

Lecture 1: Introduction to Complex Optimization

*Author: Christopher M. Bishop**Scribes: scribe-name1,2,3***Note:** *Reading notes for complex optimization.***Disclaimer:** *These notes have not been subjected to the usual scrutiny reserved for formal publications. They may be distributed outside this class only with the permission of Mr. Yan.*

1.1 Solving optimization problems

1. general optimization problem
 - (a) very difficult to solve
 - (b) methods involve some compromise, e.g. very long computation time, or not always finding the solution
- 2.

1.2 Maximum Margin Classifiers

Two-class classification problem:

$$y(x) = w^T \phi(x) + b \quad (1.1)$$

where ϕ denotes a fixed feature-space transformation, b explicit.Training set comprises N input vectors x_1, \dots, x_N with target t_1, \dots, t_N where $t_N \in \{-1, 1\}$ and new data points are classified according to the sign of $y(x)$.Training data - linearly separable in feature space, so that there exists one choice of w and b such that by 1.1 satisfies $y(x_n) > 0$ for points having $t_n = +1$ and $y(x_n) < 0$ for $t_n = -1$.

In section 4, the perceptron algorithm is guaranteed to find a solution for the linearly separable problem. The solution depends on the initial value and the order of the data points are presented - if there are multiple solutions we should try to find one with the smallest generalization error. SVM approaches this problem through the concept of the **margin** - the smallest distance between the decision boundary and any of the samples.

Perpendicular distance of a point x from a hyperplane: $|y(x)|/\|w\|$. We are only interested in solutions for which all data points are correctly classified ($t_n y(x_n) > 0$ for all n). So we have the distance of a point x_n to the decision surface is given by:

$$\frac{t_n y(x_n)}{\|w\|} = \frac{t_n (w^T \phi(x_n) + b)}{\|w\|} \quad (1.2)$$

The margin is given by the perpendicular distance to the closest point x_n from the data set, w and b need optimized in order to maximize the distance.

Then the maximum margin solution is found by

$$\arg \max_{w,b} \left\{ \frac{1}{\|w\|} \min_n [t_n(w^T \phi(x_n) + b)] \right\} \quad (1.3)$$

in which $\|w\|$ does not depend on n . The direct solution of this optimization problem would be complex \Rightarrow an equivalent problem easier to solve:

$$w \rightarrow \kappa w \quad (1.4)$$

$$b \rightarrow \kappa b \quad (1.5)$$

the rescaling would not change the distance. We then use this freedom to set

$$t_n(w^T \phi(x_n) + b) = 1 \quad (1.6)$$

for the point that is closest to the surface.

The canonical representation of the decision hyperplane:

$$t_n(w^T \phi(x_n) + b) \geq 1, n = 1, \dots, N \quad (1.7)$$

When the equality holds, the constraints are said to be active.

There would always be at least one active constraint, because there will always be a closest point, and once the margin has been maximized there will be at least two active constraints. The optimization problem minimizing $\|w\|^2$ is equivalent to maximize $\|w\|^{-1}$, so we need to solve the problem:

$$\arg \min_{w,b} \frac{1}{2} \|w\|^2 \quad (1.8)$$

subject to the constraints given by 1.7.

We introduce the Lagrange multipliers $a_n \geq 0$ with one multiplier a_n for each of the constraints in 1.7 giving the Lagrangian function:

$$L(w, b, a) = \frac{1}{2} \|w\|^2 - \sum_{n=1}^N a_n \{t_n(w^T \phi(x_n) + b) - 1\} \quad (1.9)$$

where $a = (a_1, \dots, a_N)^T$.

Setting the derivatives of $L(w, b, a)$ with respect to w and b equal to zero, we obtain the following conditions:

$$w = \sum_{n=1}^N a_n t_n \phi(x_n) \quad (1.10)$$

$$0 = \sum_{n=1}^N a_n t_n \quad (1.11)$$

Eliminating w and b from $L(w, b, a)$ using these conditions then gives the dual representation of the **maximum margin problem** in which we maximize

$$\tilde{L}(a) = \sum_{n=1}^N a_n - \frac{1}{2} \sum_{n=1}^N \sum_{m=1}^N a_n a_m t_n t_m k(x_n, x_m) \quad (1.12)$$

with respect to a subject to the constraints

$$a_n \geq 0, n = 1, \dots, N \quad (1.13)$$

$$\sum_{n=1}^N a_n t_n = 0 \quad (1.14)$$

Here the kernel function is defined by $k(x, x') = \phi(x)^T \phi(x')$. This takes the form of a **quadratic programming problem**.

Computational complexity - $O(M^3)$.

With dual formulation, the original optimization problem involved minimizing over M variables into the dual problem with N variables.

For fixed set of basis functions M is smaller than the data points number N , dual representation seems useless. However, it allows the model to be reformulated using kernels, and the maximum margin classifier can be applied efficiently to feature spaces whose dimensionality M exceeds the number of data points N , including infinite feature spaces.

The kernel formulation also makes clear the role of the constraint that the kernel function $k(x, x')$ be **positive definite** - this ensures the Lagrangian function $\tilde{J}(a)$ is bounded below, giving rise to a well-defined optimization problem.

So new data point can be evaluated by:

$$y(x) = w^T \phi(x) + b = \sum_{n=1}^N a_n t_n k(x, x_n) + b \quad (1.15)$$

For the Karush-Kuhn-Tucker KKT condition, which in this case require that the following three properties hold:

$$a_n \geq 0 \quad (1.16)$$

$$t_n y(x_n) - 1 \geq 0 \quad (1.17)$$

$$a_n \{t_n y(x_n) - 1\} = 0 \quad (1.18)$$

check the Appendix E

For every data point, either $a_n = 0$ or $t_n y(x_n) = 1$, any data point for which $a_n = 0$ will not appear in the sum in 1.15 thus play no role in making predictions for new data points. **The remaining data points are called support vectors** - and they satisfy $t_n y(x_n) = 1$, they lie on the maximum margin hyperplanes in feature space - once the model is trained only the support vectors retained.

Solving the quadratic programming problem for a , determine b by

$$t_n \left(\sum_{m \in \mathcal{S}} a_m t_m k(x_n, x_m) + b \right) = 1 \quad (1.19)$$

where \mathcal{S} denotes the set of indices of the support vectors.

A more stable solution for b is:

$$b = \frac{1}{N_S} \sum_{m \in S} (t_n - \sum_{m \in S} a_m t_m k(x_n, x_m)) \quad (1.20)$$

where N_S is the total number of support vectors.

1.2.1 Overlapping class distributions

1.2.2 Relation to logistic regression

1.2.3 Multiclass SVMs

1.2.4 SVMs for regression

1.2.5 Computational learning theory

1.3 Relevance Vector Machines

1.3.1 RVM for regression

1.3.2 Analysis of sparsity

1.3.3 RVM for classification

We now delve right into the proof.

Lemma 1.1 *This is the first lemma of the lecture.*

Proof: The proof is by induction on For fun, we throw in a figure.

Figure 1.1: A Fun Figure

This is the end of the proof, which is marked with a little box. ■

1.3.4 A few items of note

Here is an itemized list:

- this is the first item;
- this is the second item.

Here is an enumerated list:

1. this is the first item;
2. this is the second item.

Here is an exercise:

Exercise: Show that $P \neq NP$.

Here is how to define things in the proper mathematical style. Let f_k be the *AND – OR* function, defined by

$$f_k(x_1, x_2, \dots, x_{2^k}) = \begin{cases} x_1 & \text{if } k = 0; \\ \text{AND}(f_{k-1}(x_1, \dots, x_{2^{k-1}}), f_{k-1}(x_{2^{k-1}+1}, \dots, x_{2^k})) & \text{if } k \text{ is even;} \\ \text{OR}(f_{k-1}(x_1, \dots, x_{2^{k-1}}), f_{k-1}(x_{2^{k-1}+1}, \dots, x_{2^k})) & \text{otherwise.} \end{cases}$$

Theorem 1.2 *This is the first theorem.*

Proof: This is the proof of the first theorem. We show how to write pseudo-code now.

Consider a comparison between x and y :

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if  $x$  or  $y$  or both are in  $S$  then
    answer accordingly
else
    Make the element with the larger score (say  $x$ ) win the comparison
    if  $F(x) + F(y) < \frac{n}{t-1}$  then
         $F(x) \leftarrow F(x) + F(y)$ 
         $F(y) \leftarrow 0$ 
    else
         $S \leftarrow S \cup \{x\}$ 
         $r \leftarrow r + 1$ 
    endif
endif

```

This concludes the proof. ■

1.4 Next topic

Here is a citation, just for fun [CW87].

References

- [CW87] D. COPPERSMITH and S. WINOGRAD, “Matrix multiplication via arithmetic progressions,” *Proceedings of the 19th ACM Symposium on Theory of Computing*, 1987, pp. 1–6.