.66	73.95	95.82
	Mal-IDF+C4.5	27.86	27.86	27.86	27.86	27.86
	Mal-IDF+NN	27.92	27.92	27.90	27.89	27.88
	GR500BDT	29.63	29.83	29.83	29.85	29.83
	Mal-IDP+GR500BDT	29.01	29.01	29.02	28.98	28.97

Table 6: Training and Detection Time.

Malware Size	**TPR**	**Number of Malwares**	**Mean Size**
Small	0.909	675	96K
Large	0.908	174	554K

Table 7: A comparison of TPR (True Positive Rate) Mal-ID basic for small and large malwares when using maximum training size.

Malware type	**TPR**	**Mean Compression Ratio**
Obfuscated	0.932	41%
Non-obfuscated	0.893	62%

Table 8: A comparison of TPR (True Positive Rate) Mal-ID basic for obfuscated and non-obfuscated malware when using maximum training size.

Once it was established that the *Mal-ID basic* method performs well (in fact better than the best baseline method) we wanted to examine Mal-ID behavior with different train sizes to test if *Mal-ID basic* performs in a stable and "trustworthy" manner. In addition, it was interesting to determine if combining *Mal-ID basic* with ML-generated models, as explained in Section 3.3.2, would yield a better performing malware detection method.

The results presented in Figure 4 to Figure 8 show that combining Mal-ID with ML-based models enabled us to improve many aspects of the *Mal-ID basic* method when training sets are not maximal. However, as training set size increases, the benefit of combining *Mal-ID basic* with ML-based models diminishes. At maximal training set size, the *Mal-ID basic* method almost always demonstrates the best performance or a performance that is statistically equal to the combined methods. It is also important to note that, contrary to the other methods, all measures that we im-

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plemented indicated that the *Mal-ID basic* method benefited the most from training set increase and always performed in an expected manner. Thus, it may be considered more stable and "trustworthy" than the other methods.

It is interesting to note that while the performance of non-n-gram methods (*Mal-ID basic* and *Mal-IDF+RF*) continues to improve as more training data become available, the n-gram based methods show a sharp decrease in performance in terms of FPR (see Figure 10). This can be explained by the fact that n-gram methods induce relatively simple patterns that can be learned with comparatively small training sets (30%). The potential benefit of additional training data is nullified by the undesirable increase in the probability that relevant n-gram will be mistakenly considered as non-contributing features. In fact, it is well known that decision trees increase their chances of overfitting when they have more nodes. But in order to have more nodes, they need a larger training set. Thus a larger data set might increase the chance of overfitting especially in cases were there are many irrelevant and noisy features.

The comparison of our two additional methods, *Mal-IDF+RF* and *Mal-IDP+GR500BDT*, with a *GR500BDT* baseline is very important in proving the validity of Mal-ID itself and explaining its excellent performance:

1. (a) Under identical conditions, boosted decision tree, operating on *Mal-ID basic* meta-features (*Mal-IDF+RF*), outperformed boosted decision tree operating on n-gram (*GR500BDT*). The comparison suggests that Mal-ID meta-features are useful in contributing to malware detection and probably more meaningful than simple n-gram in capturing a file's essence.

   (b) Under identical conditions, boosted decision tree operating on *Mal-ID basic* patched files (*Mal-IDP+GR500BDT*) outperformed boosted decision tree operating on non-patched files (*GR500BDT*). The comparison suggests that the novel Mal-ID common segment analysis approach is better than the common approach that treats files as black boxes or which interprets files PE header only.

Since *Mal-ID basic* and *Mal-IDF+RF* methods benefit from both more meaningful features and common segment analysis, they are able to achieve a better overall performance than state-of-the-art *GR500BDT*.

Considering detection performance only when choosing a malware detection method may not be enough; it is important to consider other aspects as well.

4.1 Model Interpretability

Mal-ID basic uses only one static interpretable classification model and therefore experts in the field can be more confident when accepting or rejecting a classification. For instance, once *Mal-ID basic* has detected a yet unknown malware, it is possible to support or reject the classification. The reason is that each detected segment, that passed the Mal-ID filter stage as explained in Section 2, can be tracked back to a specific malware or malware group. Moreover, the specific offset location were the segments appear can be examined to determine the precise nature of the threat, if any exists. Disassembly or reverse engineering of the whole malware is no longer required. Even without examining the segment code, one can make an educated guess about the nature of the threat by examining the list of known malwares that the segment appears in. The other methods do not provide such benefits.

4.2 Incremental

As more malwares are discovered, it is important to update the models from time to time. With *Mal-ID basic* it is particularly easy. Since the model is static, no reconstruction is necessary; all that is required is to just to add or subtract files from the TFL. The CFL can be updated in a similar manner.

4.3 Anytime Detection

Recall that both *Mal-ID basic* and *Mal-IDF+RF* operates on segments. Because *Mal-ID basic* and *Mal-IDF+RF* use relatively large segments and the model is not comprised of combined features from the whole file, it is possible to stop detection at anytime during file scan and determine if the scanned part is malicious. n-gram-based methods are not designed to diagnose part of file but rather whole files only.

4.4 Default Signature For Real-time Malware Detection Hardware

The end result of applying *Mal-ID basic* method is a file segment or segments that appear in malware files only and thus may be used as a signature for anti-virus tools. The detected malware segments can be used, as described by Filiol (2006), to generate signatures resistant against black-box analysis. Moreover, because *Mal-ID basic* produces a simple signature and has *anytime detection traits*, the signature can be used with commercially available real-time intrusion prevention systems (IPS). IPSs require the *anytime detection trait* to act as real-time malware filtering devices and thus promote and provide users with default protection. Having both malware detection and signature generation could help shorten the window of vulnerability. Tahan et al. (2010) have presented a methodology with complete implementation for automatic signature generation, using similar and compatible techniques, which archived excellent results in the evaluation. Thus, the method presented by Tahan et al. (2010) can be easily adopted to produce signature upon detection for the solution presented in this paper.

4.5 Large Files Scalability

Nowadays it's quite common to embed large resources such as JPEG pictures and small animations into executables. This inflation is also true for malware. It is estimated[1] that the mean malware size has increased from 150K (in 2005) to 350K (in 2010). As files become larger, the effectiveness of classification with small n-gram should decrease due to the increase in file entropy. In other words, the more n-gram with equal appearance probability, the greater the misclassification probability becomes. Since *Mal-ID basic* and *Mal-IDF+RF* use relatively large segments (64 bytes) and in addition filter-out high entropy parts, they should be less susceptible to misclassification caused by large files or files with high entropy traits. Figure 10 shows that the Mal-ID methods that operate on large segments (of 64 bytes) has less FPR misclassification then the method that operated on small n-gram (of 4 bytes). We further examined this hypothesis in Table 7.

1. See `http://nakedsecurity.sophos.com/2010/07/27/large-piece-malware/`.

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4.6 Analysis of Mal-ID Performance on Obfuscated Malware

Based on the results presented so far, we hypothesize that the proposed Mal-ID method performs well in a mixed environment where both obfuscated (including compressed or encrypted) and plain executable files exist. In this sense, we referred to malware as they are found "in the Wild".

There might be several reasons that can explain why the TPR of obfuscated binaries appears to be higher than the TPR of non-obfuscated binaries. One reason can be that many obfuscated malwares are generated by automated tools that have distinctive properties. For example, malware developers are sharing tools for facilitating the generation of new malwares. For example, in the web site `http://vx.netlux.org/`, one can find many tools (such as Falckon Encrypter that is used for obfuscation) that can be used by the malware developers but are not used by benign software developers. All malware that use the Falckon Encrypter, share the same decryption segment.

The results of Table 8 agree with the previously-made observation that ML techniques can classify malware that are obfuscated (compressed or encrypted or both). For example, Kolter and Maloof (2006) have noted that ML can detect obfuscated malware. In this paper, we have independently reconfirmed the validity of the above observation using our method. In this experiment, we succeeded to keep FPR relatively low (FPR=0.006), however it should be noted that this value was obtained when our corpus contained 2,627 benign files and 849 malware files (i.e., a benign to malware ratio of 3:1). In reality this ratio can be much higher and therefore one should expect to obtain elevated FPR values.

There seem to be previously suggested explanations to this phenomenon. According to Kolter and Maloof (2006), the success in detecting obfuscated malware relies on learning certain forms of obfuscation such as run-time decompression. Kolter and Maloof (2006) conclude that "...this does not seem problematic as long as those forms are correlated with malicious executables".

Additional explanations can be suggested to the ability to identify obfuscated malware. Studies such as that presented by Newsome and Song, or by Newsome et al. (2005) noticed that in many cases malware requires fixed sequences to be used in the body of the malware (which must exist before self-decryption or self-decompression) in order to exploit a specific vulnerability and self-propagate. Such fixed sequences can be used for detection. This might explain the success in detecting obfuscated malware.

Because the performance of MAL ID is achieved with no disassembly, Op-Code analysis, executable header analysis, unpacking nor any other preprocessing, we hypothesize that the method should be scalable to other Operating Systems and hardware types. Still one can think on cases where preprocessing will be required. Theoretically an attacker can specifically design a malware that will make it hard for MAL ID to detect it. In particular, if a malware is designed such that the entropy measure will be high for all segments, it will be undiscovered by the Mal-ID basic method. In this case Mal-ID can be extended by incorporating an unpacker operating before it, such as those that are incorporated into anti-viruses tools (Kasparsky). However, similar to Kolter and Maloof (2006), we decided to evaluate the raw power of our methods without any use of an unpacker.

5. Summary and Future Work

In this paper we have described novel methods based on machine learning to detect malware in executable files without any need for preprocessing the executables. The basic method that we presented works on the segment level for detecting new malware instead of using the entire file as usually done in machine learning based techniques. The *Mal-ID basic* method and its derived

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variants were rigorously tested to evaluate their effectiveness under many conditions using a wide variety of measures. The results demonstrate the effectiveness of the methods. In all cases, most of the performance measures showed that the proposed methods significantly outperformed the baseline method *GR500BDT* which is known for its excellent performance (Kolter and Maloof, 2004, 2006). For each method we have pinpointed its strong points and suggested cases where it should be preferred over the others.

We believe this study has made several contributions to malware detection research, including the introduction of:

1. a new and effective method for malware detection based on common segment analysis and supporting algorithms. The importance of common segment analysis to the process of malware detection was identified and demonstrated. The results suggest the method can boost performance for many methods that use n-gram.

2. new kinds of features—*Mal-ID basic* meta-features. The results suggest that the meta-features are much more effective than the commonly used n-gram and probably more meaningful in terms of file representation. We believe that *Mal-ID basic* meta-features could inspire many kinds of additional meta-features that could prove useful.

3. BCR, BER, PPV, NPV and entropy decrease for measuring the performance of malware detection methods. Using these measures, in addition to the commonly used performance measures (TPR, FPR, accuracy and AUC), is not generally practiced. However, these features are helpful in describing the behavior of a new method, particularly when it is not possible to compare results under identical settings and data set imbalance.

The results also indicate that by extracting meaningful features, it is sufficient to employ one simple detection rule for classifying unknown executables.

In the future, we aim to examine the effect of systematically collecting and choosing the benign file set on the performance of the proposed methods. In the evaluations that were conducted for this study, the benign file set was collected randomly and the files used may have had a large degree of similarity. It is our assumption that systematically collecting and choosing common segments will provide a better representation of benign common segments and a more robust and lower FPR. A robust and low FPR will enable the use of more sensitive malware detection methods (or parameters that affect malware detection) without increasing the FPR too much. As a result, we hope to see further increase in the AUC measure. Finally the Mal-ID basic method was developed as a crisp classifier. Additional research is required for developing a method for ranking the examined files according to their presumed threat level. One straightforward measure is the ratio between the segments found in the TFL and the segments found in the CFL. In addition, it will be interesting to test the proposed method on live network data and on an institutional network and determine if it detects malware that is not detected by other means. Finally, future work may repeat the evaluation Mal-ID on a larger scale with thousands of malware samples and tens of thousands of non-malware samples. For this purpose, we might need to upscale software components to accommodate large data set and suitable hardware. In addition, in order to use the proposed method in practice by the industry, fine tuning of the various parameters might be required.

Additional studies might be needed to fully evaluate the performance of Mal-ID under various obfuscation scheme, including use of recursive unpacking. In this paper we focused only on "pure" Mal-ID methods and therefore we did not investigate the proper means to incorporate unpacker.

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