Privacy-Preserving Machine Learning in the Cloud

An Evaluation of Garbled Circuits for Secure Multi-Party Computation

18.10.2024

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- However, the use of cloud services for machine learning poses challenges when dealing with sensitive data, as control over data privacy is in the hands of the cloud provider
- Additionally, not all parties involved in developing or training a model should have access to the full training data

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- To address these problems, this thesis presents a proof of concept that incorporates garbled circuits into the machine learning process
- The aim is to demonstrate that the usage of *garbled circuits* is both feasible and secure by detailing an exemplary implementation of a simple linear regression model.

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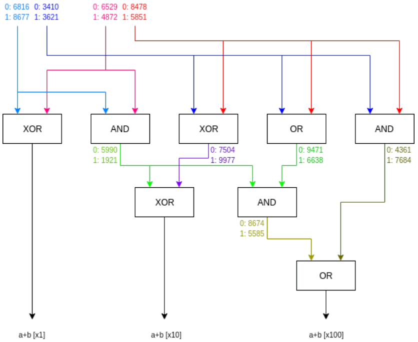

Figure 1: A two-bit-adder represented as a *garbled circuit*

Garbled Circuits

Garbling

- The garbler encrypts the input bits of each gate by creating random labels in their place. To obfuscate the truth table, it is then permuted

Garbled Circuits

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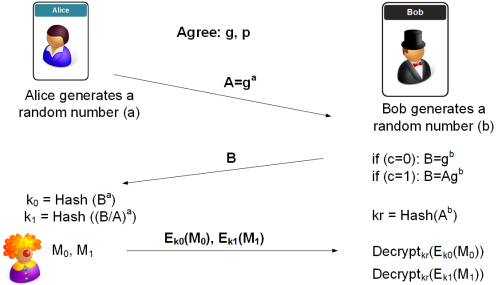

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- The protocol is particularly effective in semi-honest settings where parties follow the rules but may try to learn extra information; however, vulnerabilities can arise in malicious environments where adversaries may actively deviate from the protocol
- Despite their security strengths, garbled circuits face challenges with computational and communication overhead, especially when dealing with large or complex circuits

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- Bob sends Alice the number $k - j + 1$
- Alice computes privately the values of $y_u = D_a(k - j + u)$ for $u = 1, 2, \ldots, 10$
- Alice generates a random prime p of $N/2$ bits, and computes the values $z_u = y_u \pmod{p}$ for all u; if all z_u differ by at least 2 in the mod$p$ sense, stop; otherwise generates another random prime and repeats the process until all z_u differ by at least 2; let p, z_u denote this final set of numbers

Garbled Circuits

- Alice sends the prime p and the following 10 numbers to $B: z_1, z_2, \dots, z_i$ followed by $z_i + 1, z_{i+1} + 1, \dots, z_{10} + 1$; the above numbers should be interpreted in the $\pmod p$ sense

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- Bob looks at the j-th number (not counting p) sent from Alice, and decides that $i \geq j$ if it is equal to $x \bmod p$, and $i < j$ otherwise
- Bob tells Alice what the conclusion is.

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- Used to make predictions on these sets of data through estimating the coefficients of the underlying linear equation
- Simple linear regression calculations use the *mean squared error* function to find the best for a given set of data

The Linear Regression Model

$$\hat{y}_i = \beta_0 + \beta_1 x_i$$

- $\hat{y}_i$ is the predicted output of the dependent variable
- β_0 is the intercept or constant
- β_1 is the slope or regression coefficient
- x_i is the independent variable

Privacy-Preserving Machine Learning with Garbled Circuits

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- A breakdown of all necessary computations into smaller binary operations that can be executed without revealing sensitive data
- Conversion of training data into binary format, garbling and evaluating the circuits
- Usage of non-interactive garbled circuits to maintain confidentiality during the training phase

Privacy-Preserving Machine Learning with Garbled Circuits

Binary Operations

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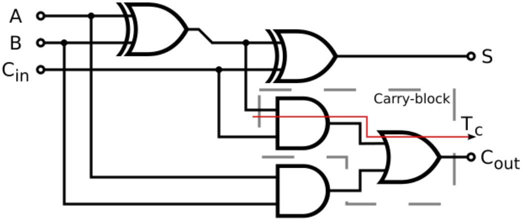

Figure 3: Full-adder schematic

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- Additionally, auxiliary functions like the *Two's Complement* are implemented

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- All binary operations are implemented, from the *half-adder* function to the *n-bit Division*

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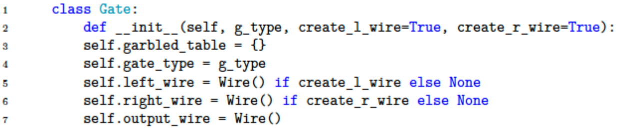

```python
class Gate:
    def __init__(self, g_type, create_l_wire=True, create_r_wire=True):
        self.garbled_table = {}
        self.gate_type = g_type
        self.left_wire = Wire() if create_l_wire else None
        self.right_wire = Wire() if create_r_wire else None
        self.output_wire = Wire()
```

Figure 4: Gate class

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- Each template provides a method for garbling and evaluation, including subcircuit evaluation when necessary

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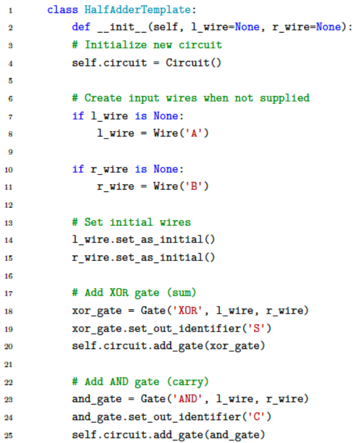
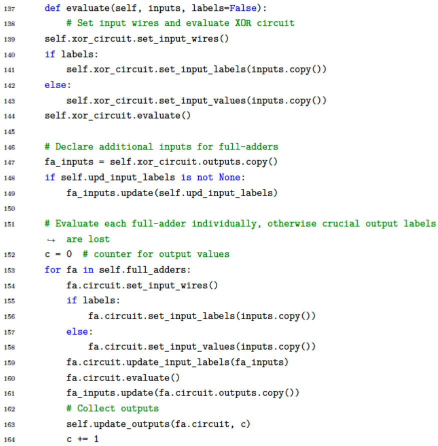


```
class HalfAdderTemplate:
    def __init__(self, l_wire=None, r_wire=None):
    # Initialize new circuit
    self.circuit = Circuit()

    # Create input wires when not supplied
    if l_wire is None:
        l_wire = Wire('A')

    if r_wire is None:
        r_wire = Wire('B')

    # Set initial wires
    l_wire.set_as_initial()
    r_wire.set_as_initial()

    # Add XOR gate (sum)
    xor_gate = Gate('XOR', l_wire, r_wire)
    xor_gate.set_out_identifier('S')
    self.circuit.add_gate(xor_gate)

    # Add AND gate (carry)
    and_gate = Gate('AND', l_wire, r_wire)
    and_gate.set_out_identifier('C')
    self.circuit.add_gate(and_gate)
```

Figure 5: The general template structure, applied to the half-adder

Proof of Concept



```
def evaluate(self, inputs, labels=False):
    # Set input wires and evaluate XOR circuit
self.xor_circuit.set_input_wires()
if labels:
    self.xor_circuit.set_input_labels(inputs.copy())
else:
    self.xor_circuit.set_input_values(inputs.copy())
self.xor_circuit.evaluate()

# Declare additional inputs for full-adders
fa_inputs = self.xor_circuit.outputs.copy()
if self.upd_input_labels is not None:
    fa_inputs.update(self.upd_input_labels)

# Evaluate each full-adder individually, otherwise crucial output labels
↪   are lost
c = 0  # counter for output values
for fa in self.full_adders:
    fa.circuit.set_input_wires()
    if labels:
        fa.circuit.set_input_labels(inputs.copy())
    else:
        fa.circuit.set_input_values(inputs.copy())
    fa.circuit.update_input_labels(fa_inputs)
    fa.circuit.evaluate()
    fa_inputs.update(fa.circuit.outputs.copy())
    # Collect outputs
    self.update_outputs(fa.circuit, c)
    c += 1
```

Figure 6: Evaluating an adder-subtractor circuit

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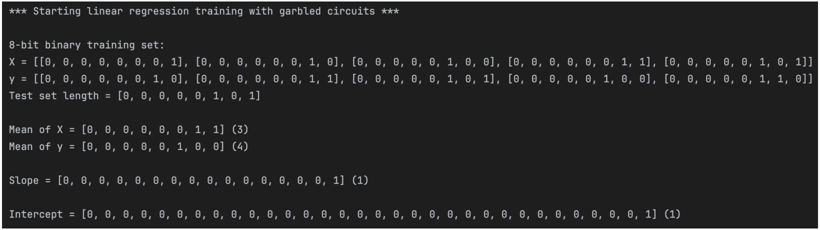
- Utilizes a simple training set that can easily be verified



```
*** Starting linear regression training with garbled circuits ***

8-bit binary training set:
X = [[0, 0, 0, 0, 0, 0, 0, 1], [0, 0, 0, 0, 0, 0, 1, 0], [0, 0, 0, 0, 0, 1, 0, 0], [0, 0, 0, 0, 0, 0, 1, 1], [0, 0, 0, 0, 0, 1, 0, 1]]
y = [[0, 0, 0, 0, 0, 0, 1, 0], [0, 0, 0, 0, 0, 0, 1, 1], [0, 0, 0, 0, 0, 1, 0, 1], [0, 0, 0, 0, 0, 1, 0, 0], [0, 0, 0, 0, 0, 1, 1, 0]]
Test set length = [0, 0, 0, 0, 0, 1, 0, 1]

Mean of X = [0, 0, 0, 0, 0, 0, 1, 1] (3)
Mean of y = [0, 0, 0, 0, 0, 1, 0, 0] (4)

Slope = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1] (1)

Intercept = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1] (1)
```

Figure 7: Result of the garbled circuit intercept calculation

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Run	Binary Circuits	Garbled Circuits
1	0.0016210079193115234	0.3389451503753662
2	0.0010771751403808594	0.3446238040924072
3	0.0011820793151855469	0.33850693702697754
4	0.0005500316619873047	0.379697322845459
5	0.0006239414215087891	0.3488502502441406

Tabelle 1: Execution duration of Linear Regression training in seconds, using binary and garbled circuits

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- Despite linear regression being one of the simplest machine learning models, combining it with garbled circuits took a comparatively high implementation effort

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- Disclosure of intermediate values necessary but not enough for an adversary to derive additional information

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- No floating point arithmetic
- Only simplest form of garbling available

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- Future work should incorporate optimizations such as the *point-permute technique* or *free XOR* to reduce the amount of ciphertexts per gate and improve overall computational efficiency
- Enabling support for *floating point arithmetic* in training models to allow for more complex datasets and algorithms
- Allowing multiple parties to contribute their training data would facilitate joint model training, further validating the practical utility of garbled circuits in real-world scenarios

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- Garbled circuits can not only be utilized for training but also for secure model inference, allowing clients to obtain predictions from a trained model without revealing their inputs or the model's structure to the server

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- Garbled circuits can not only be utilized for training but also for secure model inference, allowing clients to obtain predictions from a trained model without revealing their inputs or the model's structure to the server
- While the proof of concept focused on linear regression, it can be extended to other algorithms, such as *logistic regression* and *neural networks*

Discussion