

GAN-based Approach to Crafting Adversarial Malware Examples against a Heterogeneous Ensemble Classifier

Saad Al-Ahmadi¹ ^a and Saud Al-Eyeed² ^b

¹Computer Science, King Saud University, Riyadh, Saudi Arabia

²Computer Science, Prince Sattam Bin Abdulaziz, Kharj, Saudi Arabia

Keywords: GAN, Machine Learning, Deep Learning, Ensemble Classifier, Adversarial Malware Examples.

Abstract: The rapid advances in machine learning and deep learning algorithms have led to their adoption to tackle different security problems such as spam, intrusion, and malware detection. Malware is a type of software developed with a malicious intent to damage, exploit, or disable devices, systems, or networks. Malware authors typically operate through black-box sitting when they have a partial knowledge about the targeted detection system. It has been shown that supervised machine learning models are vulnerable to well-crafted adversarial examples. The application domain of malware classification introduces additional constraints in the adversarial sample crafting process compared to the computer vision domain: (1) the input is binary and (2) retaining the visual appearance of the malware application and its intended functionality. In this paper, we have developed a heterogeneous ensemble classifier that combines supervised and unsupervised models to hinder black-box attacks designed by two variants of generative adversarial network (GAN). We experimentally validate its soundness on a corpus of malware and legitimate files.

1 INTRODUCTION

Malware refers to a malicious software that has the intent to damage, disrupt, destroy, or perform harmful actions on a computer system. The detection of malicious software through ML-based methods has received an increasing amount of attention in cybersecurity. To build a malware classifier, the features are extracted from legitimate and malicious files either statically or dynamically. The techniques that extract static features do not execute the file and only examine the code structure and other binary properties. On the other hand, dynamic features are obtained by observing the execution behavior of the program. The selected features, be they static, dynamic features or both, are then fed into the ML model to discriminate between legitimate and malicious files. These models can be embedded in antivirus software to provide an automatic detection tool for incoming files.

The advances and presence of intelligence in the adversaries' techniques have facilitated the need to craft adversarial examples that are rarely identified by

deployed ML models such as Decision tree (DT), Support Vector Machine (SVM), Logistic Regression (LR), and Artificial Neural Network (ANN). To attack a deployed malware detection system, three assumptions are made in the literature about the knowledge available to the adversaries, namely white-box, black-box, and gray box. In the white-box scenario, the adversaries have immediate access to the ML system's architecture, its parameters, and its training data. However, adversaries in reality do not have access to this kind of information. Thus, the adversaries operate instead in a black-box threat model. They use the target classifier as an oracle to label their adversarial examples. These labels are then used to train a surrogate model to approximate the target classifier. In the gray box model, an adversary is expected to know the architecture of the target model but have no access to its parameters. A number of attack algorithms have been proposed to generate adversarial samples for the white-box threat model such as FGSM, L-BFGS, C&W attacks, JSMA, and DeepFool. These algorithms can be exploited in many black-box and gray-box settings due to the

^a  <https://orcid.org/0000-0001-9406-6809>

^b  <https://orcid.org/0000-0001-6784-1291>

transferability of the adversarial samples among the models (Liu et al., 2016; Papernot, McDaniel, & Goodfellow, 2016). However, there are two main methods of black-box attack: transferability-based methods (Hu & Tan, 2018; Papernot et al., 2017; Rosenberg et al., 2018) and GAN-based methods (Hu & Tan, 2017; Zhao et al., 2017). In this paper, we use GAN to construct adversarial examples to bypass a black-box malware detection system.

Cryptanalysts are in a battle with malware authors to develop countermeasures to solidify malware classification systems. Building a secure and robust machine learning-based detection model is considered to be an open research problem. GAN, unlike other gradient-based approaches, needs to reverse engineer the target classifier to mathematically prepare the adversarial examples. Therefore, we suggest using a heterogeneous ensemble classifier that combines classification and clustering to produce consolidated classification results. Many researchers have been focused on the use of supervised ML algorithms to detect malicious software. In this paper, we show that the combination of cluster and classifier ensembles can improve the malware detection rate. To the best of our knowledge, no study has investigated the combination of supervised and unsupervised models for malware classification. Our study makes use of the algorithm introduced in (Acharya et al., 2011), whose name is C3E (from the Consensus between Classification and Clustering Ensembles). This algorithm assumes that clusters can provide supplementary constraints that help to classify new data. The task of combining classification and clustering at the output level is mapped into an optimization problem. To classify new malware and legitimate files, we have used a C3E based on Squared loss, C3E-SL (Coletta et al., 2015). This algorithm needs two hyper-parameters: the relative importance of the classifier and cluster ensembles (σ), and the number of iterations of the algorithm (N).

The rest of this paper is organized as follows. Section 2 presents the related work, Section 3 provides a detailed description of our methodology, Section 4 explains the implementation of our proposed method, Section 5 discusses the evaluation results, and Section 6 describes the future work and concludes the paper.

2 RELATED WORK

Classifying malware programs using ML-based algorithms instead of traditional techniques such as

signature-based algorithms, heuristic-based methods and behavior-based methods has been studied intensively (Gibert et al., 2020). Several research papers have been proposed to use standalone classifiers for malware classification. Nevertheless, the findings show that using standalone classifiers is not adequate enough to generalize and identify the adversarial examples. For instance, deep learning is claimed to be vulnerable to the manipulation of its input (Szegedy et al., 2013). As a result, major recent research has been devoted to hardening the supervised learning algorithm by incorporating defensive techniques during the training phase. In this section, we initially review the most common papers that propose and investigate countermeasures and adversarial malware examples. Next, we briefly outline the ensemble learning techniques that combine either supervised models, unsupervised models, or both supervised and unsupervised models.

Grosse and her colleagues (Grosse et al., 2016) showed how to successfully implement adversarial examples to bypass feed forward neural networks. They adopted a forward derivative-based approach (Papernot, McDaniel, Jha, et al., 2016) to craft the adversarial examples. The reason for focusing on forward derivative approaches instead of gradient descent techniques is that the forward derivatives are applicable to both supervised and unsupervised models as well as allowing the adversaries to generate information for broad families of adversarial samples. This approach exploits the Jacobian Matrix which contains the forward derivative of the cost function of a trained classifier with respect of its input. These derivatives are used to estimate the direction in which a perturbation in the input sample can change the classifier's output. The adversarial example is generated by adding a perturbation with a maximal positive gradient to the benign class to a malicious sample. Their results indicate that neural networks should not be used without hardening them against adversarial samples.

Wang et al (Wang et al., 2017) proposed a Random Feature Nullification (RFN) which is an adversary resistant method that prevents attackers from creating adversarial samples by randomly nullifying features within the samples. Their techniques can be viewed as stochastically "dropping" or omitting neuronal along with their connections. The results show that the combination of RFN with Adversarial Training reaches the best level of resistance.

On the other hand, Ngoc vi et al (Vi et al., 2019) proposes a solution to the malware classification

problem in a different way which is motivated by the significant success of a convolutional neural network. Their method is based on the gradient to attack image-based malware classification systems by introducing perturbations to the resource section of PE files. They apply the FGSM method to generate adversarial images by adding perturbations to the resource section of PE files. They conclude that training with the adversarial examples created by their method can improve the robustness of a malware classifier.

Grosse et al. (Grosse et al., 2017) introduces two procedures to detect adversarial examples, namely statistical tests and training with an outlier class. The first procedure investigates the ability of a statistical test to distinguish between benign and adversarial data points. They claim that the distribution of original legitimate data is different from the distribution of adversarial examples. They empirically proved that statistical tests can be used to detect adversarial examples before they are fed into a ML model. In the second procedure, they augment their ML model with an additional class to represent the adversarial examples and train the model to recognize adversarial examples as part of this new class. They expect that the integration of the two approaches will be beneficial.

GAN (Goodfellow et al., 2014) has been used extensively to generate synthetic images to augment small datasets for DNNs models. Hu and Tan (Hu & Tan, 2017) exploited GAN to simulate attacks to evade a black-box malware detection system. The difference between their proposed algorithm – MalGAN- and the existing ones is that the adversarial examples are dynamically generated according to the feedback of the black-box detector. The generator transforms a malware binary feature vector into its adversarial version and then its output is fed to a black-box detector to label it. The substitute detector, also known as a discriminator, is used to fit the black-box detector and provide the gradient information to train the generator. Both the generator and substitute detector are part of a multi-layer feed-forward neural network.

AdvGAN (Xiao et al., 2018) has been proposed to generate adversarial examples using generative adversarial networks (GANs). Once AdvGAN is trained, the feed-forward generator can produce adversarial perturbations efficiently. The model is applied in both a semi-white-box and black-box settings with a high attack success rate. The adversarial examples generated by AdvGAN on different target models have achieved higher attack success rate under state-of-the-art defenses compared to other adversarial example generating methods.

Jin et al. (Shen et al., 2017) proposed an adversarial perturbation elimination framework named APE-GAN to eliminate the perturbation of the adversarial examples before feeding it into classification networks. They evaluated their work under different settings and the results show that the error rates of the adversarial inputs are significantly decreased after its perturbation is eliminated by APE-GAN. Unlike the previous GAN-based methods, AI-GAN (Bai et al., 2021) presents a new variant of GAN to generate adversarial examples. In AI-GAN, the attacker is added to train the discriminator adversarially. The evaluation of AI-GAN's attack ability is applied in white-box with different attack settings as well as a complicated dataset. AI-GAN achieves a high attack success rate with a low generation time in various settings as well as scalability to complicated datasets.

Ensemble learning has been used for both unsupervised and supervised models and it has a better accuracy result than its individual components. Bagging, Boosting, XG-Boost, Rule Aggregation, Stacking, and an adaptive mixture of experts are state-of-the-art supervised ensemble approaches derived from multiple base classifiers. These ensemble methods need a huge amount of labeled data and work at the raw data level. On the other hand, ensemble techniques in the unsupervised learning are mainly focused on generating more stable clustering results by combining multiple partitions or performing distribution computing under privacy or sharing constraints (Strehl & Ghosh, 2002). There have been very limited efforts that combine multiple base classifiers and clusters (Acharya et al., 2011; Ao et al., 2014; Chakraborty, 2017; Gao et al., 2011). Every attempt uses a different strategy to combine classification and clustering to refine the final classification results but all of them work at the meta-output level without accessing the raw data. For malware classification, few studies have been conducted leveraging ensemble learning techniques to improve the malware detection rate (Chen et al., 2017; Kong & Yan, 2013; Yan et al., 2018; Ye et al., 2010). As far as we know, there is no study in the literature that has considered a heterogeneous ensemble classifier that merges classification and clustering as a malware classification system.

3 METHODOLOGY

3.1 Problem Definition and Formalization

Given the deployed malware classification system under the threat model described below, the adversary attempts to bypass this system to increase the misclassification rate of adversarial examples. In short, a substitute classifier is trained on a dataset that contains a thousand of binary legitimate and malicious vectors. Then, an adversarial malicious sample is generated iteratively by modifying the limited features of malicious sample until a misclassification occurs. Finally, the deployed malware classification system is evaluated under the attacks at test time.

3.2 Threat Model

We considered black-box attacks during the test time where the adversary does not know the targeted malware classifier’s architecture and parameters. Its knowledge is limited to the type of features and the predicted class of the target classifier. The adversary’s goal is to find a sample x that is similar to an original sample x but classified differently. To achieve this, we used the MalGAN algorithm (Hu & Tan, 2017) to find the minimum perturbation to add to x to craft an adversarial example. MalGAN has three basic elements: the generator, the black-box detector, and the surrogate detector.

The generator produces a perturbation vector O from a concatenation of malware feature vector m and a random noise vector z . Each element of z is a random number sampled from normal distribution with a mean of 0 and a standard deviation of 1. Since malware feature values are binary, binarization transformation is applied to O according to whether an element is greater than 0.8 or not. This process produces a binary vector O^0 . The final generated adversarial malware example can be expressed as:

$m^0 = m \cup O^0$ where \cup is the element-wise binary OR operation.

Since m^0 is a binary vector, this will make the gradients unable to back propagate from the surrogate detector to the generator. Therefore, a smooth function G is defined to receive gradient information from the surrogate detector as shown below:

$G(m, z) = \max(m, o)$ where $\max(\dots)$ represents element-wise max operation such that : When an element of m is 1, the result of G will be 1 as well and this will prevent from back propagate the gradients. When an element of m is 0, the result of G

is the neural network’s real number output in the corresponding dimension, and the gradient information can back propagate.

The ground truth classes of training data are not used to train the surrogate detector. Alternatively, the black-box detector detects the training data that consisted of adversarial malware examples from the generator, and legitimate programs from an additional legitimate dataset to predict whether a program is benign or malware. Then the predicted labels from the black-box detector is used to train the surrogate detector.

The surrogate detector distinguishes the adversarial malware samples from legitimate files. Practically speaking, the generator is trained to minimize the probability of generated adversarial malware examples being classified as false by the surrogate detector while the surrogate detector tries to maximize the probability of generated adversarial malware. The surrogate detector tries to mimic the predications of the black-box detector and provide gradient information to train the generator. The generator and the surrogate detector work together to deceive our heterogeneous ensemble classifier.

GANs come in three popular loss functions: the original Jensen-Shanon divergence (Goodfellow et al., 2014), least squares GANs (LSGAN) (Mao et al., 2017), and Wasserstein distance (WGAN) (Arjovsky et al., 2017). In this paper, we exploit two variants of GAN: vanilla GAN and WGAN. WGAN uses Wasserstein distance for the divergence between model distribution and target distribution and it has a smoother gradient which in turn helps to stabilize training. The MalGAN algorithm does not offer a mechanism to bound the number of feature modifications. In this paper, we will tackle this weakness to ensure the functionality of the adversarial malware examples.

3.3 Victim Model

The victim model is an ensemble classifier that combines both classification and clustering. In this paper, we are trying to verify our hypothesis which states that a heterogeneous ensemble classifier is robust against GAN attacks. We adopted the algorithm introduced by (Acharya et al., 2011) to build our ensemble classifier. Their algorithm (C3E) consists of three steps.

1. An ensemble of r trained classifiers is applied to new data $X = \{x_i\}_{i=1}^n$. The output of each constitute classifier for each x_i is a k -dimensional class probability vector π_i . From

the set of such vectors $\{\pi_i^{q_1}\}_{q_1=1}^{r_1}$, an average vector can be computed for xi as:

$$\pi_i = \frac{1}{r_1} \sum_{q_1=1}^{r_1} \pi_i^{q_1}$$

2. A similarity (co-association) matrix S is computed after an ensemble of r_2 trained clusters are applied on a new data $X = \{x_i\}_{i=1}^n$, Each entry in this matrix represents the similarity between two objects which is simply the fraction of the r_2 cluster solutions in which the two objects lie in the same cluster.
3. The consolidated result of C3E is achieved after finding the minimum solution of the following objective function.

$$j = x_L(\pi_i, y_i) + \sigma^x s_{ij} L(y_i, y_j) \quad (1) \quad i \in x \quad (i, j)$$

- The quantity $L(.,.)$ denotes a loss function.
- The first term captures the dissimilarities between the class probabilities provided by the ensemble of classifiers and the output vectors $\{y_i\}_{i=1}^n$.
- The second term encodes the weighted dissimilarity between all possible pairs (y_i, y_j) . The weights of these pairs are assigned in proportion to the similarity values s_{ij} of matrix S.
- σ is a hyper-parameter which controls the relative importance of the classifier and cluster ensembles.

The problem of classifying the new data X can be approached as an optimization problem whose objective is to minimize J. In (Acharya et al., 2011), the authors state that any Bregman divergence can be used as the loss function $L(.,.)$ in the last equation. Bregman divergences include a large number of useful loss functions such as the well-known squared loss, KL-divergence, logistic loss, Mahalanobis distance, and I-divergence. As in (Coletta et al., 2015), we selected this to exploit a squared loss (SL) function, hence the optimization over $\{y_i\}_{i=1}^n$ can be a closed form solution. The objective function in equation (1) is rewritten as

$$j = x_{\|y_i - \pi_i\|^2} + \sigma^x s_{ij} L(y_i, y_j) \quad (2) \quad i \in x \quad (i, j)$$

By keeping $\{y_j\}_{j=1}^n / \{y_i\}$ fixed and sitting $\frac{\partial J}{\partial y_i} = 0$, we get

$$y_i = \frac{\pi_i + \sigma \sum_{j \neq i} s_{ij} y_j}{1 + \sigma \sum_{j \neq i} s_{ij}} \quad (3)$$

Equation (3) can be computed iteratively, for all $i \in \{1, 2, \dots, n\}$, until a maximum number of iterations is reached, in order to obtain posterior class probability distributions for the instances in X (Coletta et al., 2015). The objective of combining unsupervised models is to provide supplementary constraints for classifying new data (Banerjee & Ghosh, 2008). This point of view presumes that the similar new data points in the test set that lie in the same cluster are more likely to share the same class label. Thus, we believe these constraints will improve the generalization capability of our ensemble classifier.

4 DEFENSIVE MECHANISMS

The most common defensive mechanisms mentioned in the literature are randomness (Biggio et al., 2010), preventing overfitting, feature selection (Xu et al., 2016), distillation (Papernot, McDaniel, Wu, et al., 2016), ensemble adversarial training (Chinavle et al., 2009), denoising, random input transformation, non-linearity (Šrndić & Laskov, 2013), and micro-detectors (Saad et al., 2019). Our hybrid machine learning model introduces randomness to the classifier system through the ensemble of classifiers and clusters. This randomness prevents the adversaries accessing the parameters of the classification system. As a result, we believe this information hiding technique will be able to avoid GAN's attacks.

5 IMPLEMENTATION

5.1 Dataset

The dataset we used in our experiments was generated as a part of (Al-Dujaili et al., 2018) collected from Portable Execution (PE) files. This dataset contains 22,761 binary features. These binary features are the API calls extracted from malware and legitimate PE files. The PE format enfolds the information necessary for Windows OS to manage the wrapped code. The authors of (Al-Dujaili et al., 2018) create a corpus of 38,000 malicious and legitimate PE files. Each PE file is represented as a binary indicator feature vector. Each index of the feature vector represents a unique Windows API call where "1" represents the presence of the

corresponding API call. We divided the dataset into training, validation and test sets and the number of samples in each set is 22800, 7600, and 7600 respectively. Since the dataset is a Boolean matrix, we can visualize its sparsity using the `Matplotlib.spy()` method in Python. As shown in Figure 1, the dataset is apparently sparse as the graph is mostly white. Thus, we decided to apply `VarianceThreshold` to remove the features with a variance of less than 20%.



Figure 1: 2D plot to visualize the sparsity of our input matrix.

5.2 Threat Model's Architecture

As we mentioned in the methodology, we exploited MalGAN (Hu & Tan, 2017) to simulate evasion attacks against the proposed black-box detector. The architecture of MalGAN is presented in Figure 2. We used ANN with one hidden layer for both the generator and surrogate detector. To confirm our selection, we tried different architectures with different numbers of hidden layers. We found that using ANN with one hidden layer does not degrade the performance of both vanilla GAN and WGAN. On the contrary, it shows comparable results with ANNs with two and three hidden layers. We set the number of neurons in the hidden layer to 200 and added a dropout layer in the surrogate detector after the hidden layer to ensure it does not overfit the training set, and the L2 Regularizer applies the loss function of the generator.

The black-box detector is a trained heterogeneous ensemble classifier that combines clusters and classifiers (C3E-SL). The surrogate detector uses the black-box detector as an oracle to label the adversarial malware and legitimate files. During training, the surrogate detector tries to fit the black-box detector and push the generator to craft indistinguishable adversarial malware files.

The objective of GAN is to generate perturbations and add them to malware files to deceive our black-box detector system. In our experiments, we considered adding perturbations to modify the malware files because removing features may crack the malware files. In this paper, we want to show that crafting adversarial malware samples by GAN can transfer across different models.

Nonetheless, they hardly bypassed our hybrid model and achieved a low fooling rate.

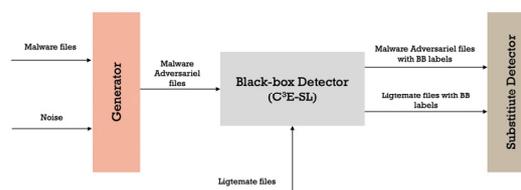


Figure 2: Architecture of our proposed method.

5.3 Restrictions on Adversarial Crafting

We applied two restrictions to the perturbations generated by the MalGAN algorithm. First, in the original implementation of MalGAN, the number of modifications applied to the original malware files were not restricted. During the training of MalGAN, the API call is enabled if the corresponding dimension of the generator's output has a value greater than 0.5. We believe that this threshold will change the malware application too much, hence it may not preserve its utility. We decided to increase this threshold to 0.8. Second, the number of epochs for training GAN model is a critical hyperparameter that should be selected carefully. GAN generally is exploited to synthesize new images that resemble real images. Thus, the GAN model should be trained for quite a long time to reach its intended purpose. However, this cannot be applied to malware files because we want the generator to enable API calls as little as possible to fool the discriminator. Therefore, we have tried a different number of epochs and discovered that 100 and 50 epochs are a reasonable choice for vanilla GAN and WGAN, respectively.

5.4 Victim Model's Architecture

As we discussed in the methodology, we consider randomness to be our defensive technique. This could be built using combination of classifiers and clusters. We leveraged (C3E-SL) to refine the initial class probabilities estimated by the ensemble of classifiers (Neural Network, SVM, Logistic Regression, and Random Forest) with the help of the ensemble of clusters (K-means, Mean-shift, and GMM). All the classifiers and clusters were trained on the reduced features set (199 dimensions) after applying `VarianceThreshold`.

According to (IBM Support, 2020), Boolean data is not preferred with K-means. Thus, we converted our categorical features to continuous features using

PCA before feeding the training set to the K-means cluster. To evaluate the clustering results of the three clusters, we exploit Adjusted Rand index (ARI), which is a function that measures the similarity of two assignments - the one given by the clustering process and the other by the true label. Unfortunately, we do not have knowledge of the ground truth for clustering. Thus, we alternatively consider analyzing how similar the clustering results generated by K-means with GMM and Mean Shift are. More specifically, we used ARI to calculate the agreement score between K-means and (GMM and Mean Shift). The aim of this test was to verify two things. First, we want to indicate whether similar objects lie in the same group/cluster in all clustering models. Secondly, is the similar score going to differ if continuous features are used instead of categorical features in the GMM and Mean Shift models? After conducting this test, we found that using continuous features yields a higher agreement score by about 99% between the clustering models.

6 EXPERIMENTAL SETUP

This section discusses the empirical evaluation of our proposed method. Since it is infeasible that the authors of malware files and antivirus vendors collect the same dataset, the attack model (MalGAN) and the victim model (an ensemble of classifiers and clusters) were trained on different training sets. The number of samples in the dataset totaled 38,000 and this total was distributed according to 22800, 7600, 7600 among the training set, validation set, and test set respectively. We split the training set into A (20%) for training the attack model and B (80%) for training the victim model. To avoid overfitting the standalone classifiers while tuning their hyper-parameters, we used the whole validation set. The Adam optimizer with a learning rate of 0.001 and RMSProp with a learning rate of 0.0001 were selected as the optimizers for vanilla GAN and WGAN, respectively.

To validate the efficiency of the proposed method in terms of the malware detection rate, we conducted two experiments where in the first experiment the adversarial malware examples are crafted by the vanilla GAN and in the second experiment, they are crafted by WGAN. In both experiments, we compared its performance with SVM, RF, LR and ANN. To guarantee a compatible comparison between our hybrid model and the base classifiers and to prevent overfitting, we utilized two generalization techniques - dropout and L2 regularization. We added

both techniques to the ANN model and L2 regularization to LR and SVM. Dropout randomly drops hidden units (along with their connections) from the neural network during training. This enhances the model generalization and provides a way of approximately combining many different neural network architectures efficiently. L2 regularization reduces the likelihood of ANN model overfitting by preventing the weight of any values from getting large in magnitude. This is done by adding a weight penalty to the cost function.

Training both vanilla and Wasserstein GAN models is hard as they require a delicate balance between the generator and discriminator. We have spent a sufficient time tuning the hyper-parameters considering the constraints we imposed in Section 4.3. We will discuss a few of the findings we noticed during the training of the threat model before giving our remarks about the empirical results. First, the user-defined parameter σ in the (C3E-SL) algorithm should be assigned a low value because values higher than 0.0001 will cause C3E-SL to be susceptible to adversarial attacks during testing. Second, the generator of WGAN starts to construct undiscriminating adversarial samples between epoch 35 and epoch 50. Third, vanilla GAN suffers from gradient fluctuations, hence the loss of the plots obtained during training is not indicative of getting highly effective adversarial samples. Table (1) shows the detection rate of the adversarial malware files according to five models. As we can see, our model has achieved the highest rate of 42.8%. The combination of clusters and classifiers is evidenced to improve the malware detection rate. It is worth noting in Figure 3 that the generated adversarial examples are increasingly rejected by our model after epoch 60. This is evidence that the surrogate detector of vanilla GAN is not strong enough to stimulate the generator to craft adversarial examples that are hardly detected. On the other hand, the ANN model attained the second highest detection rate and this is due to a couple of reasons. First, the two generalization mechanisms dropout and L2 regularization has empowered the ANN model to expose 35.6% of the adversarial malware files. Second, both the attack and victim models use the same ML algorithm, hence the adversarial malware files are readily transferred from MalGAN to ANN. For Random Forest, Logistic Regression, and SVM, the TPR ranges from 26.8% to 30%.

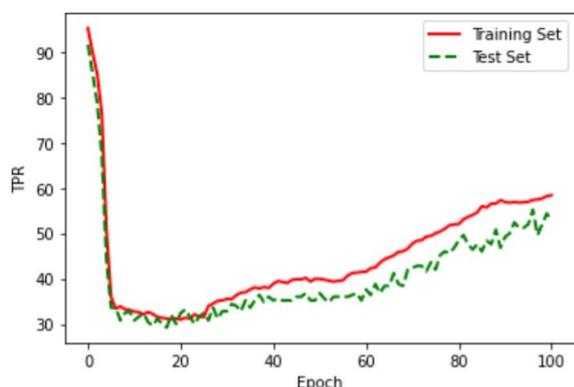


Figure 3: The change in the true positive rate of the training and test sets during the training of the GAN for 100 epochs. The black-box detector here is our heterogeneous ensemble classifier.

One of the tedious issues of training vanilla GAN is instability, which leads to gradient fluctuations (Salimans et al., 2016). Wasserstein GAN (WGAN) overcomes this difficulty. The graphs with a learning curve and accuracy line for WGAN are presented in Figure 4. The top subplot shows the line plots for the average discriminator loss for both malware and legitimate samples (blue), and the generator loss for generated adversarial malware samples (orange). We can see that the discriminator loss is somewhat erratic in the beginning of the training before stabilizing around epoch 30. The loss remains stable after that, even though the variance between the generator and discriminator increases.

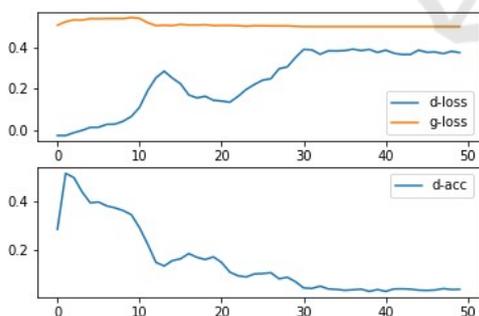


Figure 4: Line plots of loss and accuracy for WGAN.

Table (2) presents the detection rate of the adversarial examples constructed using WGAN against the proposed hybrid model. The figures dramatically decreased for all classification methods. WGAN-based attacks were able to fool our model and only 19.2% of adversarial examples were detected. We justify this result as the ensemble of the clusters was not able to cluster the adversarial examples correctly. This affected the final result of

(C3E-SL). The convergence curve of TPR on the training set and test set is shown in Figure 5. For both the training and test sets, TPR starts to fall sharply near the epoch 35. This is due to WGAN starting to create indistinguishable adversarial examples that were hardly detected by our model. For the standalone classifiers, SVM obtained the highest detection rate at 18% and LR obtained the lowest at 12.4%.

Table 1: True positive rate of the adversarial malware examples when the attack model is vanilla GAN and the victim models are four standalone classifiers and our hybrid model trained on a different training set.

Models	Test set
NN	35.6 %
LR	26.8%
SVM	30%
RF	30.4%
Hybrid model	42.8 %

Table 2: True positive rate of the adversarial malware examples when the attack model is WGAN and the victim models are four standalone classifiers and our hybrid model trained on a different training set.

Models	Test set
NN	16.4 %
LR	12.4%
SVM	18 %
RF	15.2%
Hybrid model	19.2%

The differences in the detection rate of the malware samples in Tables (1) and (2) lead us to this observation. WGAN trains the discriminator more than the generator and in turn it pushes the generator to design indistinguishable adversarial samples. Thus, the highly effective adversarial samples were solely able to bypass the black-box detector systems.

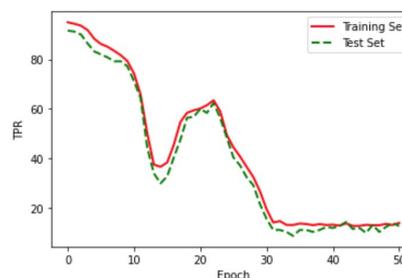


Figure 5: The change in the true positive rate of the training and test sets during the training of the WGAN for 50 epochs. The black-box detector here is our heterogeneous ensemble classifier.

7 CONCLUSION AND FUTURE WORK

In this paper, we have proposed a framework that has investigated the viability of heterogeneous machine learning model against GAN-based evasion attacks. These kinds of attack are rarely detected by ML-based malware detectors that are not backed by defensive techniques. For instance, 87.6% of adversarial malware examples constructed by WGAN bypass the Logistic Regression classifier. The presented empirical results have proven that combining supervised and unsupervised models can thwart roughly 42.8% of vanilla GAN-based attacks and 19.2% of WGAN-based attacks.

There are several aspects that can be investigated in the future. First, there is the impact of increasing the number of clusters and classifiers in C3E-SL to improve the malware detection rate. Second, there is changing the squared loss in equation (1) for another Bregman divergence. The third is by applying our model in different application examples such as spam and intrusion detection to definitely verify our claims about the hardness of our proposed method. Fourth is injecting adversarial examples in the training set and retraining the hybrid model. We believe that adversarial retraining will improve the heterogeneous model's robustness and encourage it to generalize well to unseen data.

REFERENCES

- Acharya, A., Hruschka, E. R., Ghosh, J., & Acharyya, S. (2011). C 3 e: a framework for combining ensembles of classifiers and clusterers. *International Workshop on Multiple Classifier Systems*, 269–278.
- Al-Dujaili, A., Huang, A., Hemberg, E., & O'Reilly, U.-M. (2018). Adversarial deep learning for robust detection of binary encoded malware. *2018 IEEE Security and Privacy Workshops (SPW)*, 76–82.
- Ao, X., Luo, P., Ma, X., Zhuang, F., He, Q., Shi, Z., & Shen, Z. (2014). Combining supervised and unsupervised models via unconstrained probabilistic embedding. *Information Sciences*, 257, 101–114.
- Arjovsky, M., Chintala, S., & Bottou, L. (2017). Wasserstein generative adversarial networks. *International Conference on Machine Learning*, 214–223.
- Bai, T., Zhao, J., Zhu, J., Han, S., Chen, J., Li, B., & Kot, A. (2021). Ai-gan: Attack-inspired generation of adversarial examples. *2021 IEEE International Conference on Image Processing (ICIP)*, 2543–2547.
- Banerjee, A., & Ghosh, J. (2008). Clustering with balancing constraints. *Constrained Clustering: Advances in Algorithms, Theory, and Applications*, 171–200.
- Biggio, B., Fumera, G., & Roli, F. (2010). Multiple classifier systems for robust classifier design in adversarial environments. *International Journal of Machine Learning and Cybernetics*, 1(1), 27–41.
- Chakraborty, T. (2017). Ec3: Combining clustering and classification for ensemble learning. *2017 IEEE International Conference on Data Mining (ICDM)*, 781–786.
- Chen, L., Hou, S., & Ye, Y. (2017). Securedroid: Enhancing security of machine learning-based detection against adversarial android malware attacks. *Proceedings of the 33rd Annual Computer Security Applications Conference*, 362–372.
- Chinavle, D., Kolari, P., Oates, T., & Finin, T. (2009). Ensembles in adversarial classification for spam. *Proceedings of the 18th ACM Conference on Information and Knowledge Management*, 2015–2018.
- Coletta, L. F. S., Hruschka, E. R., Acharya, A., & Ghosh, J. (2015). A differential evolution algorithm to optimise the combination of classifier and cluster ensembles. *International Journal of Bio-Inspired Computation*, 7(2), 111–124.
- Gao, J., Liang, F., Fan, W., Sun, Y., & Han, J. (2011). A graph-based consensus maximization approach for combining multiple supervised and unsupervised models. *IEEE Transactions on Knowledge and Data Engineering*, 25(1), 15–28.
- Gibert, D., Mateu, C., & Planes, J. (2020). The rise of machine learning for detection and classification of malware: Research developments, trends and challenges. *Journal of Network and Computer Applications*, 153, 102526.
- Goodfellow, I., Pouget-Abadie, J., Mirza, M., Xu, B., Warde-Farley, D., Ozair, S., Courville, A., & Bengio, Y. (2014). Generative adversarial nets. *Advances in Neural Information Processing Systems*, 27.
- Grosse, K., Manoharan, P., Papernot, N., Backes, M., & McDaniel, P. (2017). On the (statistical) detection of adversarial examples. *ArXiv Preprint ArXiv:1702.06280*.
- Grosse, K., Papernot, N., Manoharan, P., Backes, M., & McDaniel, P. (2016). Adversarial perturbations against deep neural networks for malware classification. *ArXiv Preprint ArXiv:1606.04435*.
- Hu, W., & Tan, Y. (2017). Generating adversarial malware examples for black-box attacks based on GAN. *ArXiv Preprint ArXiv:1702.05983*.
- Hu, W., & Tan, Y. (2018). Black-box attacks against RNN based malware detection algorithms. *Workshops at the Thirty-Second AAAI Conference on Artificial Intelligence*.
- IBM Support. (2020). *Clustering binary data with K-Means (should be avoided)*. IBM.
- Kong, D., & Yan, G. (2013). Discriminant malware distance learning on structural information for automated malware classification. *Proceedings of the*

- 19th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, 1357–1365.
- Liu, Y., Chen, X., Liu, C., & Song, D. (2016). Delving into transferable adversarial examples and black-box attacks. *ArXiv Preprint ArXiv:1611.02770*.
- Mao, X., Li, Q., Xie, H., Lau, R. Y. K., Wang, Z., & Paul Smolley, S. (2017). Least squares generative adversarial networks. *Proceedings of the IEEE International Conference on Computer Vision*, 2794–2802.
- Papernot, N., McDaniel, P., & Goodfellow, I. (2016). Transferability in machine learning: from phenomena to black-box attacks using adversarial samples. *ArXiv Preprint ArXiv:1605.07277*.
- Papernot, N., McDaniel, P., Goodfellow, I., Jha, S., Celik, Z. B., & Swami, A. (2017). Practical black-box attacks against machine learning. *Proceedings of the 2017 ACM on Asia Conference on Computer and Communications Security*, 506–519.
- Papernot, N., McDaniel, P., Jha, S., Fredrikson, M., Celik, Z. B., & Swami, A. (2016). The limitations of deep learning in adversarial settings. *2016 IEEE European Symposium on Security and Privacy (EuroS&P)*, 372–387.
- Papernot, N., McDaniel, P., Wu, X., Jha, S., & Swami, A. (2016). Distillation as a defense to adversarial perturbations against deep neural networks. *2016 IEEE Symposium on Security and Privacy (SP)*, 582–597.
- Rosenberg, I., Shabtai, A., Rokach, L., & Elovici, Y. (2018). Generic black-box end-to-end attack against state of the art API call based malware classifiers. *International Symposium on Research in Attacks, Intrusions, and Defenses*, 490–510.
- Saad, S., Briguglio, W., & Elmiligi, H. (2019). The curious case of machine learning in malware detection. *ArXiv Preprint ArXiv:1905.07573*.
- Salimans, T., Goodfellow, I., Zaremba, W., Cheung, V., Radford, A., & Chen, X. (2016). Improved techniques for training gans. *Advances in Neural Information Processing Systems*, 29.
- Shen, S., Jin, G., Gao, K., & Zhang, Y. (2017). Ape-gan: Adversarial perturbation elimination with gan. *ArXiv Preprint ArXiv:1707.05474*.
- Šrndić, N., & Laskov, P. (2013). Detection of malicious pdf files based on hierarchical document structure. *Proceedings of the 20th Annual Network & Distributed System Security Symposium*, 1–16.
- Strehl, A., & Ghosh, J. (2002). Cluster ensembles---a knowledge reuse framework for combining multiple partitions. *Journal of Machine Learning Research*, 3(Dec), 583–617.
- Szegedy, C., Zaremba, W., Sutskever, I., Bruna, J., Erhan, D., Goodfellow, I., & Fergus, R. (2013). Intriguing properties of neural networks. *ArXiv Preprint ArXiv:1312.6199*.
- Vi, B. N., Nguyen, H. N., Nguyen, N. T., & Tran, C. T. (2019). Adversarial examples against image-based malware classification systems. *2019 11th International Conference on Knowledge and Systems Engineering (KSE)*, 1–5.
- Wang, Q., Guo, W., Zhang, K., Ororbia, A. G., Xing, X., Liu, X., & Giles, C. L. (2017). Adversary resistant deep neural networks with an application to malware detection. *Proceedings of the 23rd ACM Sigkdd International Conference on Knowledge Discovery and Data Mining*, 1145–1153.
- Xiao, C., Li, B., Zhu, J.-Y., He, W., Liu, M., & Song, D. (2018). Generating adversarial examples with adversarial networks. *ArXiv Preprint ArXiv:1801.02610*.
- Xu, W., Qi, Y., & Evans, D. (2016). Automatically evading classifiers. *Proceedings of the 2016 Network and Distributed Systems Symposium*, 10.
- Yan, J., Qi, Y., & Rao, Q. (2018). Detecting malware with an ensemble method based on deep neural network. *Security and Communication Networks*, 2018.
- Ye, Y., Li, T., Chen, Y., & Jiang, Q. (2010). Automatic malware categorization using cluster ensemble. *Proceedings of the 16th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, 95–104.
- Zhao, Z., Dua, D., & Singh, S. (2017). Generating natural adversarial examples. *ArXiv Preprint ArXiv:1710.11342*.