

# Multiple Linear Regression

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## Multiple Linear Regression

The multiple linear regression takes the form

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_d x_d + \xi = \vec{x} \cdot \vec{\beta} + \xi$$

with  $\{\beta_i\}_{i=0}^d \in \mathbb{R}$  constants or parameters of the model. In vector notation,  $\vec{\beta} \in \mathbb{R}^{d+1}$ ,

$$\vec{\beta} = \begin{pmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_d \end{pmatrix}; \quad \vec{x} = \begin{pmatrix} 1 \\ x_1 \\ x_2 \\ \vdots \\ x_d \end{pmatrix}$$

For  $n$  data points, in matrix algebra notation, we can write  $y = X\vec{\beta} + \xi$  where  $X \in \mathcal{M}_{n \times (d+1)}$  and  $y \in \mathbb{R}^{d+1}$  with

$$X = \begin{pmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1d} \\ 1 & x_{21} & x_{22} & \cdots & x_{2d} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{n1} & x_{n2} & \cdots & x_{nd} \end{pmatrix}; \quad y = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix}; \quad \xi = \begin{pmatrix} \xi_1 \\ \xi_2 \\ \vdots \\ \xi_n \end{pmatrix}$$

We fit the  $n$  data points with the objective to minimize the loss function, mean squared error

$$MSE(\vec{\beta}) = \frac{1}{n} \sum_{i=1}^n (y_i - f_{\vec{\beta}}(\vec{x}_i))^2 = \frac{1}{n} \|\vec{y} - X\vec{\beta}\|^2$$

## Ordinary Least Square Method

The `scikit-learn` library uses **Ordinary Least Squares (OLS)** method to find the parameters. This method is good for a simple and relatively smaller dataset. Here is a short note on this method. However, when the dimension is very high and the dataset is bigger, `scikit-learn` uses another method called **Stochastic Gradient Descent** for optimization which is discussed in the next section.

The goal of OLS is to find the parameter vector  $\hat{\beta}$  that minimizes the sum of squared errors (SSE) between the observed target values  $y$  and the predicted values  $\hat{y}$ :

$$SSE = \sum_{i=1}^n (y_i - \hat{y}_i)^2 = \sum_{i=1}^n (y_i - X_i\beta)^2$$

This can be expressed in matrix form as:

$$SSE = (y - X\beta)^T (y - X\beta)$$

To minimize the SSE, let's first expand the expression:

$$SSE = (y - X\beta)^T (y - X\beta) \tag{1}$$

$$= (y^T - \beta^T X^T)(y - X\beta) \tag{2}$$

$$= y^T y - y^T X\beta - \beta^T X^T y + \beta^T X^T X\beta \tag{3}$$

Since  $\beta^T X^T y$  is a scalar (a 1x1 matrix), it is equal to its transpose. That is

$$\begin{aligned}
\beta^T X^T y &= (\beta^T X^T y)^T \\
&= ((\beta^T X^T) y)^T \\
&= y^T (\beta^T X^T)^T \\
&= y^T (\beta^T X^T)^T \\
&= y^T (X^T)^T (\beta^T)^T \\
&= y^T X \beta
\end{aligned}$$

and therefore,

$$\text{SSE} = y^T y - 2\beta^T X^T y + \beta^T X^T X \beta$$

To find the minimum of the SSE, we take the derivative with respect to  $\beta$  and set it to zero:

$$\frac{\partial \text{SSE}}{\partial \beta} = -2X^T y + 2X^T X \beta = 0$$

Now, solve for  $\beta$ :

$$X^T X \beta = X^T y$$

To isolate  $\beta$ , we multiply both sides by  $(X^T X)^{-1}$  (assuming  $X^T X$  is invertible):

$$\beta = (X^T X)^{-1} X^T y$$

The vector  $\hat{\beta} = (X^T X)^{-1} X^T y$  gives the estimated coefficients that minimize the sum of squared errors between the observed target values  $y$  and the predicted values  $\hat{y} = X\hat{\beta}$ . This method is exact and works well when  $X^T X$  is invertible and the dataset size is manageable. This method is very efficient for small to medium-sized datasets but can become computationally expensive for very large datasets due to the inversion of the matrix  $X^T X$ .

## Iterative Method

### Gradient Descent

GIF Credit: gbhat.com

Gradient Descent is an optimization algorithm used to minimize the cost function. The cost function  $f(\beta)$  measures how well a model with parameters  $\beta$  fits the data. The goal is to find the values of  $\beta$  that minimize this cost function. In terms of the iterative method, we want to find  $\beta_{k+1}$  and  $\beta_k$  such that  $f(\beta_{k+1}) < f(\beta_k)$ . For a small change in  $\beta$ , we can approximate  $f(\beta)$  using Taylor series expansion

$$f(\beta_{k+1}) = f(\beta_k + \Delta\beta_k) \approx f(\beta_k) + \nabla f(\beta_k)^T \Delta\beta_k + \text{higher-order terms}$$

The update rule for vanilla gradient descent is given by:

$$\beta_{k+1} = \beta_k - \eta \nabla f(\beta_k)$$

Where:

- $\beta_k$  is the current estimate of the parameters at iteration  $k$ .
- $\eta$  is the learning rate, a small positive scalar that controls the step size.
- $\nabla f(\beta_k)$  is the gradient of the cost function  $f$  with respect to  $\beta$  at the current point  $\beta_k$ .

The update rule comes from the idea of moving the parameter vector  $\beta$  in the direction that decreases the cost function the most.

1. **Gradient:** The gradient  $\nabla f(\beta_k)$  represents the direction and magnitude of the steepest ascent of the function  $f$  at the point  $\beta_k$ . Since we want to minimize the function, we move in the opposite direction of the gradient.
2. **Step Size:** The term  $\eta \nabla f(\beta_k)$  scales the gradient by the learning rate  $\eta$ , determining how far we move in that direction. If  $\eta$  is too large, the algorithm may overshoot the minimum; if it's too small, the convergence will be slow.
3. **Iterative Update:** Starting from an initial guess  $\beta_0$ , we repeatedly apply the update rule until the algorithm converges, meaning that the changes in  $\beta_k$  become negligible, and  $\beta_k$  is close to the optimal value  $\beta^*$ .

## Stochastic Gradient Descent (SGD)

Stochastic Gradient Descent is a variation of the vanilla gradient descent. Instead of computing the gradient using the entire dataset, SGD updates the parameters using only a single data point or a small batch of data points at each iteration. The later one we call it mini batch SGD.

Suppose our cost function is defined as the average over a dataset of size  $n$ :

$$f(\beta) = \frac{1}{n} \sum_{i=1}^n f_i(\beta)$$

Where  $f_i(\beta)$  represents the contribution of the  $i$ -th data point to the total cost function. The gradient of the cost function with respect to  $\beta$  is:

$$\nabla f(\beta) = \frac{1}{n} \sum_{i=1}^n \nabla f_i(\beta)$$

Vanilla gradient descent would update the parameters as:

$$\beta_{k+1} = \beta_k - \eta \nabla f(\beta_k)$$

Instead of using the entire dataset to compute the gradient, SGD approximates the gradient by using only a single data point (or a small batch). The update rule for SGD is:

$$\beta_{k+1} = \beta_k - \eta \nabla f_{i_k}(\beta_k)$$

Where:

- $i_k$  is the index of a randomly selected data point at iteration  $k$ .
- $\nabla f_{i_k}(\beta_k)$  is the gradient of the cost function with respect to the parameter  $\beta_k$ , evaluated only at the data point indexed by  $i_k$ .

## Python Execution

### Synthetic Data

```
import numpy as np
from sklearn.linear_model import LinearRegression
X=np.random.randn(1000,2)
y=3*X[:,0]+2*X[:,1]+1+np.random.randn(1000)
```

So for this project, our known relationship is  $y = 1 + 3x_1 + 2x_2 + \xi$ .

### Fit the data: Using scikit-learn Library

```
mlr=LinearRegression()
mlr.fit(X,y)
coefficients=mlr.coef_.tolist()
slope=mlr.intercept_.tolist()
```

So the model parameters: slope  $\beta_0 = 0.9852$  and coefficients  $\beta_1 = 2.9619$ , and  $\beta_2 = 1.9806$

### Fit the data: Using Custom Library OLS

First we create our custom `NewLinearRegression` using the OLS formula above and save this python class as `mlreg.py`

```
import numpy as np

class NewLinearRegression:
    def __init__(self) -> None:
        self.beta = None

    def fit(self, X, y):
        X = np.concatenate([np.ones((len(X), 1))], X], axis=1)
        X_transpose_X = np.dot(X.transpose(), X)
        X_transpose_X_inverse = np.linalg.inv(X_transpose_X)
        X_transpose_y = np.dot(X.transpose(), y)
        self.beta = np.dot(X_transpose_X_inverse, X_transpose_y)
```

```

def predict(self, X):
    X = np.concatenate([np.ones((len(X), 1)), X], axis=1)
    return np.dot(X, self.beta)

def coeff_(self):
    return self.beta[1:].tolist()

def interceptt_(self):
    return self.beta[0].tolist()

```

Now it's time to use the new class

```

from mlreg import NewLinearRegression
mlr1 = NewLinearRegression()
mlr1.fit(X,y)
coefficients1=mlr1.coeff_()
slope1=mlr1.interceptt_()

```

So the model parameters: slope  $\beta_0 = 0.9852$  and coefficients  $\beta_1 = 2.9619$ , and  $\beta_2 = 1.9806$

### Fit the data: Using Gradient Descent

We create the class

```

class GDLinearRegression:
    def __init__(self, learning_rate=0.01, number_of_iteration=1000) -> None:
        self.learning_rate = learning_rate
        self.number_of_iteration = number_of_iteration
        self.weights = None
        self.bias = None

    def fit(self, X, y):
        num_of_samples, num_of_features = X.shape
        self.weights = np.zeros(num_of_features)
        self.bias = 0

        for _ in range(self.number_of_iteration):
            y_predicted = np.dot(X, self.weights) + self.bias

            d_weights = (1 / num_of_samples) * np.dot(X.T, (y_predicted - y))

```

```

        d_bias = (1 / num_of_samples) * np.sum(y_predicted - y)

        self.weights -= self.learning_rate * d_weights
        self.bias -= self.learning_rate * d_bias

    def predict(self, X):
        y_predicted = np.dot(X, self.weights) + self.bias
        return y_predicted

    def coefff_(self):
        return self.weights.tolist()

    def interceptttt_(self):
        return self.bias

```

Now we use this similarly as before,

```

from mlreg import GDLinearRegression
mlr2= GDLinearRegression(learning_rate=0.008)
mlr2.fit(X,y)
coefficients2=mlr2.coefff_()
slope2=mlr2.interceptttt_()

```

So the model parameters: slope  $\beta_0 = 0.9851$  and coefficients  $\beta_1 = 2.9608$ , and  $\beta_2 = 1.9802$

## Fit the data: Using Stochastic Gradient Descent

First we define the class

```

class SGDLinearRegression:
    def __init__(self, learning_rate=0.01, num_iterations=1000, batch_size=1) -> None:
        self.learning_rate = learning_rate
        self.num_iterations = num_iterations
        self.batch_size = batch_size
        self.theta = None
        self.mse_list = None # Initialize mse_list as an instance attribute

    def _loss_function(self, X, y, beta):
        num_samples = len(y)
        y_predicted = X.dot(beta)
        mse = (1/num_samples) * np.sum(np.square(y_predicted - y))

```



```

        return mse

def _gradient_function(self, X, y, beta):
    num_samples = len(y)
    y_predicted = X.dot(beta)
    grad = (1/num_samples) * X.T.dot(y_predicted - y)
    return grad

def fit(self, X, y):
    # Adding the intercept term (bias) as a column of ones
    X = np.concatenate([np.ones((len(X), 1)), X], axis=1)
    num_features = X.shape[1]
    self.theta = np.zeros((num_features, 1))

    self.mse_list = np.zeros(self.num_iterations) # Initialize mse_list

    for i in range(self.num_iterations):
        # Randomly select a batch of data points
        indices = np.random.choice(
            len(y), size=self.batch_size, replace=False)
        X_i = X[indices]
        y_i = y[indices].reshape(-1, 1)

        # Compute the gradient and update the weights
        gradient = self._gradient_function(X_i, y_i, self.theta)
        self.theta = self.theta - self.learning_rate * gradient

        # Calculate loss for the entire dataset (optional)
        self.mse_list[i] = self._loss_function(X, y, self.theta)

    return self.theta, self.mse_list

def predict(self, X):
    # Adding the intercept term (bias) as a column of ones
    X = np.concatenate([np.ones((len(X), 1)), X], axis=1)
    return X.dot(self.theta)

def coef_(self):
    # Return the coefficients (excluding the intercept term)
    return self.theta[1:].flatten().tolist()

def intercept_(self):

```

```
# Return the intercept term
return self.theta[0].item()

def mse_losses(self):
    # Return the mse_list
    return self.mse_list.tolist()
```

Now

```
import matplotlib.pyplot as plt
from mlreg import SGDLinearRegression
mlr3=SGDLinearRegression(learning_rate=0.01, num_iterations=1000, batch_size=10)
theta, _ = mlr3.fit(X, y)
```

So the model parameters: slope  $\beta_0 = \text{array}([1.01488194])$  and coefficients  $\beta_1 = \text{array}([2.98564465])$ , and  $\beta_2 = \text{array}([1.9881868])$

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