



PDF Download  
3407023.3407045.pdf  
27 December 2025  
Total Citations: 44  
Total Downloads: 832

Latest updates: <https://dl.acm.org/doi/10.1145/3407023.3407045>

RESEARCH-ARTICLE

## MP2ML: a mixed-protocol machine learning framework for private inference

FABIAN BOEMER, Intel Corporation, Santa Clara, CA, United States

ROSARIO CAMMAROTA, Intel Corporation, Santa Clara, CA, United States

DANIEL DEMMLER, University of Hamburg, Hamburg, Hamburg, Germany

THOMAS SCHNEIDER, Technical University of Darmstadt, Darmstadt, Hessen, Germany

HOSSEIN YALAME, Technical University of Darmstadt, Darmstadt, Hessen, Germany

Open Access Support provided by:

Intel Corporation

Technical University of Darmstadt

University of Hamburg

Published: 25 August 2020

[Citation in BibTeX format](#)

ARES 2020: The 15th International  
Conference on Availability, Reliability  
and Security  
August 25 - 28, 2020  
Virtual Event, Ireland

# MP2ML: A Mixed-Protocol Machine Learning Framework for Private Inference

Fabian Boemer  
fabian.boemer@intel.com  
Intel AI  
San Diego, California, USA

Rosario Cammarota  
rosario.cammarota@intel.com  
Intel Labs  
San Diego, California, USA

Daniel Demmler  
demmler@informatik.uni-hamburg.de  
University of Hamburg  
Hamburg, Germany

Thomas Schneider  
schneider@encrypto.cs.tu-darmstadt.de  
TU Darmstadt  
Darmstadt, Germany

Hossein Yalame  
yalame@encrypto.cs.tu-darmstadt.de  
TU Darmstadt  
Darmstadt, Germany

## ABSTRACT

Privacy-preserving machine learning (PPML) has many applications, from medical image classification and anomaly detection to financial analysis. nGraph-HE enables data scientists to perform private inference of deep learning (DL) models trained using popular frameworks such as TensorFlow. nGraph-HE computes linear layers using the CKKS homomorphic encryption (HE) scheme. The non-polynomial activation functions, such as MaxPool and ReLU, are evaluated in the clear by the data owner who obtains the intermediate feature maps. This leaks the feature maps to the data owner from which it may be possible to deduce the DL model weights. As a result, such protocols may not be suitable for deployment, especially when the DL model is intellectual property.

In this work, we present MP2ML, a machine learning framework which integrates nGraph-HE and the secure two-party computation framework ABY, to overcome the limitations of leaking the intermediate feature maps to the data owner. We introduce a novel scheme for the conversion between CKKS and secure multi-party computation to execute DL inference while maintaining the privacy of both the input data and model weights. MP2ML is compatible with popular DL frameworks such as TensorFlow that can infer pre-trained neural networks with native ReLU activations. We benchmark MP2ML on the CryptoNets network with ReLU activations, on which it achieves a throughput of 33.3 images/s and an accuracy of 98.6%. This throughput matches the previous state-of-the-art work, even though our protocol is more accurate and scalable.

## CCS CONCEPTS

• Security and privacy → Privacy-preserving protocols.

## KEYWORDS

private machine learning, homomorphic encryption, secure multi-party computation.

### ACM Reference Format:

Fabian Boemer, Rosario Cammarota, Daniel Demmler, Thomas Schneider, and Hossein Yalame. 2020. MP2ML: A Mixed-Protocol Machine Learning Framework for Private Inference. In *The 15th International Conference on Availability, Reliability and Security (ARES 2020), August 25–28, 2020, Virtual Event, Ireland*. ACM, New York, NY, USA, 10 pages. <https://doi.org/10.1145/3407023.3407045>

## 1 INTRODUCTION

Several practical services have emerged that use machine learning (ML) algorithms to categorize and classify large amounts of sensitive data ranging from medical diagnosis to financial evaluation [14, 67]. However, to benefit from these services, current solutions require disclosing private data, such as biometric, financial or location information.

As a result, there is an inherent contradiction between utility and privacy: ML requires data to operate, while privacy necessitates keeping sensitive information private [71]. Therefore, one of the most important challenges in using ML services is helping data owners benefit from ML, while simultaneously preserving their privacy [69]. For instance, evaluating a private decision tree can provide a solution for private medical diagnosis where the patient’s medical data is sensitive information that needs to be protected while simultaneously protecting the model [4, 38, 64, 72].

Modern cryptographic techniques such as homomorphic encryption (HE) and secure multi-party computation (MPC) can help resolve this contradiction. Using HE, a data owner can encrypt its data with its public key, send the encrypted data for processing to an untrusted data processor, and receive the encrypted result, which only the data owner itself can decrypt with its private key [30, 56]. In secure two-party computation (2PC), a special case of MPC with two parties [7, 33, 73], the data owner secret-shares its data with the data processor and uses the secret-shared data to securely compute the result without revealing any individual values.

While HE and MPC have the potential to address the privacy issues that arise in ML, each technique has its advantages and limitations. HE has high overhead for computing non-polynomial

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from [permissions@acm.org](mailto:permissions@acm.org).  
ARES 2020, August 25–28, 2020, Virtual Event, Ireland  
© 2020 Association for Computing Machinery.  
ACM ISBN 978-1-4503-8833-7/20/08...\$15.00  
<https://doi.org/10.1145/3407023.3407045>

activations, such as ReLU and MaxPool, which are commonly used in deep learning (DL) models. While efficient HE-based inference is possible by replacing activation functions with polynomial approximations, this degrades the accuracy of the DL model [10], and requires a costly re-training of the model. MPC schemes support a larger set of functions and it is possible to perform private DL inference using only MPC schemes. However, MPC requires the structure (e.g., the Boolean circuit) of the network to be public, and involves multiple rounds of interaction between the parties.

Hybrid methods combine HE and MPC to take advantage of each method’s strengths. Recent research has demonstrated the ability to evaluate neural networks using a combination of HE and MPC [5, 6, 31, 35, 37, 46, 51, 54, 55, 59, 61]. For example GAZELLE [37], using a combination of HE and MPC, demonstrates three orders of magnitude faster online run-time when compared to the existing exclusively MPC [55] and exclusively HE [31] solutions.

DL software frameworks, such as TensorFlow [1], MXNet [18], and PyTorch [52], as well as open-source graph compilers, such as Intel’s nGraph [22] and TVM [19] accelerate the development of DL. These libraries abstract away the details of the software and hardware implementation, enabling data scientists to describe DL models and operations at a high level (e.g., tensors and compute graphs). Historically, a major challenge for building privacy-preserving machine learning (PPML) systems has been the absence of software frameworks that support privacy-preserving primitives.

To overcome this challenge, Intel recently introduced nGraph-HE [10, 11], a HE-based framework that is compatible with existing DL frameworks. Using nGraph-HE, data scientists can deploy DL networks over encrypted data without extensive knowledge of cryptography. One of the major limitations of using HE in nGraph-HE is the cleartext evaluation of non-polynomial functions such as MaxPool and ReLU, which may leak information about the DL model weights and hyper-parameters to the client.

**Outline and Our Contributions.** In this work, we introduce MP2ML, a hybrid HE-MPC framework for privacy-preserving DL inference. MP2ML extends nGraph-HE with MPC-based computation of ReLU activations, which prevents the leakage of model weights to the client. We use the ABY framework [27] to implement a 2PC version of the ReLU activation function. Our framework integrates with TensorFlow, enabling data scientists to adopt MP2ML with minimal code changes (cf. [9, Sect. 4.3]). After presenting preliminaries from privacy-preserving DL (Sect. 2), and an overview of related work (Sect. 3), we detail MP2ML (Sect. 4), which provides the following core contributions:

- A privacy-preserving mixed-protocol DL framework based on a novel combination of nGraph-HE [10, 11] and ABY [27];
- A user-friendly framework that supports private inference on direct input from TensorFlow;
- Support for privacy-preserving evaluation of the non-linear ReLU activation function with high accuracy;
- The first DL application using additive secret sharing in combination with the CKKS homomorphic encryption scheme;
- An open-source implementation of our framework, available under the permissive Apache license at <https://ngra.ph/he>.

We evaluate atomic operations and a neural network benchmark using our framework (Sect. 5). Finally, we discuss our approach and highlight differences to existing solutions (Sect. 6) and conclude (Sect. 7).

## 2 BACKGROUND

We provide an overview of the techniques used in MP2ML. We define our notation in Sect. 2.1 and provide an overview of the cryptographic methods used in our framework and the adversary model in Sect. 2.2.

### 2.1 Notation

$x$  denotes a plaintext scalar,  $X$  is a vector of  $n$  plaintext scalars  $(x_1, x_2, \dots, x_n)$ ,  $\llbracket x \rrbracket$  is a homomorphic encryption of  $x$ ,  $\llbracket X \rrbracket$  is an element-wise homomorphic encryption of  $X$ , and  $q$  is the ciphertext modulus. Let  $\lfloor \cdot \rfloor$  denote rounding to the nearest integer, and  $[\cdot]_q$  denote modular reduction into the interval  $(-q/2, q/2)$ .

### 2.2 Cryptographic Preliminaries

Modern cryptographic protocols such as homomorphic encryption (HE) and secure multi-party computation (MPC) are essential building blocks for privacy-preserving ML.

**Homomorphic Encryption (HE).** HE is a cryptographic primitive supporting computation on encrypted data. HE schemes are classified by the types of computation they support. Somewhat HE (SHE) schemes support a limited number of additions or multiplications, while fully HE (FHE) schemes support an unlimited number of additions and multiplications. In this work, we utilize the CKKS HE scheme [20] and its SHE implementation in the Microsoft Simple Encryption Arithmetic Library (SEAL) version 3.4 [63].

The security of the CKKS scheme is based on the assumed hardness of the ring learning with errors (RLWE) problem. Let  $\Phi_M(X)$  be the  $M^{\text{th}}$  cyclotomic polynomial of degree  $N = \phi(M)$ . Usually  $\deg(\Phi_M(X))$  is a power of two for both performance and security reasons. Then, the plaintext space is the ring  $\mathcal{R} = \mathbb{Z}[X]/(\Phi_M(X))$ . The ciphertext space is  $\mathcal{R}_q = \mathcal{R}/(q\mathcal{R})$ , i.e., degree- $N$  polynomials with integer coefficients mod  $q$ , where  $q$  is the *coefficient modulus*. Neural networks, however, typically operate on floating-point numbers. Hence, we need a conversion from floating-point numbers to integers, which is typically done by multiplying a floating-point number  $x$  by some scale  $s$  and encrypting  $\llbracket sx \rrbracket_q$ . However, the homomorphic product of two ciphertexts at scale  $s$  is a ciphertext with scale  $s^2$ . Subsequent multiplications increase the scale quickly until the integers exceed the range  $(-q/2, q/2)$ , at which point decryption becomes inaccurate.

To mitigate this blow-up in the scale, CKKS introduces a *rescaling* procedure. The rescaling procedure relies on a ‘layered’ ciphertext space, in which each of  $L$  layers contains a different ciphertext modulus. Let  $p_0, \dots, p_{L-1}$  be primes, and let  $q_i = \prod_{\ell=0}^i p_\ell$ . Then, the layered ciphertext space  $\mathcal{R}_{q_{L-1}}$  consists of  $L$  layers, where layer  $i$  has coefficient modulus  $q_i$ . Rescaling brings a ciphertext  $c$  with scale  $s$  from level  $\ell$  to a ciphertext at level  $\ell - 1$  with scale  $s/q_\ell$ , and reduces the ciphertext space from  $\mathcal{R}_{q_\ell}$  to  $\mathcal{R}_{q_{\ell-1}}$ . The rescaling algorithm is the homomorphic equivalent to removing inaccurate LSBs as a rounding step in approximate arithmetic.

The security of the CKKS encryption scheme is measured in bits, with  $\lambda = 128$  bits implying  $\sim 2^{128}$  operations are required to break the encryption.  $\lambda$  is a function of the encryption parameters  $\{N, L, q_0, \dots, q_{L-1}\}$ .

Unlike other HE schemes, such as BFV [13, 29], CKKS is also an approximate HE scheme. The decryption after addition and multiplication is approximate, but the error in the decryption is bounded under certain assumptions on the selection of the encryption parameters. The runtime performance of CKKS depends heavily on the choice of the encryption parameters (cf. [10, Tab.9]).

While CKKS induces a significant runtime and memory overhead compared to unencrypted computation, the use of *plaintext packing*, also referred to as *batching*, improves the amortized overhead. Plaintext packing encodes  $N/2$  complex scalars into one plaintext or ciphertext. It works by defining an encoding map  $\mathbb{C}^{N/2} \rightarrow \mathcal{R}$ , where  $\mathcal{R}$  is the plaintext space. An operation (addition or multiplication) performed on an element in  $\mathcal{R}$  corresponds to the same operation performed on  $N/2$  elements in  $\mathbb{C}^{N/2}$ . The number of  $N/2$  elements in the packing is also referred to as the number of *slots* in the plaintext. We use the *complex packing* optimization from nGraph-HE [11] to increase the slot count to  $N$ .

MP2ML uses *batch-axis plaintext packing*: encode an inference data batch of shape  $(n, c, h, w)$ , where  $n \leq N$  is the batch size, as  $c \times h \times w$  ciphertexts, with ciphertext  $c_{c,h,w}$  packing the  $n$  values  $(\cdot, c, h, w)$  in the data batch. Then, inference is performed on the  $n$  data points simultaneously. We refer to [10] for more details.

**Secure Multi-Party Computation (MPC).** MPC is a cryptographic technique, which enables two or more parties to jointly evaluate a function  $f$  without revealing their private inputs to each other. In this work, we focus on the two-party case, in which typically one of two approaches is used: Yao’s garbled circuit (GC) protocol [74] or the Goldreich-Micali-Wigderson (GMW) protocol [33]. In both protocols, the function to be computed is represented as a Boolean circuit.

In Yao’s GC protocol [74], each of the two parties – called garbler and evaluator – evaluates a function  $f$ , represented as a Boolean circuit, without exposing its input to the other party. The GC protocol consists of two phases. In the first phase, the circuit is garbled by assigning two random *labels* to each wire in the circuit, with each label corresponding to the logical values of 0 and 1. A *garbled table* maps each possible combination of these input labels to its corresponding output label, according to the logic function of each Boolean gate. The privacy of GCs stems from the fact that output labels are encrypted and only a single output label per gate can be decrypted by using the input labels as decryption keys. Since wire labels are random strings, the garbler can simply encode its own private inputs into the circuit. The evaluator receives the wire labels corresponding to its private inputs privately by using an oblivious transfer protocol [28, 39]. In the second phase, the evaluator computes the circuit outputs using the garbled tables to iteratively decrypt the outputs of each gate until the output of the entire circuit has been decrypted. The output can then be revealed to one or both parties by providing the final mapping of output labels to plaintext bits to the designated parties.

In the GMW protocol [33], the two parties secret-share all inputs and intermediate values using an XOR-based secret sharing

scheme. Then the parties interact in several communication rounds to securely compute the function  $f$  on their shared values. By exchanging their final shares and computing the XOR, one or both parties can reconstruct the plaintext outputs of the circuit.

The ABY MPC framework [27], provides an efficient implementation of both protocols and their state-of-the-art optimizations such as [3, 8, 40, 47, 62, 75].

**Adversary Model.** In this work, we use the semi-honest<sup>1</sup> adversary model, in which we assume that the adversary follows the protocol honestly, but attempts to infer additional sensitive information from the observed protocol messages. This model is weaker than the malicious (active) adversary model, where the adversary can arbitrarily deviate from the protocol. However, the semi-honest model allows to build highly efficient secure computation protocols and is therefore widely used in privacy-preserving DL applications [5, 6, 10, 11, 31, 35, 37, 51, 55, 59]. This assumption is similar to the one used in HE-based DL, where it is assumed that a server correctly computes a function on a homomorphic ciphertext. Proofs of security w.r.t. semi-honest adversaries are given for Yao’s protocol in [45], and the GMW protocol in [32].

MP2ML protects the privacy of both the client’s and the server’s inputs. In the setting where the server stores a trained neural network and the client provides encrypted data for inference, our framework provides privacy for both parties’ inputs. The client is unable to infer sensitive information about the trained model, which may be intellectual property of the server. MP2ML reveals only the total size of the model and the number and type of non-linear operations, since these values must be known in the MPC protocol. At the same time, the server cannot access the client’s plaintext inference inputs or classification outputs, which may be sensitive medical or financial information.

### 3 RELATED WORK

Previous work in privacy-preserving DL typically uses either exclusively HE or exclusively MPC. GAZELLE [37] and Delphi [48] are notable exceptions, using both HE and MPC in a hybrid scheme. Table 1 shows a comparison between MP2ML and previous work. While pure HE solutions maintain complete model privacy, they typically lack the support for non-polynomial activation functions, such as ReLU and MaxPool, with the notable exception of TFHE [21], which is used as a backend in Cingulata [16] and Chimera [12]. Pure MPC solutions, on the other hand, support non-polynomial activations at the cost of leaking the full model architecture. Hybrid HE-MPC schemes provide the advantages of both HE and MPC approaches. MP2ML provides the first hybrid HE-MPC framework that integrates with a DL framework such as TensorFlow. Similar to GAZELLE [37], our framework leaks the number of ciphertexts and the activation function used in each non-linear layer. However, MP2ML does not reveal the functionality and size of the linear layers.

Next, we summarize several different approaches for preserving-privacy DL.

**HE-based DL.** The main workload of DL models is multiplication and addition in convolution and general matrix multiply (GEMM)

<sup>1</sup>also called passive, or honest-but-curious adversary model

**Table 1: Comparison of privacy-preserving DL Frameworks. Model privacy includes preventing the data owner from deducing the weights from intermediate feature maps, protecting the activation function (i.e., ReLU or MaxPool), protecting the model architecture, and only the number of ciphertexts can be leaked. Usability includes support for non-polynomial activation functions, integration with a standard DL framework such as TensorFlow or PyTorch, and availability as open-source code.**

Framework	Protocol		Model privacy			Usability		
	HE	MPC	Weights	Act. fun.	Convolution	Non-poly Act.	TF/PyTorch Support	Open-Source
nGraph-HE2 [10]	✓	✗	✗	✗	✓	✓	✓	✓
CHET [26]	✓	✗	✓	✓	✓	✗	✗	✗
CryptoDL [35]	✓	✗	✓	✓	✓	✗	✗	✗
RAMPARTS [2]	✓	✗	✓	✓	✓	✗	✗	✗
CryptoNets [31]	✓	✗	✓	✓	✓	✗	✗	✓
nGraph-HE [11]	✓	✗	✓	✓	✓	✗	✓	✓
Chimera [12]	✓	✗	✓	✓	✓	✓	✗	✗
Cingulata [16]	✓	✗	✓	✓	✓	✓	✗	✓
TFHE [21]	✓	✗	✓	✓	✓	✓	✗	✓
SecureML [50]	✗	✓	✓	✗	✗	✓	✗	✗
Barni [5]	✗	✓	✓	✗	✗	✓	✗	✗
Sadeghi et al. [59]	✗	✓	✓	✗	✗	✓	✗	✗
Chameleon [55]	✗	✓	✓	✗	✗	✓	✗	✗
XONN [54]	✗	✓	✓	✗	✗	✓	✗	✗
SecureNN [70]	✗	✓	✓	✗	✗	✓	✗	✓
ABY3 [49]	✗	✓	✓	✗	✗	✓	✗	✓
TASTY [34]	✗	✓	✓	✗	✗	✓	✗	✓
Dalskov et. al [24]	✗	✓	✓	✗	✗	✓	✓	✓
PySyft [58]	✗	✓	✓	✗	✗	✓	✓	✓
TF Encrypted [23]	✗	✓	✓	✗	✗	✓	✓	✓
CrypTFlow [43]	✗	✓	✓	✗	✗	✓	✓	✓
GAZELLE [37]	✓	✓	✓	✗	✓	✓	✗	✗
Delphi [48]	✓	✓	✓	✗	✓	✓	✗	✓
MP2ML (This work)	✓	✓	✓	✗	✓	✓	✓	✓

operations [36], making HE an attractive solution for privacy-preserving DL. However, DL models typically consist of functions which are not suitable for HE. For example, computing ReLU or MaxPool requires a comparison operation that is not supported efficiently in all HE methods.

One solution, which requires access to the entire DL workflow including training, is re-training the DL model with polynomial activation functions [6, 51]. The CryptoNets network [31] by Microsoft Research is an HE-based private DL framework, which uses the polynomial activation function  $f(x) = x^2$  to achieve 99% accuracy on the MNIST dataset [44]. CHET [26] takes the same approach on the CIFAR-10 dataset [42] and uses the activation function  $f(x) = ax^2 + bx$ . This approach reduces the accuracy from 84% in models with ReLU to 81.5%. CryptoDL [35] uses a similar approach, which reduces the accuracy from 94.2% in the original model to 91.5% for the CIFAR-10 dataset.

Depending on the use cases, such accuracy degradation may not be acceptable. Furthermore, polynomial activations introduce further difficulties in trMPO2ML training. Polynomial activation functions are not bounded and grow faster than standard activation functions such as ReLU, possibly resulting in overflows during the training.

RAMPARTS [2] uses the Julia language to implement HE operations with the PALISADE HE library [57]. However, RAMPARTS is not open-source, and lacks support for source code outside of Julia. The Cingulata compiler [16] uses a custom implementation of the Fan-Vercauteren HE scheme [29] in C++. Cingulata translates computations to Boolean circuits, reducing performance on GeMM workloads.

**FHE-based DL.** In this setting, we assume the network has been trained with non-polynomial activation functions, and no changes can be made. Fully homomorphic encryption (FHE) schemes, which support an unlimited number of additions and multiplications, are used to provide precise polynomial approximations of non-polynomial activations. However, due to their large computational overhead, FHE schemes are typically much slower than other alternatives. For instance, using TFHE [21], FHE-based DL models have very low efficiency for arithmetic functions such as GeMM.

**MPC-based DL.** Pure MPC schemes are another method to evaluate pre-trained neural networks. For instance, in [59], Yao’s garbled circuits [74] applied to a generalization of universal circuits [41, 68] are used to evaluate neural networks and hide their topology. ABY [27] supports arithmetic and Boolean circuits and efficient switching between them, enabling arbitrary functions for

network models. ABY3 [49] combines arithmetic secret sharing and garbled circuits and optimized conversions between these protocols to improve previous work. SecureNN [70], an extension of SecureML [50], demonstrates enhanced performance using a third party. Chameleon [55] is an ABY-based framework for secure evaluation of DL models, using a somewhat-trusted third party in the offline phase to generate correlated randomness. Specially, Chameleon performs polynomial operations using arithmetic secret sharing and non-linear operations such as ReLU using Boolean sharing protocols, GC or GMW [33].

XONN [54] use GCs for private inference. However, XONN binarizes the network, i.e., evaluates networks with weights that are bits, which is costly to train and reduces accuracy. PySyft [58] and TF Encrypted [23] are two frameworks for secure DL models built on PyTorch and TensorFlow, respectively, and use only MPC to evaluate DL models. CrypTFlow [43], a system extending SecureNN [70], is a recent framework for private DL model evaluation based on TensorFlow and uses pure MPC to evaluate DL layers securely. In [24], the authors provide secure inference of ML quantized models in MP-SPDZ [25] with active and passive security, and evaluate the output by TensorFlow directly. MPC-based DL solutions tend to evaluate all DL layers with MPC protocols.

Two main disadvantages in this setting include sharing the functional form (i.e., structure/topology) of the network – which may be intellectual property – with all the parties, and the high communication overhead for multiplication operations.

**Hybrid DL.** Hybrid PPML frameworks combine different privacy-preserving protocols. Slalom [66] performs all linear layers in secure inference using Intel SGX, a trusted execution environment (TEE). TEE-based solutions are very efficient, but are prone to attacks [17].

Hybrid HE-MPC schemes compute linear layers (e.g., Fully-Connected and Convolutional) using HE and activation functions using MPC. The work of [5] combined garbled circuits with additive HE schemes. Chimera [12] is a hybrid HE-HE scheme where the ReLU activation function is performed using TFHE [21] and the other functions are performed by the FV/CKKS HE scheme [20]. The main drawback of Chimera is the expensive switching between the two HE schemes.

GAZELLE [37] and Delphi [48] are hybrid HE-MPC scheme which uses additive HE for polynomial functions and MPC (garbled circuits) for non-polynomial activation functions. GAZELLE uses a small plaintext modulus, which will result in degraded accuracy on larger networks, and does not integrate with DL frameworks.

GAZELLE [37], for instance, replaces arithmetic sharing with HE for multiplication, resulting in a 30× faster runtime than Chameleon’s MPC-based multiplication scheme [37].

## 4 THE MP2ML FRAMEWORK

In this section, we provide a detailed description of our MP2ML framework. The main idea borrows from three popular frameworks in literature, including pure MPC using the ABY framework [27], pure HE as in nGraph-HE [10], and hybrid MPC-HE frameworks such as TASTY [34] or GAZELLE [37].

nGraph-HE [10, 11], an HE-based extension of Intel’s DL graph compiler, provides compatibility with popular DL frameworks such as TensorFlow, enabling data scientists to benchmark linear layers

in DL models in a privacy-preserving manner without extensive knowledge in cryptography.

ABY [27] supports both linear and non-linear operations and can implement and securely evaluate them as arithmetic or Boolean circuit. ABY also supports single instruction multiple data (SIMD) gates for high throughput.

MP2ML is a hybrid HE-MPC framework integrating ABY and nGraph-HE, and is compatible with DL frameworks such as TensorFlow. Our work focuses on the setting in which the client can privately perform inference without disclosing his or her input to the server as well as preserving the privacy of the server’s DL model. In MP2ML, we directly build on the usability of nGraph-HE, which requires only minimal changes to existing TensorFlow code. In particular, similar to [11], only a single line of code must be added to enable evaluation with MP2ML, cf. [9, Sect. 4.3].

### 4.1 Private ML Workflow

MP2ML combines HE and MPC to enable the evaluation of neural network models in an efficient and privacy-preserving manner. Briefly summarized, the steps are as follows:

- Client: Input encryption, transmission to the server
- Private Inference
  - Server: Non-interactive evaluation of linear layers
  - Both: Conversion from HE values to MPC values
  - Both: Interactive evaluation of non-linear layers
  - Both: Conversion from MPC values to HE values
  - repeat until network output is reached
- Server: Transmission of the encrypted model output to the client
- Client: Output decryption

**Client Input Encryption.** First, the client encrypts its input using the CKKS HE scheme, as implemented by Microsoft SEAL [63], and sends it to the server. For increased throughput, multiple values are packed into a single ciphertext using batch-axis plaintext packing (cf. Sect. 2.2). Now we sequentially evaluate each layer in the DL model using HE or MPC.

**Linear Layers.** The server evaluates linear layers using the HE-based nGraph-HE [10, 11] implementation. This includes tensor computation operations, such as Convolutional, AvgPool, and Fully-Connected layers, as well as tensor manipulation operations, such as Broadcast, Reshape, Concatenate, and Slice. Using HE for the linear layers enables the server to hide the model structure/topology from the client, and results in no communication overhead.

**Non-Linear Layers.** We use an MPC protocol to privately evaluate non-linear layers, i.e., ReLU activations. This distinguishes our framework from nGraph-HE. In nGraph-HE’s client-aided model, the server sends the encrypted non-linear layers’ inputs to the client, which decrypts these inputs, performs the non-linear operation locally in the clear, encrypts the result and sends it back to the server. The client-aided protocol reveals intermediate values to the client and thus directly leaks information about the trained model, which is often considered private or intellectual property by the server.

In contrast, MP2ML evaluates the non-linear functions using a secure two-party protocol between the client and the server, such that no sensitive information about the intermediate values

is leaked. The client learns only the type of non-linear activation function and their total number, but no intermediate value. This approach protects both the server’s model as well as the client’s inputs. Next, we describe the ReLU activation function and our implementation thereof.

**ReLU Evaluation.** Fig. 1 illustrates our secure MPC-based ReLU computation. We assume that the server has previously homomorphically computed linear layers or received the client’s inputs and holds a homomorphic ciphertext  $\llbracket x \rrbracket$ . The first step is to convert the ciphertext to an MPC value.

Previous work [5, 34, 37] uses arithmetic masking to convert a homomorphic ciphertext into an MPC value: the server additively blinds  $\llbracket x \rrbracket$  with a random mask  $r$  and sends the masked ciphertext  $\llbracket x + r \rrbracket$  to the client, who decrypts. Then, both parties evaluate a subtraction circuit in MPC to remove the random mask. MP2ML extends this approach to fixed-point arithmetic.

In our private ReLU protocol, the server and the client perform the following steps:

1) *Conversion from HE to MPC:* The first step is to convert the homomorphic ciphertext to an MPC value. To do this, the server generates two random masks,  $r_1$  and  $r_2$ , which are integers chosen uniformly at random from the entire domain of the ciphertext space at the lowest level:  $(-q_0/2, q_0/2)$ . The server first rescales the ciphertext to the lowest level, such that the ciphertext space is  $\mathcal{R}_{q_0}$ . Then, the server performs the homomorphic subtraction  $r_1$  from the ciphertext  $\llbracket x \rrbracket$  with the ciphertext modulus  $q_0$ , and sends the resulting ciphertext  $\llbracket [x - r_1] \rrbracket_{q_0}$  to the client. Since  $r_1$  is chosen uniformly at random, the resulting ciphertext  $\llbracket [x - r_1] \rrbracket_{q_0}$  perfectly masks the plaintext value  $x$ .

The client decrypts  $\llbracket [x - r_1] \rrbracket$  using its private key. We now have  $r_1$  and  $r_2$  on the server side and  $[x - r_1]_q$  on the client side. Since ABY operates on unsigned integers, we map the range  $(-q_0/2, q_0/2)$  to  $(0, q)$  by performing the transformation  $\text{SignedToUnsigned}_{q_0}(x) = \begin{cases} x + q_0, & x < 0 \\ x, & x \geq 0 \end{cases}$ , with inverse transformation  $\text{UnsignedToSigned}$ . Note,  $\text{SignedToUnsigned}_{q_0}(x) \geq q_0/2 \iff x \leq 0$ . Let  $x_u$  refer to the unsigned value  $x_u = \text{SignedToUnsigned}(x)$ .

2) *MPC circuit evaluation:* We now evaluate the ReLU circuit shown in Fig. 1, which is similar to that of GAZELLE [37]. To do this, we

\* first, compute the arithmetic integer addition of  $x_u - r_1$  from the client and  $r_1$  from the server to obtain  $x_u$ , possibly outside the range  $(0, q_0)$ . A multiplexer compares the result to  $q_0$  and performs conditional arithmetic subtraction of  $q_0$  to obtain  $x_u \bmod q_0$ .

\* In the second step, we compute

$$\text{ReLU}(x_u) = \begin{cases} x_u, & x_u \leq q_0/2 \\ 0, & x_u > q_0/2 \end{cases},$$

which corresponds to ReLU in the signed floating-point domain.

\* In the last step, to prevent  $\text{ReLU}(x_u)$  from leaking to the client, we compute  $\text{ReLU}(x_u) + r_2 \bmod q_0$ , using the addition circuit and multiplexer, and output the plaintext value  $\text{ReLU}(x_u) + r_2 \bmod q_0$  to the client.

3) *Conversion from MPC to HE:* The client performs the transformation  $\text{UnsignedToSigned}$ , encrypts the resulting

$[\text{ReLU}(x_u) + r_2]_{q_0}$  value at level  $L - 1$  using the CKKS HE scheme, and sends the encrypted value  $\llbracket [\text{ReLU}(x_u) + r_2]_{q_0} \rrbracket$  to the server. The server homomorphically subtracts  $r_2$ , to obtain the corresponding ciphertext  $\llbracket [\text{ReLU}(x_u)]_{q_0} \rrbracket = \llbracket [\text{ReLU}(x)]_{q_0} \rrbracket$ .

To evaluate a complete network, MP2ML computes linear layers using HE, and the above protocol for non-polynomial activations. The encrypted final classification result is sent to the client for decryption.

One detail to note is that the MPC-to-HE conversion yields a ciphertext  $\llbracket y \rrbracket := \llbracket \text{ReLU}(x) \rrbracket$  at level  $L$ , i.e., modulo  $q_{L-1}$ , whereas the masking was performed at level 0, i.e., modulo  $q_0$ . Subsequent computation on  $\llbracket y \rrbracket$  is performed at modulo  $q_{L-1}$ . However, since  $q_{L-1}$  is a factor of  $q_0$ , the computation is still accurate modulo  $q_0$ .<sup>2</sup> Thus, the final decryption must perform modulus-switching to  $q_0$  before performing the decryption. Alternatively, the decryption output must be modified to return values modulo  $q_0$  rather than values modulo  $q_L$ .

Note, the integer results of the ReLU circuits are only accurate in the interval  $(-q_0/2, q_0/2)$ . Hence, for fixed-point numbers scaled to integers using a scaling factor  $s$ , the result is only accurate in the interval  $(-q_0/(2s), q_0/(2s))$ . Therefore,  $q_0 \gg s$  must be chosen accordingly to preserve accuracy of the computation.

Our conversion protocol achieves two important tasks. First, it enables the secure computation of non-polynomial activation functions, i.e., without leaking pre- or post-activation values to the data owner. Second, as in the client-aided model, our protocol refreshes the ciphertexts, resetting the noise and restoring the ciphertext level to the top level  $L$ . This refreshment is essential to enabling continued computation without increasing the encryption parameters. Rather than selecting encryption parameters large enough to support the entire network, they must now only be large enough to support the linear layers between non-linear activations. For instance, the client-aided model in nGraph-HE performs inference on MobileNetV2 [60], a model with 24 convolution layers, using  $N = 4096, L = 4 \ll 24$ . Without the ciphertext refreshment,  $N = 32768, L = 24$  would be required, and each ciphertext would have size  $\sim 12.58\text{MB}$  of memory, by factor 48x more than the  $\sim 262\text{KB}$  of our ciphertexts with  $N = 4096, L = 4$ .

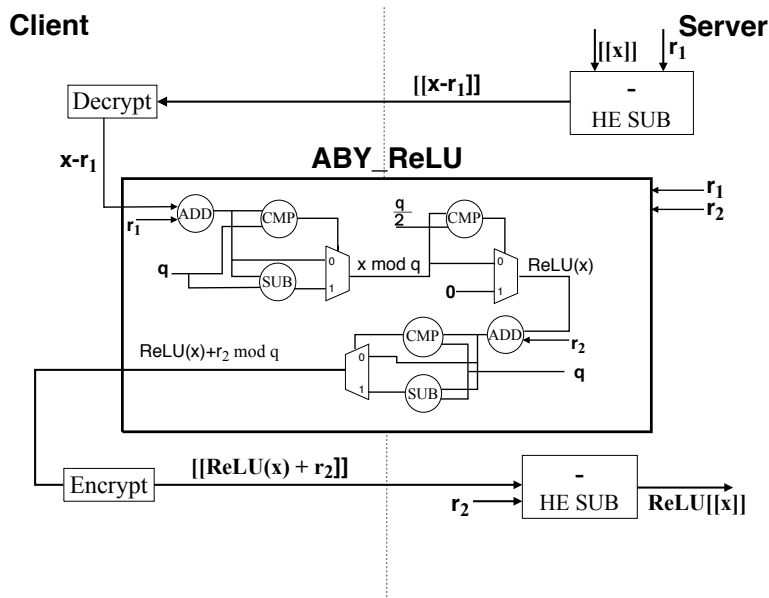
**MaxPool Evaluation.** MaxPool evaluation can be performed analogously to ReLU evaluation. For brevity, we omit its description. In fact, our use of ABY enables secure evaluation of *arbitrary* activation functions.

## 4.2 Security

MP2ML protects the client’s inference input from the server, and at the same time hides the full model structure of the server from the client, revealing only the number and type of non-linear operations. The MPC protocols we implement provide security against semi-honest adversaries (cf. Sect. 2.2).

Note that HE-based solutions generally do not provide circuit privacy, as the ciphertext of the result may leak information about the number and types of operations performed on it. However, noise flooding or an interactive decryption phase can help to mitigate this leakage [37]. These mitigations can be applied in MP2ML as well,

<sup>2</sup>This is a result of the property that  $(z \bmod pq) \bmod p = z \bmod p$  for  $z \in \mathbb{Z}, p, q \in \mathbb{N}$ .



**Figure 1: Protocol for private ReLU.** CMP, ADD, and SUB are comparison, addition, and subtraction circuits executed by ABY [27]. Other homomorphic operations are executed by nGraph-HE [11].

even though, similar to [37], they are not yet included in our implementation. We expect the overhead for a single re-randomization and an addition in MPC to be negligible. Note that this kind of leakage is arguably smaller than in purely MPC-based solutions, where the entire structure of the evaluated circuit is public and thus the full structure of the ML model is leaked to the client.

## 5 EVALUATION

We evaluate MP2ML on small atomic operations (Sect. 5.1) and on a larger deep learning model (Sect. 5.2).

**Evaluation Setup.** For the evaluation we use two Intel Xeon® Platinum-8180 2.5 GHz systems with 112 cores and 376 GB RAM, running Ubuntu 18.04. The local area network (LAN) bandwidth is 9.6 Gbit/s, while the latency is 0.165 ms.

## 5.1 Atomic Operations

Table 2 shows the runtimes of MP2ML for atomic operations. Notably, the addition and multiplication operations, which are evaluated using CKKS, require no offline computation and no communication. In contrast, pure MPC solutions require communication for every multiplication, and even for additions in the case of Boolean circuit-based protocols.

Comparing GMW and Yao’s GC protocol, we can see a correlation between required bandwidth and protocol runtime. GMW outperforms Yao’s GC in the low-latency LAN setting. We expect the opposite to happen for typical WAN connections with a higher round trip time, since GMW requires one round of interaction for each data-dependent layer of non-linear gates (depth) in the Boolean circuits, while Yao’s protocol always only requires a small constant number of rounds. Our ReLU circuits that are evaluated in each non-linear layer have a multiplicative depth of 137.

**Table 2: Runtime and throughput of MP2ML for atomic operations in the LAN setting, averaged across 10 runs. We use  $N = 2048$  and a 54-bit ciphertext modulus. ADD and MULT are offline only, and the use of plaintext packing yields the same runtime for each batch size up to  $N$ .**

Function	Outputs	MPC proto.	Time (ms)		Bandwidth (MB)	
			offline	online	offline	online
ReLU	1,000	Yao	161	57	22.3	2.0
ReLU	1,000	GMW	304	18	53.9	0.9
ReLU	2,048	Yao	314	118	45.8	4.1
ReLU	2,048	GMW	533	20	110.4	1.8
ADD	1,000	—	0	0.18	0	0
ADD	2,048	—	0	0.19	0	0
MULT	1,000	—	0	1.2	0	0
MULT	2,048	—	0	1.2	0	0

## 5.2 Neural Networks

We evaluate a deep learning application, the CryptoNets [31] network, to show how our MP2ML framework can be leveraged. CryptoNets is the seminal HE-friendly deep learning network, yielding  $\sim 99\%$  accuracy on the MNIST handwritten digits dataset, which consists of  $28 \times 28$  pixel images classified into 10 categories. The CryptoNets network has a multiplicative depth of 5, with the full architecture detailed in [9, Sect. 5.2].

As in [10], we modify the network architecture to include biases and replace the non-standard  $x^2$  activations with ReLU activations. We achieve 98.60% accuracy, a slight degradation from the 98.64% of the unencrypted model.



**Table 3: MNIST inference performance comparisons. The network topologies are not identical across previous work, resulting in variations in accuracy.**

Framework	Limitation	Accuracy (%)	Latency (s)	Throughput (images/s)
<b>Chameleon [55]</b>	3-party	99	2.24	1.0
<b>XONN [54]</b>	binarized network	98.64	0.16	6.25
<b>CryptoNets [31]</b>	polynomial activation	98.95	250	16.4
<b>GAZELLE [37]</b>	hand-optimized	98.95 <sup>1</sup>	0.03	33.3
<b>CrypTFlow [43]</b>	leaks model architecture	99.31 <sup>2</sup>	0.03	33.3
<b>CryptoDL [35]</b>	polynomial activation	99.52	320	45.5
<b>SecureNN [70]</b>	3-party	99 <sup>3</sup>	0.08	49.23
<b>nGraph-HE2 [10]</b>	reveals intermediate values	98.62	0.69	2,959
<b>MP2ML (This work)</b>	—	98.60	6.79	33.3

<sup>1</sup> Accuracy not reported, but network topology matches that of CryptoNets.

<sup>2</sup> Accuracy not reported, but network topology matches that of MiniONN [46].

<sup>3</sup> Accuracy not reported, but network topology matches that of Chameleon.

Table 3 shows the performance of MP2ML on CryptoNets in comparison with previous methods. MP2ML uses encryption parameters  $N = 8192$ ,  $L = 5$ , with coefficient moduli (47, 24, 24, 24, 30) bits, scale  $s = 2^{24}$ ,  $\lambda = 128$ -bit security, and Yao’s GC for the non-linear layers. Note, Table 3 omits several frameworks from Table 1 which do not report performance on the CryptoNets network: [2, 5, 12, 21, 23, 26, 34, 49, 58, 59, 66]. Chameleon [55] and SecureNN [70] use a semi-honest third party, which is a different setting than our two-party model. XONN [54] binarizes the network, which results in high accuracy on the MNIST dataset, but will reduce accuracy on larger datasets and models. CryptoNets [31] and CryptoDL [35] use polynomial activations, which will also reduce accuracy on larger datasets and models.

GAZELLE [37], whose method is most similar to our work, uses much smaller encryption parameters ( $N = 2048$ ,  $L = 1$ ), resulting in a significantly faster runtime (cf. [10, Tab.9]), albeit at a reduced 20-bit precision. See Sect. 6 for a detailed comparison between MP2ML and GAZELLE. nGraph-HE [11] uses a client-aided model to compute non-polynomial activations, which leaks intermediate values and potentially the model weights to the client.

## 6 DISCUSSION

In this section, we motivate our design choices and explain further aspects of our framework.

**Plaintext Packing.** Plaintext packing (cf. Sect. 2.2) is a key design choice in developing efficient frameworks for DL with HE. Harnessing the simultaneous computation enabled by plaintext packing of  $N$  values potentially reduces the memory and runtime overhead by a factor of  $N$ . MP2ML uses *batch-axis packing*, which maximizes the throughput for a given latency. Table 3 demonstrates the latency-throughput trade-off between existing privacy-preserving ML frameworks.

**Encryption Scheme.** The CKKS encryption scheme [20] is a recent optimization of the BFV HE scheme [13, 29]. Whereas BFV computation is exact, the CKKS scheme is inherently approximate. The CKKS scheme is significantly faster than the BFV scheme:  $\sim 12\times$

for the multiply-plain operation and  $\sim 20\times$  for the multiply operation [9, Tab. 1]. To our knowledge, MP2ML is the first work to demonstrate the use of CKKS in a hybrid HE-MPC framework.

**Model Extraction.** In ML model extraction attacks, an adversary attempts to deduce the ML model without prior knowledge using black-box access to inferences on the model. The feasibility of ML model extraction has been demonstrated on a variety of ML models [15, 53, 65]. Existing HE-based and MPC-based privacy-preserving ML frameworks protect user data from the model owner, or the model weights from the data owner. However, these frameworks fail to protect against model extraction attacks, since the adversary has black-box access to the inferences. We consider model extraction attacks an orthogonal issue to private DL inference using cryptographic primitives. Indeed, all the frameworks in Table 1 are vulnerable to model extraction attacks.

**Fully-Private DL Inference.** PPML inference solutions differ by their privacy guarantees. While the inference data is typically kept private, aspects of the DL model may leak. Solutions relying on fully homomorphic encryption don’t leak any information about the model (subject to model extraction attacks), though at the cost of high runtimes. Pure MPC-based approaches such as XONN [54] and CrypTFlow [43] have the lowest runtimes, but reveal the entire structure/functional form (i.e., Boolean circuit) of the DL model. In contrast, hybrid HE-MPC solutions such as GAZELLE [37], Delphi [48], and MP2ML leak only the type (i.e., ReLU or MaxPool) and dimension of each activation function.

## 7 CONCLUSION

HE and MPC have emerged as two candidate solutions for privacy-preserving DL inference. Hybrid HE-MPC protocols combine the advantages of HE and MPC to provide better efficiency and model privacy than each method individually. In this paper we presented MP2ML, the first user-friendly mixed-protocol framework for private DL inference. MP2ML is compatible with popular DL frameworks such as TensorFlow, enabling data scientist to perform secure neural network inference with ease. In addition, MP2ML is compatible with multiple activation functions and offers direct support

for many operations and transformations that are common in the ML domain. The privacy guarantees of MP2ML are stronger than those of related work because it hides the topology of the classifier, while it achieves comparable performance compared to the state-of-the-art work CryptFlow [43].

## AVAILABILITY

The open source code of MP2ML is freely available under the permissive Apache license at <https://ngraph.he>.

## ACKNOWLEDGMENTS

We thank Casimir Wierzynski, Amir Khosrowshahi, and Naveen Rao for their unconditional support. This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program (grant agreement No. 850990 PSOTI). It was co-funded by the Deutsche Forschungsgemeinschaft (DFG) — SFB 1119 CROSSING/236615297 and GRK 2050 Privacy & Trust/251805230, and by the German Federal Ministry of Education and Research and the Hessen State Ministry for Higher Education, Research and the Arts within ATHENE.

## REFERENCES

- [1] Martin Abadi, Paul Barham, Jianmin Chen, Zhifeng Chen, Andy Davis, Jeffrey Dean, Matthieu Devin, Sanjay Ghemawat, Geoffrey Irving, and Michael Isard. 2016. Tensorflow: A system for large-scale machine learning. In *USENIX Operating Systems Design and Implementation’16*.
- [2] David W Archer, José Manuel Calderón Trilla, Jason Dagit, Alex Malozemoff, Yuriy Polyakov, Kurt Rohloff, and Gerard Ryan. 2019. RAMPARTS: A Programmer-Friendly System for Building Homomorphic Encryption Applications. In *WAHC’19*.
- [3] Gilad Asharov, Yehuda Lindell, Thomas Schneider, and Michael Zohner. 2013. More efficient oblivious transfer and extensions for faster secure computation. In *CCS’13*.
- [4] Mauro Barni, Pierluigi Failla, Vladimir Kolesnikov, Riccardo Lazzeretti, Ahmad-Reza Sadeghi, and Thomas Schneider. 2009. Secure evaluation of private linear branching programs with medical applications. In *ESORICS’09*.
- [5] Mauro Barni, Pierluigi Failla, Riccardo Lazzeretti, Ahmad-Reza Sadeghi, and Thomas Schneider. 2011. Privacy-Preserving ECG Classification with Branching Programs and Neural Networks. *TIFS’11*.
- [6] Mauro Barni, Claudio Orlandi, and Alessandro Piva. 2006. A privacy-preserving protocol for neural-network-based computation. In *Workshop on Multimedia and Security*.
- [7] Donald Beaver, Silvio Micali, and Phillip Rogaway. 1990. The round complexity of secure protocols. In *STOC’90*.
- [8] Mihir Bellare, Viet Tung Hoang, Sriram Keelveedhi, and Phillip Rogaway. 2013. Efficient garbling from a fixed-key blockcipher. In *S&P’13*.
- [9] Fabian Boemer, Rosario Cammarota, Daniel Demmler, Thomas Schneider, and Hossein Yalame. 2020. MP2ML: A Mixed-Protocol Machine Learning Framework for Private Inference (full version). *IACR Cryptology ePrint Archive 2020/721*.
- [10] Fabian Boemer, Anamaria Costache, Rosario Cammarota, and Casimir Wierzynski. 2019. nGraph-HE2: A High-Throughput Framework for Neural Network Inference on Encrypted Data. In *WAHC’19*.
- [11] Fabian Boemer, Yixing Lao, Rosario Cammarota, and Casimir Wierzynski. 2019. nGraph-HE: a graph compiler for deep learning on homomorphically encrypted data. In *ACM International Conference on Computing Frontiers*.
- [12] Christina Boura, Nicolas Gama, and Mariya Georgieva. 2018. Chimera: a unified framework for B/FV, TFHE and HEAAN fully homomorphic encryption and predictions for deep learning. *IACR Cryptology ePrint Archive 2018/758* (2018).
- [13] Zvika Brakerski. 2012. Fully homomorphic encryption without modulus switching from classical GapSVP. In *CRYPTO’12*.
- [14] Justin Brickell, Donald E Porter, Vitaly Shmatikov, and Emmett Witchel. 2007. Privacy-preserving remote diagnostics. In *CCS’07*.
- [15] Nicholas Carlini, Matthew Jagielski, and Ilya Mironov. 2020. Crypt-analytic Extraction of Neural Network Models. *arXiv preprint arXiv:2003.04884* (2020).
- [16] CEA-LIST. 2019. Cingulata. <https://github.com/CEA-LIST/Cingulata>.
- [17] Guoxing Chen, Sanchuan Chen, Yuan Xiao, Yinqian Zhang, Zhiqiang Lin, and Ten H Lai. 2019. Sgxpectre attacks: Stealing intel secrets from sgx enclaves via speculative execution. *EUROS&P’19* (2019).
- [18] Tianqi Chen, Mu Li, Yutian Li, Min Lin, Naiyan Wang, Minjie Wang, Tianjun Xiao, Bing Xu, Chiyuan Zhang, and Zheng Zhang. 2015. MXNet: A flexible and efficient machine learning library for heterogeneous distributed systems. *arXiv preprint arXiv:1512.01274* (2015).
- [19] Tianqi Chen, Thierry Moreau, Ziheng Jiang, Lianmin Zheng, Eddie Yan, Haichen Shen, Meghan Cowan, Leyuan Wang, Yuwei Hu, and Luis Ceze. 2018. TVM: An automated end-to-end optimizing compiler for deep learning. In *USENIX Operating Systems Design and Implementation’18*.
- [20] Jung Hee Cheon, Andrey Kim, Miran Kim, and Yongsoo Song. 2017. Homomorphic Encryption for Arithmetic of Approximate Numbers. In *ASIACRYPT’17*.
- [21] Ilaria Chillotti, Nicolas Gama, Mariya Georgieva, and Malika Izabachene. 2016. Faster fully homomorphic encryption: Bootstrapping in less than 0.1 seconds. In *ASIACRYPT’16*.
- [22] Scott Cyphers, Arjun K Bansal, Anahita Bhiwandiwala, Jayaram Bobba, Matthew Brookhart, Avijit Chakraborty, Will Constable, Christian Convey, Leona Cook, and Omar Kanawi. 2018. Intel nGraph: an intermediate representation, compiler, and executor for deep learning. *arXiv preprint arXiv:1801.08058* (2018).
- [23] Morten Dahl, Jason Mancuso, Yann Dupis, Ben Decoste, Morgan Giraud, Ian Livingstone, Justin Patriquin, and Gavin Uhma. 2018. Private machine learning in tensorflow using secure computation. *arXiv preprint arXiv:1810.08130* (2018).
- [24] Anders Dalskov, Daniel Escudero, and Marcel Keller. 2019. Secure Evaluation of Quantized Neural Networks. *IACR Cryptology ePrint Archive, Report 2019/131*. <https://eprint.iacr.org/2019/131>.
- [25] Data61. 2019. MP-SPDZ - Versatile framework for multi-party computation. <https://github.com/data61/MP-SPDZ>.
- [26] Roshan Dathathri, Olli Saarikivi, Hao Chen, Kim Laine, Kristin Lauter, Saeed Maleki, Madanlal Musuvathi, and Todd Mytkowicz. 2019. CHET: an optimizing compiler for fully-homomorphic neural-network inferencing. In *PLDI’19*.
- [27] Daniel Demmler, Thomas Schneider, and Michael Zohner. 2015. ABY—A Framework for Efficient Mixed-Protocol Secure Two-Party Computation. In *NDSS’15*.
- [28] Ghada Dessouky, Farinaz Koushanfar, Ahmad-Reza Sadeghi, Thomas Schneider, Shaza Zeitouni, and Michael Zohner. 2017. Pushing the Communication Barrier in Secure Computation using Lookup Tables.. In *NDSS’17*.
- [29] Junfeng Fan and Frederik Vercauteren. 2012. Somewhat Practical Fully Homomorphic Encryption. *IACR Cryptology ePrint Archive 2012/144*.
- [30] Craig Gentry. 2009. *A fully homomorphic encryption scheme*. Stanford University PhD Thesis.
- [31] Ran Gilad-Bachrach, Nathan Dowlin, Kim Laine, Kristin Lauter, Michael Naehrig, and John Wernsing. 2016. Cryptonets: Applying neural networks to encrypted data with high throughput and accuracy.

- In *International Conference on Machine Learning*.
- [32] Oded Goldreich. 2004. *The Foundations of Cryptography - Volume 2, Basic Applications*. Cambridge University Press.
  - [33] Oded Goldreich, Silvio Micali, and Avi Wigderson. 1987. How to play any mental game. In *STOC'87*.
  - [34] Wilko Henecka, Stefan Kögl, Ahmad-Reza Sadeghi, Thomas Schneider, and Immo Wehrenberg. 2010. TASTY: Tool for Automating Secure Two-party Computations. In *CCS'10*.
  - [35] Ehsan Hesamifard, Hassan Takabi, Mehdi Ghasemi, and Rebecca N. Wright. 2018. Privacy-preserving Machine Learning as a Service. *PETS'18*.
  - [36] Mohamad Javadi, Hossein Yalame, and Hamid Mahdiani. 2020. Small Constant Mean-Error Imprecise Adder/Multiplier for Efficient VLSI Implementation of MAC-based Applications. *TC'20 (2020)*.
  - [37] Chiraag Juvekar, Vinod Vaikuntanathan, and Anantha Chandrakasan. 2018. *GAZELLE: A Low Latency Framework for Secure Neural Network Inference*. In *USENIX Security'18*.
  - [38] Ágnes Kiss, Masoud Naderpour, Jian Liu, N Asokan, and Thomas Schneider. 2019. SoK: Modular and efficient private decision tree evaluation. *PETS'19 (2019)*.
  - [39] Vladimir Kolesnikov and Ranjit Kumaresan. 2013. Improved OT extension for transferring short secrets. In *CRYPTO'13*.
  - [40] Vladimir Kolesnikov and Thomas Schneider. 2008. Improved garbled circuit: Free XOR gates and applications. In *ICALP'08*.
  - [41] Vladimir Kolesnikov and Thomas Schneider. 2008. A practical universal circuit construction and secure evaluation of private functions. In *FC'08*.
  - [42] Alex Krizhevsky, Vinod Nair, and Geoffrey Hinton. 2014. The CIFAR-10 dataset. <http://www.cs.toronto.edu/kriz/cifar.html>.
  - [43] Nishant Kumar, Mayank Rathee, Nishanth Chandran, Divya Gupta, Aseem Rastogi, and Rahul Sharma. 2020. CryptFlow: Secure Tensor-Flow Inference. In *S&P'20*.
  - [44] Yann LeCun and Corinna Cortes. 2010. MNIST handwritten digit database. <http://yann.lecun.com/exdb/mnist/>.
  - [45] Yehuda Lindell and Benny Pinkas. 2009. A Proof of Security of Yao's Protocol for Two-Party Computation. *Journal of Cryptology* (2009).
  - [46] Jian Liu, Mika Juuti, Yao Lu, and Nadarajah Asokan. 2017. Oblivious neural network predictions via MiniONN transformations. In *CCS'17*.
  - [47] Dahlia Malkhi, Noam Nisan, Benny Pinkas, and Yaron Sella. 2004. Fairplay—A Secure Two-Party Computation System. (2004).
  - [48] Pratyush Mishra, Ryan Lehmkuhl, Akshayaram Srinivasan, Wenting Zheng, and Raluca Ada Popa. 2020. DELPHI: A Cryptographic Inference Service for Neural Networks. In *USENIX Security*.
  - [49] Payman Mohassel and Peter Rindal. 2018. ABY3: A Mixed Protocol Framework for Machine Learning. In *CCS'18*.
  - [50] Payman Mohassel and Yupeng Zhang. 2017. SecureML: A system for scalable privacy-preserving machine learning. In *S&P'17*.
  - [51] Claudio Orlandi, Alessandro Piva, and Mauro Barni. 2007. Oblivious neural network computing via homomorphic encryption. *Journal on Information Security* (2007).
  - [52] Adam Paszke, Sam Gross, Soumith Chintala, Gregory Chanan, Edward Yang, Zachary DeVito, Zeming Lin, Alban Desmaison, Luca Antiga, and Adam Lerer. 2017. Automatic differentiation in PyTorch. In *Neural Information Processing Systems*.
  - [53] Robert Nikolai Reith, Thomas Schneider, and Oleksandr Tkachenko. 2019. Efficiently Stealing your Machine Learning Models. In *WPES'19*.
  - [54] M Sadegh Riazi, Mohammad Samragh, Hao Chen, Kim Laine, Kristin E Lauter, and Farinaz Koushanfar. 2019. XONN: XNOR-based Oblivious Deep Neural Network Inference. In *USENIX Security'19*.
  - [55] M Sadegh Riazi, Christian Weinert, Oleksandr Tkachenko, Ebrahim M Songhori, Thomas Schneider, and Farinaz Koushanfar. 2018. Chameleon: A hybrid secure computation framework for machine learning applications. In *ASIACCS'18*.
  - [56] Ronald L. Rivest, Len Adleman, and Michael L. Dertouzos. 1978. On Data Banks and Privacy Homomorphisms. *Foundations of Secure Computation, Academia Press* (1978).
  - [57] Kurt Rohloff. 2019. The PALISADE Lattice Cryptography Library. <https://git.njit.edu/palisade/PALISADE>.
  - [58] Theo Ryffel, Andrew Trask, Morten Dahl, Bobby Wagner, Jason Mancuso, Daniel Rueckert, and Jonathan Passerat-Palmbach. 2018. A generic framework for privacy preserving deep learning. *arXiv preprint arXiv:1811.04017* (2018).
  - [59] Ahmad-Reza Sadeghi and Thomas Schneider. 2008. Generalized Universal Circuits for Secure Evaluation of Private Functions with Application to Data Classification. In *ICISC'08*.
  - [60] Mark Sandler, Andrew Howard, Menglong Zhu, Andrey Zhmoginov, and Liang-Chieh Chen. 2018. MobileNetV2: Inverted residuals and linear bottlenecks. In *IEEE Conference on Computer Vision and Pattern Recognition (CVPR'18)*.
  - [61] Amartya Sanyal, Matt J Kusner, Adria Gascon, and Varun Kanade. 2018. TAPAS: Tricks to accelerate (encrypted) prediction as a service. *arXiv preprint arXiv:1806.03461* (2018).
  - [62] Thomas Schneider and Michael Zohner. 2013. GMW vs. Yao? Efficient secure two-party computation with low depth circuits. In *FC'13*.
  - [63] SEAL 2019. Microsoft SEAL (release 3.4). <https://github.com/Microsoft/SEAL>. Microsoft Research, Redmond, WA.
  - [64] Raymond KH Tai, Jack PK Ma, Yongjun Zhao, and Sherman SM Chow. 2017. Privacy-preserving decision trees evaluation via linear functions. In *ESORICS'17*.
  - [65] Florian Tramèr, Fan Zhang, Ari Juels, Michael K Reiter, and Thomas Ristenpart. 2016. Stealing machine learning models via prediction APIs. In *USENIX Security'16*.
  - [66] Florian Tramèr and Dan Boneh. 2019. Slalom: Fast, verifiable and private execution of neural networks in trusted hardware. In *International Conference on Learning Representations (ICLR'19)*.
  - [67] Amos Treiber, Alejandro Molina, Christian Weinert, Thomas Schneider, and Kristian Kersting. 2020. CryptoSPN: Privacy-preserving Sum-Product Network Inference. *ECAI'20 (2020)*.
  - [68] Leslie G Valiant. 1976. Universal circuits (preliminary report). In *STOC'76*.
  - [69] Paul Voigt and Axel Von dem Bussche. 2017. The EU General Data Protection Regulation (GDPR). *Springer* (2017).
  - [70] Sameer Wagh, Divya Gupta, and Nishanth Chandran. 2019. SecureNN: 3-Party Secure Computation for Neural Network Training. *PETS'19 (2019)*.
  - [71] Casimir Wierzynski and Abigail Wen. 2018. Advancing both A.I. and privacy is not a zero-sum game. <http://fortune.com/2018/12/27/ai-privacy>.
  - [72] David J Wu, Tony Feng, Michael Naehrig, and Kristin Lauter. 2016. Privately evaluating decision trees and random forests. *PETS'16 (2016)*.
  - [73] Hossein Yalame, Hossein Farzam, and Siavash Bayat-Sarmadi. 2017. Secure Two-Party Computation Using an Efficient Garbled Circuit by Reducing Data Transfer. In *ATIS'17*.
  - [74] Andrew Chi-Chih Yao. 1986. How to generate and exchange secrets. In *FOCS'86*.
  - [75] Samee Zahur, Mike Rosulek, and David Evans. 2015. Two halves make a whole: Reducing data transfer in garbled circuits using half gates. In *EUROCRYPT'15*.