

PICKLEBALL: Secure Deserialization of Pickle-based Machine Learning Models

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Abstract

Machine learning model repositories such as the Hugging Face Model Hub facilitate model exchanges. However, bad actors can deliver malware through compromised models. Existing defenses such as safer model formats, restrictive (but inflexible) loading policies, and model scanners have shortcomings: 44.9% of popular models on Hugging Face still use the insecure pickle format, 15% of these cannot be loaded by restrictive loading policies, and model scanners have both false positives and false negatives. Pickle remains the *de facto* standard for model exchange, and the ML community lacks a tool that offers transparent safe loading.

We present PICKLEBALL to help machine learning engineers load pickle-based models safely. PICKLEBALL statically analyzes the source code of a given machine learning library and computes a custom policy that specifies a safe load-time behavior for benign models. PICKLEBALL then dynamically enforces the policy during load time as a drop-in replacement for the pickle module. PICKLEBALL generates policies that correctly load 79.8% of benign pickle-based models in our dataset, while rejecting all (100%) malicious examples in our dataset. In comparison, evaluated model scanners fail to identify known malicious models, and the state-of-art loader loads 22% fewer benign models than PICKLEBALL. PICKLEBALL removes the threat of arbitrary function invocation from malicious pickle-based models, raising the bar for attackers to depend on code reuse techniques.

CCS Concepts

• Security and privacy → Software and application security.

*Also with Socket.

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Keywords

Secure Model Loading; Deserialization Attacks; Supply Chains

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1 Introduction

Open-source and open-weight models enable the AI ecosystem [27, 42, 55, 102]. They enable machine learning engineers to exchange pre-trained models rather than training from scratch [31], facilitating direct use or further fine-tuning [16]. Open model repositories like Hugging Face now host millions of pre-trained models for many tasks [53, 55]. These model hubs are accessed directly as well as through corporate mirrors [112], with billions of downloads per month.

Unfortunately, as with traditional software supply-chain attacks, bad actors can distribute malicious models. The most common strategy for achieving remote code execution is by tampering with the model deserialization process. Several model serialization formats, such as TorchScript [81], H5/HDF5 [93], and the Python pickle module [77], permit executable metadata or callbacks during model deserialization. Attackers can craft malicious serialized models to execute code, such as `os.system()`, on victim systems during model loading [14, 18, 25, 104]. Researchers have found malicious pickle models on Hugging Face whose payloads include system fingerprinting, credential theft, and reverse shells [18, 104, 112], with one study discovering a 5× increase in the rate of malicious models uploaded to Hugging Face year-over-year [112]. This led to alternative safe model formats like SafeTensors [45], and restricted loading APIs like the PyTorch weights-only unpickler [82]; we study their adoption in the Hugging Face ecosystem (§3) and find that nevertheless, insecure formats are still prevalent.

In this work, we propose a novel approach to secure pickle model deserialization, which we focus on for three reasons. First, pickle

is a popular exchange format for models: repositories with pickle models are downloaded over 2.1 billion times per month from the Hugging Face model hub (§3.1). Second, pickle is the most expressive format and thus presents challenges to secure; it encodes models as opcodes executed by the pickle virtual machine (the *Pickle Machine*) [43, 68] during deserialization, and permits invocations of arbitrary Python classes and functions (*callable*s). Finally, pickle is a known security target for attackers, with almost all malicious models discovered on Hugging Face using the pickle format.

Our evaluation shows that the two existing kinds of pickle deserialization defenses are inadequate. *Model scanners* [8, 14, 44, 112] maintain fixed denylists of disallowed callables to identify models that invoke them. *Safe model loaders* [82] use fixed allowlists to permit only the use of trusted callables. Our evaluation shows the limits of these inflexible approaches for ML models. For instance, the default safe deserialization loader in PyTorch [82] prevents 15% of Hugging Face pickle repositories from loading (§3.1).

To address these limitations, we present PICKLEBALL, a two-part system for securing the exchange of pickle-based models. Our insight is that we can analyze library code to determine the expected behaviors of benign models produced by the library, and enforce *tailored model loading policies*. PICKLEBALL statically analyzes the library code to learn (1) all classes used in the library’s models and their transitive attributes, and (2) all functions for restoring objects of these classes from serialized bytes. Then, PICKLEBALL’s model-loading component enforces the inferred policies.

We evaluated PICKLEBALL and the state-of-the-art approaches on a dataset of 336 models. Our dataset is meant represent the kinds of models that PICKLEBALL must handle, including malicious models from attackers presenting as benign models used for inference tasks. We used 252 benign models sourced from Hugging Face, and 84 real and synthetic malicious models. PICKLEBALL loads 79.8% of benign models for inference tasks and prevents all malicious models from executing their payloads. PICKLEBALL adds a runtime overhead of ~2.62% to safely load a model. Compared to other approaches, PICKLEBALL achieved favorable precision and recall.

In summary, we contribute:

- (1) An **ecosystem-scale study** of pickle security considerations in the Hugging Face Model Hub. Repositories with *only* pickle models are downloaded over 400 million times per month, despite the introduction of new model formats. We find that 15% of repositories with only pickle models have a model that cannot be loaded by the SOTA secure pickle model loader, the weights-only unpickler.
- (2) The **design and implementation of PICKLEBALL**, a framework for securely loading pickle models. PICKLEBALL tailors loading policies to models, and enforces these policies lazily, for secure, efficient, and robust model loading.
- (3) A **novel dataset** of 336 benign and malicious pickle-based models for evaluating pickle security efforts. It has 252 benign models collected from Hugging Face, and 84 malicious models.¹

2 Background

Here we describe the ML model reuse ecosystem and formats (§2.1), then how the pickle format is used and the risks it entails (§2.2).

¹Code and data will be published on acceptance and provided for artifact review.

2.1 Model Reuse

2.1.1 The Model Supply Chain. Training ML models from scratch requires massive compute and data [31, 73], so engineers and companies save resources by reusing machine-learning models trained by others (pre-trained models) [27, 42, 55, 102]. Open model repositories like Hugging Face host over 1.8M models [47] for many tasks [53, 55].

A supply chain of pre-trained models has grown from model reuse, which comes with risks similar to those in the traditional software supply chain [55, 69]. Bad actors apply techniques familiar in traditional software security, such as typosquatting [51, 52, 60, 66] and code injection [103], as well as ML-specific ones like data manipulation [41]. Model hubs like Hugging Face try to detect malicious models using both traditional code scanners like ClamAV [55] and domain-specific pickle scanners [8, 44] due to the proliferation of malicious pickle models [14, 112].

Machine learning libraries facilitate the development and exchange of models. Libraries like PyTorch [71], TensorFlow [6], and JAX [12] provide a core of general ML library utilities, like model training and serialization functions. Other popular but more specific libraries build upon the core libraries with task-specific utilities, like ultralytics (formerly YOLO) [99] for image recognition, PyAnnote [75] for audio processing, and flair [67] for text processing. To create a model, an engineer uses one of these libraries to write a *model saver* program, which trains a model and serializes it for reuse. To load and use the model, an engineer uses the same library (identified in documentation that accompanies the model) to write a *model loader* program. The libraries provide the interface for interacting with the shared models.

2.1.2 Model Serialization Formats. Model savers and loaders must agree on the serialization format; there are various formats available, each with its own tradeoffs in terms of security, flexibility, and performance.² Python is the primary language for using ML models, and its native serialization module, pickle [77], provides a convenient and flexible interface for saving objects; pickle proliferated for being easy to use and is used by popular libraries like PyTorch [80]. Hugging Face released the SafeTensors format in September 2022 as an alternative that prioritizes security [45]. The GGUF format, released August 2023, is optimized for fast model loading and inference tasks, especially for large language models [39, 46]. Other formats may be selected for library coupling (e.g., TensorFlow SavedModel), interoperability (e.g., ONNX), or intermediate tradeoffs between security, flexibility, and performance.

The security of a format depends on the expressivity of the operations needed to deserialize a model. The SafeTensors format requires very few different operations to load a model, because it effectively only encodes model weight values, and is considered a secure format after independent security audits [72, 94]. Some formats, like TensorFlow SavedModel and ONNX, are known to permit operations that could be abused in specific settings [95, 113], but with no observed real-world attacks. Pickle is an extremely expressive format that permits nearly arbitrary operations during deserialization, and numerous malicious pickle models are discovered on Hugging Face [14, 18, 104, 108, 112].

²A convenient table showing these tradeoffs is provided in the SafeTensors repository README: <https://github.com/huggingface/safetensors>.

```

1 import pickle
2
3 def read_weights_to_tensor(filename: str) -> Tensor:
4     # Read a file containing weights and
5     # return a Tensor object.
6
7 class Tensor(object):
8     ...
9     def __reduce__(self):
10         return (read_weights_to_tensor, self.filename)
11
12 class Model(object):
13     def __init__(self, weights: library.Tensor):
14         self.weights = weights
15
16     def save(self, filename):
17         pickle.dump(filename, self)
18
19     @classmethod
20     def load(path)
21         return pickle.load(path)
22     ...

```

Figure 1: Example of a machine learning library with a model that can be pickled. The `Tensor` class’s `__reduce__` method registers the `read_weights_to_tensor` function for execution during deserialization.

We focus our efforts on pickle models due to their insecure format (explained in §2.2) and their continued popularity (measured in §3).

2.2 Pickle Serialization and Risks

Pickle is popular because of its flexibility and convenience, due to its ability to represent almost any Python object. The pickle module implements a virtual machine, the *Pickle Machine (PM)*, that executes a sequence of opcodes [56] to deserialize an object. The expressiveness of the PM allows it to serialize and reconstruct complex Python data structures, but also make it vulnerable to attacks, allowing attackers to invoke arbitrary Python callables [68].

Pickle Program Structure and Semantics: A pickle program consists of opcode sequences interpreted by the PM, a stack-based VM implemented in the Python pickle module [68]. When the pickle program halts, the object at the top of the PM stack is returned to the Python interpreter as the deserialized object.

The Pickle Machine is integrated into the Python interpreter. Many of the PM’s opcodes create or manipulate native-type objects, e.g., `NEWFALSE` to create a `bool`, while others import and invoke Python *callable*s (classes and functions) [78]. Specifically, the *callable importing* opcodes `GLOBAL` and `STACK_GLOBAL` take a callable’s name, import it, and push it to the top of the PM stack. Class instances are instantiated using *callable allocating* opcodes, like `NEWOBJ`, which calls the class’s `__new__` method. Function references are called via *callable invoking* opcodes like `REDUCE`. Arguments can be passed to both allocations and invocations, and the return value is pushed to the PM stack. Lastly, the *callable building* `BUILD` opcode can modify an object (e.g., set/change its attributes).

Pickle allows users to define custom deserializing behaviors per class with the `__reduce__` method. The method must return a reference to a function and arguments. During serialization, an object’s `__reduce__` method is called and the returned function reference and argument values are written to the serialized output

opcodes. During deserialization, the function is invoked with the arguments, and the return value is pushed onto the Pickle Machine stack. This provides a primitive to invoke arbitrary functions in a pickle program. Figure 1 shows an example class that registers a handler function (line 10) that is invoked with a *callable invoking* opcode during deserialization.

Pickle Deserialization Attacks: Pickle’s opcodes allow a pickle program to *import* and *invoke* arbitrary Python callables during unpickling. In particular, an attacker can make use of pickle’s *callable importing* and *callable invoking* opcodes to achieve arbitrary code execution—for example by executing an arbitrary shell command by invoking the `os.system` function. The dangers of deserializing arbitrary pickle programs have been publicized for over a decade [19, 32, 68, 77].

Protecting Pickle Models: Two existing approaches help engineers load pickle models more securely:

- (1) **Model scanners** identify malicious models using denylists of unsafe callables. As with many denylist approaches, model scanners are useful for identifying recognizable malicious content, but are bypassed by malicious models that avoid denied callables, or that *indirectly* invoke callables [97].³ Examples are Hugging Face’s picklescan [44] and ProtectAI’s scanner [74].
- (2) **Restricted loaders** restrict the PM to execute only allowed, safe callables. The only available restricted pickle model loader is PyTorch’s weights-only unpickler [82]. Its default allowlist is specialized for models produced by PyTorch.

3 Motivation

To summarize Section 2: it is dangerous to load untrusted pickle models, but alternative secure formats exist. Do pickle models remain a security threat? We answer this with a longitudinal study of pickle model usage (§3.1), and assessments of the usability of the PyTorch weights-only unpickler (§3.2).

3.1 Study of Pickle Models on Hugging Face

To determine whether pickle models are used despite the availability of alternate formats, we conducted a longitudinal study of the Hugging Face ecosystem. We investigated Hugging Face because it is the largest repository of pre-trained models [55], and because malicious pickled models have been reported on it [14, 18, 104, 108, 112]. At 10 points in time over a ~2-year period, we measured the download rates and model formats in repositories with ≥ 1000 monthly downloads (as a proxy for real-world impact).⁴ The number of repositories in a measurement ranged from 2,296 in the first measurement to 16,661 in the last, with the number increasing monotonically at each point. We mined two existing datasets that covered January–October 2023 (PTMTorrent [54] and HFCommunity [10]), and added new measurements in August 2024, November 2024, and March 2025 via the `huggingface_hub` API. In accordance with previous research [112], we determined model formats using file extensions; interested readers can refer to Appendix A for details.

³We demonstrate this in Appendix B by creating two backdoored models that bypass two state-of-the-art scanners. One model uses callables that are missed by the scanners, and the other model uses disallowed callables by invoking them indirectly.

⁴Downloads are tracked using Hugging Face metrics.

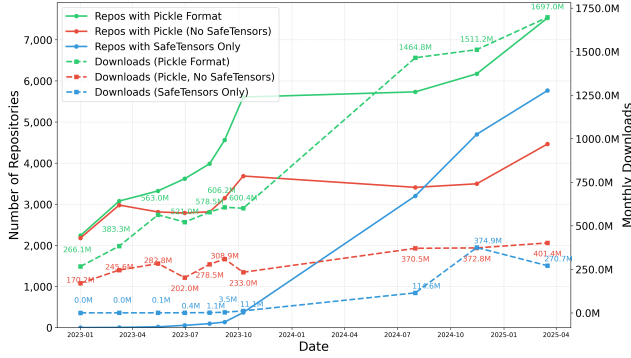


Figure 2: A longitudinal analysis of Hugging Face model formats for repositories with ≥ 1000 monthly downloads. Repositories can contain multiple models, each in different formats. Each color groups repositories by the model formats they contain: at least one pickle model (green), exclusively pickle (red), and exclusively SafeTensor (blue).

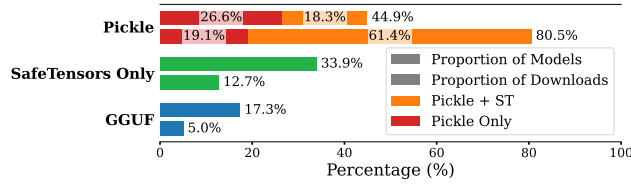


Figure 3: Proportions of model formats and downloads in March 2025, the final month of our longitudinal study. Notation: “Pickle+ST” indicates repositories with both formats.

Figure 2 summarizes our results. First, as the red lines show, many important models continue to use only the pickle format, and these pickle-only models are downloaded 400M+ times per month. Following the green lines, repositories that contain both pickle and SafeTensor versions of models are also increasingly downloaded, with 1.70 billion monthly downloads. As models are converted to the SafeTensor format, the associated pickle model is often kept for legacy purposes, and can still present security risks [62].

Figure 3 represents present-day usage with data from the final month of our study. Repositories with only SafeTensors or GGUF models are downloaded infrequently, in comparison to those with pickle models. Overall, $\sim 44.9\%$ of repositories contain pickle models, which aligns with previous estimates of 41%–55% [14, 112].

We anticipate that pickle models will continue to pose risks to the Hugging Face community for the next few years (cf. §7). Monthly download rates of pickle models are *increasing*, and many (21%) models are still exclusively in the pickle format, including 29 models in the top-100 most downloaded and over 500 models from Meta, Google, Microsoft, NVIDIA, and Intel. PyTorch remains the primary framework for model development, which reinforces reliance on pickle due to user familiarity [91]. Interoperability challenges persist during model conversion [22, 50, 105], complicating movement to other formats.

Summary: Despite positive steps to introduce secure alternative model formats like SafeTensors, pickle models are still prevalent and monthly downloads are *increasing*.

3.2 PyTorch Weights-Only Unpickler Usability

Our longitudinal study showed that pickle remains popular. Next, we assess whether the state-of-the-art safe loading approach, the PyTorch weights-only unpickler, can effectively load the pickle models we identify.

3.2.1 Measurements. The weights-only unpickler, introduced in PyTorch 1.13 (Nov. 2022) and enabled by default in PyTorch 2.6 (Nov. 2024) [84], prevents access to insecure callables, but can only load models that use callables from a small allowed set of PyTorch APIs.⁵ Models that use more callables cannot be loaded without user intervention; convenience and pressure from end-users results in library maintainers explicitly disabling the weights-only unpickler to maintain compatibility.⁶ We investigate a sample of the pickle models in our study to determine whether they use callables disallowed by the weights-only unpickler, which affects the usability of the weights-only unpickler as a solution.

Methods: We sampled the most popular 1,500 of the 4,553 pickle-only repositories in our survey (§3.1). For each repository, we used the Hugging Face API to download its pickle models and used the fickle tool [68] to statically trace and inspect the callables used. We compared the callables in the model trace to the callables permitted by the weights-only unpickler’s default policy. Models from 74 repositories failed to download or trace, leaving us with a sample of 1,426 repositories.

Results: Of the 1,426 model repositories surveyed, 219 repositories (15.4%) contained at least one pickle-based model that cannot be loaded by the weights-only unpickler due to disallowed Python callables. These 219 repositories were downloaded 79.6 million times in the final month of our longitudinal study. In total, 36 unique disallowed callables appear in the 219 repositories. Many come from major libraries (e.g., numpy and Hugging Face Transformers). We list all disallowed callables that appear in traces in Figure 8 (Appendix A). These models cannot be loaded securely by the weights-only unpickler, so users must instead rely on the weaker model scanners (§2.2) and their own assessments of the models’ safety.

3.2.2 Motivating Example. We use an example to show the implications of these weights-only unpickler incompatibilities. Consider the `flair ner-english-fast` [35] model, a pre-trained pickle model for named entity recognition of English text that gained over 1 million downloads. To load the model, its documentation refers to the `flair` library’s `SequenceTagger.load` API.

The `flair` loading API exposes the user to risk. `Flair` models, like this one, use callables that are not part of the weights-only unpickler allowlist, so the API explicitly disables the weights-only unpickler to load its models. To protect themselves during loading, the user must depend on scanners. For this (benign) model, the Hugging Face pickle scanner [44] warns the user that some

⁵PyTorch provides a mechanism for the user to manually expand the set of allowed callables [83], but the user is left to determine by themselves *which* callables to allow.

⁶As in the case of the `flairNLP` model (<https://github.com/flairNLP/flair/commit/79aa33706e7f753f2edf962feb1d75de22af0d1d>).

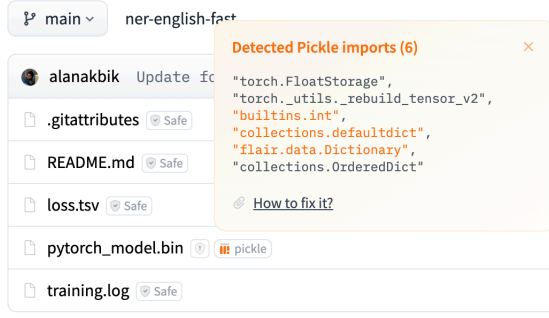


Figure 4: The Hugging Face repository for the `flair/ner-english-fast` model shows the results of the Hugging Face pickle scanning tool directly in the web application interface [35]. The pickle scanning tool warns that some imports in the model’s pickle file are suspicious and require attention (highlighted).

imports in the model pickle file are suspicious and require attention (Figure 4). We determined that the model is benign by manually reviewing its operations, and then reviewing the source code of the `flair` library to ensure that these operations are expected. This task is costly for every user to perform for every model. Our system successfully infers the expected operations and securely loads this model (§6.3) without manual effort.

Summary: While the weights-only unpickler offers security, 15.4% of sampled pickle repositories, with 79.6 million monthly downloads, contain a model that cannot use it. Library APIs disable the weights-only unpickler to load models, leaving users to rely on (incomplete) model scanners and manual assessments to determine if models are malicious.

4 System and Threat Model

Our motivational study shows the need for a new defense that is both usable and secure. Here, we model the system we aim to protect, and the adversary to be thwarted:

System Model: The system loads a pickle-based model from an untrusted source (e.g., Hugging Face Model Hub) using APIs provided by a trusted ML library (e.g., PyTorch). We specifically aim to protect the system from the code introduced by the pickle program and executed by the Pickle Machine.

Threat Model: The attacker provides a maliciously crafted pickle to the victim with the intention of compromising the system. The attacker’s goal is to execute arbitrary Python code (a “payload”), either directly during model loading, or after by e.g., overwriting a method in the model object with a reference to the payload.

- *In scope:* Manipulation of a pickle program in a pickle-based serialized model to execute arbitrary code.
- *Out of scope:* Manipulation of the data or code in the serialized model beyond the pickle program (e.g., model weights, data pipeline programs); manipulation of the trusted library code (e.g., PyTorch) used to load the serialized model.

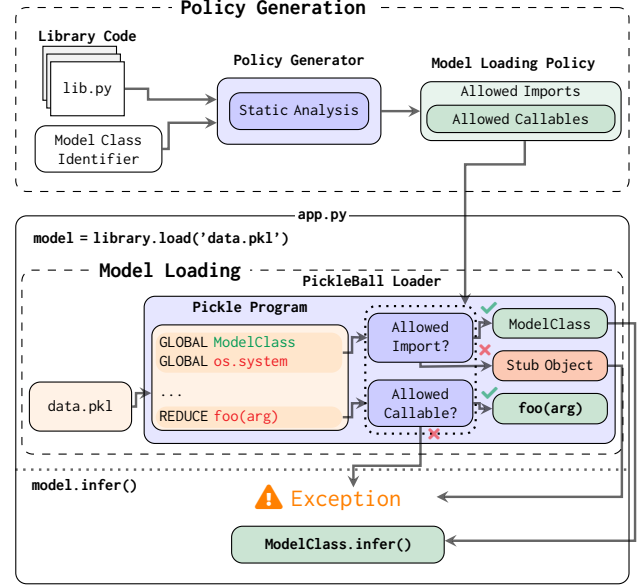


Figure 5: PICKLEBALL works in two phases: 1) policy generation and 2) safe model loading. During policy generation, PICKLEBALL takes as input the source code of a ML library and a class definition to analyze, and outputs a policy of allowed imports and invocations. During safe model loading, PICKLEBALL enforces the extracted policy to protect the loading process. The loading application specifies the policy to enforce, based on the expected class of the model, and begins loading the model with the library API. The loading application can trust that any invocations of the Pickle Machine will be restricted to the configured policy.

We focus on the threat of pickle program code execution, and exclude other threats from untrusted ML models. Other ML supply chain attacks are orthogonal and can be approached with layered defenses, like manipulating model weights to insert “backdoors” [17] and compromising other model components. We don’t consider other forms of attacks that manipulate pickle programs, e.g., for denial of service [20] due to their weaker attack primitives.

5 PICKLEBALL Design and Implementation

PICKLEBALL is designed to protect applications that use libraries to load untrusted pickle models. The desired system guarantee is that PICKLEBALL raises a security exception when an adversary invokes an unnecessary callable during model loading, while transparently loading benign models. The idea behind PICKLEBALL is to first generate a policy describing a minimal set of operations (i.e., the callables that need to be imported and invoked) for instantiating a given model object during an offline policy generation phase (§5.1), and then to enforce the generated policy during unpickling, rejecting spurious operations performed by malicious models (§5.2). Figure 5 provides an overview of the aforementioned PICKLEBALL components. PICKLEBALL guarantees that, given correct AST and type information, PICKLEBALL raises a security exception when the

adversary invokes an unnecessary callable (§5.3). We implement the design of PICKLEBALL as a software artifact (§5.4).

5.1 Policy Generation

PICKLEBALL’s policy generation component is designed to automatically create a policy that describes the set of operations (i.e., the set of callables imported and invoked) permitted when loading a model for a given loading API. The policy is generated before loading the untrusted pickle model, and restricts the loading behaviors to only those that are necessary for the library API.

Design Rationale: We guide our design by studying how pickle models make use of Python callables. In regular usage, a pickle program needs a callable to construct non-primitive objects and (recursively) initialize the values of its attributes. Callables that are not needed to instantiate a given object should not appear in a pickle program; malicious payloads insert new code that does not have a role in object initialization.

The challenging task of policy generation is determining *which* callables are needed to instantiate an object. Python is a dynamic language that permits a single variable to receive different types at various program paths, and for objects to receive new attribute variables after initialization. Identifying all attribute types requires a path-sensitive analysis of the object creation code up to the point that the object is serialized. Further, in the ML setting, the code that creates the object (model) is not provided: the model saving program is not provided alongside the serialized model, since it is used to train the model; the goal of sharing the serialized model to obviate the need for executing a training program.

However, we recognize that we can generate approximate policies for serialized models by analyzing the class definition of the model, even without access to the model saving program. The majority of the class instance attribute information is contained in the class definition, in the shared library code, rather than in the model saving application. Intuitively, for the object to be reusable, it has to conform to an expected interface that is defined in the library.

We hypothesize that any unobserved object writes after the model is created will either not introduce new types to the variables, or will describe specialized metadata that is not necessary for the general-use operations that the model loading application is likely to perform, like inference. If new types are introduced, the model class interface shared between the saving and loading programs is violated. This is supported by our evaluation (§6.3.2).

Policy Generation Algorithm: Given an ML library and model class definition, PICKLEBALL analyzes the class definition to generate a model loading policy as the sets of *allowed imports* and *allowed invocations*; these represent the operations that a pickle program needs to instantiate an instance of the class:

- (1) **Allowed imports:** the set of callables permitted as arguments to Pickle Machine import operations.
- (2) **Allowed invocations:** the set of callables permitted arguments to Pickle Machine invoking operations.

The set of *allowed invocations* is a sub-set of *allowed imports*—before being invoked, the callable must be imported. However, a callable that is imported but not invoked may only be used as a reference or as a constructor with its allocator method (`__new__`).

To statically generate the policy for a given class, PICKLEBALL implements and applies rules starting at the class definition, and proceeds until the analysis terminates. PICKLEBALL maintains a *candidate queue* of classes that is initialized with the class definition. PICKLEBALL adds new classes to the queue as they are discovered by the analysis rules, and removes them as each class is analyzed. A class is only added to the candidate queue once to ensure that the analysis terminates.

PICKLEBALL applies the following class-analysis rules:

- (1) If the class implements a `__reduce__` method: identify the method return values (a callable, arguments for the callable, and optional state initialization values); add the returned callable to the *allowed imports* and *allowed invocations* sets; identify the types of all arguments for the callable and state initialization values, and add their class definitions to the *candidate queue*.
- (2) Otherwise: add the class to the *allowed imports* sets; add all sub-classes of the class to the *candidate queue*; add all types of the class’s attributes (including attributes inherited) to the *candidate queue*.

The PICKLEBALL policy generation algorithm, shown in Algorithm 1, operates over an abstract syntax tree (AST) representation of the analyzed program, and expects recovered type information to be labeled in the AST.

PICKLEBALL’s static analysis cannot produce perfectly sound and precise policies due to fundamental challenges in statically analyzing Python code, which is dynamically typed [11, 40, 106]. When recovered type information is over-approximate, PICKLEBALL produces policies that contain more callables than is strictly necessary. Python’s dynamic features, like dynamic typing and runtime attribute manipulation, can lead to unaccounted data dependencies during type recovery, resulting in missing type information and therefore in policies that incorrectly exclude callables. To account for these potential errors, we design for security by separately enforcing allowed import and allowed invocations, and for robustness with a lazy enforcement mechanism (§5.2). We discuss how static analysis limitations affect the whole-system analysis in Section 5.3.

5.2 Policy Enforcement

PICKLEBALL’s policy enforcement module is designed to protect the model loading application during loading. It is a drop-in replacement for the system pickle module. It restricts the behavior of the Pickle Machine operations that import, initialize, and invoke Python callables, so that only the callables permitted by the model loading policy are accessible to the pickle program in the model.

The module receives the loading policy and pickle program as inputs, and either outputs the deserialized object from the pickle program, or raises a security exception. “Importing opcodes” can only access callables that are allowed by the *allowed imports* policy. “Allocating opcodes” are allowed to create instances of objects listed in the *allowed imports* set by invoking their `__new__` methods. Callable-invoking opcodes are either removed entirely, or restricted to only invoke callables that are in the *allowed invocations*. To enforce this, the module verifies that the name of a given callable is present in the allowed invocations set. Conceptually, an attacker could bypass the allowed imports/allowed invocations separation by importing a callable present in the allowed imports set but not in

Algorithm 1: The pseudocode algorithm designed to generate a model loading policy for a given class, performed over an AST augmented with recovered type information. Errors in the recovered type information introduce incorrectness in the results of `GetReduceReturnTypes` and `GetAttributeTypes`.

```

Input: ModelClass
Output: AllowedImports
Output: AllowedInvocations
1 Candidates := UniqueQueue(ModelClass)
2 AllowedImports := EmptySet
3 AllowedInvocations := EmptySet
4 while NotEmpty(Candidates) do
5   Candidate := Pop(Candidates)
6   if HasReduceMethods(Candidate) then
7     AllowedImports += GetReduceReturn(Candidate)
8     AllowedInvocations += GetReduceReturn(Candidate)
9     Candidates += GetReduceReturnTypes(Candidate)
10  else
11    AllowedImports += Candidate
12    Candidates += GetSubclasses(Candidate)
13    Candidates += GetAttributeTypes(Candidate)

```

the allowed invocations set, then “renaming” it into a callable that is in the allowed invocations set. To mitigate against this, the policy enforcement module prevents building opcodes from modifying the `__name__` and `__module__` attributes of callables.

As described in Section 5.1, PICKLEBALL policies may exclude valid callables when PICKLEBALL fails to analyze dynamic Python features; PICKLEBALL is designed to be robust against this with *lazy enforcement*. PICKLEBALL aims to handle cases where the excluded callables are not accessed in the model’s downstream use cases. When PICKLEBALL’s loader encounters a disallowed import operation, it creates a stub object instead of immediately raising an exception. The stub object records the name of the callable, and implements no functionality other than raising a security exception when invoked or accessed. This permits the loader to proceed to completion in the event that the stub object is never used, deferring the violation until access. The security exception is also raised when the stub object is accessed after initialization, preventing an attacker from overwriting methods of the returned object with denied callables that are later invoked.

5.3 Security Guarantees and Limitations

Whole-system Guarantees: PICKLEBALL’s design thwarts the adversary described in our Threat Model (§4) by restricting the Pickle Machine’s access to Python callables. The design guarantees that when provided a correct AST with type information for a Python class definition and its dependencies, PICKLEBALL (1) raises a security exception when the adversary invokes a spurious callable, while (2) successfully instantiating any object that respects the attribute and type information defined class definition. In our evaluation of PICKLEBALL, we show that existing state-of-the-art static analysis tools provide sufficient AST and type-recovery information for practical use (§6).

Policy Generation Guarantees: When the PICKLEBALL is provided a correct AST with type information, it is guaranteed to output a loading policy that includes all *allowed imports* and *allowed invocations* that can appear in when an object is saved in the pickle format, provided that the object is not manipulated to add attribute types outside of its object prototype.

Policy Enforcement Guarantees: When PICKLEBALL loads a model, it is guaranteed to prevent the invocation of any Python callable that is not in the configured set of *allowed invocations*, and to create sanitized stub objects for any callable that is not in the configured set of *allowed imports*. The stub objects raise security exceptions when accessed/invoked.

Whole-system Limitations: PICKLEBALL is limited fundamentally by the challenges of analyzing dynamic Python code with static analysis techniques, but PICKLEBALL takes steps to mitigate these. Python’s dynamic features, like runtime attribute manipulation and dynamic typing, prevent PICKLEBALL’s static analyses from creating an AST with sound and precise type information; this makes PICKLEBALL’s policies unsound and incomplete. Over-approximations in the AST result in policies that permit more Python callables than necessary; PICKLEBALL mitigates this by having separate *allowed invocations* and *allowed imports* policies, so that only a small set of callables may be invoked. Under-approximations in the AST result in policies that omit benign callables from valid models; PICKLEBALL mitigates this with *lazy policy enforcement* so that omitted callables only raise exceptions if they are invoked by the model, rather than just initialized but unused. We evaluate PICKLEBALL in Section 6 to determine whether these limitations restrict it in practical settings (and find that they do not).

Remaining Attack Surface: PICKLEBALL prevents attackers from importing and invoking arbitrary callables for malicious payloads. However, akin to return-to-libc attacks, PICKLEBALL does not prevent the attacker from invoking permitted callables in sequences or with parameters that result in unintended outcomes. We are unaware of attacks leveraging these primitives, but whether this remaining capability is exploitable is a subject for further research (§7).

5.4 Implementation

PICKLEBALL is implemented in a total of ~1,300 Scala lines of code (LoC) and ~300 Python LoC divided between two primary components: a static program analysis that builds upon the Joern framework [107]; and a dynamic loader that modifies the existing Pickle Machine. In the static analysis, ~700 Scala LoC implement Algorithm 1, ~600 Scala LoC extend and fix Joern features, and ~200 Python LoC integrate components. In the loader, ~100 Python LoC modify the Pickle Machine to implement lazy policy enforcement. Joern provides a program analysis platform for PICKLEBALL by generating a Code Property Graph (CPG) with recovered type information for the target code; we extend Joern to improve type recovery features and class inheritance tracking (for more details, see Appendix C). Our analysis then queries Joern’s AST nodes for the relevant information.

Limitations: PICKLEBALL inherits some limitations from the Joern program analysis framework. The limitations include that PICKLEBALL:

- Cannot parse new Python syntax features (e.g., generic types).

- Cannot recognize type hints provided in docstring comments, but it can process type annotations introduced in Python 3.5.
- May fail to resolve dependencies, especially of builtin types.
- Cannot identify attributes of classes implemented in C.

These are engineering limitations and can be addressed with improvements to the underlying static analysis framework; they are not fundamental limitations of the PICKLEBALL approach for determining model loading policies from library class definitions.

To account for these limitations when evaluating the PICKLEBALL approach, we apply some manual library pre-processing before analysis (§6.1), and discuss future work to reduce the need for manual changes (§7).

6 Evaluation

We evaluate PICKLEBALL with four Research Questions (RQs):

- **RQ1: Malicious Model Blocking.** How well does PICKLEBALL block malicious pickled models from executing their payloads?
- **RQ2: Benign Model Loading.** How well does PICKLEBALL correctly load benign pickled models?
- **RQ3: Performance.** Is PICKLEBALL’s runtime overhead practical for deployment?
- **RQ4: Comparison to SOTA.** How does PICKLEBALL compare to the state-of-the-art security tools for protecting model loading applications?

6.1 Constructing an Evaluation Dataset

To answer these questions, we need a comprehensive dataset of pickle models consisting of both malicious and benign examples. The dataset must contain models created by different libraries to represent the diversity of loading APIs. We created our dataset by combining existing datasets, open models on Hugging Face, and constructing synthetic models. Our dataset contains 252 benign and 84 malicious models, for a total of 336.

Benign Models and Trusted Libraries: Our dataset must represent the typical model reuse tasks of loading and inference; therefore, we need a set of benign models and the libraries used to load and interact with them. We first searched for libraries that meet three criteria: (1) they load pickle models; (2) they have a model class type that is returned by a loading API; and (3) if a foundational library (e.g., PyTorch or transformers) type is used, the custom class adds new attributes to the type. These criteria are motivated by PICKLEBALL’s purpose: to restrict the pickle operations permitted by a library loading API based on analysis of the intended class type.

We identified candidate libraries by identifying popular pickle models on Hugging Face and working backwards. We first searched Hugging Face programmatically for pickle models, ordered by monthly download rate, that had model loading documentation directing users to a model loading library API. We manually reviewed the top 400 models (approximately 2 hours of review time) to determine whether the identified libraries meet our criteria; this resulted in 16 accepted libraries. All libraries and their associated version information are listed in Appendix D (Table 3).

Then, we identified candidate models associated with each library. We again queried Hugging Face to identify models associated with the library, either directly (as a piece of repository metadata)

or by mention in the model documentation or name. We collect models with ≥ 100 monthly downloads at time of collection. In total, we accumulated 252 models produced by 16 different libraries. All collected models are listed in Appendix D (Table 4).

We acknowledge that these models could themselves be malicious. We partially mitigate this by sampling from the most frequently downloaded models and libraries, checking model scanner indications, and investigating unexpected callables when identified by the restricted model loaders by checking for their origin in library source code.

Malicious Models: Our dataset must also represent the models created by our intended adversary (cf. our threat model – §4); therefore, we need a set of malicious pickle models. We first collected 82 malicious models and pickle programs that were identified on Hugging Face by two state-of-the-art model scanners [14, 112]. We add our 2 malicious models constructed to bypass scanners (see Appendix B), for a total of 84. All malicious models contain pickle programs with payloads that import and invoke Python spurious functions; payload behaviors include accessing sensitive files, making network connections, and creating reverse shells.

We acknowledge that these models do not represent the complete set of malicious model behaviors; it is a best-effort collection of real-world pickle model malware that represents today’s attackers. We aim to thwart the adversary that executes arbitrary Python functions during pickle loading, and the existing attacks all exercise this feature.

Test Harnesses: PICKLEBALL protects loading applications from untrusted models during and after loading; therefore, we need a representative set of loading programs to secure. We create one test harness for each library in our dataset; the harness loads a model using the library API and performs an inference task.

Library Pre-processing: We pre-process the libraries before analyzing them to account for limitations in the static analysis framework (§5.4) and improve the correctness of the AST. We make manual source code modifications (<10 LoC) when the library class uses newer Python features of Python that Joern’s front-end parser does not support, like generic type inheritance and type variables, or when the analysis misidentifies an imported library alias. For libraries that provide type hints in docstrings, which Joern does not parse, we copy (but do not modify) the hints as type annotations (<100 LoC). We manually copy dependencies into the analysis scope when discovered during policy generation. Because model loading policies are compositional, we pre-compute policies for some frequently reused dependencies, including classes from the Python standard library and PyTorch, and save them in a class “cache” for PICKLEBALL to access when it recognizes one of the classes in its analysis. Due to the complexity and prevalence of dynamically dispatched and C code implementations in PyTorch, we supplement our analysis of PyTorch modules with the weights-only unpickler in the class cache.

6.2 RQ1: Malicious Model Blocking

PICKLEBALL must protect loading programs from pickle models with malicious payloads. To evaluate this, we assess whether any of our test harness PICKLEBALL policies permit any malicious model executions.

6.2.1 Methods. For each harness program in our dataset, PICKLEBALL generates a loading policy by analyzing the library and associated model class. We use PICKLEBALL to enforce the generated policy while the harness attempts to load all malicious models in our dataset. For each malicious model, we consider the model blocked if PICKLEBALL raises a security exception during model loading or inference, preventing the payload from executing.

Some library APIs only load the pickle model after validating that the accompanying model metadata is well-formatted (e.g., architecture, name, version). For these libraries, we directly invoke `pickle.loads` on the malicious model, while enforcing the associated PICKLEBALL policy.

6.2.2 Results. For all generated policies, PICKLEBALL prevents all (100%) malicious models from executing their payloads. Since PICKLEBALL’s generated policies do not contain the dangerous callables leveraged by the malicious models (e.g., `eval()`, `system()`), PICKLEBALL’s loader raises an exception for all malicious models.

RQ1 Summary: PICKLEBALL generates policies that effectively prevent all malicious pickled models in our dataset from executing their payloads.

6.3 RQ2: Benign Model Loading

PICKLEBALL must enable users to load and perform tasks with benign models. Its policies must not be so restrictive that the models are unusable. We therefore evaluate PICKLEBALL’s policies for loading and correctly using the benign models in our dataset (§6.3.1 and §6.3.2). To ensure robustness of the loaded model despite lazy enforcement, we perform a dataset test of successfully loaded models with stub objects (§6.3.3 and §6.3.4).

6.3.1 Methods. We measure PICKLEBALL’s ability to generate and enforce policies that correctly load and execute benign models. For each library in our dataset, we generate a model loading policy. Then, we enforce the policy while using the library’s test harness to load each library’s models. Once loaded, we test the model by performing one inference task with a test input, and capture the output. For comparison, we then re-execute the test harness *without* enforcing any policy (by using the regular pickle module), and capture the inference result. We consider the model load a success when (1) PICKLEBALL loads the model without raising exceptions, and (2) the inference results are equivalent between the PICKLEBALL and unrestricted environments.

6.3.2 Results. PICKLEBALL generates policies that, when enforced, correctly load and execute 79.8% of benign models in the dataset (Table 1). In most cases, the policies contain all callables (Table 1 – Imports and Invocations Allowed) that are seen in the model traces (Imports and Invocations Observed). In some cases, PICKLEBALL’s policies do not include callables that are included in the models (flair, PyAnnote, YOLOv5, and YOLOv11), resulting in the creation of a stub object, and which is occasionally invoked, resulting in a security violation.

We investigated the failed models to determine their causes:

- **Attributes set after initialization:** PICKLEBALL fails to identify attribute types that are set outside of the type declaration. For

example, after initializing the model object, some libraries allow users to write training metadata to the model, including data for the optimizer used and paths to output files. In many cases (e.g., 12 flair models), PICKLEBALL misses callable types set this way but still successfully loads the model, since this metadata is not used. However, for one flair model and three PyAnnote models, a metadata object is invoked during loading.

- **Follow-on pickle loading:** PICKLEBALL fails to load two models from the MeloTTS library after they have been loaded, due to additional pickle loading during inference. PICKLEBALL’s policy includes all callables needed to load the MeloTTS models. However, during inference, an additional pickle model is loaded; this model invokes a disallowed callable, resulting in a security violation.
- **Library version drift:** one PyAnnote model fails to load for legacy reasons: it uses a callable that was included in models created with previous versions of PyAnnote. The callable’s class declaration exists in the library code base as an unused stub, with a comment that it is needed for backward compatibility reasons, but is otherwise unused. Therefore, PICKLEBALL’s analysis failed to recognize it as necessary for model loading.
- **Namespace inconsistency:** the remaining YOLOv5 and YOLOv11 models use inconsistent naming conventions. For example, a policy includes the callable `yolov5.models.common.Conv`; however, the model refers to this callable as `models.common.Conv`, while referring to other callables by the full `yolov5.*` namespace.

6.3.3 Lazy Enforcement Robustness – Methods. Due to PICKLEBALL’s lazy enforcement, models can load successfully despite being instantiated with stub objects. To further ensure that our benign models are robustly instantiated for inference, we evaluate these models with a more rigorous test suite of inputs during inference. We investigated the libraries that successfully load models with stub objects, i.e., Flair, PyAnnote, YOLOv5, and YOLOv11.

For each library, we find an extensive evaluation dataset to test each loaded model with: for Flair, we used various Named Entity Recognition and Universal Dependencies [30] datasets that come pre-packaged with the Flair library [36]; for PyAnnote, we used the AISHELL-4 speech dataset [37]; for YOLOv5 and YOLOv11, we used the 2017 Test Images Common Objects in Context dataset [59].

For each model that PICKLEBALL successfully loads, we evaluate the model on the dataset and ensure that the models do not raise security errors (i.e., they do not access any stub objects).

6.3.4 Lazy Enforcement Robustness – Results. All models yield the same results when loaded with PICKLEBALL, compared to when loaded with the regular, unrestricted Pickle Machine. None of the models raise security errors during dataset evaluation, indicating that models are correctly instantiated, despite using stub objects.

RQ2 Summary: PICKLEBALL generates policies that safely load and execute 79.8% of benign pickled models in our dataset.

6.4 RQ3: Performance

PICKLEBALL must be fast enough for practical use in developer and user tasks. We analyze two aspects of PICKLEBALL’s performance: (1) the time to generate a policy for a class, which is an offline,

Table 1: PICKLEBALL generates loading policies for popular libraries (see GitHub Stars), which are evaluated by loading popular models (see cumulative model downloads in March 2025). We compare the number callables observed in the models to the callables allowed by the policies, and the number of stub objects that are created or invoked when the policies exclude callables. We compare PICKLEBALL’s loading success rate with the weights-only unpickler.

Library	Popularity		Imports			Invocations			Loading		
	Stars	Downloads	Observed	Allowed	Stub Objects	Observed	Allowed	Stub Calls	# Models	WOUp (%)	PICKLEBALL (%)
CONCH [21]	342	13.7K	3	822	0	2	61	0	1	1 (100.0%)	1 (100.0%)
FlagEmbedding [34]	9.3K	11.1M	4	773	0	2	61	0	14	14 (100.0%)	14 (100.0%)
flair [67]	14.1K	3.05M	34	1186	17	6	62	2	18	0 (0.0%)	17 (94.4%)
GLiNER [109]	1.9K	760K	3	870	0	2	61	0	17	17 (100.0%)	17 (100.0%)
huggingsound [48]	447	56.1M	3	767	0	2	61	0	17	17 (100.0%)	17 (100.0%)
LanguageBind [57]	800	495K	4	992	0	2	61	0	8	8 (100.0%)	8 (100.0%)
MeloTTS [64]	5.9k	406K	3	852	0	2	61	0	8	8 (100.0%)	6 (75.0%)
Parrot_Paraphraser [24]	890	911K	3	774	0	2	61	0	1	1 (100.0%)	1 (100.0%)
PyAnnote [75]	7.2k	32.6M	18	1085	9	5	64	0	14	0 (0.0%)	10 (71.4%)
pysentimiento [85]	588	1.31M	4	777	0	2	61	0	4	4 (100.0%)	4 (100.0%)
sentence_transformers [87]	16.4k	204M	5	1087	0	2	61	0	76	76 (100.0%)	76 (100.0%)
super-image [33]	170	64.9K	3	1016	0	2	61	0	6	6 (100.0%)	6 (100.0%)
TNER [100]	387	25.0K	4	769	0	2	61	0	4	4 (100.0%)	4 (100.0%)
tweetnlp [13]	341	80.7K	4	778	0	2	61	0	1	1 (100.0%)	1 (100.0%)
YOLOv5 [98]	53.4k	24.8K	28	920	7	4	61	0	12	0 (0.0%)	4 (33.3%)
YOLOv11 (ultralytics) [99]	39.2k	38.4M	63	1816	13	11	61	6	51	0 (0.0%)	15 (29.4%)
Total									252	157 (62.3%)	201 (79.8%)
Average										75.0%	87.7%

one-time analysis cost (see §5.1), and (2) the additional runtime overhead of enforcing a policy to load and use a model, compared to the regular Pickle Machine.

6.4.1 Methods. To measure the time to generate policies, we execute PICKLEBALL’s policy generator three times for each library in our dataset and compute the average between the three. We measure the real time using the Python time library. We run this experiment on a laptop with a 14-core Intel i7 CPU and 32GB of RAM (Linux Mint 22), representing a commodity developer environment.

To measure the additional runtime overhead of PICKLEBALL’s policy enforcer, we isolate and record the time each harness program spends invoking the pickleload function during model loading. We first execute harness program with the unrestricted Pickle Machine environment to load a benign model. Then, we perform the same execution with PICKLEBALL enabled. For fair comparison, we ensure that the unrestricted environment always uses the Python implementation of the Pickle Machine, instead of an optimized C implementation. We run this experiment on a server with a 32-core AMD EPYC 7502 processor and 256GB of RAM (Ubuntu 24.04); this is used for the attached hard-drive space for interacting with the hundreds of models in our dataset.

6.4.2 Results. PICKLEBALL generates policies for all libraries in a median of 14.0 seconds, with minimum 9.0 seconds (CONCH library) and maximum 29.8 seconds (YOLOv11 library) (Figure 6). This policy generation execution time is reasonable for integration within project build systems, as the policy needs only to be generated when the analyzed library source code is modified. PICKLEBALL’s policy enforcer incurs negligible overhead, with a 0.42ms (1.75%) median runtime overhead compared to the unrestricted Pickle Machine, as depicted in Figure 7.

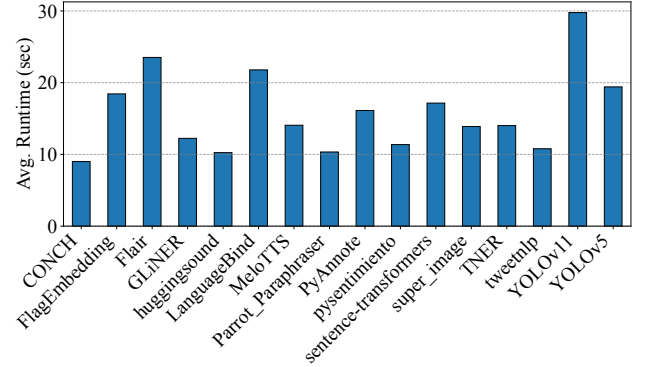


Figure 6: Time to generate a policy for each library class in dataset (averaged over 3 runs). This is a one-time step that can be integrated into existing workflows — either by library maintainers in the library’s release process, or by a user, prior to loading the model.

RQ3 Summary: PICKLEBALL policies are generated in a median 14.0 seconds across the evaluation libraries, PICKLEBALL incurs a median runtime overhead of 0.42ms when loading models.

6.5 RQ4: Comparison to SOTA

We compare PICKLEBALL with three existing state-of-the-art (SOTA) tools that share the same goal of defending against our threat model described in §4. As discussed in §2.2, existing pickle model defense tools fall into two categories: model scanners and restricted loading environments (like PICKLEBALL). We compare against two model scanners: MODELSCAN [8], and the scanner implemented by Casey *et al.* [14] (henceforth, MODELTRACER).⁷

⁷The authors provided access to the tool for evaluation purposes.

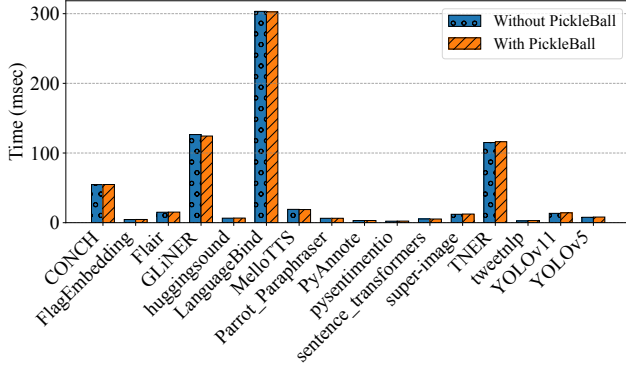


Figure 7: Time spent executing `pickle.load` in test loading program, with and without PICKLEBALL (averaged over 3 runs after 1 warmup run). PICKLEBALL incurs a median runtime overhead of 1.75% and average runtime overhead of 2.62%.

Table 2: Comparison of PICKLEBALL to SOTA alternatives. Model scanning tools achieve low false positives on our dataset, but misclassify malicious models. Restricted loaders (including PICKLEBALL) are secure, at the cost of blocking benign models. PICKLEBALL loads more benign models than the weights-only unpickler due to its custom policies for each model class.

Tool	# TP	# TN	# FP	# FN	FPR	FNR
MODELSCAN [8]	75	236	16	9	6.3%	10.7%
MODELTRACER [14]	44	252	0	40	0%	47.6%
Weights-Only Unpickler [82]	84	157	95	0	37.7%	0%
PICKLEBALL (our work)	84	201	51	0	20.2%	0%

MODELSCAN is a static analysis tool that applies a rigid denylist to make determinations about models, and is integrated into Hugging Face. MODELTRACER is a dynamic analysis tool that traces the model’s invocations while it is loaded via `pickle.loads()` and `torch.load()`, and similarly applies a rigid denylist to make its determinations.

We compare against one restricted loading environment: the weights-only unpickler [82]. The weights-only unpickler loads models by only permitting them access to callables in a rigid (but manually configurable) allowlist policy.

6.5.1 Methods. We evaluate the model scanning tools by providing each model in our dataset as an input to the tool. We expect the model scanners to alert when provided a malicious model input, and otherwise not to alert. We consider correctly identified malicious models as true positives, correctly identified benign models as true negatives, incorrectly identified malicious models as false negatives, and incorrectly identified benign models as false positives.

We evaluate the weights-only unpickler by attempting to load each model in our dataset using the PyTorch loading API with the weights-only unpickler enabled. We use the weights-only unpickler’s default policy while loading models. We expect restricted loading environments like the weights-only unpickler and PICKLEBALL

to correctly load benign models and to raise exceptions when loading malicious models. For parity when comparing with the model scanning tools, we consider raising an exception during malicious model loading as a true positive, correctly loading a benign model as a true negative, incorrectly rejecting a benign model as a false positive, and incorrectly loading a malicious model as a false negative. We apply the same criteria to compare PICKLEBALL with these tools, using the dataset and results obtained in Section 6.2 and Section 6.3.

6.5.2 Results. Comparisons of the tools are shown in Table 2. The model scanning tools resulted in few (16) false positives, while the restricted loaders resulted in 0 false negatives. Table 1 compares the success rate of PICKLEBALL and the weights-only unpickler when loading benign models.

MODELSCAN incorrectly identified 9 malicious models as benign (false negatives) and did not report false positives. We identified three categories of MODELSCAN’s false negatives: (1) five models implement payloads using callables that are not included in MODELSCAN’s rigid denylist; (2) three models use dynamic runtime operations (e.g., `numpy.load()`) to load additional payloads that MODELSCAN fails to statically identify; and (3) one model uses multiple STOP pickle opcodes, resulting in MODELSCAN terminating its analysis after reaching the first one and missing the rest of the malicious payload. While this last model would not execute its malicious payload when executed by the Pickle Machine, it could be loaded in non-standard ways by another malicious pickle program to execute its payload. Categories (1) and (2) are fundamental limitations to using a static analysis denylist approach: the denylist cannot be complete and can be subverted.

MODELTRACER successfully identified 44 malicious models but missed the remaining 40, resulting in a high false negative rate of 47.6%, but did not report false any positives. MODELTRACER’s false negatives appear from its limited denylist: it alerts on models that invoke the `execve`, `connect`, `socket`, or `chmod` system calls. MODELTRACER does not consider file access operations to be indicators of malicious behavior, so malicious models that perform dangerous file reads and writes are not identified. This once again highlights the scanning limitation of relying on an incomplete denylist to indicate malicious behavior.

The weights-only unpickler, like PICKLEBALL, prevents all malicious models from loading. However, it incorrectly blocks 95 benign models from loading, compared to PICKLEBALL’s 51. However, PICKLEBALL’s custom generated policies load additional models that the weights-only unpickler can not.

RQ4 Summary: While PICKLEBALL prevents all malicious models from loading, model scanning tools fail to identify all malicious models. The weights-only unpickler is also effective at preventing malicious models from loading, but is less effective than PICKLEBALL at loading benign models due to its rigid default policy.

7 Discussion and Future Work

PICKLEBALL’s remaining attack surface: PICKLEBALL reduces the available attack surface by significantly restricting access to callables, but it does not guarantee that the remaining callables

cannot be composed in a malicious payload (§5.3). Related software security approaches provide desirable-yet-imperfect reductions in attack surfaces, whether by removing access to system calls [29, 38] or executable gadgets and control flows [7, 101, 110]. Similarly, PICKLEBALL could be compromised by code reuse or property-oriented programming-like techniques [23, 70] to stitch together permitted calls to construct an exploit. Thus far, no such attacks have been observed, but the question remains: can we generate malicious payloads that obey the policy constraints enforced by PICKLEBALL and the weights-only unpickler?

Huang et al. [43] studied manual implementations of restricted unpicklers in the general (non-ML) setting, and devised attack strategies to try to overcome callable allowlists. When faced with well-implemented restricted unpicklers (i.e., when recursive attribute look-ups and indexing are disallowed by design, as in PICKLEBALL and the weights-only unpickler), their approach degrades to manual policy inspection. Future work should identify properties of callables to automatically distinguish whether a callable can be used maliciously.

Long-term outlook for pickle in ML: Pickle remains a popular model format (§3), despite more secure alternatives. Each major model format provides tradeoffs in flexibility (pickle), security (SafeTensors), and efficiency (GGUF). Pickle is flexible, as it can serialize virtually any Python object, including complex models with custom operators and non-standard data structures. SafeTensors was developed for security-sensitive deployments, with a structured, memory-mapped format. GGUF maximizes performance on inference-optimized runtimes. *Because these formats are complementary and used as defaults in different popular frameworks and ecosystems, we expect them to coexist going forward.* PICKLEBALL does not discourage the adoption of secure alternatives to pickle, but provides a secure option for the (as our data show, large and growing) pickle population.

One rapidly evolving area of ML models is large language models (LLMs), where pickle still appears despite major industry leaders releasing foundation models in the SafeTensors and GGUF formats. Popular foundation models like LLaMA-4 [63], Qwen-3 [86], and Deepseek-R1 [28] are encouragingly released with the SafeTensors format (although some, like LLaMA-3.1 [62], still provide a pickle model backup). However, foundation models are often adapted (e.g., fine-tuned) and redistributed, often with new formats and artifacts, including pickle. For example, we observed instances of models that are fine-tuned from LLaMA-4 [49, 61], Qwen-3 [88, 92], and Deepseek-R1 [96] and distributed with an additional pickle file that represents the training arguments used during fine-tuning. Even when secure formats are adopted for foundation LLM models, pickle continues to persist in the LLM ecosystem, which is consistent with our analysis (§3.1) and justifies the need for PICKLEBALL.

Generalizing PICKLEBALL: PICKLEBALL is designed to protect pickle model loading and is evaluated on models found on Hugging Face, but its approach can generalize to protect (1) other model formats; and (2) other pickle applications.

PICKLEBALL aims to protect pickle deserialization in the context of ML models, but its policy generation and enforcement modules do not rely on any ML-specific properties. This approach allows PICKLEBALL to protect other applications that receive pickle data. To generalize, PICKLEBALL’s analysis requires that *the intended type of*

the pickle object is known before loading (§5.1). In the ML setting, this is reasonable because the protected program is a *client application*. Other approaches are needed when the security analysis does not know *a priori* the intended type of the serialized object [26, 111].

PICKLEBALL’s approach works for the pickle format because it has (dangerously) expressive deserialization operations, and is used by trusted libraries that implement their own custom model classes — which are analyzed to learn a specification for allowed behaviors. Other model formats that meet these criteria are candidates for protection in the PICKLEBALL approach. Zhu et al. show that the TensorFlow SavedModel format has undesirable operations [113]; libraries that extend the TensorFlow model class with their own custom behaviors could use a PICKLEBALL approach to restrict the allowed behaviors, but we are not aware of any that do. Formats like SafeTensors and GGUF are not known to have dangerous operations; if any were discovered, then a PICKLEBALL approach might apply for identifying when to permit certain operations. We aim to explore which other model formats meet these criteria for PICKLEBALL to assist in securely loading.

We evaluated PICKLEBALL using models sourced from Hugging Face, but PICKLEBALL will work similarly for models from any platform. The inputs to PICKLEBALL are ML libraries and pickle models, which are ML artifacts that are not tied to the hosting platform. Hugging Face is the largest model hosting platform, with over 1.8M models available in July 2025. ModelScope [1] is a recent hub managed by China’s Alibaba and hosts 80K models. It imitates Hugging Face’s design and likewise has models with varying serialization formats. Other model communities, including Qualcomm AI Hub [4], PyTorch Hub [3], and TensorFlow Hub [5], have fewer than 500 models each and many are also hosted on Hugging Face. The ONNX Model Zoo [2] is now deprecated and archived on Hugging Face. Hugging Face models are representative of the kinds of models that PICKLEBALL can harden.

Policy maintenance and distribution: PICKLEBALL’s intended workflow is that when a library is updated, its PICKLEBALL policy would be updated as well. PICKLEBALL makes policy maintenance easy for users with fast policy generation, incremental changes, and opportunities for seamless distribution.

PICKLEBALL generates policies quickly, completing in under 30 seconds for each library in our evaluation (see §6.4, Figure 6). This is reasonable for a task that must only occur when the library changes, and not every time PICKLEBALL loads a model.

In practice, library updates result in either incremental policy changes or clearly documented breaks in supported model versions, leading to easier policy maintenance. After our evaluation concluded, we noticed one library, FlagEmbedding, receive updates (commit bf6b649 to 875fd4f), but PICKLEBALL produced policies before and after with a 90% Jaccard similarity index, and which successfully loaded the same models in our dataset. When the library model class changes significantly, the library cannot load existing models, but we find it easy in practice to match models with a supported library version, due to the model documentation, as we do in our evaluation (§6.3.2). For example, we easily distinguish all models belonging to YOLOv5 and its newer version, ultralytics.

PICKLEBALL provides opportunities for easier policy maintenance when it is adopted further upstream in the model development life cycle. PICKLEBALL enables model consumers to protect themselves from malicious model producers by trusting only code from library maintainers. Library maintainers can adopt PICKLEBALL themselves to generate policies automatically, as part of the library release process, and provide the updated policies alongside the libraries.

Removing library pre-processing: To account for implementation limitations (§5.4) when evaluating the fundamental PICKLEBALL idea, we perform manual pre-processing of some libraries (§6.1), but future engineering work will remove this step. The purpose of the pre-processing is to overcome implementation limitations of the underlying static analysis framework that PICKLEBALL depends on to produce an accurate type-annotated AST. To account for these limitations, we apply the following pre-processing steps:

- Remove generic type syntax from class inheritance statements.
- Copy type hints in comments into type annotation form.
- Copy relevant dependencies into the analysis scope.
- Reference the weights-only unpickler policy when a class inherits the `torch.nn.Module` class.

Manual source code modifications are applied to five out of 16 libraries in our dataset, and each account for between ~10 and ~100 modified LoC. Future engineering work to improve the underlying static analysis framework will remove the need for manual source code pre-processing.

8 Related Work

ML Model Loading Security: Pickle is not intended for untrusted data, but its proliferation as a model format created a security problem. To bring attention to the issue, security company Trail of Bits released the *fickling* tool for manipulating and analyzing pickle programs in ML models [68]. New proposals for identifying malicious pickle models include dynamic [14] and static [112] scanners. Scanners take a model as input, and attempt to make an assessment of it based on fixed rules about malicious behaviors. Instead, PICKLEBALL takes a model and the source code library that allegedly produced the model for context, and produces policies for the model based on that context. We showed in Section 6.5 that PICKLEBALL’s tailor-made policies result in no false negatives while comparative model scanners do produce false negatives due to their fixed rules.

Deserialization Attacks and Defenses: Deserialization vulnerabilities exist beyond the ML context. PainPickle [43] explored Python pickle security by creating a taxonomy of errors in custom Unpickler implementations, and devised attack strategies. We use their contributions to guide the proper implementation of PICKLEBALL’s loader.

Other programming languages have also have insecure deserialization APIs that need to be secured. Quack [26] propose a generic deserialization defenses for PHP by employing a “static duck typing” static analysis, and Zhang et al. [110] propose a static analysis defense for Java. Python’s pickle deserialization is a more expressive interface than in PHP or Java, which are unable to directly invoke functions; this expressivity adds complexity to security policies.

Querying Code-graphs for Software Security: Graph representations are well-established for general program analysis tasks.

For security specific tasks, Joern [107] introduced the Code Property Graph (CPG), a data structure that combines classic program analysis concepts into a representation that is easy queried to identify vulnerabilities. Follow on work ODGEN [58] extended Joern’s CPGs into an Object Dependence Graph (ODG), capturing interactions from the object’s point of view to detect vulnerabilities in Node.js packages. RogueOne [90] further evolved ODGs to form a data-flow relationship graph, fully capturing data-flows among objects. QL [65] and Datalog [89] based approaches inspired the CodeQL [15] query platform, which is used for vulnerability variant analysis tasks. PICKLEBALL’s implementation uses these code querying features and extends them to improve the accuracy of the program types recovered. Improvements to these program representations can lead to improved accuracy of PICKLEBALL’s policies.

9 Conclusion

Serialization and deserialization enable code and data exchange, enabling software re-use. Many recent works observe security vulnerabilities in deserialization, across various programming languages and contexts. We specifically examined the security vulnerabilities in pre-trained model deserialization that result from the use of (dynamically typed) Python and the reliance on Python’s (insecure) pickle format. We found that pickle use is common among the most popular models on Hugging Face, and that existing defenses are insecure or inapplicable to a substantial fraction of these models. Our PICKLEBALL approach applies a novel program analysis to add greater type-safety to model deserialization. In our evaluation, PICKLEBALL supported most existing benign models transparently while preventing all known attacks in malicious models. We believe PICKLEBALL is a promising complement to existing security resources in the pre-trained model ecosystem.

Data Accessibility

Upon acceptance, we will open-source PICKLEBALL, our evaluation scripts, and our pickle +ML security dataset.

Research Ethics

Our primary contribution is PICKLEBALL, a defense that improves security for ML models. Our Hugging Face study abides by the platform policies for API use. We did identify some possible shortcomings of existing security approaches, and have followed a responsible disclosure process—we privately disclosed the MODELSCAN bypass described in Appendix B to its author, the company Protect AI, and similarly to the MODELTRACER team.

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Outline of Appendices

The appendix contains the following material:

- Appendix A: Hugging Face Measurement Supplemental Details.
- Appendix B: Techniques for Bypassing Model Scanners.
- Appendix C: PICKLEBALL Implementation Details.
- Appendix D: Libraries and Models in Benign Dataset.

A Hugging Face Measurement

Our measurement of model serialization formats in Hugging Face used file extensions to determine model serialization format. The mapping from extension to format assignment is as follows:

- *pickle*: We used the core pickle file extension and those of variants and wrappers (.pkl, .pickle, .joblib, and .dill). We also used those of PyTorch-specific variants: .pt, .pth, and .bin.
- *SafeTensor*: We used the .safetensor extension.
- *GUFF*: We used the .gguf extension.
- *Other or missing*: We included additional extensions often associated with serialized model data, such as .h5, .hdf5, .ckpt, .model, .pb, .npy, .npz, .onnx, .msgpack, .nemo, .wav, and .keras. Some models do not include actual model files; instead, their model cards provide instructions for loading the model from a third-party library. In our study, we marked these models as “missing files”.

When models included files with multiple extensions, we categorized them as having multiple file types available. Our analysis focuses on the package level within Hugging Face, i.e., on the most recent version of each package. While some packages may have multiple versions, the package name is the primary indicator of a new package, as noted in prior work [52, 53].

We acknowledge that file extensions serve as a proxy for the file’s actual content. While they suggest the type of content, they do not attest it.

“Unusual” Callables: We analyzed 1,426 repositories containing pickled models, and identified 219 repositories containing models with “unusual” callables, i.e., those that are rejected during loading by the weights-only unpickler. We show the set of observed “unusual” callables in Figure 8.

B Bypassing Model Scanners

Model scanners use a denylist approach to determine whether a model is malicious, but pickle denylists are circumventable, which we demonstrate by example: we construct “malicious” pickle programs that state-of-the-art scanners misclassify as benign.

We identify two strategies for bypassing model denylists to guide the implementation of the models:

- (1) invoking callables that are *missed by the denylist*; and
- (2) *indirectly* importing and invoking disallowed callables.

We demonstrate the efficacy of each strategy with constructed pickle programs that bypass both static (i.e., MODELSCAN [8]) and dynamic (i.e., MODELTRACER [14]) scanners, and disclose the bypasses to the scanner authors.

To demonstrate (1), we constructed a malicious pickle program that writes to an attacker-chosen file using APIs from the `pathlib` [79] Python library, rather than the builtin `open` and `write`

functions. MODELSCAN fails to recognize this as malicious because the `pathlib` APIs are not part of its denylist [9]; MODELTRACER fails because it does not classify file write operations as malicious.

To demonstrate (2), we constructed a pickle program that invokes the `os.system` function (which is *disallowed* by the MODELSCAN scanner), by importing it through an allowed module (in our case, `torch.serialization.os.system`). MODELSCAN fails to recognize this as malicious because the malicious callable appears to be part of an allowed module, and the scanner does not inspect deeper; MODELTRACER successfully identifies this malicious behavior, but only after the malicious call has been invoked and its underlying system call appears in the execution trace (this is by design, as a dynamic scanning tool).

C PICKLEBALL Implementation

In Section 5.4 we summarized the implementation of PICKLEBALL. Here we provide more details.

Integrated components: We built PICKLEBALL’s policy generation using the Joern framework [107], a static program analysis tool which supports Python code. We use it to construct an AST with recovered type information for the analyzed library code. In our implementation, forked from Joern version 2.0.385, we found several limitations in Joern’s type recovery pass for Python features, which we reported and fixed, such as failures to: (1) track types of variables assigned to collection objects, (2) recover types of nested attributes, (3) recover type information without an assignment expression, even when provided type annotations, and (4) correctly record class inheritance information. PICKLEBALL’s policy generation component is implemented as a Scala program that interfaces with the Joern CPG and implements Algorithm 1 by querying for the required class properties.

We built PICKLEBALL’s policy enforcement component by modifying the existing CPython implementation of the Pickle Machine (commit a365dd6) [76] to take model loading policies as inputs and to lazily load pickle programs. We changed the semantics of the `GLOBAL`, `STACK_GLOBAL`, and `REDUCE` opcodes to respect policy settings, removed the `OBJ` and `INST` legacy opcodes, and removed support for extension codes, in line with best practices when securing the Pickle Machine [82]. We also modified the `BUILD` opcode to prevent altering the `__name__` and `__module__` attributes of callables. We made no changes to the interface to invoke our modified Pickle Machine (`pickle.load`) so that it serves as a drop-in replacement for the unrestricted Pickle Machine in the CPython runtime.

D Libraries and Models in Benign Dataset

PICKLEBALL generates policies for ML libraries to correctly load models using those libraries. To evaluate this, we constructed a dataset of 16 libraries and 252 benign models sourced from Hugging Face (§6.1). Table 3 lists the libraries and identifying information, including the git commit used during the evaluation. Table 4 lists the models and identifying information, including the Hugging Face git commit for the model version that PICKLEBALL loads. Further information, like generated policies for each library and model load success rates, are available in the accompanying software artifact.

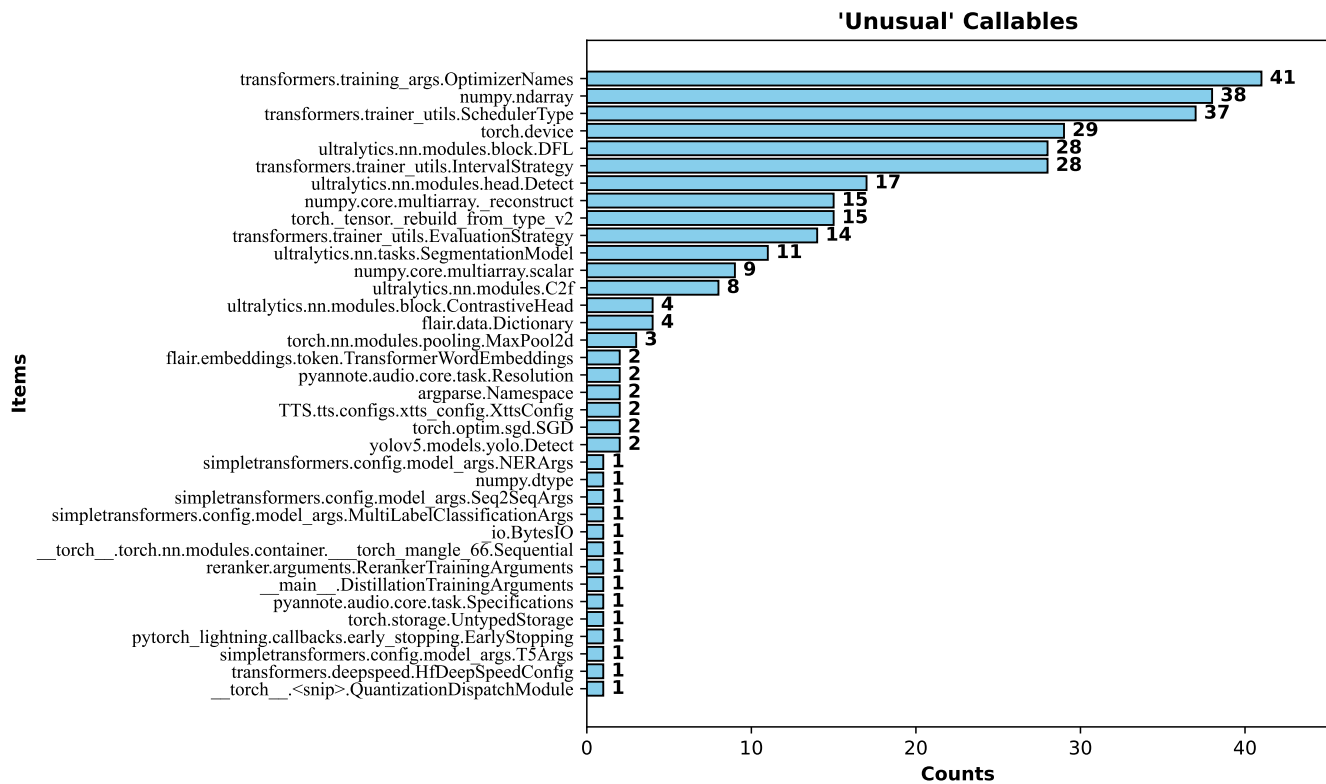


Figure 8: Callables observed in the 219 model repositories that cannot be loaded by the weights-only unpickler. A few callables from popular libraries (Hugging Face transformers, numpy) dominate, but a tail of callables come from small ML libraries (flair, fairseq, yolov5).

Table 3: Source and commit information for all libraries in the PICKLEBALL evaluation. A ✓ in the Modified column indicates that we performed manual modifications to the library source code before analysis, described in Section 6.1.

Library	Modified	GitHub Repository	Git Commit
CONCH	-	mahmoodlab/CONCH	02d6ac5
FlagEmbedding	-	FlagOpen/FlagEmbedding	bf6b649
flair	✓	flairNLP/flair	c674212
GLiNER	-	urchade/GLiNER	1169120
huggingsound	-	jonatasgrosmann/huggingsound	50e9fba
LanguageBind	-	PKU-YuanGroup/LanguageBind	7070c53
MeloTTS	-	myshell-ai/MeloTTS	5b53848
Parrot_Paraphraser	-	PrithivirajDamodaran/Parrot_Paraphraser	03084c5
PyAnnote	✓	pyannote/pyannote-audio	0ea4c02
pysentimiento	-	pysentimiento/pysentimiento	60822ac
sentence_transformers	✓	UKPLab/sentence-transformers	a1db32d
super-image	-	eugeniesiow/super-image	50439ea
TNER	-	asahi417/tner	7730a62
tweetnlp	-	cardiffnlp/tweetnlp	68b08c8
YOLOv5	✓	fcakyon/yolov5-pip	40a1887
YOLOv11 (ultralytics)	✓	ultralytics/ultralytics	b18007e

Table 4: Source and version information for all benign models in the PICKLEBALL evaluation dataset (§6.1). When a single repository contains multiple pickle models, we list the repository once per model with the model name listed in parentheses. The Git Commit refers to the Hugging Face repository commit containing the version of the model in the dataset. Two models in the dataset were removed from Hugging Face after the evaluation concluded and we were unable to record their commit hashes; these are recorded as “N/A”.

Library	Hugging Face Repository (Model Name)	Git Commit
CONCH	MahmoodLab/CONCH	f9ca9f8
FlagEmbedding	BAAI/bge-base-en	b737bf5
FlagEmbedding	BAAI/bge-base-en-v1.5	a5beb1e
FlagEmbedding	BAAI/bge-base-zh-v1.5	f03589c
FlagEmbedding	BAAI/bge-large-en	abe7d9d
FlagEmbedding	BAAI/bge-large-en-v1.5	d4aa690
FlagEmbedding	BAAI/bge-large-zh	b5d9f5c
FlagEmbedding	BAAI/bge-large-zh-v1.5	79e7739
FlagEmbedding	BAAI/bge-reranker-base	2cfc18c
FlagEmbedding	BAAI/bge-reranker-large	55611d7
FlagEmbedding	BAAI/bge-small-en	2275a7b
FlagEmbedding	BAAI/bge-small-en-v1.5	5c38ec7
FlagEmbedding	BAAI/bge-small-zh	1d2363c
FlagEmbedding	BAAI/bge-small-zh-v1.5	7999e1d
FlagEmbedding	BAAI/llm-embedder	c3e8ac8
flair	flair/chunk-english-fast	34cdda2
flair	flair/ner-dutch-large	44c2859
flair	flair/ner-english	b13c26b
flair	flair/ner-english-fast	f75577b
flair	flair/ner-english-large	e2b1caa
flair	flair/ner-english-ontonotes	ffa7600
flair	flair/ner-english-ontonotes-fast	4f31790
flair	flair/ner-english-ontonotes-large	4ffb359
flair	flair/ner-french	27fb2ba
flair	flair/ner-german	4e3f3d1
flair	flair/ner-german-large	4b459fa
flair	flair/ner-multi	9e5dc17
flair	flair/ner-spanish-large	9d4671d
flair	flair/pos-english	b32242e
flair	flair/pos-english-fast	78bf413
flair	flair/upos-english	dbd8c36
flair	flair/upos-english-fast	8748c22
flair	flair/upos-multi	0ee3d86
GLiNER	DeepMount00/GLiNER_ITA_BASE	8dadd43
GLiNER	DeepMount00/GLiNER_ITA_LARGE	7f74be0
GLiNER	DeepMount00/GLiNER_PII_ITA	b31700c
GLiNER	DeepMount00/universal_ner_ita	158e11d
GLiNER	EmergentMethods/gliner_medium_news-v2.1	2450430
GLiNER	gliner-community/gliner_large-v2.5	3b3bcae
GLiNER	gliner-community/gliner_medium-v2.5	ed16f26
GLiNER	numind/NuNER_Zero	9c23c20
GLiNER	urchade/gliner_base	b448aaf
GLiNER	urchade/gliner_large-v1	1f55b52
GLiNER	urchade/gliner_large-v2	416a9b8
GLiNER	urchade/gliner_large-v2.1	abd49a1
GLiNER	urchade/gliner_medium-v2.1	a3f776a
GLiNER	urchade/gliner_multi	b5720ab
GLiNER	urchade/gliner_multi-v2.1	853ce23
GLiNER	urchade/gliner_multi_pii-v1	1fcf13e

Library	Hugging Face Repository (Model Name)	Git Commit
GLiNER	urchade/gliner_small-v2.1	4e09141
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-arabic	af46c2d
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-chinese-zh-cn	99ccb27
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-dutch	46f2213
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-english	569a623
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-finnish	a497f86
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-french	7c79e10
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-german	4b8a029
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-greek	489b34f
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-hungarian	2bd0786
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-italian	dab04a3
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-japanese	cf031e0
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-persian	2347140
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-polish	6b1cea3
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-portuguese	634ac65
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-russian	2329100
huggingsound	jonatasgrosman/wav2vec2-large-xlsr-53-spanish	96d7e9b
huggingsound	jonatasgrosman/wav2vec2-xls-r-1b-portuguese	8926743
LanguageBind	LanguageBind/LanguageBind_Audio	7aea390
LanguageBind	LanguageBind/LanguageBind_Audio_FT	4820c49
LanguageBind	LanguageBind/LanguageBind_Image	d8c2e37
LanguageBind	LanguageBind/LanguageBind_Video	84bed6c
LanguageBind	LanguageBind/LanguageBind_Video_FT	13f52c2
LanguageBind	LanguageBind/LanguageBind_Video_Huge_V1.5_FT	dd4bbe0
LanguageBind	LanguageBind/LanguageBind_Video_merge	efc40ec
LanguageBind	LanguageBind/LanguageBind_Video_V1.5_FT	5d53aab
MeloTTS	myshell-ai/MeloTTS-Chinese	af5d207
MeloTTS	myshell-ai/MeloTTS-English	bb4fb73
MeloTTS	myshell-ai/MeloTTS-English-v2	a53e350
MeloTTS	myshell-ai/MeloTTS-English-v3	f7c4a35
MeloTTS	myshell-ai/MeloTTS-French	1e9bf59
MeloTTS	myshell-ai/MeloTTS-Japanese	367f879
MeloTTS	myshell-ai/MeloTTS-Korean	0207e5a
MeloTTS	myshell-ai/MeloTTS-Spanish	dbb5496
Parrot_Paraphraser	prithivida/parrot_paraphraser_on_T5	9f32aa1
PyAnnote	collinbarnwell/pyannote-segmentation-30	f47575f
PyAnnote	EonNextPlatform/pyannote-wespeaker-voxceleb-resnet34-LM	N/A
PyAnnote	EonNextPlatform/segmentation-3.0	N/A
PyAnnote	fatymatariq/pyannote-wespeaker-voxceleb-resnet34-LM	27e7027
PyAnnote	fatymatariq/segmentation-3.0	e1b9697
PyAnnote	philschmid/pyannote-segmentation	d13283c
PyAnnote	pyannote/brouhaha	c93c9b5
PyAnnote	pyannote/embedding	4db4899
PyAnnote	pyannote/segmentation	660b9e2
PyAnnote	pyannote/segmentation-3.0	e66f3d3
PyAnnote	pyannote/wespeaker-voxceleb-resnet34-LM	837717d
PyAnnote	Revai/reverb-diarization-v1	4ad4567
PyAnnote	Revai/reverb-diarization-v2	f086648
PyAnnote	tensorlake/segmentation-3.0	035d994
pysentimiento	pysentimiento/bertweet-pt-sentiment	7266128
pysentimiento	pysentimiento/robertuito-ner	43dde63
pysentimiento	pysentimiento/robertuito-sentiment-analysis	a2cc0f6
sentence_transformers	avsolatorio/GIST-all-MiniLM-L6-v2	ea89dfa
sentence_transformers	avsolatorio/GIST-Embedding-v0	bf6b2e5
sentence_transformers	avsolatorio/GIST-small-Embedding-v0	d6c4190

Library	Hugging Face Repository (Model Name)	Git Commit
sentence_transformers	BAAI/bge-base-en	b737bf5
sentence_transformers	BAAI/bge-base-en-v1.5	a5beb1e
sentence_transformers	BAAI/bge-large-en	abe7d9d
sentence_transformers	BAAI/bge-large-en-v1.5	d4aa690
sentence_transformers	BAAI/bge-large-zh-v1.5	79e7739
sentence_transformers	BAAI/bge-reranker-base	2cfc18c
sentence_transformers	BAAI/bge-reranker-large	55611d7
sentence_transformers	BAAI/bge-small-en	2275a7b
sentence_transformers	BAAI/bge-small-en-v1.5	5c38ec7
sentence_transformers	BAAI/llm-embedder	c3e8ac8
sentence_transformers	cointegrated/rubert-tiny2	dad72b8
sentence_transformers	DMetaSoul/sbert-chinese-general-v2	14b486c
sentence_transformers	flax-sentence-embeddings/all_datasets_v4_MiniLM-L6	a407cc0
sentence_transformers	hiiamsid/sentence_similarity_spanish_es	3118431
sentence_transformers	intfloat/e5-base-v2	1c644c9
sentence_transformers	intfloat/e5-large-v2	b322e09
sentence_transformers	intfloat/e5-mistral-7b-instruct	07163b7
sentence_transformers	intfloat/e5-small-v2	dca8b1a
sentence_transformers	intfloat/multilingual-e5-base	d13f1b2
sentence_transformers	intfloat/multilingual-e5-large	ab10c1a
sentence_transformers	intfloat/multilingual-e5-small	fd1525a
sentence_transformers	jhgan/ko-sbert-nli	b78c95e
sentence_transformers	jhgan/ko-sroberta-multitask	ab957ae
sentence_transformers	naufalihsan/indonesian-sbert-large	a5cbfbd
sentence_transformers	NeuML/pubmedbert-base-embeddings	ba210f4
sentence_transformers	nomic-ai/nomic-embed-text-v1	cc62377
sentence_transformers	pritamdeka/BioBERT-mnli-snli-scinli-scitail-mednli-stsb	82d4468
sentence_transformers	pritamdeka/S-PubMedBert-MS-MARCO	96786c7
sentence_transformers	sentence-transformers-testing/stsb-bert-tiny-safetensors	f3cb857
sentence_transformers	sentence-transformers/all-distilroberta-v1	8d88b92
sentence_transformers	sentence-transformers/all-MiniLM-L12-v2	364dd28
sentence_transformers	sentence-transformers/all-MiniLM-L6-v2	fa97f6e
sentence_transformers	sentence-transformers/all-mpnet-base-v2	9a32259
sentence_transformers	sentence-transformers/all-roberta-large-v1	c8b9f2a
sentence_transformers	sentence-transformers/bert-base-nli-mean-tokens	2511498
sentence_transformers	sentence-transformers/bert-base-nli-stsb-mean-tokens	767076a
sentence_transformers	sentence-transformers/clip-ViT-B-32-multilingual-v1	58edf8c
sentence_transformers	sentence-transformers/distilbert-base-nli-mean-tokens	5aa678b
sentence_transformers	sentence-transformers/distilbert-base-nli-stsb-mean-tokens	cb8a28f
sentence_transformers	sentence-transformers/distilbert-multilingual-nli-stsb-quora-ranking	57cf088
sentence_transformers	sentence-transformers/distiluse-base-multilingual-cased-v1	457e815
sentence_transformers	sentence-transformers/distiluse-base-multilingual-cased-v2	dad0fa1
sentence_transformers	sentence-transformers/LaBSE	b7f9471
sentence_transformers	sentence-transformers/msmarco-bert-base-dot-v5	c45bf94
sentence_transformers	sentence-transformers/msmarco-distilbert-base-dot-prod-v3	0cf6cf1
sentence_transformers	sentence-transformers/msmarco-distilbert-base-tas-b	136d171
sentence_transformers	sentence-transformers/msmarco-distilbert-base-v4	19f0f4c
sentence_transformers	sentence-transformers/msmarco-distilbert-cos-v5	c598d92
sentence_transformers	sentence-transformers/msmarco-distilbert-dot-v5	6ad1718
sentence_transformers	sentence-transformers/msmarco-MiniLM-L-6-v3	d273900
sentence_transformers	sentence-transformers/msmarco-MiniLM-L12-cos-v5	09660d8
sentence_transformers	sentence-transformers/msmarco-MiniLM-L6-cos-v5	14ca9be
sentence_transformers	sentence-transformers/multi-qa-distilbert-cos-v1	bc2339d
sentence_transformers	sentence-transformers/multi-qa-MiniLM-L6-cos-v1	b207367
sentence_transformers	sentence-transformers/multi-qa-mpnet-base-cos-v1	822dbc9

Library	Hugging Face Repository (Model Name)	Git Commit
sentence_transformers	sentence-transformers/multi-qa-mpnet-base-dot-v1	4633e80
sentence_transformers	sentence-transformers/nli-mpnet-base-v2	688eb0a
sentence_transformers	sentence-transformers/paraphrase-albert-small-v2	39d5b65
sentence_transformers	sentence-transformers/paraphrase-MiniLM-L12-v2	3f21b01
sentence_transformers	sentence-transformers/paraphrase-MiniLM-L3-v2	029a79d
sentence_transformers	sentence-transformers/paraphrase-MiniLM-L6-v2	9a27583
sentence_transformers	sentence-transformers/paraphrase-mpnet-base-v2	bef3689
sentence_transformers	sentence-transformers/paraphrase-multilingual-MiniLM-L12-v2	8d6b950
sentence_transformers	sentence-transformers/paraphrase-multilingual-mpnet-base-v2	75c5775
sentence_transformers	sentence-transformers/sentence-t5-base	50c53e2
sentence_transformers	sentence-transformers/sentence-t5-xl	2965d31
sentence_transformers	sentence-transformers/stsb-roberta-base	fb8c0e7
sentence_transformers	sentence-transformers/stsb-xml-r-multilingual	18f85ee
sentence_transformers	shibing624/text2vec-base-chinese	183bb99
sentence_transformers	shibing624/text2vec-base-multilingual	6633dc4
sentence_transformers	Supabase/gte-small	93b36ff
sentence_transformers	thenlper/gte-base	c078288
sentence_transformers	thenlper/gte-large	4bef63f
sentence_transformers	thenlper/gte-small	17e1f34
super-image	eugenesiow/edsr (pytorch_model_2x.pt)	8f214a5
super-image	eugenesiow/edsr (pytorch_model_3x.pt)	8f214a5
super-image	eugenesiow/edsr (pytorch_model_4x.pt)	8f214a5
super-image	eugenesiow/edsr-base (pytorch_model_2x.pt)	d622f68
super-image	eugenesiow/edsr-base (pytorch_model_3x.pt)	d622f68
super-image	eugenesiow/edsr-base (pytorch_model_4x.pt)	d622f68
TNER	tner/deberta-v3-large-ontonotes5	98a5818
TNER	tner/roberta-large-ontonotes5	0bce50f
TNER	tner/roberta-large-tweetner7-all	e7fbeeec
TNER	tner/roberta-large-wnut2017	e2e15e4
tweetnlp	cardiffnlp/twitter-xml-roberta-base-sentiment-multilingual	82107f4
YOLOv5	keremberke/yolov5m-smoke	79dc392
YOLOv5	keremberke/yolov5m-license-plate	2bc5d84
YOLOv5	keremberke/yolov5n-license-plate	b9a03ec
YOLOv5	Ultralytics/YOLOv5 (yolov5s.pt)	73fb27f
YOLOv5	Ultralytics/YOLOv5 (yolov5s6.pt)	73fb27f
YOLOv5	Ultralytics/YOLOv5 (yolov5n.pt)	73fb27f
YOLOv5	Ultralytics/YOLOv5 (yolov5n6.pt)	73fb27f
YOLOv5	Ultralytics/YOLOv5 (yolov5m.pt)	73fb27f
YOLOv5	Ultralytics/YOLOv5 (yolov5m6.pt)	73fb27f
YOLOv5	Ultralytics/YOLOv5 (yolov5l.pt)	73fb27f
YOLOv5	Ultralytics/YOLOv5 (yolov5l6.pt)	73fb27f
YOLOv5	keremberke/yolov5s-license-plate	038440e
YOLOv11 (ultralytics)	Bingsu/yolo-world-mirror (yolov8l-world.pt)	414d0ee
YOLOv11 (ultralytics)	Bingsu/yolo-world-mirror (yolov8l-worldv2.pt)	414d0ee
YOLOv11 (ultralytics)	Bingsu/yolo-world-mirror (yolov8m-world.pt)	414d0ee
YOLOv11 (ultralytics)	Bingsu/yolo-world-mirror (yolov8m-worldv2.pt)	414d0ee
YOLOv11 (ultralytics)	Bingsu/yolo-world-mirror (yolov8s-world.pt)	414d0ee
YOLOv11 (ultralytics)	Bingsu/yolo-world-mirror (yolov8s-worldv2.pt)	414d0ee
YOLOv11 (ultralytics)	Bingsu/yolo-world-mirror (yolov8x-world.pt)	414d0ee
YOLOv11 (ultralytics)	Bingsu/yolo-world-mirror (yolov8x-worldv2.pt)	414d0ee
YOLOv11 (ultralytics)	keremberke/yolov8m-table-extraction	8826513
YOLOv11 (ultralytics)	keremberke/yolov8s-table-extraction	fc8bf12
YOLOv11 (ultralytics)	Ultralytics/YOLOv8 (yolov8l.pt)	5d9ba66
YOLOv11 (ultralytics)	Ultralytics/YOLOv8 (yolov8m.pt)	5d9ba66
YOLOv11 (ultralytics)	Ultralytics/YOLOv8 (yolov8n.pt)	5d9ba66

Library	Hugging Face Repository (Model Name)	Git Commit
YOLOv11 (ultralytics)	Ultralytics/YOLOv8 (yolov8s.pt)	5d9ba66
YOLOv11 (ultralytics)	Ultralytics/YOLOv8 (yolov8x.pt)	5d9ba66
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11l-pose.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11l.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11l-seg.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11m-pose.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11m.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11m-seg.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11n-pose.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11n.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11n-seg.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11s-pose.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11s.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11s-seg.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11x-pose.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11x.pt)	9cc3192
YOLOv11 (ultralytics)	Ultralytics/YOLO11 (yolo11x-seg.pt)	9cc3192
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc Breasts Seg v1 1024m.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc Breasts Seg v1 1024n.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc Breasts Seg v1 1024s.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc Eyes -seg-hd.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc Face seg 1024 v2 y8n.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc Face seg 640 v2 y8n.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc Face seg 640 v3 y11n.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc Face seg 768MS v2 y8n.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc Face seg 768 v2 y8n.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc Face -seg.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc HeadHair seg y8m.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc HeadHair seg y8n.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhc Manga Panels -seg.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhcs Drones v03 1024 y11n.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhcs ManFace v02 1024 y8n.pt)	4bb7d18
YOLOv11 (ultralytics)	Anzhc/Anzhcs_YOLOs (Anzhcs WomanFace v05 1024 y8n.pt)	4bb7d18
YOLOv11 (ultralytics)	tech4humans/yolov8s-signature-detector	c891f02
YOLOv11 (ultralytics)	foducom/stockmarket-pattern-detection-yolov8	31bbb9a
YOLOv11 (ultralytics)	pitangent-ds/YOLOv8-human-detection-thermal	a5d30f1
YOLOv11 (ultralytics)	arnabdhhar/YOLOv8-nano-aadhar-card	d5f938d
YOLOv11 (ultralytics)	keremberke/yolov8n-building-segmentation	eb61328