

Solving Non-Linear SVM in Linear Time? A Nyström Approximated SVM with Applications to Image Classification

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Outline

- Introduction
- The Nyström Method for Kernel Approximation
- The Nyström Method for Linear SVM Classification
- Experiments and Conclusions

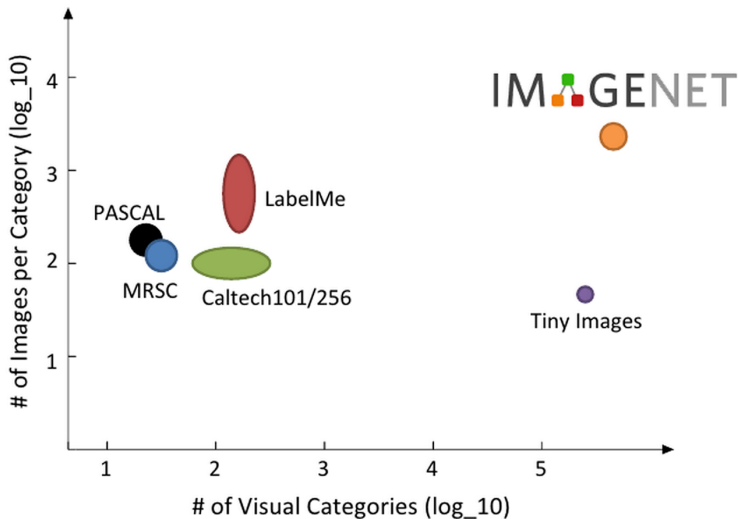
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Visual Classification: Faces, Objects, and Beyond



Example: Some Image Classification Data Sets



We Have Known...

- Non-linear SVM: powerful but slow
- Linear SVM: simple but fast

Paper: “Training Linear SVMs in Linear Time” by Joachims
KDD’06

Software: LIBLINEAR, VW, etc.

We Had Always Wondered...

- But we want something **powerful** and **fast**: train faster than non-linear SVM and generate a more accurate model than linear SVM.

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Yes. Do approximation!

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Definitions and a Brief Review (1/2)

- Input Data: $\{(\mathbf{y}, X)\} = \{(y_i, \mathbf{x}_i)\}_{i=1}^{\ell}$. y_i : label, \mathbf{x}_i : feature vector.
- (Non-zero) dimension of \mathbf{x}_i : d
- Non-linear mapping $\phi(\mathbf{x})$ (e.g. bi-gram features)
- Kernel function: $K(\mathbf{u}, \mathbf{v}) = \phi(\mathbf{u})^T \phi(\mathbf{v})$, usually computed in linear time.
- For ease of representation, for $U = [\mathbf{u}_1, \dots, \mathbf{u}_{\ell}]$ and $V = [\mathbf{v}_1, \dots, \mathbf{v}_{\ell}]$, we define $Q = K(U, V)$, where $Q_{ij} = K(\mathbf{u}_i, \mathbf{v}_j)$

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- Lower bound for data storage and training: $\Omega(\ell d)$.

Definitions and a Brief Review (2/2)

- Primal SVM:

$$\min_{\mathbf{w}, b} \frac{1}{2} \mathbf{w}^T \mathbf{w} + C \sum_{i=1}^{\ell} \max(1 - y_i \mathbf{w}^T \phi(\mathbf{x}_i), 0)$$

- Dual SVM:

$$\begin{aligned} \min_{\alpha} \quad & \frac{1}{2} \alpha^T Q \alpha - \mathbf{e}^T \alpha \\ \text{s.t.} \quad & 0 \leq \alpha_i \leq C \quad \forall i. \end{aligned}$$

- Primal-Dual Correspondence: $\mathbf{w} = \sum_{i=1}^{\ell} y_i \alpha_i \phi(\mathbf{x}_i)$

Kernel in Non-linear SVM

- Dual form:

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Space: $O(\ell^2)$.
- $1M$ images: $1M$ times more computational time than the linear counterpart.

Nyström Method

- Sample $\tilde{\ell} (\ll \ell)$ feature vectors from X with a basis set $B = \{\mathbf{b}_i\}_{i=1}^{\tilde{\ell}}$.
- The approximated kernel: $Q \sim \tilde{Q} = P^T W^{-1} P$, where $P_{ij} = K(\mathbf{x}_i \mathbf{b}_j)$ and $W_{ij} = K(\mathbf{b}_i, \mathbf{b}_j)$.

$$Q \approx P \times W_{\tilde{\ell}}^{-1} \times P^T$$

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- Time: Basis Selection + $O(\ell^2 \max(\tilde{\ell}, d))$ overall. (Alright...)
Space: $O(\ell \max(\tilde{\ell}, d))$. (Good! Don't know how large is $\tilde{\ell}$..)

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- Time: Basis Selection + $O(\ell^2 \max(\tilde{\ell}, d))$ overall. (Alright...)
Space: $O(\ell \max(\tilde{\ell}, d))$. (Good! Don't know how large is $\tilde{\ell}$..)
- Exists studies on how to get a compact and representative B .

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An Equivalent Representation (1/2)

- Bottleneck: kernel matrix Q of size $O(\ell^2)$.
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- $Q = \tilde{X}^T \tilde{X}$ by Cholesky decomposition. (This is valid because Q is PSD by definition.)
- Investigate the columns of $\tilde{X} = [\tilde{\mathbf{x}}_1 \dots \tilde{\mathbf{x}}_\ell]$. We have $\tilde{\mathbf{x}}_i^T \tilde{\mathbf{x}}_j = Q_{ij} = \phi(\mathbf{x}_i)^T \phi(\mathbf{x}_j) = K(\mathbf{x}_i, \mathbf{x}_j)$.

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- We represent the kernelized linear products as regular linear products. Let's call \tilde{X} a compact representation.

An Equivalent Representation (2/2)

- SVM Dual:

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- Issue: computing $\tilde{\mathbf{x}}_i$ requires the computation of the ℓ^2 -sized kernel.

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Time: Basis selection time + $O(\ell \tilde{\ell} n)$ overall.
Space: $O(\ell \max(\tilde{\ell}, d))$.
- If we set our basis size, $\tilde{\ell}$, as d . The space consumption is optimal, but the speed still depends on the basis selection part.

Another View of Basis Selection (1/2)

- We view RP as input data and do feature selection on it to get a more compact feature set.
- Recall that: $P_{:,i} = [K(\mathbf{x}_i, \mathbf{b}_1), \dots, K(\mathbf{x}_i, \mathbf{b}_{\tilde{\ell}})]^T$
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- This is not a basis selection algorithm because R introduces dependency between dimensions.
- We remove R ! Each dimension is then independent of other basis vector, we can view P as our linear SVM input data and do feature selection for basis selection.
- L1-regularized linear SVM which runs linear time in data size is used in the work.

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- $R^{-1} \mathbf{w}$ separates $R \mathbf{p}_+$ and $R \mathbf{p}_-$.
- When doing the linear transformation by R , we preserve separability.

A Linear Feature Selection Algorithm

Algorithm 2 Selection Algorithm, \mathcal{A}

Input Training data with labels (\mathbf{y}, X) . A kernel functions K . A number s , the total size of the bases. (Optional)

1. Get a set of basis, B^{big} , each with size $\sqrt{\ell}$. Randomly sample $\sqrt{\ell}$ instances with labels, $(\mathbf{y}^{subset}, X^{subset})$.
2. $X^{select} \leftarrow K(X^{subset}, B^{big})$.
3. Train L1-regularized SVM on $(\mathbf{y}^{subset}, X^{select})$ and a sparsity pattern \mathbf{w} for each class.
4. $B \leftarrow$ columns in B^{big} where the corresponding element in \mathbf{w} is not zero.
5. If s is defined, $B \leftarrow$ the s centroid generated by k-means of B_i (as proposed in [12].)

Return B

The Algorithm Workflow

- 1 Input data: (\mathbf{y}, X) , a kernel K .
- 2 Run some basis selection algorithm in linear time and get the basis B .
- 3 Compute the new data $\tilde{X} = K(X, B)\text{Chol}(K(B, B)^{-1})$.
- 4 Train on (\mathbf{y}, \tilde{X})

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Time: $O(\sqrt{\ell}\sqrt{\tilde{\ell}}d) + O(\ell\tilde{\ell}d)$ overall.

Space: $O(\ell \max(\tilde{\ell}, d))$.

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Experimental Settings

- We conduct experiments on two benchmark datasets: USPS and MNIST.
- We randomly split 70% of the data for training and the remaining 30% for testing.
- Repeat random split five times.
- We perform a five-fold cross validation to select the parameters γ and C .

Table: Dataset descriptions (with the number ℓ of instances and the dimension d of the data). The sizes for storing the data ℓd and the associated kernel matrices ℓ^2 are also listed.

	ℓ	d	kernel size ℓ^2	data size ℓd
USPS	7291	256	53M	2M
MNIST	60000	780	3.6G	47M

Discussions

- Our method achieved improved accuracy than linear SVMs
- The time for training and testing using our proposed model is comparable to that of linear SVMs
- The standard nonlinear SVM utilizes the full kernel matrix whose time complexity is quadratically scaled-up with ℓ .

Table: Comparisons of accuracy and computation time (in sec.) on three datasets. We denote our proposed Nyström approximated SVM as Nyström primal SVM below.

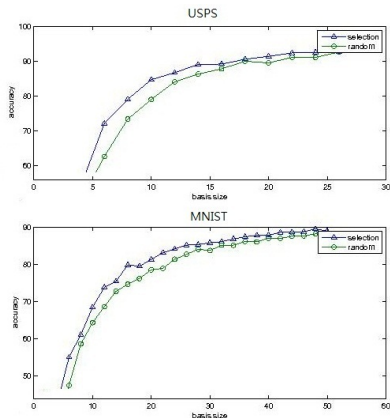
USPS	Accuracy	Training Time	Testing Time
Nyström primal SVM	97.057 ± 0.402	3.764	0.320
nonlinear SVM	98.007 ± 0.198	14.507	4.129
linear SVM	95.009 ± 0.275	2.274	0.079
MNIST	Accuracy	Training Time	Testing Time
Nyström primal SVM	93.833 ± 0.115	24.6092	2.006
nonlinear SVM	98.547 ± 0.066	3650.334	524.487
linear SVM	91.917 ± 0.077	14.510	0.381

Comparisons to Random Basis Selection

- To verify the effectiveness of our proposed basis selection approach, we compare the performance
 - Using the basis matrix determined by our method
 - Using the random sampling strategy
- We plot the recognition rates using these two different methods on the two datasets.
- Our selection method yields higher accuracy than random sampling when choosing the same basis size for most scenarios.

Comparisons to Random Basis Selection

Figure: Performance using our basis selection method (in blue) vs. random sampling (in green) on USPS (top) and MNIST (bottom) datasets.



Conclusion

- We proposed a method to solve an approximated dual SVM in the primal based on Nyström approximation. The new method scales linearly in time and space.
- Experiments compared by linear SVM, our method
 - achieved improved recognition accuracy
 - reported comparable computation time
- Both training and testing time and space using our approximated model was remarkably reduced compared to that of nonlinear SVMs.