CHEME 5820: Machine Learning for Engineers **Spring 2025**

Lecture 3c: Logistic Regression for Binary Classification Problems

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Disclaimer: *These notes have not been subjected to the usual scrutiny reserved for formal publications.*

1 Introduction

In this lecture, we will introduce logistic regression for binary classification problems. We will start by discussing the logistic regression model and then the maximum likelihood estimation of the model parameters. We will also discuss the gradient descent algorithm for estimating the model parameters. Finally, we will discuss evaluating the logistic regression model using the confusion matrix, accuracy, precision, recall, and the F1 score. The key concepts covered in this lecture include:

- **Logistic regression** is a statistical method used for binary classification that models the relationship between a dependent categorical variable (label) and one or more independent variables (features) by estimating probabilities through the logistic function.
- **Maximum likelihood estimation (MLE)** is a statistical technique to estimate the parameters of a probability distribution by maximizing the likelihood function, thereby determining the parameter values that make the observed data most probable.
- **Gradient descent** is an optimization algorithm used to minimize a function by iteratively adjusting parameters in the opposite direction of the gradient. Iteration continues until a local minimum of the function is found.
- **Performance assesment**. Evaluating the performance of a logistic regression model involves assessing its accuracy and predictive power through various metrics such as accuracy, precision, recall, F1-score, and the area under the receiver operating characteristic (ROC) curve. These metrics provide insights into how well the model distinguishes between the binary classes and help fine-tune its parameters for improved performance.

2 Logistic Regression

Logistic regression is a statistical method used for binary classification problems, where the dependent variable (label) is a binary categorical variable (e.g., ± 1, etc), and the independent variables (features) are continuous or categorical variables. Unlike the Perceptron model, which outputs the class label directly, logistic regression models the probability that a given input belongs to a particular class based on the input features. The logistic regression model estimates the probability that a given input belongs to a particular class based on the input features. In particular, logistic regression is a discriminative model, which means it directly models the conditional probability of the label given the features, i.e., $P(y|\mathbf{x})$. This is in contrast to generative models, e.g., Naive Bayes, which we'll explore later, which model the joint probability of the features and the label, i.e., $P(y, \mathbf{x}) = P(\mathbf{x}|y) \cdot P(y)$. The logistic regression model uses the logistic function to model the probability of the binary label $y \in \{-1, +1\}$ given the feature vector $\mathbf{x}$:

$$P(y|\mathbf{x};\theta) = \frac{1}{1 + e^{-y \cdot \theta^T \mathbf{x}}} \tag{1}$$

where $\theta \in \mathbb{R}^n$ is an (unknown) parameter vector (that we need to estimate somehow), and e is the base of the natural logarithm. The logistic function is a sigmoid function that maps the input, i.e., $-y \cdot \theta^T \mathbf{x}$ to the range $[0, 1]$, which is suitable for modeling probabilities. The logistic regression model predicts the label $y \in \{-1, +1\}$ for a given feature vector $\mathbf{x}$ by comparing the probability $P(y|\mathbf{x}; \theta)$ to a threshold, e.g., 0.5. The model predicts the positive class if the probability exceeds the threshold ($y = 1$). Otherwise, it predicts the negative class ($y = -1$). The logistic regression model is trained by estimating the parameters θ that maximize the likelihood of the observed labels given the features. The next section will discuss the maximum likelihood estimation of the logistic regression model parameters.

2.1 Maximum Likelihood Estimation (MLE)

Maximum likelihood estimation (MLE) is a technique to estimate the parameters of a probability distribution by maximizing the likelihood function. In logistic regression, MLE estimates the parameters of the logistic regression model that make the observed label conditioned on the features the most probable. Given a set of training examples $\mathcal{D} = \{(\mathbf{x}_1, y_1), \ldots, (\mathbf{x}_m, y_m)\}$, where $\mathbf{x}_i \in \mathbb{R}^n$ is an n-dimensional feature vector and $y_i \in \mathbb{R}$ is the binary (scalar) label, the likelihood function is defined as:

$$\mathcal{L}(\theta) = \prod_{i=1}^{m} P(y_i|\mathbf{x}_i; \theta) \tag{2}$$

where $P(y_i|\mathbf{x}_i; \theta)$ is the probability of observing the label y_i given the feature vector $\mathbf{x}_i$ and the model parameters θ. It's hard to maximize the likelihood function directly (because of the product), so we take the logarithm of the likelihood function to simplify the optimization:

$$\log \mathcal{L}(\theta) = \sum_{i=1}^{m} \log P(y_i|\mathbf{x}_i; \theta) \tag{3}$$

The `log` is a monotonic function, so maximizing the log-likelihood is equivalent to maximizing the likelihood. The logistic regression model uses the logistic function to model the probability of the binary label:

$$P(y_i|\mathbf{x}_i; \theta) = \frac{1}{1 + e^{-y_i \cdot (\theta^T \mathbf{x}_i)}} \tag{4}$$

where $\theta \in \mathbb{R}^n$ is the parameter vector, θ^T is the transpose of θ, and e is the base of the natural logarithm. Substituting the $P(y_i|\mathbf{x}_i; \theta)$ function into the log-likelihood function gives:

$$\log \mathcal{L}(\theta) = -\sum_{i=1}^{m} \log \left(1 + e^{-y_i \cdot \theta^T \mathbf{x}_i}\right) \tag{5}$$

where we inverted the $P(y_i|\mathbf{x}_i; \theta)$ function to get the log-likelihood function. The maximum likelihood estimation (MLE) of the logistic regression model parameters $\theta^\star$ is obtained by maximizing the log-likelihood function $\log \mathcal{L}(\theta)$:

$$\theta^\star = \arg\max_{\theta} \left[-\sum_{i=1}^{m} \log \left(1 + e^{-y_i \cdot \theta^T \mathbf{x}_i}\right) \right] \tag{6}$$

No closed-form analytical solution exists to this optimization problem, so we must estimate the model parameters using a numerical algorithm. To solve this optimization problem, we can use the gradient descent algorithm (or one of many other approaches) to iteratively update the parameters θ to maximize the log-likelihood function, alternatively, minimize the negative log-likelihood function, i.e., $l(\theta) = \sum_{i=1}^{m} \log \left(1 + e^{-y_i \cdot \theta^T \mathbf{x}_i}\right)$.

We'll start by discussing the gradient descent algorithm and then consider some alternatives to gradient descent.

2.2 Gradient Descent

Gradient descent is an optimization algorithm that minimizes a function by iteratively adjusting the parameters in the opposite direction of the gradient. Suppose there exists an objective function $l(\theta)$ that we want to minimize with respect to the parameter θ, i.e., the negative log-likelihood function. In general, an objective function measures the difference between the predicted values and the observed values in some way, e.g., the mean squared error (MSE), the cross-entropy loss, or the negative log-likelihood. In logistic regression, the objective function is the negative log-likelihood function, which measures the difference between the predicted probabilities and the observed labels. However, whatever form the objective function takes, we assume that it is differentiable and that we can compute the gradient, i.e., $\nabla l(\theta)$ for the negative log-likelihood function, which points in the direction of the steepest increase of the function. This gives us a way to update the parameters to minimize the objective function using the update rule:

$$\theta_{k+1} = \theta_k - \alpha(k) \cdot \nabla l(\theta_k) \quad \text{where } k = 0, 1, 2, \ldots$$

The (hyper) parameter $\alpha(k) > 0$ is the learning rate (which can be a function of the iteration count k), and $\nabla l(\theta)$ is the gradient of the negative log-likelihood function with respect to the parameters. We iterate until a stopping criterion is met, i.e., $||\theta_{k+1} - \theta_k|| \leq \epsilon$, the maximum number of iterations is reached, or some other stopping criterion is met.

Algorithm 1 Gradient Descent for Negative Log-Likelihood

Input: Initial parameters θ_0, learning rate η, stopping criterion ϵ, maximum iterations N
Output: Optimal parameters θ^*
Initialize $\theta \leftarrow \theta_0$
$k \leftarrow 0$
while $k < N$ **and** $\|\nabla \mathcal{L}(\theta)\| > \epsilon$ **do**
    Compute gradient $\nabla \mathcal{L}(\theta)$ of the negative log-likelihood $\mathcal{L}(\theta)$
    Update parameters: $\theta \leftarrow \theta - \eta \cdot \nabla \mathcal{L}(\theta)$
    $k \leftarrow k + 1$
end while
return θ

2.3 Alternatives to Gradient Descent

The central issue with gradient descent is that it can be slow to converge, especially when the objective function is non-convex or has many local minima. The choice of the learning rate α is crucial, as a too-large value can cause the algorithm to diverge, while a too-small value can slow down convergence. Further, the objective function may not be differentiable, or the gradient may be challenging to compute. In these cases, alternative heuristic optimization algorithms can be used to estimate the model parameters. Let's walk through some of the alternatives to gradient descent.

Simulated Annealing

Simulated annealing, originally developed by Kirkpatrick et al (1), is a probabilistic optimization algorithm inspired by the physical process of heating and then slowly cooling (annealing) materials to minimize defects.

Simulated annealing works by iteratively exploring the solution space by accepting worse solutions with a certain probability, allowing for a more thorough exploration of the solution space and avoiding local minima. This method effectively solves complex optimization problems with large search spaces, where traditional techniques may struggle to find the global optimum. However, simulated annealing can be computationally expensive and may require tuning of hyperparameters, particularly the annealing schedule, i.e., the decrease is temperature to achieve optimal performance.

Algorithm 2 Simulated Annealing

Initialize current solution $x \leftarrow x_0$
Initialize temperature $T \leftarrow T_0$
Define cooling schedule $T \leftarrow \alpha \cdot T$, where $0 < \alpha < 1$
Define maximum iterations N
Initialize best solution $x_{\text{best}} \leftarrow x$
for $i = 1$ to N **do**
    Generate a new candidate solution x_{new} in the neighborhood of x
    Compute $\Delta E \leftarrow f(x_{\text{new}}) - f(x)$
    if $\Delta E < 0$ **then**
        Accept x_{new}: $x \leftarrow x_{\text{new}}$
    else
        Accept x_{new} with probability $P \leftarrow e^{-\Delta E/T}$
        Draw a random number $r \in [0, 1]$
        if $r < P$ **then**
            $x \leftarrow x_{\text{new}}$
        end if
    end if
    if $f(x) < f(x_{\text{best}})$ **then**
        Update $x_{\text{best}} \leftarrow x$
    end if
    Update temperature: $T \leftarrow \alpha \cdot T$
    if T is below a threshold T_{min} **then**
        break
    end if
end for
return x_{best}

Genetic Algorithms

Genetic algorithms (GAs), popularized by John Holland in the 1970s (2), are adaptive heuristic search techniques inspired by natural selection and genetics principles. They are designed to solve optimization and search problems by iteratively evolving a population of candidate solutions through selection, crossover, and mutation. By mimicking the evolutionary process, GAs aim to improve solution quality over generations, making them particularly effective for complex problems that may be discontinuous, non-differentiable, or highly nonlinear.

Algorithm 3 Genetic Algorithm

Input: Population size P, crossover rate p_c, mutation rate p_m, maximum generations G, fitness function f
Output: Best solution found after G generations (individual with highest fitness)
Initialize population P_0 randomly
Evaluate fitness of each individual in P_0
$t \leftarrow 0$
while $t < G$ **do**
    Select parents from P_t based on fitness
    Apply crossover with probability p_c to produce offspring
    Apply mutation with probability p_m to offspring
    Evaluate fitness of offspring
    Form new population P_{t+1} by selecting the best individuals from parents and offspring
    $t \leftarrow t + 1$
end while
Identify the best individual in P_t
return Best individual

Particle Swarm Optimization

Particle Swarm Optimization (PSO), developed by Kennedy and Eberhart in the mid-1990s (3) is an example of a meta-heuristic optimization algorithm inspired by the social behavior of birds and fish, which utilizes a population of candidate solutions, referred to as particles, that move through the search space to find optimal solutions. Each particle adjusts its position based on its own experience and the collective knowledge of the swarm, allowing for efficient exploration and exploitation of the solution space to address complex optimization problems across various fields.

Algorithm 4 Particle Swarm Optimization (PSO)

Input: Number of particles N, maximum iterations T, inertia weight ω, cognitive parameter c_1, social parameter c_2, objective function f
Output: Best solution found x_{best}
Initialize particles' positions x_i and velocities v_i randomly for $i = 1, \ldots, N$
Evaluate fitness of each particle and initialize personal best positions $p_i \leftarrow x_i$
Set global best position $g \leftarrow \arg\min_{p_i} f(p_i)$
for $t = 1$ to T **do**
    for each particle $i = 1$ to N **do**
        Update velocity:

$$v_i \leftarrow \omega v_i + c_1 r_1 (p_i - x_i) + c_2 r_2 (g - x_i)$$

    where $r_1, r_2 \sim U(0, 1)$
        Update position:

$$x_i \leftarrow x_i + v_i$$

        Evaluate fitness $f(x_i)$
        if $f(x_i) < f(p_i)$ **then**
            Update personal best: $p_i \leftarrow x_i$
        end if
        if $f(p_i) < f(g)$ **then**
            Update global best: $g \leftarrow p_i$
        end if
    end for
end for
return g

3 Performance Evaluation

Evaluating the performance of a logistic regression model involves assessing its accuracy and predictive power through various metrics such as accuracy, precision, recall, F1-score, and the area under the receiver operating characteristic (ROC) curve. The accuracy of a model is the proportion of correctly classified instances, while precision measures the proportion of true positive predictions among all positive predictions. The recall is the proportion of true positive predictions among all actual positive instances, and the F1-score is the harmonic mean of precision and recall. The area under the ROC curve measures the model's ability to distinguish between the two classes, with a higher AUC indicating better performance. See Sidey-Gibbon et al (4) for a detailed discussion of these metrics in the context of medical classification problems.

4 Summary and Conclusions

In this lecture, we introduced logistic regression for binary classification problems and discussed the maximum likelihood estimation of the model parameters. We also covered the gradient descent algorithm for estimating model parameters and evaluated the logistic regression model using the confusion matrix, accuracy, precision, recall, and F1 score. Gradient descent is an optimization algorithm employed to minimize a function by iteratively adjusting parameters in the opposite direction of the gradient. However, various other optimization algorithms can estimate model parameters without relying on the gradient. For instance, simulated annealing, genetic algorithms, and particle swarm optimization are all methods that can be utilized

to estimate the model parameters. Finally, we examined the logistic regression model's performance using various metrics, including accuracy, precision, recall, F1 score, and the area under the ROC curve. Logistic regression is a powerful tool for binary classification and is widely applied in numerous fields, including healthcare, finance, and marketing.

References

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