EOOP 20L Preliminary project - Neural Network

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Disclaimer: This document is not meant to be an explanation of the inner workings of a Neural Network. It will strictly focus on the interface and implementation.

1. Description

This project will focus on implementing a basic multilayer perceptron (known as an ANN: Artificial Neural Network) stripped of all of the more advanced concepts like normalizing weights, mini-batch training, or vectorized computation. The implementation will consist of 5 classes in total, each handling a separate part of what a Neural Network forms.

As a Proof of Concept I will train a NN to solve the XOR problem: it is known as a simple non-linear problem that requires at least one hidden layer in order to be solved, thus solving it proves that a given NN is able to solve other arbitrary non-linear problems. More or less effectively, but still. If time allows, the NN will be also put against the MNIST database.

Classes

Serializer This class only exists as a base of a different one; it is an abstract class. It requires that deriving classes have implemented a serialize method and a static deserialize method. Then, the `Serializer` is able to provide such methods as `from_file` or `to_file`, allowing for easy serialization handling no matter who is the parent class.

This class will prove to be very useful when saving the NN's weights to a file and then loading them back in whenever needed. This allows for an interruptible training cycle. Additionally it unlocks the ability of configuring the NN from a text file rather than fiddling with code.

Config `Config` conforms `Serializable`[1]. Stores the learning rate and the sizes of the network: input, output, hidden layers, hidden neurons.

[1] Serializable: a class that implements the `serialize` and `deserialize` methods

Matrix The main purpose of the `Matrix` class is to simplify matrix operations. It will override the 4 basic arithmetic operators `*/-+` providing a layer of abstraction when using 2d arrays. `*-+` will work for both scalars and other matrices while `/` will be constrained to just scalars. Additionally there will be 2 other linear algebraic operations: transposition and the dot product. Cross product will be omitted on purpose: while it would be great for completeness, the usefulness is minimal.

`Matrix` conforms `Serializable` as well.

NNFunctions `NNFunctions` stores function used by the NN: activation function, derivative of the activation function, output layer function, derivative of the output layer function, and cost function. Constructing a `NNFunction` object consists of providing the previously mentioned functions, or choosing ready functions from an enum.

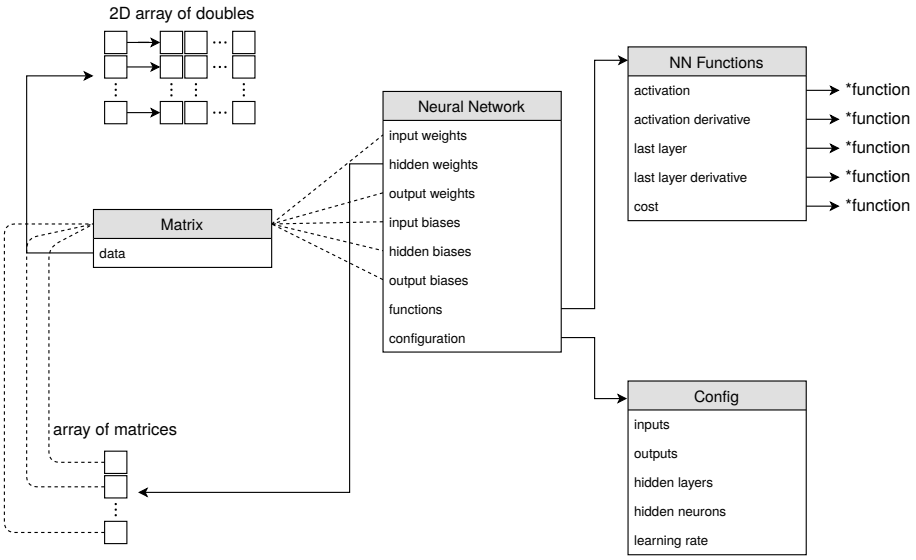
`NNFunctions` is `Serializable` only if the chosen functions are from the preset, custom ones can't be serialized.

NeuralNetwork This is the *brain* class. Uses all of the classes above to construct a friendly interface for training and performing guesses.

2. Memory map

The neural network owns all of its data (except pointers to functions which have static lifetimes).

Dotted lines indicate that the data has a structure of the connected type (they don't all point to the same `Matrix` instance).



3. Class declarations

The lack of raw pointers is a conscious decision. They are a source of bugs and if a need for pointers will arise, smart pointers will be used instead. Because all properties are auto-cleaned/copied no destructors or copy constructors are present.

Serializer

```
template <typename T>
class Serializer {
 protected:
  /// protected on purpose, Serializer is an abstract class
  Serializer();

 public:
  /// deserializes a file into the parent object.
  /// throws if file does not exist
  static auto from_file(const string& path) -> T;

  /// takes a path and serializes the parent into the pointed file.
  /// overwrites all content if the file already exists
  auto to_file(const string& path) const -> void;
```

```
  /// prints the serialized object
  // friend auto operator<<<>(ostream& os, const T& obj) -> ostream&;

  /// virtual methods that have to be implemented by parent classes
  /// then the serializer can work properly
  virtual auto serialize() const -> string = 0;
  /// this is impossible in c++, therefore it only serves purely as
  /// documentation
  // virtual static auto deserialize(const string& str) -> T = 0;
};
```

Config

```
class Config : Serializer<Config> {
 public:
  /// properties of a neural network
  /// because they are constant, there is no need encapsulating them
  const unsigned int inputs, outputs, layers, hidden_neurons;
  const double learning_rate;

  /// constructor accepting all 4 parameters
  Config(const unsigned int inputs, const unsigned int outputs,
         const unsigned int layers, const unsigned int hidden_neurons,
         const double learning_rate);

  /// overriding the virtual methods of Serializer
  auto serialize() const -> string override;
  static auto deserialize(const string& str) -> Config;
};
```

Matrix

```
class Matrix : Serializer<Matrix> {
 public:
  /// size of the matrix
  const unsigned int rows, columns;

  /// constructor takes the dimensions of the matrix
  Matrix(const unsigned int rows, const unsigned int columns);

  /// randomizes the matrix with a given range
  auto randomize(const double min = -1.0, const double max = 1.0) -> void;

  /// operator overloads for matrix operations
```

```
  /// if on both sides of the operation theres a matrix then the operation is
  /// done element wise, unless it is * where a matrix multiplication is
  /// performed instead
  /// in-place
  auto operator+=(const Matrix& rhs) -> Matrix&;
  auto operator+=(const double& rhs) -> Matrix&;
  auto operator-=(const Matrix& rhs) -> Matrix&;
  auto operator-=(const double& rhs) -> Matrix&;
  auto operator*=(const double& rhs) -> Matrix&;
  auto operator/=(const double& rhs) -> Matrix&;
  /// global
  friend auto operator+(const Matrix& lhs, const Matrix& rhs) -> Matrix;
  friend auto operator+(const Matrix& lhs, const double& rhs) -> Matrix;
  friend auto operator-(const Matrix& lhs, const Matrix& rhs) -> Matrix;
  friend auto operator-(const Matrix& lhs, const double& rhs) -> Matrix;
  friend auto operator*(const Matrix& lhs, const Matrix& rhs) -> Matrix;
  friend auto operator*(const Matrix& lhs, const double& rhs) -> Matrix;
  friend auto operator/(const Matrix& lhs, const double& rhs) -> Matrix;
  /// indexing
  auto operator[](size_t idx) const -> vector<double>&;

  /// transposing flips the x and y axis
  auto transpose() const -> Matrix;

  /// overriding the virtual methods of Serializer
  auto serialize() const -> string override;
  static auto deserialize(const string& str) -> Matrix;

 private:
  /// thats where the data is stored. Vector was chosen because while the
  /// size is immutable and array would seem like a more fitting choice, vector
  /// provides a much safer interface with negligible overhead
  vector<vector<double>> data_;
};
```

NNFunctions

```
class NNFunctions : Serializer<NNFunctions> {
 public:
  /// enums listing available function
  /// __custom means the function was provided
  enum class Activation { sigmoid, relu, tanh, __custom };
  enum class LastLayer { softmax, __custom };
  enum class Cost { mean_square, __custom };
```

```
  /// type definitions of the functions
  /// a function that takes a double and decides if its active
  typedef auto (*Activating)(double) -> double;
  /// a function that takes an array of doubles and maps it to different values
  typedef auto (*Mapping)(vector<double>) -> vector<double>;
  /// a function that takes an array of doubles and reduces it to a single value
  typedef auto (*Reducing)(const vector<double>&) -> double;

  /// collection of functions
  const Activating activation, d_activation;
  const Mapping last_layer, d_last_layer;
  const Reducing cost;

  /// constructor accepting enums describing pre-made functions
  NNFunctions(Activation af, LastLayer llf, Cost cf);
  /// constructor accepting functions
  NNFunctions(const Activating af, const Activating daf, const Mapping llf,
              const Mapping dllf, const Reducing cf);

  /// overriding the virtual methods of Serializer
  auto serialize() const -> string override;
  static auto deserialize(const string& str) -> NNFunctions;

 private:
  /// remembering which functions were chosen, this information is needed for
  /// serialization
  Activation af_;
  LastLayer llf_;
  Cost cf_;
};
```

NeuralNetwork

```
class NeuralNetwork : Serializer<Matrix> {
 public:
  /// constructor takes the previously defined configuration
  NeuralNetwork(Config config, NNFunctions funcs);

  /// performs a classification guess, it is not meant for regression problems
  auto guess(const Matrix& inputs) const -> unsigned int;

  /// trains the network `n` amount of times using online training
  /// inputs and expected have to me linearly aligned: first element of inputs
  /// have to correspond to first element from expected and so on
  auto train(const vector<Matrix>& inputs, const vector<Matrix>& expected,
```

```
            unsigned int n) -> void;

  /// overriding the virtual methods of Serializer
  auto serialize() const -> string override;
  static auto deserialize(const string& str) -> NeuralNetwork;

 private:
  /// weights of the connections
  Matrix input_w_;
  vector<Matrix> hidden_w_;
  Matrix output_w_;

  /// biases of the neurons
  Matrix input_b_;
  Matrix hidden_b_;
  Matrix output_b_;

  /// functions
  NNFunctions funcs_;

  /// config
  Config config_;

  /// sends inputs through the whole network and returns the output layer
  auto feedforward(const Matrix& inputs) const -> Matrix;

  /// backpropagates the expected output from some input, adjusts the weights,
  /// then returns the cost of the network
  auto backpropagate(const Matrix& inputs, const Matrix& expected) -> double;
};
```

4. Demos

Objects are easily saveable

```
Matrix m(10, 12);
m.save_to("/path/to/file");
```

Not all of them though

```
NNFunctions f(NNFunctions::Activation::relu, NNFunctions::LastLayer::__custom,
              NNFunctions::Cost::mean_square);

m.serialize(); // throws an exception, a custom function was used    ^^^^^^^^
```

Matrices can be multiplied only if the sizes align

```
Matrix m1(1, 2);
Matrix m2(2, 2);
Matrix m3(3, 2);

m1 * m2; // ok
m1 * m3; // error!
```

They can be also scaled/moved by scalars

```
Matrix m(10, 10);

m += 1;
m -= 2;
m *= 3;
m /= 4;
```

Or added element wise

```
Matrix m1(2, 2);
Matrix m2(2, 2);
Matrix m3(3, 2);

m1 += m2;
m1 -= m2;
m1 += m3; // error, sizes do not align
```

Elements can be accessed (for reading and writing) with the index operator

```
Matrix m(3, 2);

m[1][0] = 1.2;

Matrix m2 = m.transpose();

assert(m2[0][1] == 1.2); // ok
```

The neural network provides a very high level API, only `guess` and `train` methods are available

```
// XOR example
auto nn = NeuralNetwork::from_file("./backup");

vector<Matrix> inputs;
vector<Matrix> expected;

// false false -> false
{
  Matrix i(2, 1);
  i[0][0] = 0.0;
  i[1][0] = 0.0;
```

```
  inputs.push_back(i);

  Matrix e(2, 1);
  e[0][0] = 1.0;
  e[1][0] = 0.0;
  expected.push_back(e);
}

// false true -> true
{
  Matrix i(2, 1);
  i[0][0] = 0.0;
  i[1][0] = 1.0;
  inputs.push_back(i);

  Matrix e(2, 1);
  e[0][0] = 0.0;
  e[1][0] = 1.0;
  expected.push_back(e);
}

// true false -> true
{
  Matrix i(2, 1);
  i[0][0] = 2.0;
  i[1][0] = 0.0;
  inputs.push_back(i);

  Matrix e(2, 1);
  e[0][0] = 0.0;
  e[1][0] = 1.0;
  expected.push_back(e);
}

// true true -> false
{
  Matrix i(2, 1);
  i[0][0] = 1.0;
  i[1][0] = 1.0;
  inputs.push_back(i);

  Matrix e(2, 1);
  e[0][0] = 1.0;
  e[1][0] = 0.0;
  expected.push_back(e);
}
```

```
nn.train(inputs, expected, 1000);

assert(nn.guess(inputs[0]) == 0);
assert(nn.guess(inputs[1]) == 1);
assert(nn.guess(inputs[2]) == 1);
assert(nn.guess(inputs[3]) == 0);
```

There are unit tests for every method. They can be found on GitHub.

- The code is formatted using `clang-format` with the `Google` preset
- Compiled with `g++` version 9.2 with the `-std=c++2a` flag
- Naming convention:
  - Type aliases, classes, structs, enums, concepts: PascalCase
  - Private fields: snake_case with an underscore at the end
  - All of the rest: snake_case
- Return types will be annotated with the `auto <name>() → <type>` syntax
- Project is hosted on GitHub