

Semi-supervised learning by search of optimal target vector

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Abstract

We introduce a semi-supervised learning estimator which tends to the first kernel principal component as the number of labeled points vanishes. We show application of the proposed method for dimensionality reduction and develop a semi-supervised regression and classification algorithm for transductive inference.

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1. Introduction

The problem of effectively combining *unlabeled* data with *labeled* data, semi-supervised learning, is of central importance in machine learning; see, for example, [Zhu et al. \(2003b, 2004\)](#) and [Chapelle and Zien \(2005\)](#) and references therein. Semi-supervised learning methods usually assume that adjacent points and/or points in the same structure (group, cluster) should have similar labels; one may assume that data are situated on a low dimensional manifold which can be approximated by a weighted discrete graph whose vertices are identified with the empirical (labeled and unlabeled) data points. This can be seen as a form of regularization ([Smola and Kondor, 2003](#)). A common feature of these methods, see also [Argyriou et al. \(2006\)](#), is that, as the number of labeled points vanishes, the solution tends to the constant vector. An interesting survey on semi-supervised learning literature may be found on the web ([Zhu, 2006](#)). Improving regression with unlabeled data is the problem considered in ([Zhou and Li, 2005](#)), where co-training is achieved using k -NN regressors.

A statistical physics approach, based on the Potts model, is described in ([Getz et al., 2005](#)). An issue closely related to semi-supervised learning is active learning: some attempts to combine active learning and semi-supervised learning has been made ([Zhu et al., 2003a](#)).

The purpose of this work is to introduce a semi-supervised learning estimator which, as the number of labeled points vanishes, tends to the first kernel principal component ([Schölkopf et al., 1998](#)); when a suitable number of labeled points is available, it may be used for transductive inference ([Vapnik, 1982](#)). Our approach is based on the following fact. Given an unlabeled data-set, its first kernel principal component is such that, treating it as target vector, supervised kernel ridge regression provides the minimum training error. Now, suppose that you are given a partially labeled data-set: as it will be described in the next section, still one may look for the target vector minimizing the training error. This optimal target vector may be seen as the generalization of the first kernel principal component to the semi-supervised case.

The paper is organized as follows. In Section 2 we describe our approach, while in Section 3 the experiments we performed are described. Some conclusions are drawn in Section 4.

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2. Methods

2.1. Kernel ridge regression

We briefly recall the properties of kernel ridge regression (KRR), while referring the reader to [Shawe-Taylor and Cristianini \(2004\)](#) for further technical details. Let us consider a set of ℓ independent, identically distributed data $S = \{(\mathbf{x}_i, y_i)\}_{i=1}^{\ell}$, where \mathbf{x}_i is the n -dimensional vector of input variables and y_i is the scalar output variable. Data are drawn from an unknown probability distribution; we assume that both \mathbf{x} and y have been centered, i.e. they have been linearly transformed to have zero mean. The regularized linear predictor is $y = \mathbf{w} \cdot \mathbf{x}$, where \mathbf{w} minimizes the following functional:

$$L(\mathbf{w}) = \sum_{i=1}^{\ell} (y_i - \mathbf{w} \cdot \mathbf{x}_i)^2 + \lambda \|\mathbf{w}\|^2. \quad (1)$$

Here $\|\mathbf{w}\| = \sqrt{\mathbf{w} \cdot \mathbf{w}}$ and $\lambda > 0$ is the regularization parameter. For $\lambda = 0$, the predictor (1) has the following property, called IIV property and introduced in ([Ancona and Stramaglia, 2006](#)): it is invariant when new variables, statistically independent of input and target variables, are added to the set of input variables. One may show that this invariance property holds, for (1), also at finite $\lambda > 0$.

KRR is the *kernel* version of the previous predictor. Calling $\mathbf{y} = (y_1, y_2, \dots, y_{\ell})^{\top}$ the vector formed by the ℓ values of the output variable and $K(\cdot, \cdot)$ being a positive definite symmetric function, the predictor has the following form:

$$y = f(\mathbf{x}) = \sum_{i=1}^{\ell} c_i K(\mathbf{x}_i, \mathbf{x}), \quad (2)$$

where coefficients $\{c_i\}$ are given by

$$\mathbf{c} = (\mathbf{K} + \lambda \mathbf{I})^{-1} \mathbf{y}, \quad (3)$$

\mathbf{K} being the $\ell \times \ell$ matrix with elements $K(\mathbf{x}_i, \mathbf{x}_j)$. Eq. (2) may be seen to correspond to a linear predictor in the feature space

$$\Phi(\mathbf{x}) = (\sqrt{\alpha_1} \psi_1(\mathbf{x}), \sqrt{\alpha_2} \psi_2(\mathbf{x}), \dots, \sqrt{\alpha_N} \psi_N(\mathbf{x}), \dots),$$

where α_i and ψ_i are the eigenvalues and eigenfunctions of the integral operator with kernel K . One may show ([Ancona and Stramaglia, unpublished](#)) that, for KRR predictors with nonlinear kernels, the IIV property does not generically hold, even for those kernels, discussed in ([Ancona and Stramaglia, 2006](#)), for which the property holds at $\lambda = 0$. Regularization breaks the IIV invariance in those cases.

Due to (2) and (3), the predicted output vector $\bar{\mathbf{y}}$, in correspondence of the *true* target vector \mathbf{y} , is given by $\bar{\mathbf{y}} = \mathbf{G}\mathbf{y}$, where the symmetric matrix \mathbf{G} is given by

$$\mathbf{G} = \mathbf{K}(\mathbf{K} + \lambda \mathbf{I})^{-1}. \quad (4)$$

Note that matrix \mathbf{G} depends only on the distribution of $\{\mathbf{x}\}$ values: \mathbf{G} embodies information about the structures pres-

ent in $\{\mathbf{x}\}$ data-set. Indeed, for $i \neq j$, the matrix element G_{ij} quantifies how much the target value of the j th point influences the estimate of the target of point i . Let us now consider the leave-one-out scheme; let data point i be removed from the data-set and the model be trained using the remaining $\ell - 1$ points. We denote \tilde{y}_i the target value thus predicted, in correspondence of \mathbf{x}_i . It is well known ([Shawe-Taylor and Cristianini, 2004](#)) that the leave-one-out-error $\tilde{y}_i - y_i$ and the training error obtained using the whole data-set $\bar{y}_i - y_i$ satisfy:

$$\tilde{y}_i - y_i = \frac{\bar{y}_i - y_i}{1 - G_{ii}}. \quad (5)$$

It is worth stressing that, given a kernel function, the corresponding features $\psi_{\gamma}(\mathbf{x})$ are not centered in general. One can show ([Schölkopf et al., 1998](#)) that centering the features ($\psi_{\gamma} \rightarrow \psi_{\gamma} - \langle \psi_{\gamma} \rangle$, for all γ) amounts to perform the following transformation on the kernel matrix:

$$\mathbf{K} \rightarrow \tilde{\mathbf{K}} = \mathbf{K} - \mathbf{I}_{\ell} \mathbf{K} - \mathbf{K} \mathbf{I}_{\ell} + \mathbf{I}_{\ell} \mathbf{K} \mathbf{I}_{\ell},$$

where $(\mathbf{I}_{\ell})_{ij} = 1/\ell$, and to work with the centered kernel $\tilde{\mathbf{K}}$. In the following we will assume that the kernel matrix \mathbf{K} has been centered.

2.2. Optimal target vector

The training error of the KRR model is proportional to $(\mathbf{y} - \mathbf{G}\mathbf{y})^{\top}(\mathbf{y} - \mathbf{G}\mathbf{y}) = \mathbf{y}^{\top} \mathbf{H} \mathbf{y}$, where $\mathbf{H} = \mathbf{I} - 2\mathbf{G} + \mathbf{G}\mathbf{G}$ is a symmetric and positive matrix. In the unsupervised case the data-set is made of \mathbf{x} points, $\{\mathbf{x}_i\}_{i=1}^{\ell}$, the target function \mathbf{y} is missing. However we may pose the following question: what is the vector $\mathbf{y} \in \mathbf{R}^{\ell}$ such that treating it as the target vector leads to the best fit, i.e. the minimum training error $\mathbf{y}^{\top} \mathbf{H} \mathbf{y}$? We expect that this *optimal* target vector would bring information about the structures present in the data. To avoid the trivial solution $\mathbf{y} = \mathbf{0}$, we constrain the target vector to have unit norm, $\mathbf{y}^{\top} \mathbf{y} = 1$; it follows that the optimal vector is the normalized eigenvector of \mathbf{H} with the smallest eigenvalue. On the other hand, matrix \mathbf{H} is a function of matrix \mathbf{K} : hence it has the same eigenvectors of \mathbf{K} while the corresponding eigenvalues μ_H and μ_K are related by the following monotonically decreasing correspondence:

$$\mu_H = \left(1 - \frac{\mu_K}{\mu_K + \lambda}\right)^2.$$

Therefore, independently of λ , the smallest eigenvalue of \mathbf{H} corresponds to the largest eigenvalue of \mathbf{K} , and the optimal vector coincides with the first kernel principal component. To conclude this subsection, we have shown that the method in ([Schölkopf et al., 1998](#)) may be motivated also as the search for the optimal target vector.

The notion of optimal target vector has been introduced in ([Angelini et al., 2006](#)), where it was supposed to have binary entries, thus leading to a kernel method for dichotomic clustering consisting in finding the ground state of a class of Ising models. In this work the entries of the optimal target vector are assumed to be real valued.

2.3. Semi-supervised learning

Now we consider the case that we are given a set $S = \{\mathbf{x}_i\}_{i=1}^{\ell}$ of data points with unknown targets $\{t_i\}_{i=1}^{\ell}$, and a set $S' = \{(\mathbf{x}_j, u_j)\}_{j=\ell+1}^N$, where $N = \ell + m$, of input–output data. Without loss of generality we assume that the labeled points belong to two classes, and take $u_j \in \{-1/\sqrt{N}, +1/\sqrt{N}\}$ for all j 's. The N dimensional full vector of targets \mathbf{y} is obtained appending $\{t\}$ (unknown) and $\{u\}$ (known) values:

$$\mathbf{y} = (\mathbf{t}^\top \mathbf{u}^\top)^\top.$$

Keeping the kernel and λ fixed, we look for the unit norm target vector \mathbf{y} minimizing the training error $\mathbf{y}^\top \mathbf{H} \mathbf{y}$. The $N \times N$ matrix \mathbf{H} has the block structure

$$\mathbf{H} = \begin{pmatrix} \mathbf{H}_0 & \mathbf{H}_1 \\ \mathbf{H}_1^\top & \mathbf{H}_2 \end{pmatrix},$$

where \mathbf{H}_0 is an $\ell \times \ell$ matrix. Neglecting a constant term, the optimal vector is determined by the vector \mathbf{t} minimizing

$$\mathcal{E}(\mathbf{t}) = \mathbf{t}^\top \mathbf{H}_0 \mathbf{t} + 2\mathbf{t}^\top \mathbf{H}_1 \mathbf{u} \quad (6)$$

under the constraint $\|\mathbf{t}\|^2 = 1 - \|\mathbf{u}\|^2$. The first term of \mathcal{E} favors projections of the ℓ points with great variance, whereas the second term measures their consistency with labeled points. Let us denote $\{\Psi_{\alpha'}\}$ and $\{\mu_{\alpha'}\}$ the eigenvectors and eigenvalues of \mathbf{H}_0 , sorted into increasing $\mu_{\alpha'}$. We express $\mathbf{t} = \sum_{\alpha'=1}^{\ell} \xi_{\alpha'} \Psi_{\alpha'}$. The coefficients $\xi_{\alpha'}$ for the minimum are given by

$$\xi_{\alpha'} = \frac{f_{\alpha'}}{\mu - \mu_{\alpha'}},$$

where $f_{\alpha'} = \Psi_{\alpha'}^\top \mathbf{H}_1 \mathbf{u}$, and μ is a Lagrange multiplier which must to be tuned to satisfy:

$$g(\mu) = \sum_{\alpha'=1}^{\ell} \left(\frac{f_{\alpha'}}{\mu - \mu_{\alpha'}} \right)^2 = 1 - \|\mathbf{u}\|^2. \quad (7)$$

Eq. (7) has always at least one solution with $\mu < \mu_1$, see Fig. 1, and usually this is the one minimizing \mathcal{E} . However all the solutions of (7) must be compared according to their energies \mathcal{E} ; those corresponding to the lowest \mathcal{E} , \mathbf{y}^\star , is then selected. Clearly as $m \rightarrow 0$ one recovers the first eigenvector of \mathbf{H}_0 , i.e. the first kernel principal component: \mathbf{y}^\star thus constitutes a generalization of the latter to the semi-supervised case. To construct the other generalized kernel principal components, we make the following transformation on matrix \mathbf{H} :

$$\widetilde{\mathbf{H}} = \mathbf{H} - \mathbf{P}^\star \mathbf{H} - \mathbf{H} \mathbf{P}^\star + \mathbf{P}^\star \mathbf{H} \mathbf{P}^\star,$$

where $\mathbf{P}^\star = \mathbf{y}^\star \mathbf{y}^{\star\top}$ is the projector on the linear subspace spanned by \mathbf{y}^\star . The symmetric matrix $\widetilde{\mathbf{H}}$ has the lowest eigenvalue equal to zero and corresponding to eigenvector \mathbf{y}^\star . The system of eigenvectors of $\widetilde{\mathbf{H}}$ constitutes a generalization of kernel principal components to the semi-supervised case.

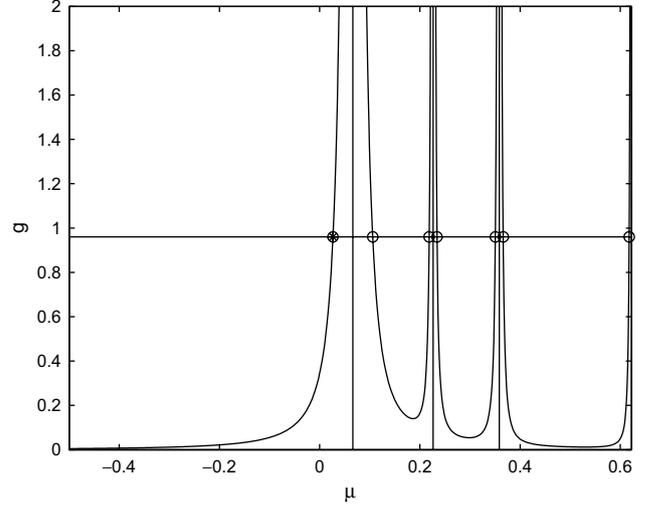


Fig. 1. The solutions of Eq. (7) are depicted, for a typical instance of four labeled points in the IRIS data-set. The star corresponds to the solution with $\mu < \mu_1$, which has the smallest energy \mathcal{E} .

3. Experiments

3.1. Generalizing kernel principal components

Now we present some simulations of the proposed method, focusing on the dimensionality reduction issue and comparing with fully unsupervised kernel principal component analysis. We consider three well-known datasets: IRIS (100 points in a four-dimensional space, second and third classes, versicolor and virginica); colon cancer data-set of Alon (1999), consisting in 40 tumor and 22 normal colon tissues samples, each sample being described by the 100 most discriminant genes; the leukemia data-set of Golub (1999), consisting of samples of tissues of bone marrow samples, 47 affected by acute myeloid leukemia (AML) and 25 by acute lymphoblastic leukemia (ALL), each sample being described by the 500 most discriminant genes. The following question is addressed: is \mathbf{y}^\star more correlated to the true labels than the fully unsupervised first kernel principal component? Here we restrict our analysis to the linear kernel, and take $\lambda = 1$ (results are stable against variations of λ).

We start with IRIS and proceed as follows. We randomly select $m = 4$ points and, treating them as labeled, we find the system of eigenvectors of $\widetilde{\mathbf{H}}$. Then we evaluate the linear correlation R between the eigenvectors and the true labels of the whole data-set. The distributions of R for the four eigenvectors are depicted in Fig. 2. We observe that in most cases the vector \mathbf{y}^\star is more correlated with the true classes than the fully unsupervised principal component: the one-dimensional projection of data onto \mathbf{y}^\star is more informative than the first principal component. However there are situations where use of labeled points leads to poor results; a typical example is depicted in Fig. 3. In Fig. 4, a situation is depicted where knowledge of labeled points leads to a relevant improvement: indeed the linear

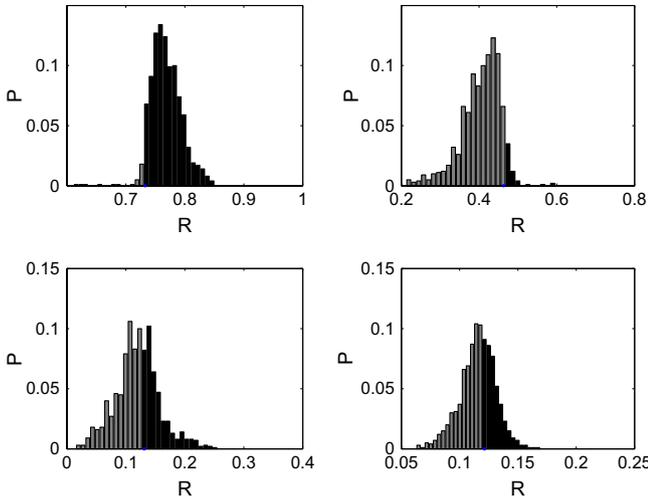


Fig. 2. Concerning IRIS data-set and $m = 4$, we depict the distribution (over 10,000 random selections of labeled points) of the linear correlation R between eigenvectors of \tilde{H} and the true labels. From the left to the right and the top to the bottom, we refer to the first, the second, the third and the fourth eigenvector. Grey (black) histogram bars denote values of R lower (greater) than those of the corresponding fully unsupervised principal component.

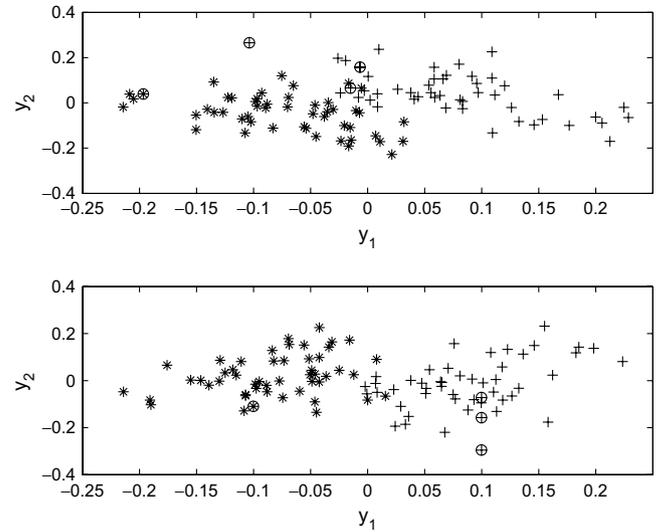


Fig. 4. (Top) The IRIS data-set is depicted in the plane of the first two principal components, \star versicolor, $+$ virginica. Four selected points are surrounded by a circle. (Bottom) The data-set is represented in the plane of the first two eigenvectors of \tilde{H} . The linear correlation between \mathbf{y}^\star and the true labels is, in this case, $R = 0.846$.

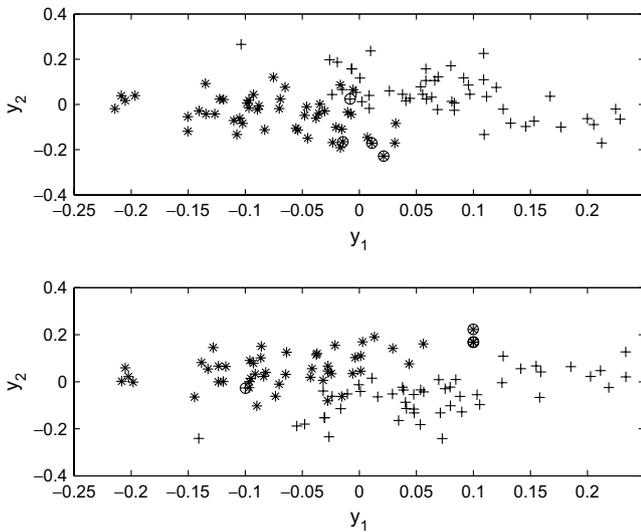


Fig. 3. (Top) The IRIS data-set is depicted in the plane of the first two principal components, \star versicolor, $+$ virginica. The linear correlation of the first principal component with the true labels is $R = 0.732$. Four selected points are surrounded by a circle. (Bottom) The data-set is represented in the plane of the first two eigenvectors of \tilde{H} . The linear correlation between \mathbf{y}^\star and the true labels is $R = 0.615$. (Note that two circles are almost overlapping and thus difficult to distinguish.)

correlation between \mathbf{y}^\star and the true labels is, in this case, $R = 0.846$, whilst for the first principal component it is $R = 0.732$.

In general, we denote f the fraction of instances such that \mathbf{y}^\star is more correlated to the true labels than the first principal component. In Fig. 5 we depict f as a function of $\bar{m} = m/N$ for the three data-sets here considered. At $\bar{m} = 0.16$ f is already nearly one. The semi-supervised

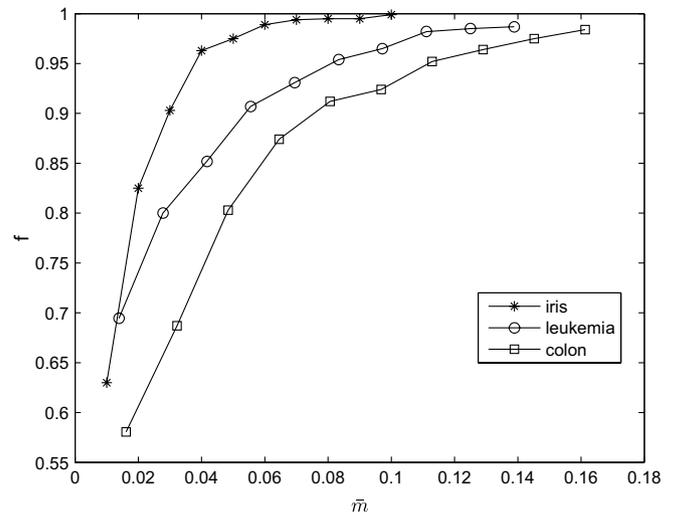


Fig. 5. The fraction f (see the text) is depicted as a function of \bar{m} for three data-sets here considered. 10,000 random selections of the labeled points are considered for each value of m and for each data-set.

method here proposed outperforms principal components almost always for large \bar{m} .

3.2. Transductive inference

In this subsection we demonstrate the effectiveness of the proposed approach for estimating the values of a function at a set of test points, given a set of input–output data points, without estimating (as an intermediate step) the regression function. First of all we note that, concerning transductive inference, our approach is similar to the transductive linear discrimination (TLD) approach developed in

(Chapelle et al., 1999), the main differences being that our definition of optimal vector deals with the training error whilst TLD deals with the LOO error, and a different constraint on \mathbf{t} .

The boston data-set is a well-known problem where one is required to estimate house prices according to various statistics based on 13 locational, economic and structural features from data collected by US Census Service in the Boston Massachusetts area. For $\ell = 5, 10, 15, 20, 25$, we partition the data-set of $N = 506$ observations randomly 100 times into a training set of $N - \ell$ observations and a testing set of ℓ observations. We use a Gaussian kernel with $\sigma = 1$ and set $\lambda = 1$; we check that these results are stable against variations of 30% for these parameters. The following constraint is used in the case of regression:

$$\|\mathbf{t}\|^2 = \frac{\ell}{m} \|\mathbf{u}\|^2.$$

In Table 1 we report the mean squared error (MSE) on the test set averaged over the 100 runs, for each value of ℓ , we obtain using the optimal target vector \mathbf{y}^* . In Table 1 we also report the MSE obtained using the classical KRR in the two step procedure: (i) estimation of the regression function using the training data-set (ii) calculation of the regression function at points of interest (test data-set). The improvement achieved using the optimal target approach, over classical KRR, is clear: the MSE by our method is always smaller than those by KRR.

We also consider five well-known data-sets of pattern recognition from UCI database: we evaluate the optimal target vector, points are then attributed to classes according to the sign of \mathbf{y}^* . We compare with the transductive linear discrimination (TLD) approach developed in (Chapelle et al., 1999); the performance of a classifier is measured by its average error over 100 partitions of the data-sets into training and testing sets. We use the linear kernel with $\lambda = 1$, still the results are stable to variations of λ . Obviously, our approach and TLD are applied to the same partitions of data-sets, so that the comparison is meaningful. The results are shown in Table 2: our approach outperforms TLD.

It is worth stressing that our results are obtained without a fine-tuning of parameters. The analysis of parameter λ , connected with regularization, will be discussed elsewhere. In particular, note that our definition of optimal

Table 1

The mean square error on the Boston data-set obtained using the optimal target (OT) approach and the classical kernel ridge regression (KRR) method

ℓ	OT	KRR
5	2.3790	3.6312
10	2.7938	4.0111
15	2.9460	4.1057
20	3.1024	4.1802
25	3.1569	4.1653

The size of the test set is ℓ .

Table 2

The percentage test error of transductive linear discrimination and optimal target approach, on five data-sets from UCI database

	TLD	OT
Diabetes	23.3	11.98
Titanic	22.4	6.52
Breast cancer	25.7	16.7
Heart	15.7	3.3
Thyroid	4.0	4.0

target vector fixes the relative importance of the two terms in Eq. (6).

4. Conclusions

We have presented a new approach to semi-supervised learning based on the notion of optimal target vector, the target vector such that KRR provides the minimum training error over all the possible target vectors. The proposed algorithm is characterized by the fact that the first kernel principal component is recovered as the cardinality of labeled points vanishes; hence it may be seen as a semi-supervised generalization of kernel principal components analysis. The effectiveness of the proposed approach for transductive inference has also been demonstrated.

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