



SVMs with Slack

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Based roughly on the slides of David Sontag

$$\max_{\lambda \geq 0} -\frac{1}{2} \sum_i \sum_j \lambda_i \lambda_j y_i y_j x^{(i)T} x^{(j)} + \sum_i \lambda_i$$

such that

$$\sum_i \lambda_i y_i = 0$$

- The dual formulation only depends on inner products between the data points
 - Same thing is true if we use feature vectors instead

$$\max_{\lambda \geq 0} -\frac{1}{2} \sum_i \sum_j \lambda_i \lambda_j y_i y_j \Phi(x^{(i)})^T \Phi(x^{(j)}) + \sum_i \lambda_i$$

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- The dual formulation only depends on inner products between the data points
 - Same thing is true if we use feature vectors instead

The Kernel Trick



- For some feature vectors, we can compute the inner products quickly, even if the feature vectors are very large
- This is best illustrated by example

- Let $\phi(x_1, x_2) = \begin{bmatrix} x_1 x_2 \\ x_2 x_1 \\ x_1^2 \\ x_2^2 \end{bmatrix}$

- $$\begin{aligned} \phi(x_1, x_2)^T \phi(z_1, z_2) &= x_1^2 z_1^2 + 2x_1 x_2 z_1 z_2 + x_2^2 z_2^2 \\ &= (x_1 z_1 + x_2 z_2)^2 \\ &= (x^T z)^2 \end{aligned}$$

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- $\phi(x_1, x_2)^T \phi(z_1, z_2) = x_1^2 z_1^2 + 2x_1 x_2 z_1 z_2 + x_2^2 z_2^2$
 $= (x_1 z_1 + x_2 z_2)^2$
 $= (x^T z)^2$

Reduces to a dot product in the original space

The Kernel Trick



- The same idea can be applied for the feature vector ϕ of all polynomials of degree (exactly) d
 - $\phi(x)^T \phi(z) = (x^T z)^d$
- More generally, a **kernel** is a function $k(x, z) = \phi(x)^T \phi(z)$ for some feature map ϕ
- Rewrite the dual objective

$$\max_{\lambda \geq 0, \sum_i \lambda_i y_i = 0} -\frac{1}{2} \sum_i \sum_j \lambda_i \lambda_j y_i y_j k(x^{(i)}, x^{(j)}) + \sum_i \lambda_i$$

Examples of Kernels



- Polynomial kernel of degree exactly d
 - $k(x, z) = (x^T z)^d$
- General polynomial kernel of degree d for some c
 - $k(x, z) = (x^T z + c)^d$
- Gaussian kernel for some σ
 - $k(x, z) = \exp\left(\frac{-\|x-z\|^2}{2\sigma^2}\right)$
 - The corresponding ϕ is infinite dimensional!
- So many more...

- Consider the Gaussian kernel

$$\begin{aligned}\exp\left(\frac{-\|x - z\|^2}{2\sigma^2}\right) &= \exp\left(\frac{-(x - z)^T(x - z)}{2\sigma^2}\right) \\ &= \exp\left(\frac{-\|x\|^2 + 2x^T z - \|z\|^2}{2\sigma^2}\right) \\ &= \exp\left(-\frac{\|x\|^2}{2\sigma^2}\right) \exp\left(-\frac{\|z\|^2}{2\sigma^2}\right) \exp\left(\frac{x^T z}{\sigma^2}\right)\end{aligned}$$

- Use the Taylor expansion for $\exp()$

$$\exp\left(\frac{x^T z}{\sigma^2}\right) = \sum_{n=0}^{\infty} \frac{(x^T z)^n}{\sigma^{2n} n!}$$

- Consider the Gaussian kernel

$$\begin{aligned}\exp\left(\frac{-\|x - z\|^2}{2\sigma^2}\right) &= \exp\left(\frac{-(x - z)^T(x - z)}{2\sigma^2}\right) \\ &= \exp\left(\frac{-\|x\|^2 + 2x^T z - \|z\|^2}{2\sigma^2}\right) \\ &= \exp\left(-\frac{\|x\|^2}{2\sigma^2}\right) \exp\left(-\frac{\|z\|^2}{2\sigma^2}\right) \exp\left(\frac{x^T z}{\sigma^2}\right)\end{aligned}$$

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Polynomial kernels of every degree!

- Bigger feature space increases the possibility of overfitting
 - Large margin solutions may still generalize reasonably well
- Alternative: add “penalties” to the objective to disincentivize complicated solutions

$$\min_w \frac{1}{2} \|w\|^2 + c \cdot (\# \text{ of misclassifications})$$

- Not a quadratic program anymore (in fact, it’s NP-hard)
- Similar problem to counting the number of misclassifications, no notion of how badly the data is misclassified

- Allow misclassification
 - Penalize misclassification linearly (just like in the perceptron algorithm)
 - Again, easier to work with than counting misclassifications
 - Objective stays convex
- Will let us handle data that isn't linearly separable!

$$\min_{w,b,\xi} \frac{1}{2} \|w\|^2 + c \sum_i \xi_i$$

such that

$$y_i(w^T x^{(i)} + b) \geq 1 - \xi_i, \text{ for all } i$$

$$\xi_i \geq 0, \text{ for all } i$$

$$\min_{w,b,\xi} \frac{1}{2} \|w\|^2 + c \sum_i \xi_i$$

such that

$$y_i(w^T x^{(i)} + b) \geq 1 - \xi_i, \text{ for all } i$$

$$\xi_i \geq 0, \text{ for all } i$$

Potentially allows some points to be misclassified/inside the margin

$$\min_{w,b,\xi} \frac{1}{2} \|w\|^2 + c \sum_i \xi_i$$

Constant c determines degree to which slack is penalized

such that

$$y_i(w^T x^{(i)} + b) \geq 1 - \xi_i, \text{ for all } i$$

$$\xi_i \geq 0, \text{ for all } i$$

$$\min_{w,b,\xi} \frac{1}{2} \|w\|^2 + c \sum_i \xi_i$$

such that

$$y_i(w^T x^{(i)} + b) \geq 1 - \xi_i, \text{ for all } i$$

$$\xi_i \geq 0, \text{ for all } i$$

- How does this objective change with c ?

$$\min_{w,b,\xi} \frac{1}{2} \|w\|^2 + c \sum_i \xi_i$$

such that

$$y_i(w^T x^{(i)} + b) \geq 1 - \xi_i, \text{ for all } i$$

$$\xi_i \geq 0, \text{ for all } i$$

- How does this objective change with c ?
 - As $c \rightarrow \infty$, requires a perfect classifier
 - As $c \rightarrow 0$, allows arbitrary classifiers (i.e., ignores the data)

$$\min_{w,b,\xi} \frac{1}{2} \|w\|^2 + c \sum_i \xi_i$$

such that

$$y_i(w^T x^{(i)} + b) \geq 1 - \xi_i, \text{ for all } i$$

$$\xi_i \geq 0, \text{ for all } i$$

- How should we pick c ?

$$\min_{w,b,\xi} \frac{1}{2} \|w\|^2 + c \sum_i \xi_i$$

such that

$$y_i(w^T x^{(i)} + b) \geq 1 - \xi_i, \text{ for all } i$$

$$\xi_i \geq 0, \text{ for all } i$$

- How should we pick c ?
 - Divide the data into three pieces training, testing, and **validation**
 - Use the validation set to tune the value of the **hyperparameter** c

- General learning strategy
 - Build a classifier using the training data
 - Select hyperparameters using validation data
 - Evaluate the chosen model with the selected hyperparameters on the test data

How can we tell if we overfit the training data?

- Gather Data + Labels
- Select feature vectors
- Randomly split into three groups
 - Training set
 - Validation set
 - Test set
- Experimentation cycle
 - Select a “good” hypothesis from the hypothesis space
 - Tune hyperparameters using validation set
 - Compute accuracy on test set (fraction of correctly classified instances)

$$\min_{w,b,\xi} \frac{1}{2} \|w\|^2 + c \sum_i \xi_i$$

such that

$$y_i(w^T x^{(i)} + b) \geq 1 - \xi_i, \text{ for all } i$$

$$\xi_i \geq 0, \text{ for all } i$$

- What is the optimal value of ξ for fixed w and b ?

$$\min_{w,b,\xi} \frac{1}{2} \|w\|^2 + c \sum_i \xi_i$$

such that

$$y_i(w^T x^{(i)} + b) \geq 1 - \xi_i, \text{ for all } i$$

$$\xi_i \geq 0, \text{ for all } i$$

- What is the optimal value of ξ for fixed w and b ?
 - If $y_i(w^T x^{(i)} + b) \geq 1$, then $\xi_i = 0$
 - If $y_i(w^T x^{(i)} + b) < 1$, then $\xi_i = 1 - y_i(w^T x^{(i)} + b)$

$$\min_{w,b,\xi} \frac{1}{2} \|w\|^2 + c \sum_i \xi_i$$

such that

$$y_i(w^T x^{(i)} + b) \geq 1 - \xi_i, \text{ for all } i$$

$$\xi_i \geq 0, \text{ for all } i$$

- We can formulate this slightly differently
 - $\xi_i = \max\{0, 1 - y_i(w^T x^{(i)} + b)\}$
 - Does this look familiar?
 - Hinge loss provides an upper bound on Hamming loss

Hinge Loss Formulation



- Obtain a new objective by substituting in for ξ

$$\min_{w,b} \frac{1}{2} \|w\|^2 + c \sum_i \max\{0, 1 - y_i(w^T x^{(i)} + b)\}$$

Can minimize with gradient descent!

Hinge Loss Formulation



- Obtain a new objective by substituting in for ξ

$$\min_{w,b} \frac{1}{2} \|w\|^2 + c \sum_i \max\{0, 1 - y_i(w^T x^{(i)} + b)\}$$



- If the data is imbalanced (i.e., more positive examples than negative examples), may want to evenly distribute the error between the two classes

$$\min_{w,b,\xi} \frac{1}{2} \|w\|^2 + \frac{c}{N_+} \sum_{i:y_i=1} \xi_i + \frac{c}{N_-} \sum_{i:y_i=-1} \xi_i$$

such that

$$y_i(w^T x^{(i)} + b) \geq 1 - \xi_i, \text{ for all } i$$

$$\xi_i \geq 0, \text{ for all } i$$

Dual of Slack Formulation



$$\min_{w,b,\xi} \frac{1}{2} \|w\|^2 + c \sum_i \xi_i$$

such that

$$y_i(w^T x^{(i)} + b) \geq 1 - \xi_i, \text{ for all } i$$

$$\xi_i \geq 0, \text{ for all } i$$

Dual of Slack Formulation



$$L(w, b, \xi, \lambda, \mu) = \frac{1}{2} w^T w + c \sum_i \xi_i + \sum_i \lambda_i (1 - \xi_i - y_i (w^T x^{(i)} + b)) + \sum_i -\mu_i \xi_i$$

Convex in w, b, ξ , so take derivatives to form the dual

$$\frac{\partial L}{\partial w_k} = w_k + \sum_i -\lambda_i y_i x_k^{(i)} = 0$$

$$\frac{\partial L}{\partial b} = \sum_i -\lambda_i y_i = 0$$

$$\frac{\partial L}{\partial \xi_k} = c - \lambda_k - \mu_k = 0$$

Dual of Slack Formulation



$$\max_{\lambda \geq 0} -\frac{1}{2} \sum_i \sum_j \lambda_i \lambda_j y_i y_j x^{(i)T} x^{(j)} + \sum_i \lambda_i$$

such that

$$\sum_i \lambda_i y_i = 0$$

$$c \geq \lambda_i \geq 0, \text{ for all } i$$

- We argued, intuitively, that SVMs generalize better than the perceptron algorithm
 - How can we make this precise?
 - Coming soon... but first...

- Where are we headed?
 - Other simple hypothesis spaces for supervised learning
 - k nearest neighbor
 - Decision trees
 - Learning theory
 - Generalization and PAC bounds
 - VC dimension
 - Bias/variance tradeoff