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A Taxonomy and Terminology of Attacks and Mitigations

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A Taxonomy and Terminology of Attacks and Mitigations

Alina Oprea
Northeastern University

Apostol Vassilev
Computer Security Division
Information Technology Laboratory

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NIST Author ORCID iDs

Alina Oprea: 0000-0002-4979-5292
Apostol Vassilev: 0000-0002-9081-3042

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ai-100-2@nist.gov

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Abstract

This NIST NIST AI report develops a taxonomy of concepts and defines terminology in the field of adversarial machine learning (AML). The taxonomy is built on survey of the AML literature and is arranged in a conceptual hierarchy that includes key types of ML methods and lifecycle stage of attack, attacker goals and objectives, and attacker capabilities and knowledge of the learning process. The report also provides corresponding methods for mitigating and managing the consequences of attacks and points out relevant open challenges to take into account in the lifecycle of AI systems. The terminology used in the report is consistent with the literature on AML and is complemented by a glossary that defines key terms associated with the security of AI systems and is intended to assist non-expert readers. Taken together, the taxonomy and terminology are meant to inform other standards and future practice guides for assessing and managing the security of AI systems, by establishing a common language and understanding of the rapidly developing AML landscape.

Keywords

artificial intelligence; machine learning; attack taxonomy; evasion; data poisoning; privacy breach; attack mitigation; data modality; trojan attack, backdoor attack; chatbot.

NIST AI Reports (NIST AI)

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Audience

The intended primary audience for this document includes individuals and groups who are responsible for designing, developing, deploying, evaluating, and governing AI systems.

Background

This document is a result of an extensive literature review, conversations with experts from the area of adversarial machine learning, and research performed by the authors in adversarial machine learning.

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This NIST NIST AI report focuses on identifying, addressing, and managing risks associated with adversarial machine learning. While practical guidance[1] published by NIST may serve as an informative reference, this guidance remains voluntary.

The content of this document reflects recommended practices. This document is not intended to serve as or supersede existing regulations, laws, or other mandatory guidance.

[1]The term 'practice guide,' 'guide,' 'guidance' or the like, in the context of this paper, is a consensus-created, informative reference intended for voluntary use; it should not be interpreted as equal to the use of the term 'guidance' in a legal or regulatory context. This document does not establish any legal standard or any other legal requirement or defense under any law, nor have the force or effect of law.

How to read this document

This document uses terms such as AI technology, AI system, and AI applications interchangeably. Terms related to the machine learning pipeline, such as ML model or algorithm, are also used interchangeably in this document. Depending on context, the term "system" may refer to the broader organizational and/or social ecosystem within which the technology was designed, developed, deployed, and used instead of the more traditional use related to computational hardware or software.

Important reading notes:

- The document includes a series of blue callout boxes that highlight interesting nuances and important takeaways.
- Terms that are used but not defined/explained in the text are listed and defined in the GLOSSARY. They are displayed in small caps in the text. Clicking on a word shown in small caps (e.g., ADVERSARIAL EXAMPLES) takes the reader directly to the definition of that term in the Glossary. From there, one may click on the page number shown at the end of the definition to return.

Acknowledgments

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Author Contributions

Authors contributed equally and are listed in alphabetical order.

Executive Summary

This NIST AI report is intended to be a step toward developing a taxonomy and terminology of adversarial machine learning (AML), which in turn may aid in securing applications of artificial intelligence (AI) against adversarial manipulations of AI systems. The components of an AI system include – at a minimum – the data, model, and processes for training, testing, and deploying the machine learning (ML) models and the infrastructure required for using them. The data-driven approach of ML introduces additional security and privacy challenges in different phases of ML operations besides the classical security and privacy threats faced by most operational systems. These security and privacy challenges include the potential for adversarial manipulation of training data, adversarial exploitation of model vulnerabilities to adversely affect the performance of ML classification and regression, and even malicious manipulations, modifications or mere interaction with models to exfiltrate sensitive information about people represented in the data or about the model itself. Such attacks have been demonstrated under real-world conditions, and their sophistication and potential impact have been increasing steadily. AML is concerned with studying the capabilities of attackers and their goals, as well as the design of attack methods that exploit the vulnerabilities of ML during the development, training, and deployment phase of the ML life cycle. AML is also concerned with the design of ML algorithms that can withstand these security and privacy challenges. When attacks are launched with malevolent intent, the robustness of ML refers to mitigations intended to manage the consequences of such attacks.

This report adopts the notions of security, resilience, and robustness of ML systems from the NIST AI Risk Management Framework [170]. Security, resilience, and robustness are gauged by risk, which is a measure of the extent to which an entity (e.g., a system) is threatened by a potential circumstance or event (e.g., an attack) and the severity of the outcome should such an event occur. However, this report does not make recommendations on risk tolerance (the level of risk that is acceptable to organizations or society) because it is highly contextual and application/use-case specific. This general notion of risk offers a useful approach for assessing and managing the security, resilience, and robustness of AI system components. Quantifying these likelihoods is beyond the scope of this document. Correspondingly, the taxonomy of AML is defined with respect to the following four dimensions of AML risk assessment: (i) learning method and stage of the ML life cycle process when the attack is mounted, (ii) attacker goals and objectives, (iii) attacker capabilities, (iv) and attacker knowledge of the learning process and beyond.

The spectrum of effective attacks against ML is wide, rapidly evolving, and covers all phases of the ML life cycle – from design and implementation to training, testing, and finally, to deployment in the real world. The nature and power of these attacks are different and can exploit not just vulnerabilities of the ML models but also weaknesses of the infrastructure in which the AI systems are deployed. Although AI system components may also be adversely affected by various unintentional factors, such as design and implemen-

tation flaws and data or algorithm biases, these factors are not intentional attacks. Even though these factors might be exploited by an adversary, they are not within the scope of the literature on AML or this report.

This document defines a taxonomy of attacks and introduces terminology in the field of AML. The taxonomy is built on a survey of the AML literature and is arranged in a conceptual hierarchy that includes key types of ML methods and life cycle stages of attack, attacker goals and objectives, and attacker capabilities and knowledge of the learning process. The report also provides corresponding methods for mitigating and managing the consequences of attacks and points out relevant open challenges to take into account in the life cycle of AI systems. The terminology used in the report is consistent with the literature on AML and is complemented by a glossary that defines key terms associated with the security of AI systems in order to assist non-expert readers. Taken together, the taxonomy and terminology are meant to inform other standards and future practice guides for assessing and managing the security of AI systems by establishing a common language and understanding for the rapidly developing AML landscape. Like the taxonomy, the terminology and definitions are not intended to be exhaustive but rather to aid in understanding key concepts that have emerged in AML literature.

1. Introduction

Artificial intelligence (AI) systems [165] are on a global multi-year accelerating expansion trajectory. These systems are being developed by and widely deployed into the economies of numerous countries, leading to the emergence of AI-based services for people to use in many spheres of their lives, both real and virtual [57]. Advances in the generative capabilities of AI in text and images are directly impacting society at unprecedented levels. As these systems permeate the digital economy and become inextricably essential parts of daily life, the need for their secure, robust, and resilient operation grows. These operational attributes are critical elements of Trustworthy AI in the NIST AI Risk Management Framework [170] and in the taxonomy of AI Trustworthiness [167].

However, despite the significant progress that AI and machine learning (ML) have made in a number of different application domains, these technologies are also vulnerable to attacks that can cause spectacular failures with dire consequences. For example, in computer vision applications to image classification, well-known cases of adversarial perturbations of input images have caused autonomous vehicles to swerve into the opposite direction lane and the misclassification of stop signs as speed limit signs, the disappearance of critical objects from images, and even the misidentification of people wearing glasses in high-security settings [76, 116, 194, 207]. Similarly, in the medical field where more and more ML models are being deployed to assist doctors, there is the potential for medical record leaks from ML models that can expose deeply personal information [8, 103]. Attackers can also manipulate the training data of ML algorithms, thus making the AI system trained on it vulnerable to attacks [191]. Scraping of training data from the Internet also opens up the possibility of hackers poisoning the data to create vulnerabilities that allow for security breaches down the pipeline.

Large language models (LLMs) [27, 50, 62, 155, 206, 257] are also becoming an integral part of the Internet infrastructure. LLMs are being used to create more powerful online search, help software developers write code, and even power chatbots that help with customer service. With the exception of BLOOM [155], most of the companies developing such models do not release detailed information about the data sets that have been used to build their language models, but these data sets inevitably include some sensitive personal information, such as addresses, phone numbers, and email addresses. This creates serious risks for user privacy online. The more often a piece of information appears in a data set, the more likely a model is to leak it in response to random or specifically designed queries or prompts. This could perpetuate wrong and harmful associations with damaging consequences for the people involved and bring additional security and safety concerns [34, 148].

As ML models continue to grow in size, many organizations rely on pre-trained models that could either be used directly for prediction or be fine-tuned with new datasets to enable different predictive tasks. This creates opportunities for malicious modifications of pre-trained models by inserting TROJANS to enable attackers to compromise the model availability, force incorrect processing, or leak the data when instructed [91].

This report offers guidance for the development of:

- Standardized terminology in AML to be used by the ML and cybersecurity communities;
- A taxonomy of the most widely studied and effective attacks in AML, including evasion, poisoning, and privacy attacks; and
- A discussion of potential mitigations in AML that have withstood the test of time and limitations of some of the existing mitigations.

As AML is a fast evolving field, we envision the need to update the report regularly as new developments emerge on both the attack and mitigation fronts.

> The goal of this report is not to provide an exhaustive survey of all literature on AML. In fact, this by itself is an almost impossible task as a search on arXiv for AML articles in 2021 and 2022 yielded more than 5000 references. Rather, this report provides a categorization of attacks and their mitigations, starting with the three main types of attacks: 1) evasion, 2) data and model poisoning, and 3) data and model privacy.

Historically, modality-specific ML modeling technology has emerged for each input modality (e.g., text, images, speech, tabular data), each of which is susceptible to domain-specific attacks. For example, the attack approaches for image classification tasks do not directly translate to attacks against natural language processing (NLP) models. Recently, the transformer technology from NLP has entered the computer vision domain [68]. In addition, multimodal ML has made exciting progress in many tasks, and there have been attempts to use multimodal learning as a potential mitigation of single-modality attacks [245]. However, powerful simultaneous attacks against all modalities in a multimodal model have also emerged [44, 195, 243]. The report discusses attacks against all viable learning methods (e.g., supervised, unsupervised, semi-supervised, federated learning, reinforcement learning) across multiple data modalities.

Fundamentally, the machine learning methodology used in modern AI systems is susceptible to attacks through the public APIs that the model provides and against the platforms on which they are deployed. This report focuses on the former and considers the latter to be out of scope. Attackers can breach the confidentiality and privacy protections of the data and model by simply exercising the public interfaces of the model and supplying data inputs that are within the acceptable range. In this sense, the challenges facing AML are similar to those facing cryptography. Modern cryptography relies on algorithms that are secure in an information-theoretic sense. Thus, people need to focus only on implementing them robustly and securely, which is no small task by itself. Unlike cryptography, there are no information-theoretic security proofs for the widely used machine learning algorithms.

As a result, many of the advances in developing mitigations against different classes of attacks tend to be empirical in nature.

This report is organized as follows. Section 2 introduces the taxonomy of attacks. The taxonomy is organized by first defining the broad categories of attacker objectives/goals. Based on that, we define the categories of capabilities the adversary must be able to leverage to achieve the corresponding objectives. Then, we introduce specific attack classes for each type of capability. Sections 3, 4, and 5 discuss the major classes of attacks: evasion, poisoning, and privacy, respectively. A corresponding set of mitigations for each class of attacks is provided in the attack class sections. Section 6 discusses the remaining challenges in the field.

2. Attack Classification

Figure 1 introduces a taxonomy of attacks in adversarial machine learning. The attacker's objectives are shown as disjointed circles with the attacker's goal at the center of each circle: **Availability** breakdown, **Integrity** violations, and **Privacy** compromise. The capabilities that an adversary must leverage to achieve their objectives are shown in the outer layer of the objective circles. Attack classes are shown as callouts connected to the capabilities required to mount each attack. Multiple attack classes that requiring same capabilities for reaching the same objective are shown in a single callout. Related attack classes that require different capabilities for reaching the same objective are connected with dotted lines.

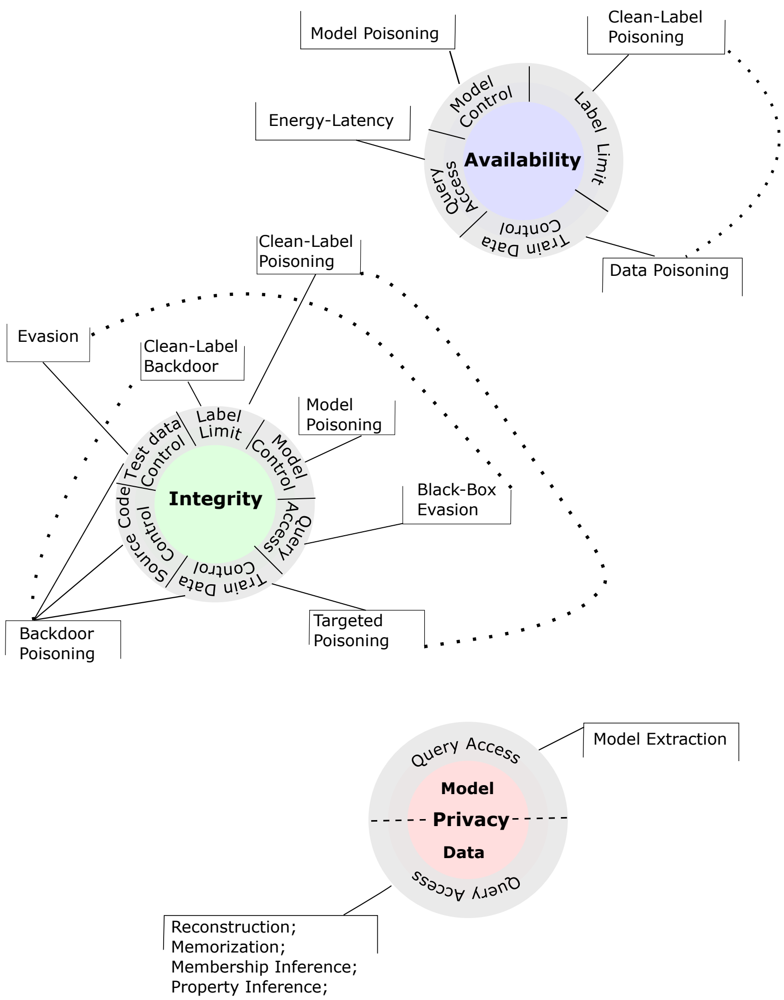

Fig. 1. Taxonomy of attacks on AI systems.

These attacks are classified according to the following dimensions: 1) learning method and stage of the learning process when the attack is mounted, 2) attacker goals and objectives, 3) attacker capabilities, and 4) attacker knowledge of the learning process. Several adversarial attack classification frameworks have been introduced in prior works [23, 212], and the goal here is to create a standard terminology for adversarial attacks on ML that unifies existing work.

2.1. Stages of Learning

Machine learning involves a TRAINING STAGE, in which a model is learned, and a DEPLOYMENT STAGE, in which the model is deployed on new, unlabeled data samples to generate predictions. In the case of SUPERVISED LEARNING in the training stage labeled training data is given as input to a training algorithm and the ML model is optimized to minimize a specific loss function. Validation and testing of the ML model is usually performed before the model is deployed in the real world. Common supervised learning techniques include CLASSIFICATION, in which the predicted labels or *classes* are discrete, and LOGISTIC REGRESSION, in which the predicted labels or *response variables* are continuous.

ML models may be GENERATIVE (i.e., learn the distribution of training data and generate similar examples, such as generative adversarial metworks [GAN] and large language models [LLM]) or DISCRIMINATIVE (i.e., learn only a decision boundary, such as LOGISTIC REGRESSION, SUPPORT VECTOR MACHINES, and CONVOLUTIONAL NEURAL NETWORKS).

Other learning paradigms in the ML literature are UNSUPERVISED LEARNING, which trains models using unlabeled data at training time; SEMI-SUPERVISED LEARNING, in which a small set of examples have labels, while the majority of samples are unlabeled; REINFORCEMENT LEARNING, in which an agent interacts with an environment and learns an optimal policy to maximize its reward; FEDERATED LEARNING, in which a set of clients jointly train an ML model by communicating with a server, which performs an aggregation of model updates; ENSEMBLE LEARNING which is an approach in machine learning that seeks better predictive performance by combining the predictions from multiple models.

Adversarial machine learning literature predominantly considers adversarial attacks against AI systems that could occur at either the training stage or the ML deployment stage. During the ML training stage, the attacker might control part of the training data, their labels, the model parameters, or the code of ML algorithms, resulting in different types of poisoning attacks. During the ML deployment stage, the ML model is already trained, and the adversary could mount evasion attacks to create integrity violations and change the ML model's predictions, as well as privacy attacks to infer sensitive information about the training data or the ML model.

Training-time attacks. Attacks during the ML training stage are called POISONING ATTACKS [21]. In a DATA POISONING attack [21, 94], an adversary controls a subset of the training data by either inserting or modifying training samples. In a MODEL POISONING attack [138], the adversary controls the model and its parameters. Data poisoning attacks are applicable to all learning paradigms, while model poisoning attacks are most prevalent in federated learning [118], where clients send local model updates to the aggregating server, and in supply-chain attacks where malicious code may be added to the model by suppliers of model technology.

Deployment-time attacks. Two different types of attacks can be mounted at testing/deployment time. First, evasion attacks modify testing samples to create ADVERSARIAL EXAMPLES [19, 93, 216], which are similar to the original sample (according to certain distance metrics) but alter the model predictions to the attacker's choices. Second, privacy attacks, such as membership inference [200] and data reconstruction [67], are typically mounted by attackers with query access to an ML model. They could be further divided into data privacy attacks and model privacy attacks.

2.2. Attacker Goals and Objectives

The attacker's objectives are classified along three dimensions according to the three main types of security violations considered when analyzing the security of a system (i.e., availability, integrity, confidentiality): availability breakdown, integrity violations, and privacy compromise. Figure 1 separates attacks into three disjointed circles according to their objective, and the attacker's objective is shown at the center of each circle.

Availability Breakdown. An AVAILABILITY ATTACK is an indiscriminate attack against ML in which the attacker attempts to break down the performance of the model at testing/deployment time. Availability attacks can be mounted via data poisoning, when the attacker controls a fraction of the training set; via model poisoning, when the attacker controls the model parameters; or as energy-latency attacks via query access. Data poisoning availability attacks have been proposed for SUPPORT VECTOR MACHINES [21], linear regression [110], and even neural networks [141, 161], while model poisoning attacks have been designed for neural networks [138] and federated learning [6]. Recently, ENERGY-LATENCY ATTACKS that require only black-box access to the model have been developed for neural networks across many different tasks in computer vision and NLP [203].

Integrity Violations. An INTEGRITY ATTACK targets the integrity of an ML model's output, resulting in incorrect predictions performed by an ML model. An attacker can cause an integrity violation by mounting an evasion attack at testing/deployment time or a poisoning attack at training time. Evasion attacks require the modification of testing samples to create adversarial examples that are mis-classified by the model to a different class, while remaining stealthy and imperceptible to humans [19, 93, 216]. Integrity attacks via poisoning can be classified as TARGETED POISONING ATTACKS [89, 193], BACKDOOR POISONING ATTACKS [94], and MODEL POISONING [6, 17, 78]. Targeted poisoning tries to violate the integrity of a few targeted samples and assumes that the attacker has training data control to insert the poisoned samples. Backdoor poisoning attacks require the generation of a

BACKDOOR PATTERN, which is added to both the poisoned samples and the testing samples to cause misclassification. Backdoor attacks are the only attacks in the literature that require both training and testing data control. Model poisoning attacks could result in either targeted or backdoor attacks, and the attacker modifies model parameters to cause an integrity violation. They have been designed for centralized learning [138] and federated learning [6, 17].

Privacy Compromise. Attackers might be interested in learning information about the training data (resulting in DATA PRIVACY attacks) or about the ML model (resulting in MODEL PRIVACY attacks). The attacker could have different objectives for compromising the privacy of training data, such as DATA RECONSTRUCTION [67] (inferring content or features of training data), MEMBERSHIP-INFERENCE ATTACKS [99, 201] (inferring the presence of data in the training set), data MEMORIZATION [33, 34] (ability to extract training data from generative models), and PROPERTY INFERENCE [86] (inferring properties about the training data distribution). MODEL EXTRACTION is a model privacy attack in which attackers aim to extract information about the model [108].

2.3. Attacker Capabilities

An adversary might leverage six types of capabilities to achieve their objectives, as shown in the outer layer of the objective circles in Figure 1:

- TRAINING DATA CONTROL: The attacker might take control of a subset of the training data by inserting or modifying training samples. This capability is used in data poisoning attacks (e.g., availability poisoning, targeted or backdoor poisoning).
- MODEL CONTROL: The attacker might take control of the model parameters by either generating a Trojan trigger and inserting it in the model or by sending malicious local model updates in federated learning.
- TESTING DATA CONTROL: The attacker may utilize this to add perturbations to testing samples at model deployment time, as performed in evasion attacks to generate adversarial examples or in backdoor poisoning attacks.
- LABEL LIMIT: This capability is relevant to restrict the adversarial control over the labels of training samples in supervised learning. Clean-label poisoning attacks assume that the attacker does not control the label of the poisoned samples – a realistic poisoning scenario, while regular poisoning attacks assume label control over the poisoned samples.
- SOURCE CODE CONTROL: The attacker might modify the source code of the ML algorithm, such as the random number generator or any third-party libraries, which are often open source.
- QUERY ACCESS: When the ML model is managed by a cloud provider (using Machine Learning as a Service – MLaaS), the attacker might submit queries to the model

and receive predictions (either labels or model confidences). This capability is used by black-box evasion attacks, energy-latency attacks, and all privacy attacks.

Note that even if an attacker does not have the ability to modify training/testing data, source code, or model parameters, access to these are still crucial for mounting white-box attacks. See Section 2.4 for more details on attacker knowledge.

Figure 1 connects each attack class with the capabilities required to mount the attack. For instance, backdoor attacks that cause integrity violations require control of training data and testing data to insert the backdoor pattern. Backdoor attacks can also be mounted via source code control, particularly when training is outsourced to a more powerful entity. Clean-label backdoor attacks do not allow label control on the poisoned samples, in addition to the capabilities needed for backdoor attacks.

2.4. Attacker Knowledge

Another dimension for attack classification is how much knowledge the attacker has about the ML system. There are three main types of attacks: white-box, black-box, and gray-box.

White-box attacks. These assume that the attacker operates with *full* knowledge about the ML system, including the training data, model architecture, and model hyper-parameters. While these attacks operate under very strong assumptions, the main reason for analyzing them is to test the vulnerability of a system against worst-case adversaries and to evaluate potential mitigations. Note that this definition is more general and encompasses the notion of adaptive attacks where the knowledge of the mitigations applied to the model or the system is explicitly tracked.

Black-box attacks. These attacks assume minimal knowledge about the ML system. An adversary might get query access to the model, but they have no other information about how the model is trained. These attacks are the most practical since they assume that the attacker has no knowledge of the AI system and utilize system interfaces readily available for normal use.

Gray-box attacks. There are a range of gray-box attacks that capture adversarial knowledge between black-box and white-box attacks. Suciu et al. [212] introduced a framework to classify gray-box attacks. An attacker might know the model architecture but not its parameters, or the attacker might know the model and its parameters but not the training data. Other common assumptions for gray-box attacks are that the attacker has access to data distributed identically to the training data and knows the feature representation. The latter assumption is important in applications where feature extraction is used before training an ML model, such as cybersecurity, finance, and healthcare.

2.5. Data Modality

Adversarial attacks against ML have been discovered in a range of data modalities used in many application domains. Until recently, most attacks and defenses have operated under a single modality, but a new ML trend is to use multimodal data. The taxonomy of attacks defined in Figure 1 is independent of the modality of the data in specific applications.

The most common data modalities in the adversarial ML literature include:

1. **Image:** Adversarial examples of image data modality [93, 216] have the advantage of a continuous domain, and gradient-based methods can be applied directly for optimization. Backdoor poisoning attacks were first invented for images [94], and many privacy attacks are run on image datasets (e.g., [200]).

2. **Text:** Natural language processing (NLP) is a popular modality, and all classes of attacks have been proposed for NLP applications, including evasion [96], poisoning [48, 132], and privacy [252]. Audio systems and text generated from audio signals have also been attacked [37].

3. **Cybersecurity[2]:** The first poisoning attacks were discovered in cybersecurity for worm signature generation (2006) [177] and spam email classification (2008) [166]. Since then, poisoning attacks have been shown for malware classification, malicious PDF detection, and Android malicious app classification [192]. Evasion attacks against the same data modalities have been proposed as well: malware classification [63, 211], PDF malware classification [209, 242], and Android malicious app detection [179]. Clements et al. [58] developed a mechanism for effective generation of evasion attacks on small, weak routers in network intrusion detection. Poisoning unsupervised learning models has been shown for clustering used in malware classification [22] and network traffic anomaly detection [185].

   Industrial Control Systems (ICS) and Supervisory Control and Data Acquisition (SCADA) systems are part of modern Critical Infrastructure (CI) such as power grids, power plants (nuclear, fossil fuel, renewable energy), water treatment plants, oil refineries, etc. ICS are an attractive target for adversaries because of the potential for highly consequential disruptions of CI [38, 128]. The existence of targeted stealth attacks has led to the development of defense-in-depth mechanisms for their detection and mitigation. Anomaly detection based on data-centric approaches allows automated feature learning through ML algorithms. However, the application of ML to such problems comes with specific challenges related to the need for a very low false negative and low false positive rates, ability to catch zero-day attacks, account for plant operational drift, etc. This challenge is compounded by the fact that trying to accommodate all these together makes ML models susceptible to adversarial attacks [123, 180, 264].

[2] Strictly speaking, cybersecurity data may not include a single modality, but rather multiple modalities such as network-level, host-level, or program-level data.

4. **Tabular data:** Numerous attacks against ML models working on tabular data in finance, business, and healthcare applications have been demonstrated. For example, poisoning availability attacks have been shown against healthcare and business applications [110]; privacy attacks have been shown against healthcare data [249]; and evasion attacks have been shown against financial applications [90].

Recently, the use of ML models trained on multimodal data has gained traction, particularly the combination of image and text data modalities. Several papers have shown that multimodal models may provide some resilience against attacks [245], but other papers show that multimodal models themselves could be vulnerable to attacks mounted on all modalities at the same time [44, 195, 243]. See Section 6.2 for additional discussion.

> An interesting open challenge is to test and characterize the resilience of a variety of multimodal ML against evasion, poisoning, and privacy attacks.

3. Evasion Attacks and Mitigations

The discovery of evasion attacks against machine learning models has generated increased interest in adversarial machine learning, leading to significant growth in this research space over the last decade. In an evasion attack, the adversary's goal is to generate adversarial examples, which are defined as testing samples whose classification can be changed at deployment time to an arbitrary class of the attacker's choice with only minimal perturbation [216]. Early known instances of evasion attacks date back to 1988 with the work of Kearns and Li [120], and to 2004, when Dalvi et al. [61], and Lowd and Meek [140] demonstrated the existence of adversarial examples for linear classifiers used in spam filters. Adversarial examples became even more intriguing to the research community when Szedegy et al. [216] showed that deep neural networks used for image classification can be easily manipulated, and adversarial examples were visualized. In the context of image classification, the perturbation of the original sample must be small so that a human cannot observe the transformation of the input. Therefore, while the ML model can be tricked to classify the adversarial example in the target class selected by the attacker, humans still recognize it as part of the original class.

In 2013, Szedegy et al. [216] and Biggio et al. [19] independently discovered an effective method for generating adversarial examples against linear models and neural networks by applying gradient optimization to an adversarial objective function. Both of these techniques require white-box access to the model and were improved by subsequent methods that generated adversarial examples with even smaller perturbations [5, 36, 144]. Adversarial examples are also applicable in more realistic black-box settings in which attackers only obtain query access capabilities to the trained model. Even in the more challenging black-box setting in which attackers obtain the model's predicted labels or confidence scores, deep neural networks are still vulnerable to adversarial examples. Methods for creating adversarial examples in black-box settings include zeroth-order optimization [47], discrete optimization [156], and Bayesian optimization [202], as well as *transferability*, which involves the white-box generation of adversarial examples on a different model architecture before transferring them to the target model [173, 174, 223]. Cybersecurity and image classifications were the first application domains that showcased evasion attacks. However, with the increasing interest in adversarial machine learning, ML technology used in many other application domains went under scrutiny, including speech recognition [37], natural language processing [115], and video classification [134, 236].

Mitigating adversarial examples is a well-known challenge in the community and deserves additional research and investigation. The field has a history of publishing defenses evaluated under relatively weak adversarial models that are subsequently broken by more powerful attacks, a process that appears to iterate in perpetuity. Mitigations need to be evaluated against strong adaptive attacks, and guidelines for the rigorous evaluation of newly proposed mitigation techniques have been established [60, 221]. The most promising directions for mitigating the critical threat of evasion attacks are adversarial training [93, 144] (iteratively generating and inserting adversarial examples with their correct labels at training time); certified techniques, such as randomized smoothing [59] (evaluating ML prediction under noise); and formal verification techniques [88, 119] (applying formal method techniques to verify the model's output). Nevertheless, these methods come with different limitations, such as decreased accuracy for adversarial training and randomized smoothing, and computational complexity for formal methods. There is an inherent trade-off between robustness and accuracy [220, 225, 255]. Similarly, there are trade-offs between a model's robustness and fairness guarantees [41].

This section discusses white-box and black-box evasion attack techniques, attack transferability, and the potential mitigation of adversarial examples in more detail.

3.1. White-Box Evasion Attacks

There are several optimization-based methods for designing evasion attacks that generate adversarial examples at small distances from the original testing samples. There are also several choices for distance metrics, universal evasion attacks, and physically realizable attacks, as well as examples of evasion attacks developed for multiple data modalities, including NLP, audio, video, and cybersecurity domains.

Optimization-based methods. Szedegy et al. [216] and Biggio et al. [19] independently proposed the use of optimization techniques to generate adversarial examples. In their threat models, the adversary is allowed to inspect the entirety of the ML model and compute gradients relative to the model's loss function. These attacks can be targeted, in which the adversarial example's class is selected by the attacker, or untargeted, in which the adversarial examples are misclassified to any other incorrect class.

Szedegy et al. [216] coined the widely used term *adversarial examples*. They considered an objective that minimized the ℓ_2 norm of the perturbation, subject to the model prediction changing to the target class. The optimization is solved using the Limited-memory Broyden–Fletcher–Goldfarb–Shanno (L-BFGS) method. Biggio et al. [19] considered the setting of a binary classifier with malicious and benign classes with continuous and differentiable discriminant function. The objective of the optimization is to minimize the discriminant function in order to generate adversarial examples of maximum confidence.

While Biggio et al. [19] apply their method to linear classifiers, kernel SVM, and multi-layer perceptrons, Szedegy et al. [216] show the existence of adversarial examples on deep learning models used for image classification. Goodfellow et al. [93] introduced an efficient method for generating adversarial examples for deep learning: the Fast Gradient Sign Method (FGSM), which performs a single iteration of gradient descent for solving the optimization. This method has been extended to an iterative FGSM attack by Kurakin et al. [125].

Subsequent work on generating adversarial examples have proposed new objectives and methods for optimizing the generation of adversarial examples with the goals of minimizing the perturbations and supporting multiple distance metrics. Some notable attacks include:

1. DeepFool is an untargeted evasion attack for ℓ_2 norms, which uses a linear approximation of the neural network to construct the adversarial examples [158].

2. The Carlini-Wagner attack uses multiple objectives that minimize the loss or logits on the target class and the distance between the adversarial example and original sample. The attack is optimized via the penalty method [36] and considers three distance metrics to measure the perturbations of adversarial examples: ℓ_0, ℓ_2, and ℓ_∞. The attack has been effective against the defensive distillation defense [175].

3. The Projected Gradient Descent (PGD) attack [144] minimizes the loss function and projects the adversarial examples to the space of allowed perturbations at each iteration of gradient descent. PGD can be applied to the ℓ_2 and ℓ_∞ distance metrics for measuring the perturbation of adversarial examples.

Universal evasion attacks. Moosavi-Dezfooli et al. [157] showed how to construct small universal perturbations (with respect to some norm), which can be added to most images and induce a misclassification. Their technique relies on successive optimization of the universal perturbation using a set of points sampled from the data distribution. An interesting observation is that the universal perturbations generalize across deep network architectures, suggesting similarity in the decision boundaries trained by different models for the same task.

Physically realizable attacks. These are attacks against machine learning systems that become feasible in the physical world. One of the first physically realizable attacks in the literature is the attack on facial recognition systems by Sharif et al. [194]. The attack can be realized by printing a pair of eyeglass frames, which misleads facial recognition systems to either evade detection or impersonate another individual. Eykholt et al. [77] proposed an attack to generate robust perturbations under different conditions, resulting in adversarial examples that can evade vision classifiers in various physical environments. The attack is applied to evade a road sign detection classifier by physically applying black and white stickers to the road signs.

Other data modalities. In computer vision applications, adversarial examples must be imperceptible to humans. Therefore, the perturbations introduced by attackers need to be so small that a human correctly recognizes the images, while the ML classifier is tricked into changing its prediction. The concept of adversarial examples has been extended to other domains, such as audio, video, natural language processing (NLP), and cybersecurity. In some of these settings, there are additional constraints that need to be respected by adversarial examples, such as text semantics in NLP and the application constraints in cybersecurity. Several representative works are discussed below:

- **Audio:** Carlini and Wagner [37] showed a targeted attack on models that generate text from speech. They can generate an audio waveform that is very similar to an existing one but that can be transcribed to any text of the attacker's choice.

- **Video:** Adversarial evasion attacks against video classification models can be split into sparse attacks that perturb a small number of video frames [236] and dense attacks that perturb all of the frames in a video [134]. The goal of the attacker is to change the classification label of the video.

- **NLP:** Jia and Liang [115] developed a methodology for generating adversarial NLP examples. This pioneering work was followed by many advances in developing adversarial attacks on NLP models (see a comprehensive survey on the topic [259]). Recently, La Malfa and Kwiatkowska [126] proposed a method for formalizing perturbation definitions in NLP by introducing the concept of semantic robustness. The main challenges in NLP are that the domain is discrete rather than continuous (e.g., image, audio, and video classification), and adversarial examples need to respect text semantics.

- **Cybersecurity:** In cybersecurity applications, adversarial examples must respect the constraints imposed by the application semantics and feature representation of cyber data, such as network traffic or program binaries. FENCE is a general framework for crafting white-box evasion attacks using gradient optimization in discrete domains and supports a range of linear and statistical feature dependencies [53]. FENCE has been applied to two network security applications: malicious domain detection and malicious network traffic classification. Sheatsley et al. [196] propose a method that learns the constraints in feature space using formal logic and crafts adversarial examples by projecting them onto a constraint-compliant space. They apply the technique to network intrusion detection and phishing classifiers. Both papers observe that attacks from continuous domains cannot be readily applied in constrained environments, as they result in infeasible adversarial examples. Pierazzi et al. [179] discuss the difficulty of mounting feasible evasion attacks in cyber security due to constraints in feature space and the challenge of mapping attacks from feature space to problem space. They formalize evasion attacks in problem space and construct feasible adversarial examples for Android malware.

3.2. Black-Box Evasion Attacks

Black-box evasion attacks are designed under a realistic adversarial model, in which the attacker has no prior knowledge of the model architecture or training data. Instead, the adversary can interact with a trained ML model by querying it on various data samples and obtaining the model's predictions. Similar APIs are provided by machine learning as a service (MLaaS) offered by public cloud providers, in which users can obtain the model's predictions on selected queries without information about how the model was trained. There are two main classes of black-box evasion attacks in the literature:

- **Score-based attacks:** In this setting, attackers obtain the model's confidence scores or logits and can use various optimization techniques to create the adversarial examples. A popular method is zeroth-order optimization, which estimates the model's gradients without explicitly computing derivatives [47, 105]. Other optimization techniques include discrete optimization [156], natural evolution strategies [104], and random walks [162].

- **Decision-based attacks:** In this more restrictive setting, attackers obtain only the final predicted labels of the model. The first method for generating evasion attacks was the Boundary Attack based on random walks along the decision boundary and rejection sampling [25], which was extended with an improved gradient estimation to reduce the number of queries in the HopSkipJumpAttack [46]. More recently, several optimization methods search for the direction of the nearest decision boundary (the OPT attack [51]), use sign SGD instead of binary searches (the Sign-OPT attack [52]), or use Bayesian optimization [202].

The main challenge in creating adversarial examples in black-box settings is reducing the number of queries to the ML models. Recent techniques can successfully evade the ML classifiers with a relatively small number of queries, typically less than 1000 [202].

3.3. Transferability of Attacks

Another method for generating adversarial attacks under restrictive threat models is via transferability of an attack crafted on a different ML model. Typically, an attacker trains a substitute ML model, generates white-box adversarial attacks on the substitute model, and transfers the attacks to the target model. Various methods differ in how the substitute models are trained. For example, Papernot et al. [173, 174] train the substitute model with score-based queries to the target model, while several papers train an ensemble of models without explicitly querying the target model [136, 223, 235].

Attack transferability is an intriguing phenomenon, and existing literature attempts to understand the fundamental reasons why adversarial examples transfer across models. Several papers have observed that different models learn intersecting decision boundaries in both benign and adversarial dimensions, which leads to better transferability [93, 157, 223]. Demontis et al. [64] identified two main factors that contribute to attack transferability for both evasion and poisoning: the intrinsic adversarial vulnerability of the target model and the complexity of the surrogate model used to optimize the attack.

3.4. Mitigations

Mitigating evasion attacks is challenging because adversarial examples are widespread in a variety of ML model architectures and application domains, as discussed above. Possible explanations for the existence of adversarial examples are that ML models rely on non-robust features that are not aligned with human perception in the computer vision domain [106]. In the last few years, many of the proposed mitigations against adversarial examples have been ineffective against stronger attacks. Furthermore, several papers have performed extensive evaluations and defeated a large number of proposed mitigations:

- Carlini and Wagner showed how to bypass 10 methods for detecting adversarial examples and described several guidelines for evaluating defenses [35]. Recent work shows that detecting adversarial examples is as difficult as building a defense [219]. Therefore, this direction for mitigating adversarial examples is similarly challenging when designing defenses.

- The Obfuscated Gradients attack [5] was specifically designed to defeat several proposed defenses that mask the gradients using the ℓ_0 and ℓ_∞ distance metrics. It relies on a new technique, Backward Pass Differentiable Approximation, which approximates the gradient during the backward pass of backpropagation. It bypasses seven proposed defenses.

- Tramèr et al. [221] described a methodology for designing adaptive attacks against proposed defenses and circumvented 13 existing defenses. They advocate designing adaptive attacks to test newly proposed defenses rather than merely testing the defenses against well-known attacks.

From the wide range of proposed defenses against adversarial evasion attacks, three main classes have proved resilient and have the potential to provide mitigation against evasion attacks:

1. **Adversarial training:** Introduced by Goodfellow et al. [93] and further developed by Madry et al. [144], adversarial training is a general method that augments the training data with adversarial examples generated iteratively during training using their correct labels. The stronger the adversarial attacks for generating adversarial examples are, the more resilient the trained model becomes. Interestingly, adversarial training results in models with more semantic meaning than standard models [225], but this benefit usually comes at the cost of decreased model accuracy on clean data. Additionally, adversarial training is expensive due to the iterative generation of adversarial examples during training.

2. **Randomized smoothing:** Proposed by Lecuyer et al. [129] and further improved by Cohen et al. [59], randomized smoothing is a method that transforms any classifier into a certifiable robust smooth classifier by producing the most likely predictions under Gaussian noise perturbations. This method results in provable robustness for ℓ_2 evasion attacks, even for classifiers trained on large-scale datasets, such as ImageNet. Randomized smoothing typically provides certified prediction to a subset of testing samples (the exact number depends on the radius of the ℓ_2 ball and the characteristics of the training data and model).

3. **Formal verification:** Another method for certifying the adversarial robustness of a neural network is based on techniques from FORMAL METHODS. Reluplex uses satisfiability modulo theories (SMT) solvers to verify the robustness of small feed-

forward neural networks [119]. AI^2 is the first verification method applicable to convolutional neural networks using abstract interpretation techniques [88]. These methods have been extended and scaled up to larger networks in follow-up verification systems, such as DeepPoly [204], ReluVal [233], and Fast Geometric Projections (FGP) [85]. Formal verification techniques have significant potential for certifying neural network robustness, but their main limitations are their lack of scalability, computational cost, and restriction in the type of supported operations.

All of these proposed mitigations exhibit inherent trade-offs between robustness and accuracy, and they come with additional computational costs during training. Therefore, designing ML models that resist evasion while maintaining accuracy remains an open problem.

4. Poisoning Attacks and Mitigations

Another relevant threat against machine learning systems is the risk of adversaries mounting poisoning attacks, which are broadly defined as adversarial attacks during the training stage of the ML algorithm. Poisoning attacks have a long history in cybersecurity, as the first known poisoning attack was developed for worm signature generation in 2006 [177]. Since then, poisoning attacks have been studied extensively in several application domains: computer security (for spam detection [166]), network intrusion detection [227], vulnerability prediction [187], malware classification [192, 240]), computer vision [89, 94, 193], natural language processing [48, 132, 229], and tabular data in healthcare and financial domains [110]. Recently, poisoning attacks have gained more attention in industrial applications as well. A Microsoft report revealed that they are considered to be the most critical vulnerability of machine learning systems deployed in production [124].

Poisoning attacks are very powerful and can cause either an availability violation or an integrity violation. In particular, availability poisoning attacks cause indiscriminate degradation of the machine learning model on all samples, while targeted and backdoor poisoning attacks are stealthier and induce integrity violations on a small set of target samples. Poisoning attacks leverage a wide range of adversarial capabilities, such as data poisoning, model poisoning, label control, source code control, and test data control, resulting in several subcategories of poisoning attacks. They have been developed in white-box adversarial scenarios [21, 110, 240], gray-box settings [110], and black-box models [20]. This section discusses the threat of availability poisoning, targeted poisoning, backdoor poisoning, and model poisoning attacks classified according to their adversarial objective. For each poisoning attack category, techniques for mounting the attacks as well as existing mitigations and their limitations are also discussed. Our classification of poisoning attacks is inspired by the framework developed by Cinà et al. [56], which includes additional references to poisoning attacks and mitigations.

4.1. Availability Poisoning

The first poisoning attacks discovered in cybersecurity applications were availability attacks against worm signature generation and spam classifiers, which indiscriminately impact the entire machine learning model and, in essence, cause a denial-of-service attack on users of the AI system. Perdisci et al. [177] generated suspicious flows with fake invariants that mislead the worm signature generation algorithm in Polygraph [168]. Nelson et al. [166] designed poisoning attacks against Bayes-based spam classifiers, which generate spam emails that contain long sequences of words appearing in legitimate emails to induce the misclassification of spam emails. Both of these attacks were conducted under the white-box setting in which adversaries are aware of the ML training algorithm, feature representations, training datasets, and ML models. ML-based methods have been proposed for the detection of cybersecurity attacks targeting ICS. Such detectors are often retrained using data collected during system operation to account for plant operational drift of the monitored signals. This retraining procedure creates opportunities for an attacker to mimic the signals of corrupted sensors at training time and poison the learning process of the detector such that attacks remain undetected at deployment time [123].

A simple black-box poisoning attack strategy is LABEL FLIPPING, which generates training examples with a victim label selected by the adversary [20]. This method requires a large percentage of poisoning samples for mounting an availability attack, and it has been improved via optimization-based poisoning attacks introduced for the first time against SUPPORT VECTOR MACHINES (SVM) [21]. In this approach, the attacker solves a bilevel optimization problem to determine the optimal poisoning samples that will achieve the adversarial objective (i.e., maximize the hinge loss for SVM [21] or maximize the mean square error [MSE] for regression [110]). These optimization-based poisoning attacks have been subsequently designed against linear regression [110] and neural networks [161], and they require white-box access to the model and training data. In gray-box adversarial settings, the most popular method for generating availability poisoning attacks is transferability, in which poisoning samples are generated for a surrogate model and transferred to the target model [64, 212].

A realistic threat model for supervised learning is that of clean-label poisoning attacks in which adversaries can only control the training examples but not their labels. This case models scenarios in which the labeling process is external to the training algorithm, as in malware classification where binary files can be submitted by attackers to threat intelligence platforms, and labeling is performed using anti-virus signatures or other external methods. Clean-label availability attacks have been introduced for neural network classifiers by training a generative model and adding noise to training samples to maximize the adversarial objective [82]. A different approach for clean-label poisoning is to use gradient alignment and minimally modify the training data [83].

Availability poisoning attacks have also been designed for unsupervised learning against centroid-based anomaly detection [121] and behavioral clustering for malware [22]. In federated learning, an adversary can mount a model poisoning attack to induce availability violations in the globally trained model [78, 197, 198]. More details on model poisoning attacks are provided in Section 4.4.

Mitigations.

Availability poisoning attacks are usually detectable by monitoring the standard performance metrics of ML models – such as precision, recall, accuracy, F1 scores, and area under the curve – as they cause a large degradation in the classifier metrics. Nevertheless, detecting these attacks during the testing or deployment stages of ML is less desirable, and existing mitigations aim to proactively prevent these attacks during the training stage to generate robust ML models. Among the existing mitigations, some generally promising techniques include:

- **Training data sanitization:** These methods leverage the insight that poisoned samples are typically different than regular training samples not controlled by adversaries. As such, data sanitization techniques are designed to clean the training set and remove the poisoned samples before the machine learning training is performed. Nelson et al. [166] propose the Region of Non-Interest (RONI) method, which examines each sample and excludes it from training if the accuracy of the model decreases when the sample is added. Subsequently proposed sanitization methods improved upon this early approach by reducing its computational complexity. Paudice et al. [176] introduced a method for label cleaning that was specifically designed for label flipping attacks. Steinhardt et al. [210] propose the use of outlier detection methods for identifying poisoned samples. Clustering methods have also been used for detecting poisoned samples [127, 217]. In the context of network intrusion detection, computing the variance of predictions made by an ensemble of multiple ML models has proven to be an effective data sanitization method [227]. Once sanitized, the datasets should be protected by cybersecurity mechanisms for dataset origin and integrity attestation [165].

- **Robust training:** An alternative approach to mitigating availability poisoning attacks is to modify the ML training algorithm and perform robust training instead of regular training. The defender can train an ensemble of multiple models and generate predictions via model voting [18, 131, 234]. Several papers apply techniques from robust optimization, such as using a trimmed loss function [66, 110]. Rosenfeld et al. [184] proposed the use of randomized smoothing for adding noise during training and obtaining certification against label flipping attacks.

4.2. Targeted Poisoning

In contrast to availability attacks, targeted poisoning attacks induce a change in the ML model's prediction on a small number of targeted samples. If the adversary can control the labeling function of the training data, then label flipping is an effective targeted poisoning attack. The adversary simply inserts several poisoned samples with the target label, and the model will learn the wrong label. Therefore, targeted poisoning attacks are mostly studied in the clean-label setting in which the attacker does not have access to the labeling function.

Several techniques for mounting clean-label targeted attacks have been proposed. Koh and Liang [122] showed how influence functions – a statistical method that determines the most influential training samples for a prediction – can be leveraged for creating poisoned samples in the fine-tuning setting in which a pre-trained model is fine-tuned on new data. Suciu et al. [212] designed StingRay, a targeted poisoning attack that modifies samples in feature space and adds poisoned samples to each mini batch of training. An optimization procedure based on feature collision was crafted by Shafahi et al. [193] to generate clean-label targeted poisoning for fine-tuning and end-to-end learning. ConvexPolytope [263] and BullseyePolytope [2] optimized the poisoning samples against ensemble models, which offers better advantages for attack transferability. MetaPoison [101] uses a meta-learning algorithm to optimize the poisoned samples, while Witches' Brew [89] performs optimization by gradient alignment, resulting in a state-of-the-art targeted poisoning attack.

All of the above attacks impact a small set of targeted samples that are selected by the attacker during training, and they have only been tested for continuous image datasets (with the exception of StingRay, which requires adversarial control of a large fraction of the training set). Subpopulation poisoning attacks [111] were designed to poison samples from an entire subpopulation, defined by matching on a subset of features or creating clusters in representation space. Poisoned samples are generated using label flipping (for NLP and tabular modalities) or a first-order optimization method (for continuous data, such as images). The attack generalizes to all samples in a subpopulation and requires minimal knowledge about the ML model and a small number of poisoned samples (proportional to the subpopulation size).

Targeted poisoning attacks have also been introduced for semi-supervised learning algorithms [29], such as MixMatch [15], FixMatch [205], and Unsupervised Data Augmentation (UDA) [241] in which the adversary poisons a small fraction of the unlabeled training dataset to change the prediction on targeted samples at deployment time.

Mitigations. Targeted poisoning attacks are notoriously challenging to defend against. Jagielski et al. [111] showed an impossibility result for subpopulation poisoning attacks. To mitigate some of the risks associated with such attacks, cybersecurity mechanisms for dataset origin and integrity attestation [165] should be used judiciously. Ma et al. [142] proposed the use of differential privacy (DP) as a defense (which follows directly from the definition of differential privacy), but it is well known that differentially private ML models have lower accuracy than standard models. The trade-off between robustness and accuracy needs to be considered in each application. If the application has strong data privacy requirements, and differentially private training is used for privacy, then an additional benefit is protection against targeted poisoning attacks. However, the robustness offered by DP starts to fade once the targeted attack requires multiple poisoning samples (as in subpopulation poisoning attacks) because the group privacy bound will not provide meaningful guarantees for large poisoned sets.

4.3. Backdoor Poisoning

In 2017, Gu et al. [94] proposed BadNets, the first backdoor poisoning attack. They observed that image classifiers can be poisoned by adding a small patch trigger in a subset of images at training time and changing their label to a target class. The classifier learns to associate the trigger with the target class, and any image – including the trigger or backdoor pattern – will be misclassified to the target class at testing time. Concurrently, Chen et al. [49] introduced backdoor attacks in which the trigger is blended into the training data. Follow-up work introduced the concept of clean-label backdoor attacks [226] in which the adversary is restricted in preserving the label of the poisoned examples. Clean-label attacks typically require more poisoning samples to be effective, but the attack model is more realistic.

In the last few years, backdoor attacks have become more sophisticated and stealthy, making them harder to detect and mitigate. Latent backdoor attacks were designed to survive even upon model fine-tuning of the last few layers using clean data [247]. Backdoor Generating Network (BaN) [189] is a dynamic backdoor attack in which the location of the trigger changes in the poisoned samples so that the model learns the trigger in a location-invariant manner. Functional triggers are embedded throughout the image or change according to the input. For instance, Li et al. [133] used steganography algorithms to hide the trigger in the training data. Liu et al. [139] introduced a clean-label attack that uses natural reflection on images as a backdoor trigger. Wenger et al. [237] poisoned facial recognition systems by using physical objects as triggers, such as sunglasses and earrings.

Other data modalities. While the majority of backdoor poisoning attacks are designed for computer vision applications, this attack vector has been effective in other application domains with different data modalities, such as audio, NLP, and cybersecurity settings.

- **Audio:** In audio domains, Shi et al. [199] showed how an adversary can inject an unnoticeable audio trigger into live speech, which is jointly optimized with the target model during training.
- **NLP:** In natural language processing, the construction of meaningful poisoning samples is more challenging as the text data is discrete, and the semantic meaning of sentences would ideally be preserved for the attack to remain unnoticeable. Recent work has shown that backdoor attacks in NLP domains are becoming feasible. For instance, Chen et al. [48] introduced semantic-preserving backdoors at the character, word, and sentence level for sentiment analysis and neural machine translation applications. Li et al. [132] generated hidden backdoors against transformer models using generative language models in three NLP tasks: toxic comment detection, neural machine translation, and question answering.
- **Cybersecurity:** Early poisoning attacks in cybersecurity were designed against worm signature generation in 2006 [177] and spam detectors in 2008 [166], well before rising interest in adversarial machine learning. More recently, Severi et al. [192] showed how AI explainability techniques can be leveraged to generate clean-label poisoning attacks with small triggers against malware classifiers. They attacked multiple models (i.e., neural networks, gradient boosting, random forests, and SVMs), using three malware datasets: Ember for Windows PE file classification, Contagio for PDF file classification, and DREBIN for Android app classification. Jigsaw Puzzle [246] designed a backdoor poisoning attack for Android malware classifiers that uses realizable software triggers harvested from benign code.

Mitigations. The literature on backdoor attack mitigation is vast compared to other poisoning attacks. Below we discuss several classes of defenses, including data sanitization, trigger reconstruction, model inspection and sanitization, and also their limitations.

- **Training Data Sanitization:** Similar to poisoning availability attacks, training data sanitization can be applied to detecting backdoor poisoning attacks. For instance, outlier detection in the latent feature space [98, 178, 224] has been effective for convolutional neural networks used for computer vision applications. Activation Clustering [43] performs clustering of training data in representation space with the goal of isolating the backdoored samples in a separate cluster. Data sanitization achieves better results when the poisoning attack controls a relatively large fraction of training data, but is not that effective against stealthy poisoning attacks. Overall, this leads to a trade-off between attack success and detectability of malicious samples.
- **Trigger reconstruction:** This class of mitigations aims to reconstruct the backdoor trigger, assuming that it is at a fixed location in the poisoned training samples. NeuralCleanse by Wang et al. [230] developed the first trigger reconstruction approach and used optimization to determine the most likely backdoor pattern that reliably misclassifies the test samples. The initial technique has been improved to reduce performance time on several classes and simultaneously support multiple triggers inserted into the model [100, 239]. A representative system in this class is Artificial Brain Simulation (ABS) by Liu et al. [137], which stimulates multiple neurons and measures the activations to reconstruct the trigger patterns.
- **Model inspection and sanitization:** Model inspection analyzes the trained ML model before its deployment to determine whether it was poisoned. An early work in this space is NeuronInspect [102], which is based on explainability methods to determine different features between clean and backdoored models that are subsequently used for outlier detection. DeepInspect [45] uses a conditional generative model to learn the probability distribution of trigger patterns and performs model patching to remove the trigger. Xu et al. [244] proposed the Meta Neural Trojan Detection (MNTD) framework, which trains a meta-classifier to predict whether a given ML model is backdoored (or Trojaned, in the authors' terminology). This technique is general and can be applied to multiple data modalities, such as vision, speech, tabular data, and NLP. Once a backdoor is detected, model sanitization can be performed via pruning [238], retraining [253], or fine-tuning [135] to restore the model's accuracy.

Most of these mitigations have been designed against computer vision classifiers based on convolutional neural networks using backdoors with fixed trigger patterns. Severi et al. [192] showed that some of the data sanitization techniques (e.g., spectral signatures [224] and Activation Clustering [43]) are ineffective against clean-label backdoor poisoning on malware classifiers. Most recent semantic and functional backdoor triggers would also pose challenges to approaches based on trigger reconstruction or model inspection, which generally assume fixed backdoor patterns. The limitation of using meta classifiers for predicting a Trojaned model [244] is the high computational complexity of the training stage of the meta classifier, which requires training thousands of SHADOW MODELS. Additional research is required to design strong backdoor mitigation strategies that can protect ML models against this important attack vector without suffering from these limitations.

In cybersecurity, Rubinstein et al. [185] proposed a principal component analysis (PCA)-based approach to mitigate poisoning attacks against PCA subspace anomaly detection method in backbone networks. It maximized Median Absolute Deviation (MAD) instead of variance to compute principal components, and used a threshold value based on Laplace distribution instead of Gaussian. Madani and Vlajic [143] built an autoencoder-based intrusion detection system, assuming malicious poisoning attack instances were under 2%.

4.4. Model Poisoning

Model poisoning attacks attempt to directly modify the trained ML model to inject malicious functionality into the model. In centralized learning, TrojNN [138] reverse engineers the trigger from a trained neural network and then retrains the model by embedding the trigger in external data to poison it. Most model poisoning attacks have been designed in the federated learning setting in which clients send local model updates to a server that aggregates them into a global model. Compromised clients can send malicious updates to poison the global model. Model poisoning attacks can cause both availability and integrity violation in federated models:

- Poisoning availability attacks that degrade the global model's accuracy have been effective, but they usually require a large percentage of clients to be under the control of the adversary [78, 197].
- Targeted model poisoning attacks induce integrity violations on a small set of samples at testing time. They can be mounted by a model replacement or model boosting attack in which the compromised client replaces the local model update according to the targeted objective [7, 16, 214].
- Backdoor model poisoning attacks introduce a trigger via malicious client updates to induce the misclassification of all samples with the trigger at testing time [7, 16, 214, 232]. Most of these backdoors are forgotten if the compromised clients do not regularly participate in training, but the backdoor becomes more durable if injected in the lowest utilized model parameters [260].

Model poisoning attacks are also possible in supply-chain scenarios where models or components of the model provided by suppliers are poisoned with malicious code.

Mitigations. To defend federated learning from model poisoning attacks, a variety of Byzantine-resilient aggregation rules have been designed and evaluated. Most of them attempt to identify and exclude the malicious updates when performing the aggregation at the server [3, 24, 28, 95, 149–151, 213, 250]. However, motivated adversaries can bypass these defenses by adding constraints in the attack generation optimization problem [7, 78, 197]. Gradient clipping and differential privacy have the potential to mitigate model poisoning attacks to some extent [7, 169, 214], but they usually decrease accuracy and do not provide complete mitigation.

Designing federated learning models that are fully robust against model poisoning attacks remains an open research problem in the community.

5. Privacy Attacks

Although privacy issues have long been a concern, privacy attacks against aggregate statistical information collected from user records started with the seminal work of Dinur and Nissim [67] on *reconstruction attacks*. The goal of reconstruction attacks is to reverse engineer private information about an individual user record or sensitive critical infrastructure data from access to aggregate statistical information. More recently, *memorization* attacks that reconstruct or regenerate the training data have been shown in the context of large generative language models, such as GPT-2 [34]. A less devastating privacy attack is that of *membership inference* in which an adversary can determine whether a particular record was included in the dataset used for computing statistical information or training a machine learning model. Membership inference attacks were first introduced by Homer et al. [99] for genomic data. Recent literature focuses on membership attacks against ML models in mostly black-box settings in which adversaries have query access to a trained ML model [30, 200, 249]. Another privacy violation for MLaaS is model extraction attacks, which are designed to extract information about an ML model such as its architecture or model parameters [32, 40, 108, 222]. Property inference attacks [4, 42, 86, 145, 215, 258] aim to extract global information about a training dataset, such as the fraction of training examples with a certain sensitive attribute.

This section discusses privacy attacks related to data reconstruction, the memorization of training data, membership inference, model extraction, and property inference, as well as mitigations for some of these attacks and open problems in designing general mitigation strategies.

5.1. Data Reconstruction

Data reconstruction attacks are the most concerning privacy attacks as they have the ability to recover an individual's data from released aggregate statistical information. Dinur and Nissim [67] were the first to introduce reconstruction attacks that recover user data from linear statistics. Their original attack requires an exponential number of queries for reconstruction, but subsequent work has shown how to perform reconstruction with a polynomial number of queries [74]. A survey of privacy attacks, including reconstruction attacks, is given by Dwork et al. [72]. More recently, the U.S. Census Bureau performed a large-scale study on the risk of data reconstruction attacks on census data [87], which motivated the use of differential privacy in the decennial release of the U.S. Census in 2020.

In the context of ML classifiers, Fredrickson et al. [84] introduced model inversion attacks that reconstruct class representatives from the training data of an ML model. While model inversion generates semantically similar images with those in the training set, it cannot directly reconstruct the training data of the model. Recently, Balle et al. [9] trained a reconstructor network that can recover a data sample from a neural network model, assuming a powerful adversary with information about all other training samples. Haim et al. [97] showed how the training data of a neural network can be reconstructed from access to the model parameters by leveraging theoretical insights about implicit bias in neural networks. Another relevant privacy attack is attribute inference, in which the attacker extracts a sensitive attribute of the training set [114].

5.2. Memorization

Memorization attacks are a powerful class of techniques that allow an adversary to extract training data from generative ML models, such as language models. Carlini et al. [33] were the first to practically demonstrate memorization attacks in language models. By inserting synthetic canaries in the training data, they developed a methodology for extracting the canaries and introduced a metric called *exposure* to measure memorization. Subsequent work demonstrated the risk of memorization in large language models, such as GPT-2 [34], and showed that models with a larger capacity tend to memorize more [31].

An orthogonal line of work is analyzing the connection between memorization and generalization in ML models. Zhang et al. [254] discussed how neural networks can memorize randomly selected datasets. Feldman [80] showed that the memorization of training labels is necessary to achieving almost optimal generalization error in ML. Brown et al. [26] constructed two learning tasks based on next-symbol prediction and cluster labeling in which memorization is required for high-accuracy learning. Feldman and Zhang empirically evaluated the benefit of memorization for generalization using an influence estimation method [81].

5.3. Membership Inference

Membership inference attacks generally expose less private information about an individual than reconstruction or memorization attacks but are still of great concern when releasing aggregate statistical information or ML models trained on user data. In certain situations, determining that an individual is part of the training set already has privacy implications, such as in a medical study of patients with a rare disease. Moreover, membership inference can be used as a building block for mounting extraction attacks [33, 34].

In membership inference, the attacker's goal is to determine whether a particular record or data sample was part of the training dataset used for the statistical or ML algorithm. These attacks were introduced by Homer et al. [99] for statistical computations on genomic data under the name *tracing attacks*. Robust tracing attacks have been analyzed when an adversary gains access to noisy statistical information about the dataset [73]. In the last five years, the literature has used the terminology *membership inference* for attacks against ML models. Most of the attacks in the literature are performed against deep neural networks used for classification [30, 54, 130, 200, 248, 249]. Similar to other attacks in adversarial machine learning, membership inference can be performed in white-box settings [130, 163, 186] in which attackers have knowledge of the model's architecture and parameters, but most of the attacks have been developed for black-box settings in which the adversary generates queries to the trained ML model [30, 54, 200, 248, 249].

The attacker's success in membership inference has been formally defined using a cryptographically inspired privacy game in which the attacker interacts with a challenger and needs to determine whether a target sample was used in training the queried ML model [113, 188, 249]. In terms of techniques for mounting membership inference attacks, the loss-based attack by Yeom et al. [249] is one of the most efficient and widely used method. Using the knowledge that the ML model minimizes the loss on training samples, the attack determines that a target sample is part of training if its loss is lower than a fixed threshold (selected as the average loss of training examples). Sablayrolles et al. [186] refined the loss-based attack by scaling the loss using a per-example threshold. Another popular technique introduced by Shokri et al. [200] is that of *shadow models*, which trains a meta-classifier on examples in and out of the training set obtained from training thousands of shadow ML models on the same task as the original model. This technique is generally expensive, and while it might improve upon the simple loss-based attack, its computational cost is high and requires access to many samples from the distribution to train the shadow models. These two techniques are at opposite ends of the spectrum in terms of their complexity, but they perform similarly in terms of precision at low false positive rates [30].

An intermediary method that is currently attaining state-of-the-art performance in terms of the AREA UNDER THE CURVE (AUC) metric is the LiRA attack by Carlini et al. [30], which trains a smaller number of shadow models to learn the distribution of model logits on examples in and out of the training set. Using the assumption that the model logit distributions are Gaussian, LiRA performs a hypothesis test for membership inference by estimating the mean and standard deviation of the Gaussian distributions. Ye et al. [248] designed a similar attack that performs a one-sided hypothesis test, which does not make any assumptions on the loss distribution but achieves slightly lower performance than LiRA. Membership inference attacks have also been designed under the stricter label-only threat model in which the adversary only has access to the predicted labels of the queried samples [54].

There are several public privacy libraries that offer implementations of membership inference attacks: the TensorFlow Privacy library [208] and the ML Privacy Meter [160].

5.4. Model Extraction

In MLaaS scenarios, cloud providers typically train large ML models using proprietary data and would like to keep the model architecture and parameters confidential. The goal of an attacker performing a model extraction attack is to extract information about the model architecture and parameters by submitting queries to the ML model trained by an MLaaS provider. The first model stealing attacks were shown by Tramer at al. [222] on several online ML services for different ML models, including logistic regression, decision trees, and neural networks. However, Jagielski et al. [108] have shown the exact extraction of ML models to be impossible. Instead, a functionally equivalent model can be reconstructed that is different than the original model but achieves similar performance at the prediction task. Jagielski et al. [108] have shown that even the weaker task of extracting functionally equivalent models is *NP*-hard.

Several techniques for mounting model extraction attacks have been introduced in the literature. The first method is that of direct extraction based on the mathematical formulation of the operations performed in deep neural networks, which allows the adversary to compute model weights algebraically [32, 108, 222]. A second technique explored in a series of papers is to use learning methods for extraction. For instance, active learning [40] can guide the queries to the ML model for more efficient extraction of model weights, and reinforcement learning can train an adaptive strategy that reduces the number of queries [172]. A third technique is the use of SIDE CHANNEL information for model extraction. Batina et al. [12] used electromagnetic side channels to recover simple neural network models, while Rakin et al. [182] recently showed how ROWHAMMER ATTACKS can be used for model extraction of more complex convolutional neural network architectures.

5.5. Property Inference

In property inference attacks, the attacker tries to learn global information about the training data distribution by interacting with an ML model. For instance, an attacker can determine the fraction of the training set with a certain sensitive attribute, such as demographic information, that might reveal potentially confidential information about the training set that is not intended to be released.

Property inference attacks were introduced by Ateniese et al. [4] and formalized as a distinguishing game between the attacker and the challenger training two models with different fractions of the sensitive data [215]. Property inference attacks were designed in white-box settings in which the attacker has access to the full ML model [4, 86, 215] and black-box settings in which the attacker issues queries to the model and learns either the predicted labels [145] or the class probabilities [42, 258]. These attacks have been demonstrated for HIDDEN MARKOV MODELS, SUPPORT VECTOR MACHINES [4], FEED-FORWARD NEURAL NETWORKS [86, 145, 258], CONVOLUTIONAL NEURAL NETWORKS [215], FEDERATED LEARNING MODELS [147], GENERATIVE ADVERSARIAL NETWORKS [262], and GRAPH NEURAL NETWORKS [261]. Mahloujifar et al. [145] and Chaudhauri et al. [42] showed that poisoning the property of interest can help design a more effective distinguishing test for property inference. Moreover, Chaudhauri et al. [42] designed an efficient property size estimation attack that recovers the exact fraction of the population of interest.

Several papers have reported negative results on various mitigation strategies against these attacks, including differential privacy which was designed to reveal aggregate statistics about a dataset [42, 145]. It seems inherent that a high accuracy ML model will reveal some aggregate information about its training dataset. While property inference might not be easy to mitigate, an open problem is understanding whether these attacks pose real privacy risk to users who contribute their data to ML training.

5.6. Mitigations

The discovery of reconstruction attacks against aggregate statistical information motivated the rigorous definition of *differential privacy* (DP) [70, 71]. Differential privacy is an extremely strong definition of privacy that guarantees a bound on how much an attacker with access to the algorithm output can learn about each individual record in the dataset. The original *pure* definition of DP has a privacy parameter ε (i.e., privacy budget), which bounds the probability that the attacker with access to the algorithm's output can determine whether a particular record was included in the dataset. DP has been extended to the notions of approximate DP, which includes a second parameter δ that is interpreted as the probability of information accidentally being leaked in addition to ε and Rènyi DP [154].

DP has been widely adopted due to several useful properties: group privacy (i.e., the extension of the definition to two datasets differing in k records), post-processing (i.e., privacy is preserved even after processing the output), and composition (i.e., privacy is composed if multiple computations that are performed on the dataset). DP mechanisms for statistical computations include the Gaussian mechanism [71], the Laplace mechanism [71], and the Exponential mechanism [146]. The most widely used DP algorithm for training ML models is DP-SGD [1], with recent improvements such as DP-FTRL [117] and DP matrix factorization [65].

By definition, DP provides mitigation against reconstruction attacks, the memorization of training data, and membership inference attacks. In fact, the definition of DP immediately implies an upper bound on the success of a membership inference attack. Tight bounds on the success of membership inference have been derived by Thudi et al. [218]. However, DP does not provide guarantees against model extraction or property inference attacks [42, 145]. One of the main challenges of using DP in practice is setting up the privacy parameters to achieve a trade-off between privacy and utility, which is typically measured in terms of accuracy for ML models. Analysis of privacy-preserving algorithms, such as DP-SGD, is often worst case, and selecting privacy parameters based purely on theoretical analysis results in utility loss. Therefore, large privacy parameters are often used in practice (e.g., the 2020 U.S. Census release used $\varepsilon = 19.61$), and the exact privacy obtained in practice is difficult to estimate. Recently, a promising line of work is that of *privacy auditing* introduced by Jagielski et al. [112] with the goal of empirically measuring the actual privacy guarantees of an algorithm and determining privacy lower bounds by mounting privacy attacks. Auditing can be performed with membership inference attacks [113], but poisoning attacks are much more effective for empirical privacy auditing [112, 164].

Other mitigation techniques against model extraction, such as limiting user queries to the model, detecting suspicious queries to the model, or creating more robust architectures to prevent side channel attacks exist in the literature. However, these techniques can be circumvented by motivated and well-resourced attackers and should be used with caution. We refer the reader to available practice guides for securing machine learning deployments [39, 170].

6. Discussion and Remaining Challenges

The literature on AML shows a trend of designing new attacks with higher power and stealthier behavior. The attacks considered above and those discussed in Section 6.2 illustrate this well. Moreover, Goldwasser et al. [91] recently introduced a new class of attacks: information-theoretically undetectable Trojans that can be planted in ML models. Such attacks can only be prevented or detected and mitigated by procedures that restrict and control who in the organization has access to the model throughout the life cycle and by thoroughly vetting third-party components coming through the supply chain. The NIST AI Risk Management Framework [170] offers more information on this.

One of the ongoing challenges facing the AML field is the ability to detect when the model is under attack. Knowing this would provide an opportunity to counter the attack before any information is lost or an adverse behaviour is triggered in the model. Tramèr [219] has shown that designing techniques to detect adversarial examples is equivalent to robust classification, which is inherently hard to construct, up to computational complexity and a factor of 2 in the robustness radius.

Adversarial examples may be from the same data distribution on which the model is trained and to which it expects the inputs to belong or may be OUT-OF-DISTRIBUTION (OOD) inputs. Thus, the ability to detect OOD inputs is also an important challenge in AML. Fang et al. [79] established useful theoretical bounds on detectability, particularly an impossibility result when there is an overlap between the in-distribution and OOD data.

Given the onslaught of powerful attacks, designing appropriate mitigations is a challenge that needs to be addressed before deploying AI systems in critical domains. This challenge is exacerbated by the lack of information-theoretically secure machine learning algorithms for many tasks in the field, as we discussed in Section 1. This implies that presently designing mitigations is an inherently ad hoc and fallible process. We refer the readers to available practice guides for securing machine learning deployments [39, 170], as well as existing guidelines for mitigating AML attacks [75].

The data and model sanitization techniques discussed in Section 4 reduce the impact of a range of poisoning attacks and should be widely used. However, they should be combined with cryptographic techniques for origin and integrity attestation to provide assurances downstream, as recommended in the final report of the National Security Commission on AI [165].

The robust training techniques discussed in Section 4 offer different approaches to providing theoretically certified defenses against data poisoning attacks with the intention of providing much-needed information-theoretic guarantees for security. The results are encouraging, but more research is needed to extend this methodology to more general assumptions about the data distributions, the ability to handle OOD inputs, more complex models, and multiple data modalities. Another challenge is applying these techniques to very large models like LLMs and generative models, which are quickly becoming targets of attacks [55].

Another general problem of AML mitigations for both evasion and poisoning attacks is the lack of reliable benchmarks which causes results from AML papers to be routinely incomparable, as they do not rely on the same assumptions and methods. While there have been some promising developments into this direction [60, 191], more research and encouragement is needed to foster the creation of standardized benchmarks to allow gaining reliable insights into the actual performance of proposed mitigations.

Formal methods verification has a long history in other fields where high assurance is required, such as avionics and cryptography. The lessons learned there teach us that although the results from applying this methodology are excellent in terms of security and safety assurances, they come at a very high cost, which has prevented formal methods from being widely adopted. Currently, formal methods in these fields are primarily used in applications mandated by regulations. Applying formal methods to neural networks has significant potential to provide much-needed security guarantees, especially in high-risk applications. However, the viability of this technology will be determined by a combination of technical and business criteria – namely, the ability to handle today's complex machine learning models of interest at acceptable costs. More research is needed to extend this technology to all algebraic operations used in machine learning algorithms, to scale it up to the large models used today, and to accommodate rapid changes in the code of AI systems while limiting the costs of applying formal verification.

There is an imbalance between the large number of privacy attacks listed in Section 5 (i.e., memorization, membership inference, model extraction, and property inference) and available reliable mitigation techniques. In some sense, this is a normal state of affairs: a rapidly evolving technology gaining widespread adoption – even "hype" – which attracts the attention of adversaries, who try to expose and exploit its weaknesses before the technology has matured enough for society to assess and manage it effectively. To be sure, not all adversaries have malevolent intent. Some simply want to warn the public of potential breakdowns that can cause harm and erode trust in the technology. Additionally, not all attacks are as practical as they need to be to pose real threats to AI system deployments of interest. Yet the race between developers and adversaries has begun, and both sides are making great progress. This poses many difficult questions for the AI community of stakeholders, such as:

- What is the best way to mitigate the potential exploits of memorized data from Section 5.2 as models grow and ingest larger amounts of data?
- What is the best way to prevent attackers from inferring membership in the training set or other properties of the training data using the attacks listed in Sections 5.3 and 5.5?
- How can developers protect their ML models and associated intellectual property from the emerging threats of algebraic methods that utilize the public API of the ML

model to query and exploit its secret weights or the side-channel leakage attacks from Section 5.4? The known mechanisms of preventing large numbers of queries through the API are ineffective in configurations with anonymous or unauthenticated access to the model.

As answers to these questions become available, it is important for the community of stakeholders to develop specific guidelines to complement the NIST AI RMF [170] for use cases where privacy is of utmost importance.

6.1. Trade-Offs Between the Attributes of Trustworthy AI

The trustworthiness of an AI system depends on all of the attributes that characterize it [170]. For example, an AI system that is accurate but easily susceptible to adversarial exploits is unlikely to be trusted. Similarly, an AI system that produces harmfully biased or unfair outcomes is unlikely to be trusted even if it is robust. There are also trade-offs between explainability and adversarial robustness [107, 153]. In cases where fairness is important and privacy is necessary to maintain, the trade-off between privacy and fairness needs to be considered [109]. Unfortunately, it is not possible to simultaneously maximize the performance of the AI system with respect to these attributes. For instance, AI systems optimized for accuracy alone tend to underperform in terms of adversarial robustness and fairness [41, 69, 181, 225, 255]. Conversely, an AI system optimized for adversarial robustness may exhibit lower accuracy and deteriorated fairness outcomes [14, 231, 255].

The full characterization of the trade-offs between the different attributes of trustworthy AI is still an open research problem that is gaining increasing importance with the adoption of AI technology in many areas of modern life.

In most cases, organizations will need to accept trade-offs between these properties and decide which of them to prioritize depending on the AI system, the use case, and potentially many other considerations about the economic, environmental, social, cultural, political, and global implications of the AI technology [170].

6.2. Multimodal Models: Are They More Robust?

MULTIMODAL MODELS have shown great potential for achieving high performance on many machine learning tasks [10, 13, 159, 183, 256]. It is natural to assume that because there is redundancy of information across the different modalities, the model should be more robust against adversarial perturbations of a single modality. However, emerging evidence from practice shows that this is not necessarily the case. Combining modalities and training the model on clean data alone does not seem to improve adversarial robustness. In addition, one of the most effective defenses against evasion attacks based on adversarial training, which is widely used in single modality applications, is prohibitively expensive in practical applications of multimodal learning. Additional effort is required to benefit from the redundant information in order to improve robustness against single modality attacks [245]. Without such an effort, single modality attacks can be effective and compromise multimodal models across a wide range of multimodal tasks despite the information contained in the remaining unperturbed modalities [245, 251]. Moreover, researchers have devised efficient mechanisms for constructing simultaneous attacks on multiple modalities, which suggests that multimodal models might not be more robust against adversarial attacks despite improved performance [44, 195, 243].

The existence of simultaneous attacks on multimodal models suggests that mitigation techniques that only rely on single modality perturbations are not likely to be robust. Attackers in real life do not constrain themselves to attacks within a given security model but employ any attack that is available to them.

6.3. Beyond Models and Data

As pointed out in the Introduction, chatbots [50, 62, 152, 171] enabled by recent advances in deep learning have emerged as a powerful technology with great potential for numerous business applications, from entertainment to more critical fields. AI-enabled chatbots use NLP to process and respond to human input, but these chatbots have more complicated architectures than just a language model. For example, a critical element of a conversational chatbot is the dialog component whose task is to determine the purpose of the user input and identify relevant intents (i.e., establish the context for the conversation). Only then is the chatbot able to determine an appropriate response and return it to the user. Traditional attacks on chatbots have focused on overwhelming the chatbot with toxic input in order to alter its behaviour [190]. Recently, specific attacks using ”PROMPT INJECTIONS” have emerged as effective ways to trigger bad behaviour in the bot [228].

However, the design of AI systems that can communicate with humans is not just a technical problem but a deeply socio-technical challenge. In addition, the potential for attacks that could compromise the function of the dialog component and maliciously change the subject of the conversation for the unsuspecting user can lead to the chatbot offering misleading or even harmful advice. The potential harms in this case go beyond the traditional harms considered by AML and defined in Section 2.

Despite progress in the ability of chatbots to perform well on certain tasks [171], this technology is still limited and should not be deployed in applications that require a high degree of trust in the information they generate.

As the development of AI-enabled chatbots continues and their deployment becomes more prevalent online, these concerns will come to the forefront and be pursued by adversaries to discover and exploit vulnerabilities and by companies developing the technology to improve their design and implementation to protect against such attacks.

Realistic risk management throughout the entire life cycle of the technology is critically important to identify risks and plan early corresponding mitigation approaches [170]. For example, incorporating human adversarial input in the process of training the system (i.e., red teaming) or employing reinforcement learning from human feedback appear to offer benefits in terms of making the chatbot more resilient against toxic input or prompt injections [62]. Barrett et al. [11] have developed detailed risk profiles for cutting-edge generative AI systems that map well to the NIST AI RMF [57] and should be used for assessing and mitigating potentially catastrophic risks to society that may arise from this technology.

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Note: one may click on the page number shown at the end of the definition of each glossary entry to go to the page where the term is used.

A. Appendix: Glossary

adversarial examples Modified testing samples which induce mis-classification of a machine learning model at deployment time. v, 8

Area Under the Curve In ML the Area Under the Curve (AUC) is a measure of the ability of a classifier to distinguish between classes. The higher the AUC, the better the performance of the model at distinguishing between the two classes. AUC measures the entire two-dimensional area underneath the RECEIVER OPERATING CHARACTERISTICS (ROC) curve. 30

availability attack Adversarial attacks against machine learning which degrade the overall model performance. 8

backdoor pattern A trigger pattern inserted into a data sample to induce mis-classification of a poisoned model. For example, in computer vision it may be constructed from a set of neighboring pixels, e.g., a white square, and added to a specific target label. To mount a backdoor attack, the adversary first poisons the data by adding the trigger to a subset of the clean data and changing their corresponding labels to the target label. 9

backdoor poisoning attacks Poisoning attacks against machine learning which change the prediction on samples including a backdoor pattern. 8

classification Type of supervised learning in which data labels are discrete. 7

convolutional neural networks A Convolutional Neural Network (CNN) is a class of artificial neural networks whose architecture connects neurons from one layer to the next layer and includes at least one layer performing convolution operations. CNNs are typically applied to image analysis and classification. See [92] for further details. 7, 31

data poisoning Poisoning attacks in which a part of the training data is under the control of the adversary. 7

data privacy Attacks against machine learning models to extract sensitive information about training data. 9

data reconstruction Data privacy attacks which reconstruct sensitive information about training data records. 9

deployment stage Stage of ML pipeline in which the model is deployed on new data. 7

discriminative Type of machine learning methods which learn to discriminate between classes. 7

energy-latency attacks Attacks that exploit the performance dependency on hardware and model optimizations to negate the effects of hardware optimizations, increase computation latency, increase hardware temperature and massively increase the amount of energy consumed. 8

ensemble learning Type of a meta machine learning approach that combines the predictions of several models to improve the performance of the combination. 7

federated learning Type of collaborative machine learning, in which multiple users train jointly a machine learning model. 7

federated learning models Federated learning is a methodology to train a decentralized machine learning model (e.g., deep neural networks or a pre-trained large language model) across multiple end-devices without sharing the data residing on each device. Thus, the end-devices collaboratively train a global model by exchanging model updates with a server that aggregates the updates. Compared to traditional centralized learning where the data are pooled, federated learning has advantages in terms of data privacy and security but these may come as tradeoffs to the capabilities of the models learned through federated data. Other potential problems one needs to contend with here concern the trustworthiness of the end-devices and the impact of malicious actors on the learned model. 31

feed-forward neural networks A Feed Forward Neural Network is an artificial neural network in which the connections between nodes is from one layer to the next and do not form a cycle. See [92] for further details. 31

formal methods Formal methods are mathematically rigorous techniques for the specification, development, and verification of software systems. 18

generative Type of machine learning methods which learn the data distribution and can generate new examples from distribution. 7

generative adversarial networks A generative adversarial network (GAN) is a class of machine learning frameworks in which two neural networks contest with each other in the form of a zero-sum game, where one agent's gain is another agent's loss. GAN's learn to generate new data with the same statistics as the training set. See [92] for further details. 31

graph neural networks A Graph Neural Network (GNN) is an optimizable transformation on all attributes of the graph (nodes, edges, global-context) that preserves the graph symmetries (permutation invariances). GNNs utilize a "graph-in, graph-out" architecture that takes an input graph with information loaded into its nodes, edges and global-context, and progressively transform these embeddings into an output graph with the same connectivity as that of the input graph. 31

hidden Markov models A hidden Markov model (HMM) is a statistical Markov model in which the system being modeled is assumed to be a Markov process with unobservable states. In addition, the model provides an observable process whose outcomes are ”influenced” by the outcomes of Markov model in a known way. HMM can be used to describe the evolution of observable events that depend on internal factors, which are not directly observable. In machine learning it is assumed that the internal state of a model is hidden but not the hyperparameters. 31

integrity attack Adversarial attacks against machine learning which change the output prediction of the machine learning model. 8

label flipping a type of data poisoning attack where the adversary is restricted to changing the training labels. 21

label limit Capability in which the attacker in some scenarios does not control the labels of training samples in supervised learning. 9

logistic regression Type of linear classifier that predicts the probability of an observation to be part of a class.. 7

membership-inference attacks Data privacy attacks to determine if a data sample was part of the training set of a machine learning model. 9

memorization The ability of a machine learning model to encode, remember, and potentially emit the training data. 9

model control Capability in which the attacker has control over machine learning model parameters. 9

model extraction Type of privacy attack to extract model architecture and parameters. 9

model poisoning Poisoning attacks in which the model parameters are under the control of the adversary. 8

model privacy Attacks against machine learning models to extract sensitive information about the model. 9

multimodal models Modality is associated with the sensory modalities which represent primary human channels of communication and sensation, such as vision or touch. Multimodal models process and relate information from multiple modalities. 35

out-of-distribution This term refers to data that was collected at a different time, and possibly under different conditions or in a different environment, than the data collected to train the model. 33

poisoning attacks Adversarial attacks against machine learning at training time. 7

prompt injections Malicious plain text instructions to a generative AI system that uses textual instructions (a "prompt") to accomplish a task causing the AI system to generate text on a topic prohibited by the designers of the system. 36

property inference Data privacy attacks which infer global property about the training data of a machine learning model. 9

query access Capability in which the attacker can issue queries to a trained machine learning model and obtain predictions. 9

Receiver Operating Characteristics (ROC) In ML the Receiver Operating Characteristics (ROC) curve plots true positive rate versus false positive rate for a classifier. 62

reinforcement learning Type of machine learning in which an agent interacts with the environment and learns to take actions which optimize a reward function. 7

rowhammer attacks Rowhammer is a software-based fault-injection attack that exploits DRAM disturbance errors via user-space applications and allows the attacker to infer information about certain victim secrets stored in memory cells. Mounting this attack requires attacker's control of a user-space unprivileged process that runs on the same machine as the victim's ML model. 31

semi-supervised learning Type of machine learning in which a small number of training samples are labeled, while the majority are unlabeled. 7

shadow models Shadow models imitate the behavior of the target model. The training datasets and thus the ground truth about membership in these datasets are known for these models. Typically, the attack model is trained on the labeled inputs and outputs of the shadow models. 25

side channel side channels allow an attacker to infer information about a secret by observing nonfunctional characteristics of a program, such as execution time or memory or by measuring or exploiting indirect coincidental effects of the system or its hardware, like power consumption variation, electromagnetic emanations, while the program is executing. Most commonly, such attacks aim to exfiltrate sensitive information, including cryptographic keys. 31

source code control Capability in which the attacker has control over the source code of the machine learning algorithm. 9

supervised learning Type of machine learning methods based on labeled data. 7

Support Vector Machines A Support Vector Machine implements a decision function in the form of a hyperplane that serves to separate (i.e., classify) observations belonging to one class from another based on patterns of information about those observations (i.e., features). . 7, 8, 21, 31

targeted poisoning attacks Poisoning attacks against machine learning which change the prediction on a small number of targeted samples. 8

testing data control Capability in which the attacker has control over the testing data input to the machine learning model. 9

training data control Capability in which the attacker has control over a part of the training data of a machine learning model. 9

training stage Stage of machine learning pipeline in which the model is trained using training data. 7

trojans A malicious code/logic inserted into the code of a software or hardware system, typically without the knowledge and consent of the organization that owns/develops the system, that is difficult to detect and may appear harmless, but can alter the intended function of the system upon a signal from an attacker to cause a malicious behavior desired by the attacker. 3

unsupervised learning Type of machine learning methods based on unlabeled data. 7