Introduction to Machine Learning

Optimization

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Outline

Contents

0.1 Machine Learning as Optimization

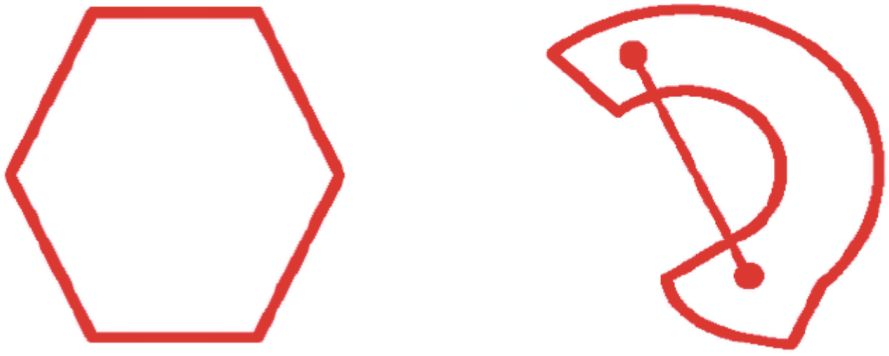
At this point, we move away from the situation where a perfect solution exists, and the learning task it to reach the perfect solution. Instead, we focus on finding the *best possible* solution which optimizes certain criterion.

- Learning is optimization
- Faster optimization methods for faster learning
- Let $w \in \mathbb{R}^d$ and $f_0(w), f_1(w), \ldots, f_m(w)$ be real-valued functions.
- Standard optimization formulation is:

$$\begin{aligned} \underset{w}{\text{minimize}} \quad & f_0(w) \\ \text{subject to} \quad & f_i(w) \leq 0,\ i = 1, \ldots, m. \end{aligned}$$

[1]Adapted from `http://ttic.uchicago.edu/~gregory/courses/ml2012/lectures/tutorial_optimization.pdf`. Also see, `http://www.stanford.edu/~boyd/cvxbook/` and `http://scipy-lectures.github.io/advanced/mathematical_optimization/`.

- Methods for **general optimization problems**
  - Simulated annealing, genetic algorithms
- Exploiting *structure* in the optimization problem
  - **Convexity**, Lipschitz continuity, smoothness
- Convex Sets



Convexity is a property of certain functions which can be exploited by optimization algorithms. The idea of convexity can be understood by first considering *convex sets*. A convex set is a set of points in a coordinate space such that every point on the line segment joining any two points in the set are also within the set. Mathematically, this can be written as:

$$w_1, w_2 \in S \Rightarrow \lambda w_1 + (1 - \lambda) w_2 \in S$$

where $\lambda \in [0, 1]$. A *convex function* is defined as follows:

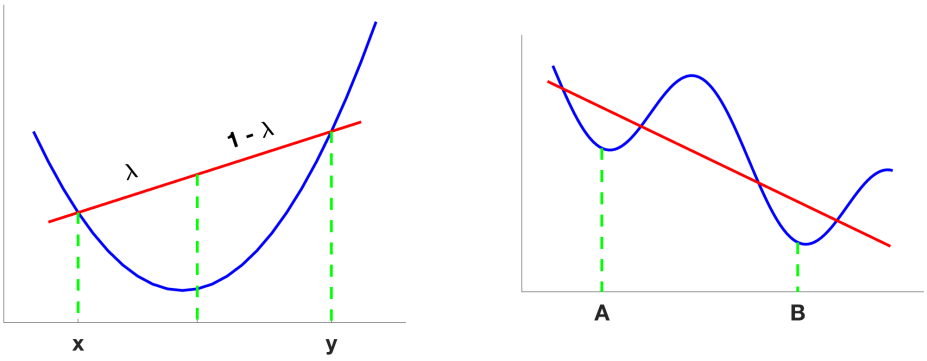
- $f : \mathbb{R}^d \to \mathbb{R}$ is a convex function if the domain of f is a convex set and for all $\lambda \in [0, 1]$:

$$f(\lambda w_1 + (1 - \lambda) w_2) \leq \lambda f(w_1) + (1 - \lambda) f(w_2)$$

Some examples of convex functions are:

- Affine functions: $w^\top x + b$

- $||w||_p$ for $p \geq 1$
- Logistic loss: $\log(1 + e^{-yw^\top x})$
- Convex function



0.2 Convex Optimization

- Optimality Criterion

$$\begin{aligned} \underset{w}{\text{minimize}} \quad & f_0(w) \\ \text{subject to} \quad & f_i(w) \leq 0, \ i = 1, \ldots, m. \end{aligned}$$

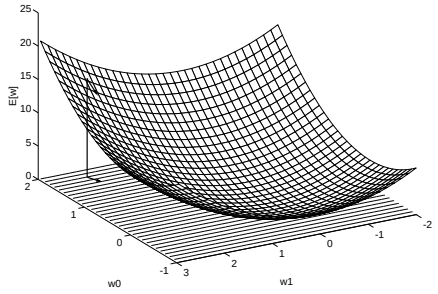
  where all $f_i(w)$ are **convex functions**.

- w_0 is feasible if $w_0 \in Dom\ f_0$ and all constraints are satisfied
- A feasible w^* is optimal if $f_0(w^*) \leq f_0(w)$ for all w satisfying the constraints

0.3 Gradient Descent

- Denotes the direction of steepest ascent

$$\nabla E(\mathbf{w}) = \begin{bmatrix} \frac{\partial E}{\partial w_0} \\ \frac{\partial E}{\partial w_1} \\ \vdots \\ \frac{\partial E}{\partial w_d} \end{bmatrix}$$



A small step in the weight space from $\mathbf{w}$ to $\mathbf{w} + \delta\mathbf{w}$ changes the objective (or error) function. This change is maximum if $\delta\mathbf{w}$ is along the direction of the gradient at $\mathbf{w}$ and is given by:

$$\delta E \simeq \delta\mathbf{w}^\top \nabla E(\mathbf{w})$$

Since $E(\mathbf{w})$ is a smooth continuous function of $\mathbf{w}$, the extreme values of E will occur at the location in the input space ($\mathbf{w}$) where the gradient of the error function vanishes, such that:

$$\nabla E(\mathbf{w}) = 0$$

The vanishing points can be further analyzed to identify them as saddle, minima, or maxima points.

One can also derive the local approximations done by first order and second order methods using the Taylor expansion of $E(\mathbf{w})$ around some point $\mathbf{w}'$ in the weight space.

$$E(\mathbf{w}') \simeq E(\mathbf{w}) + (\mathbf{w}' - \mathbf{w})^\top \nabla + \frac{1}{2}(\mathbf{w}' - \mathbf{w})^\top \mathbf{H}(\mathbf{w}' - \mathbf{w})$$

For first order optimization methods, we ignore the second order derivative (denoted by $\mathbf{H}$ or the *Hessian*). It is easy to see that for $\mathbf{w}$ to be the local

minimum, $E(\mathbf{w}) - E(\mathbf{w}') \leq 0$, $\forall \mathbf{w}'$ in the vicinity of $\mathbf{w}$. Since we can choose any arbitrary $\mathbf{w}'$, it means that every component of the gradient ∇ must be zero.

- Set derivative to 0
- Second derivative for minima or maxima

1. Start from any point in variable space
2. Move along the direction of the steepest descent (or ascent)
    - By how much?
    - A learning rate (η)
    - What is the direction of steepest descent?
        - Gradient of E at $\mathbf{w}$

Gradient descent is a first-order optimization method for convex optimization problems. It is analogous to "hill-climbing" where the gradient indicates the direction of steepest ascent in the local sense.

Training Rule for Gradient Descent

$$\mathbf{w} = \mathbf{w} - \eta \nabla E(\mathbf{w})$$

For each weight component:

$$w_j = w_j - \eta \frac{\partial E}{\partial w_j}$$

The key operation in the above update step is the calculation of each partial derivative. This can be computed for perceptron error function as follows:

$$\begin{aligned}
\frac{\partial E}{\partial w_j} &= \frac{\partial}{\partial w_j} \frac{1}{2} \sum_i (y_i - \mathbf{w}^\top \mathbf{x}_i)^2 \\
&= \frac{1}{2} \sum_i \frac{\partial}{\partial w_j} (y_i - \mathbf{w}^\top \mathbf{x}_i)^2 \\
&= \frac{1}{2} \sum_i 2(y_i - \mathbf{w}^\top \mathbf{x}_i) \frac{\partial}{\partial w_j} (y_i - \mathbf{w}^\top \mathbf{x}_i) \\
&= \sum_i (y_i - \mathbf{w}^\top \mathbf{x}_i)(-x_{ij})
\end{aligned}$$

where x_{ij} denotes the j^{th} attribute value for the i^{th} training example. The final weight update rule becomes:

$$w_j = w_j + \eta \sum_i (y_i - \mathbf{w}^\top \mathbf{x}_i) x_{ij}$$

- Error surface contains only one global minimum
- Algorithm *will* converge
  - Examples need not be linearly separable
- η should be *small enough*
- Impact of too large η?
- Too small η?

If the learning rate is set very large, the algorithm runs the risk of overshooting the target minima. For very small values, the algorithm will converge very slowly. Often, η is set to a moderately high value and reduced after each iteration.

0.4 Issues with Gradient Descent

- Slow convergence
- Stuck in local minima

One should note that the second issue will not arise in the case of Perceptron training as the error surface has only one global minima. But for general setting, including multi-layer perceptrons, this is a typical issue.

More efficient algorithms exist for batch optimization, including *Conjugate Gradient Descent* and other *quasi*-Newton methods. Another approach is to consider training examples in an online or incremental fashion, resulting in an online algorithm called **Stochastic Gradient Descent** [1], which will be discussed next.

0.5 Stochastic Gradient Descent

- **Update weights after every training example or a batch of examples.**
- For sufficiently small η, closely approximates Gradient Descent.

Gradient Descent	**Stochastic Gradient Descent**
Weights updated after summing error over all examples	Weights updated after examining a batch of examples
More computations per weight update step	Significantly lesser computations
Risk of local minima	Reduce the risk of local minima but can't avoid it

References

References

[1] Y. LeCun, B. Boser, J. S. Denker, D. Henderson, R. E. Howard, W. Hubbard, and L. D. Jackel. Backpropagation applied to handwritten zip code recognition. *Neural Comput.*, 1(4):541–551, Dec. 1989.