

# Scalability of Struct SVM approaches

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<https://github.com/SoliElvis/structuredPredictionProject>

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# 1 Introduction

Structured prediction in machine learning is tasked with learning predictors where the labels on the data-points are more than simple tags but have inherent structure which implies the following:

- The number of potential labels for a given feature vector can grow exponentially with the input which makes traditional classification procedures intractable
- A certain intelligibility of the structure; hence a hope to leverage it to improve tractability

It is often quite hard to know in advance whether we can tackle a structured prediction problem with known approaches.

In this paper we discuss two different approaches to solving structured prediction problems, both focusing on a *large-margin approach* which translates into a support-vector machine - like problem formulation.

Let us introduce some notation which we will use throughout the paper. Define the dataset to be

$$S = \{x^{(i)}, y^{(i)}\}_{i=1}^n \in (\mathcal{X} \times \mathcal{Y})^n \quad (1)$$

If one were to frame the machine learning goal in the concisest and simplest way possible we could say that the goal is to *learn* a (parametrized) *predictor* function:

$$\begin{aligned} h_w &: \mathcal{X} \rightarrow \mathcal{Y} \\ &: \hat{x} \mapsto y \quad y \in \mathcal{Y}(\hat{x}) \end{aligned}$$

where  $\hat{x}$  is just some arbitrary sampled  $\hat{x}$  and we abuse notation and mean the set valued mapping which outputs the feasible label set for a given  $x$  by  $\mathcal{Y}(x)$

The traditional probabilistic approach is to compute  $h$  or its parameter by calculating the most likely parameter given conditioned on the observed data. However this is more often than not untractable in the structured prediction context as summed up in Taskar, Lacoste-Julien, and Jordan (2006)

In a large margin approach we wish to compute the predictor function the following way :

$$h_w(x) = \arg \max_{y \in \mathcal{Y}} \langle w, \phi(x, y) \rangle \quad (2)$$

where  $\phi$  is just the feature map for the dataset.

This is a constrained optimization problem and the structure of  $\mathcal{Y}$  clearly has a big influence on how well we can solve the problem as well as which method should work well.

The dual extragradient approach presented in Taskar, Lacoste-Julien, and Jordan (ibid.) leverages a saddle-point approach to the problem to tackle the problem with a first order method and moreover “this approach allows us to exploit the structure of  $W$  and  $Z$  separately, allowing for efficient solutions for a wider range of parameterizations and structures.”(ibid.)

Despite its improvements at the time the dual extragradient approach suffers from two main computational draw-backs:

1. It is not seperable/'stochasizable' which is a severe problem as machine learning has seen much of its success in recent years by optimizing through first-order sampled method, i.e. first order method which use a probabilistic approximation of the gradient through sampling instead of computing the actual gradient (which might be unfeasible).
2. The algorithm requires a projection step which can be expensive depending on the structure of  $\mathcal{Y}$ .

This leads us to consider the Block Seperable Frank Wolfe algorithm presented in Lacoste-Julien et al. (2013)

## 2 Preliminaries

### 2.1 Structured SVM N-slack formulation

Let us recall the basic goal; to construct an accurate linear classifier<sup>1</sup>

$$h_w(x) = \arg \max_{y \in \mathcal{Y}} \langle w, \phi(x, y) \rangle \quad (3)$$

In general finding the optimal separating hyperplane is an ill-defined problem. In the support vector machine (SVM) setting we want to find the separating hyperplane with the *largest margin*. The support vectors are the datapoints which lie on the the defined margins. It is not obvious that we should strive to completely separate the sets so we can include some slack variables. Indeed, some set of points might not be linearly separable but adding slack variables might allow one to misclassify some point but get a higher proportion of correctly classified points.

We call the following way to pose problem the  $n$ -slack formulation <sup>2</sup> of the problem :

$$\min_{w, \xi} \quad \frac{\lambda}{2} \|w\|^2 + \frac{1}{n} \sum_{i=1}^n \varepsilon_i \quad (4)$$

$$s.t. \quad \langle w, \psi_i(y) \rangle \geq L(y_i, y) - \varepsilon_i, \quad \forall i, \forall y \in \mathcal{Y}(x) = \mathcal{Y}_i \quad (5)$$

### 2.2 Loss-Augmented Decoding

Define  $\psi(y) := \phi(x^{(i)}, y^{(i)}) - \phi(x^{(i)}, y)$  and  $L_i(y) = L(y^{(i)}, y)$

$$H_i = \max_{y \in \mathcal{Y}_i} \{L_i(y) - \langle w, \psi_i(y) \rangle\} \quad (6)$$

$$\mathcal{H}_i = \arg \max_{y \in \mathcal{Y}_i} \{L_i(y) - \langle w, \psi_i(y) \rangle\} \quad (7)$$

**Proposition.** The max oracle is a convex upper bound to the task loss.

*Proof sketch:* The maximum of two convex (linear) functions is convex, and

$$L(y_i, h_w(x_i)) \leq L(y_i, h_w(x_i)) + \underbrace{\langle w, \psi_i(y) \rangle}_{\geq 0 \text{ by definition}} \quad (8)$$

$$\leq \max_{y \in \mathcal{Y}_i} L_i(y) - \langle w, \psi_i(y) \rangle \quad (9)$$

It is not hard to see thus that learning  $w$  amounts to the unconstrained problem,

$$\min_w \quad \frac{\lambda}{2} \|w\|^2 + \frac{1}{n} \sum_{i=1}^n \tilde{H}_i(w) \quad (10)$$

This last formulation into a non-smooth unconstrained problem is the one we will focus throughout this paper. Indeed it allows us to leverage convex analysis tools which emphasize replacing constraint sets with appropriate additions to the objective value (which often results in non-smooth problems)

<sup>1</sup>clearly we can easily extend to non-linear cases, with kernel maps for example

<sup>2</sup>see Moguerza and Muñoz (2006) for example

### 3 Extra Gradient Algorithm

#### 3.1 Saddle Point Formulation and Intuition

Let us focus on the loss-augmented formulation

$$\min_w \frac{\lambda}{2} \|w\|^2 + \frac{1}{n} \sum_{i=1}^n \tilde{H}_i(w) \quad (11)$$

which is an unconstrained convex (strongly ? TODO) problem, however it is non-smooth. What is important to note is that *objective functions is defined through the solution of another smaller optimization (maximization) problem*. Clearly it would be naive to just solve one after the other in batch. There are multiple approaches to this. A decade or so ago one formulation one could find was a QP formulation (TODO cite other than taskar).

In Taskar, Lacoste-Julien, and Jordan (2006) it is proposed to use first-order algorithms designed for saddle point problems in order to leverage the saddle point structure intrisc to the problem eventhough it is talked of as a minimization problem. Intuitively one could say that the harder the inference/decoding problem is, the closer we are to a true s

This enables us to consider a richer class of problems that we can tackle, especially for problems where dualizing yields a quadratic program (QP) that is not necessarily efficiently solvable; mainly because we are not leveraging the structure of the problem.

We first take a stab at the saddle-point formulation. It is not hard to see that the objective function of the non-smooth formulation of struct-svm is equivalent to the following:

$$\min_{\mathbf{w} \in W} \max_{\mathbf{z} \in Z} \sum_i (\mathbf{w}^T \mathbf{F}_i \mathbf{z}_i + \mathbf{c}_i^T \mathbf{z}_i - \mathbf{w}^T \mathbf{f}_i(\mathbf{y}_i)) \quad (12)$$

where the  $\mathbf{z}_i$ 's can be identified with the edge and node potentials of a markov network and satisfy the constraints of the structured problem. The terms  $\mathbf{F}_i$  correspond to the matrix with columns  $f(\mathbf{x}_i, \mathbf{y})$  over labels  $\mathbf{y}_i$ . The  $\mathbf{c}_i$ 's correspond to the costs of a  $\mathbf{z}_i$  and can be identified with the loss  $l$  for a label  $\mathbf{y}'_i$ .

In equation 12, the term that is opitmized is defined as:

$$L(\mathbf{w}, \mathbf{z}) \triangleq \sum_i \mathbf{w}^T \mathbf{F}_i \mathbf{z}_i + \mathbf{c}_i^T \mathbf{z}_i - \mathbf{w}^T \mathbf{f}_i(\mathbf{y}_i) \quad (13)$$

It is bilinear in  $w$  and  $z$ . We can then imagine two players represented by  $\mathbf{w}$  and  $\mathbf{z}$  that play a zero-sum game. They perform updates using gradients of the objective w.r.t. their parameters. They then project the result to the set of feasible points given by the constraints imposed on the structure. We usually consider Euclidean projections, as there are well-known problems where they are efficient to compute. However, as seen later, this is not the case for all problem. This is why Bregman projections will be introduced. Going back to the zero-sum game, we have the following operator that is used to perform the updates for both

players at the same time.

$$\begin{pmatrix} \nabla_{\mathbf{w}} L(\mathbf{w}, \mathbf{z}) \\ -\nabla_{\mathbf{z}_1} L(\mathbf{w}, \mathbf{z}) \\ \vdots \\ -\nabla_{\mathbf{z}_m} L(\mathbf{w}, \mathbf{z}) \end{pmatrix} = \underbrace{\begin{pmatrix} 0 & \mathbf{F}_1 & \dots & \mathbf{F}_m \\ -\mathbf{F}_1^T & & & \\ \vdots & \mathbf{0} & & \\ -\mathbf{F}_m^T & & & \end{pmatrix}}_{\mathbf{F}} \underbrace{\begin{pmatrix} \mathbf{w} \\ \mathbf{z}_1 \\ \vdots \\ \mathbf{z}_m \end{pmatrix}}_{\mathbf{u}} - \underbrace{\begin{pmatrix} \sum_i \mathbf{f}_i(\mathbf{y}_i) \\ \mathbf{c}_1 \\ \vdots \\ \mathbf{c}_m \end{pmatrix}}_{\mathbf{a}} = \mathbf{F}\mathbf{u} - \mathbf{a} \quad (14)$$

### 3.2 Duality and Gap function

We can measure the “goodness” of the parameters using the gap function  $G$ :

$$G(\mathbf{w}, \mathbf{z}) \triangleq \left[ \max_{\mathbf{z}' \in Z} L(\mathbf{w}, \mathbf{z}') - L^* \right] + \left[ L^* - \min_{\mathbf{w}' \in W} L(\mathbf{w}', \mathbf{z}) \right] \quad (15)$$

where  $L^*$  gives the result of the min-max of the objective  $L$ . When we have a non-optimal point (i.e. not a saddle point), the gap is strictly positive. At an optimal point, the gap is exactly equal to 0. Now the restricted gap is exactly the same but the min and max are computed over a set of parameters that are within a certain distance of the start point  $(\hat{\mathbf{u}}_{\mathbf{w}}, \hat{\mathbf{u}}_{\mathbf{z}}) \in U$ :

$$G_{D_{\mathbf{w}}, D_{\mathbf{z}}}(\mathbf{w}, \mathbf{z}) = \max_{\mathbf{z}' \in Z} [L(\mathbf{w}', \mathbf{z}') : d(\mathbf{z}, \mathbf{z}') \leq D_{\mathbf{z}}] - \left[ \min_{\mathbf{w}' \in W} L(\mathbf{w}', \mathbf{z}) : d(\mathbf{w}, \mathbf{w}') \leq D_{\mathbf{w}'} \right] \quad (16)$$

The motivation for using this restricted gap function is that if we start “close” to an optimal point, of course we will converge more rapidly to it. This can be seen in the convergence analysis of the method.

We mainly follow the intuition and proofs of Taskar, Lacoste-Julien, and Jordan, 2006.

The dual extragradient algorithm from Nesterov gives a convergence guarantee for the objective  $L$ .

We present a simple formulation of the algorithm:

**Initialize:** Choose  $\hat{\mathbf{u}} \in U$ , set  $\mathbf{s}^{-1} = 0$ .

**for**  $t = 0$  to  $t = \tau$  **do**

$\mathbf{v} = \Pi_U(\hat{\mathbf{u}} + \eta \mathbf{s}^{t-1})$

$\mathbf{u}^t = \Pi_U(\mathbf{v} - \eta(\mathbf{F}\mathbf{v} - \mathbf{a}))$

$\mathbf{s}^t = \mathbf{s}^{t-1} - (\mathbf{F}\mathbf{u}^t - \mathbf{a})$

**end for**

**return**  $\overline{\mathbf{u}}^\tau = \frac{1}{1+\tau} \sum_{t=0}^{\tau} \mathbf{u}^t$

Algorithm 1: Dual ExtraGradient

This algorithm has a lookahead step (i.e.  $\mathbf{v}$ ) that serves to perform the actual gradient update  $\mathbf{u}^t$ . The intuition behind the lookahead step is that given a function to optimize that is Lipschitz, Nesterov was able to show that we can upper bound  $f_D(\bar{\mathbf{u}}^n) = \max_y \{ \langle g(y), \bar{\mathbf{u}}^n - y \rangle : d(\hat{\mathbf{u}}, y) \leq D \}$ , where  $\bar{\mathbf{u}}^n$  is the weighted average over all the updates  $\mathbf{u}^t$  up to iteration  $n$ . The function  $g$  corresponds to the objective  $L$  in our setting. When value of  $f_D(\bar{\mathbf{u}}^n)$  gets close to 0, we have that the value  $g(y^*)$  for an optimal  $y^*$  is close to 0, which signifies that we have reached saddle point (i.e. what we wanted). Note that in the definition of  $f_D$ , we used a distance metric  $d$ . This corresponds to the Euclidean distance (or Bregman distance in non-Euclidean setting). The rojection operator  $\Pi_U$  in the algorithm simply projects a point back to the set  $U$  by finding the nearest point with respect to the distance metric used.



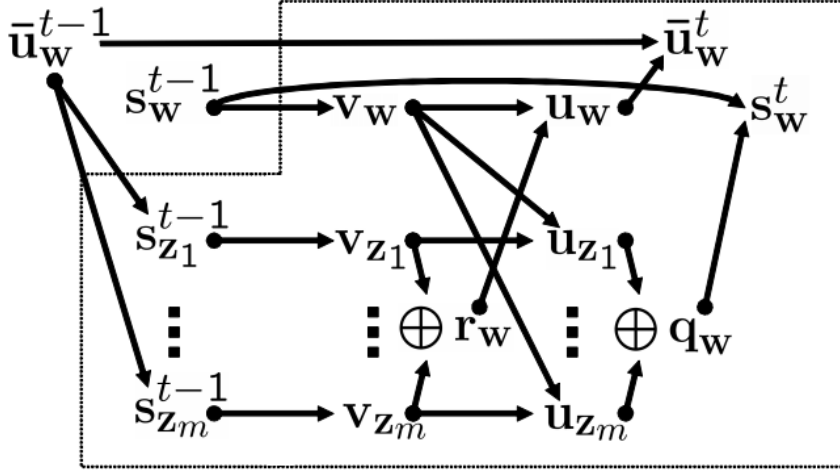


Figure 1: Memory efficient algorithm

### 3.2.1 Non-Euclidean setting

The main problem with the Euclidean projection operator is that for many problems, it is hard to compute the projection. Indeed for min-cut, we need to compute the partition function first, which is #P-complete. Thus, the authors of the paper introduced the Bregman operator, which computes the projection using the Bregman divergence. Using this operator has the great advantage of being easier to compute. We can see this for  $L1$  regularization. Computing a projection using  $L1$  distance is hard since it is not differentiable. Using the negative entropy as our function  $h$  (see 6), we get that the Bregman divergence is the KL divergence. This implies that we can differentiate the divergence to get the parameter that minimizes it. It is worth mentioning that for some problems, projections can still be hard to compute. This is why it may be wise to move to the FW algorithm especially if solving a linear problem over constraints the constraints is easy (or “easier”).

### 3.2.2 Memory-efficient tweak

In the dual extragradient algorithm, both a vector  $s^t$  and a vector  $\bar{u}^t$  are maintained. However, we can observe that the  $s_t$ ’s can be found using the running average  $\bar{u}^t$  since  $s^t = -(t+1) \sum_{i=0}^t (F\bar{u}^i - a)$ . We only have to store the vector  $\bar{u}^t$ . We can even do better when  $|Z| \gg |W|$  since  $\bar{u}^t = \{\bar{u}_w^t, \bar{u}_z^t\}$  and we only care about the part that corresponds to  $w$ .  $\bar{u}_z^t$  is maintained implicitly by storing a vector of size  $|W|$  (although we now need to store  $s_w^t$ ). It can be reconstructed using  $\bar{u}_w^t$ .

## 4 Frank Wolfe and Variants

### 4.1 FrankWolfe, the conditional gradient algorithm

Throughout this section we consider the problem of minimizing a continuously differentiable convex function - say  $f$  - over some convex set  $\mathcal{M}$ .

**Definition 1.** A linear minimization oracle over a set  $\mathcal{M}$  is a map defined the following way:

$$LMO_{\mathcal{M}}(d) \triangleq \arg \min_{s \in \mathcal{M}} \langle d, s \rangle \quad (17)$$

Intuitively the classical FW is a descent method where starting from some arbitrary feasible point we repeatedly take convex combinations with outputs of the oracle  $s_t = LMO_{\mathcal{M}}(\nabla f(x_t))$ . The convex combination “weight”, usually denoted  $\gamma$ , can be computed exactly analytically. This is a key feature of the algorithm as many other require to compute the gradient’s lipschitz constant and/or the strong-convexity parameter, usually denoted  $\mu$ .

Let  $\alpha \in \mathcal{M}$

**for**  $k = 0$  **to**  $K$  **do**

    Compute  $s = \operatorname{argmin}_{s \in \mathcal{M}} \langle s, \nabla f(\alpha^k) \rangle$

    Let  $\gamma = \frac{2}{k+2}$  (simple version) or optimize for line-search

    Update  $\alpha^{k+1} = (1 - \gamma)\alpha^k + \gamma s$

**end for**

Algorithm 2: Classical Frank-Wolf

There has recently been a resurgence of interest into FW in the machine learning literature which can be explained by the following table from a tutorial on FW by Martin Jaggi Jaggi (2014)

	Frank-Wolfe	Gradient Descent and Proximal Methods
Iteration cost	solve linear problem	Projection or prox operation more generally
Iterates	sparse	<b>dense</b>

Sparsity is obviously a key feature for preventing the memory required to explode. Moreover projection and proximal operations can be very expensive in certain contexts.

Many variants and extensions of the basic classical FW algorithm but Jaggi lists the main ones and the active research areas at the time of writing his paper in 2014.

In this paper we mainly focus on the Block-Seperable variant applied to struct-svm problems as presented in Lacoste-Julien et al. (2013)

## 4.2 Block Coordinate Frank Wolfe

Due to the exponential number of dual variables in the structured SVM setting, classical algorithms like projected gradient are intractable. Stochastic subgradient methods, on the other hand, achieve a sublinear convergence rate while only requiring a single call to the maximization oracle every step. They are nonetheless very sensitive to the sequence of stepsizes and it is unclear when to terminate the iterations.

In fact many algorithms with good theoretical guarantees introduce a dependency between the stepsize to be chosen and some constants which characterize the function, e.g. the lipschitz constant of the gradient ( $L$ ) and the strong-convexity constant ( $\mu$ ), they are however not necessarily computable. One of the main interests in FW approaches is that we get an optimality certificate *for free* which ties in elegantly with convex analysis results. Moreover we have many good options for the choice of step-size with theoretical guarantees.

Leveraging those aspects the Block-Separable Frank Wolfe algorithm proposed by Lacoste-Julien et al., 2013 has a stepsize which can be computed exactly analytically and a computable duality gap while still retaining a sublinear convergence rate. Moreover, despite the exponential number of constraints, the algorithm has sparse iterates alleviating the memory issues which come with the exponential number of dual variables.

We are considering separability of an algorithm hence the following well known result is essential:

**Theorem 1.** *Given a convex, differentiable objective  $f : \mathcal{M}^1 \times \dots \times \mathcal{M}^n \rightarrow \mathbb{R}$ , where  $\forall i \in \{1..n\}$ , each factor  $\mathcal{M}^i \subseteq \mathbb{R}^n$  is convex and compact, if we are at a point  $x$  such that  $f(x)$  is minimized along each coordinate axis, then  $x$  is a global minimum.*

The BCFW algorithm as presented in Lacoste-Julien et al. (ibid.)

Let  $\alpha \in \mathcal{M}$

Let  $w^0 = 0, l^0 = 0$

**for**  $k = 0, \dots, K$  **do**

**for**  $i = 1, \dots, n$  **do**

    Solve  $y_i^* = \max_{y_i \in \mathcal{Y}_i} H_i(y, w^k)$

    Let  $w_s = \sum_{i=1}^n \frac{1}{n\lambda} \psi_i(y_i^*)$ , and  $l_s = \frac{1}{n} \sum_{i=1}^n L_i(y_i^*)$

    Let  $\gamma = \frac{\lambda(w^k - w_s)^T w^k - l^k + l_s}{\lambda \|w^k - w_s\|^2}$ , and clip to  $[0, 1]$

    Update  $w^{k+1} = (1 - \gamma)w^k + \gamma w_s$ , and  $l^{k+1} = (1 - \gamma)l^k + \gamma l_s$

**end for**

**end for**

Algorithm 3: Block Separable Frank-Wolf

## 5 Empirical

### 5.1 Experiments

In this section, we describe the implementation we performed for this project. The goal was to see how the Dual Extragradient algorithm compared to the Block-coordinate Frank-Wolfe algorithm. The task on which we performed the evaluation was word alignment in machine translation. We extracted the dataset from the Europarl dataset *Europarl Parallel Corpus* 2019. The data consisted of approximately 2 million sentence pairs in both english and french. Each the sentences in each pair were translations of one another. We extracted all sentences and performed a clean by splitting longer sentences into shorter ones. The goal of this step was to reduce the eventual number of matchings in training, which could take long to solve using a LP solver. Of course, each sentence was tokenized beforehand.

We then proceeded to implement the Dual Extragradient and BCFW algorithms using a SVM. We had to define a feature mapping for an input sentence pair. The features were extracted using the fastText library **fastText**. This library included a model that was previously trained to learn embeddings of words in both english and french. We later combined the embeddings in the two languages by applying a transformation found in Chojnacki and Kłopotek (2010). This transformation consisted in applying a matrix to each vector in each language (matrix  $W$  for english and  $Q$  for french). These matrices are in fact orthogonal (i.e.  $Q^T W = I$ ). The idea behind such a transformation is that we sort of “put” or “align” both languages in the same vector space, a sort of “middle ground”. This way we can better compare the words “cat” and “chat” by getting their cosine similarity measure. We combined the cosine measure of each pair of words in the alignment by summing. The following blog post *Aligning Vector Representations* (2017) provides a good intuition using maps that are aligned. As an example, consider the following two sentences:

- This assignment was hard
- Ce travail etait ardu

We would compute the cosine distance for each word tuple (e.g. this/ce, this/travail, ..., hard/ardu). We were then able to get the highest match of each english word for french translation. This was how we extracted the “labels”. As the dataset was not annotated with alignments, we had to compute those according to the procedure mentioned.

For the features, we used the concatenated embeddings of each word pairs in the alignment. This gave us our edge score. Then, we simply performed a weighted combination of these vectors using the edge labels as weights. To clarify what we mean by edge labels, suppose that the edge linking “assignment” and “travail” has a value of 1. Then, we weight the vector extracted from these two words with 1. As another example, if the edge between “ce” and “ardu” has a value of 0 (i.e. no link between the words), we do not include the vector computed from the statistics of this word pair. This is exactly what was done in Taskar Taskar, Lacoste-Julien, and Jordan, n.d. modulo some other features.

In the implementation of BCFW, we used the solver from scipy with the simplex method. Since the constraint matrix given by the optimization of  $H_i$  in the algorithm is unimodular, when we relax the LP, we still get a solution to the ILP without relaxation. Thus, we take advantage of this fact and indeed use the LP solver. The loss that we used was the  $L_1$  distance between the two labels, the proposal and the ground truth.

### 5.1.1 Results

Since running the experiments was computationally intensive and we did not dispose of a lot of computing power, we had to restrict the training set to a number a relatively small number of sentence pairs (100). This sanity check was simply a hint to the general applicability of the method as we scale up the number of training examples. We used the default  $\lambda$  value of 0.01 as our regularizer since, we did not want to train for too many iterations before getting decent results as per Theorem 3 found in Lacoste-Julien et al. (2013). We were able to get the following results for the BCFW algorithm:

To further motivate our intuition and to make sure the algorithm ran properly, we used the local scene dataset Müller and Behnke, 2014 from PyStruct to train a SVM using BCFW. It consisted of vectors of size 294 for the features of each training example (images). Each image was labeled according to the type of objects that were present in the scene.

These were:

$$beach \quad \cdot \quad sunset \quad \cdot \quad fall \quad \cdot \quad foilage \quad \cdot \quad field \quad \cdot \quad mountain \quad \cdot \quad urban \quad (18)$$

These 6 classes were not mutually exclusive so we had a total of  $2^6 = 64$  possible labels. Training using all possible edges allowed to fully capture the complex relationships between them. The duality gap on the training data is given by the figure 3.

For the dual extragradient, we were only able to run the algorithm on a dataset of images Vemulapalli and Agarwala (2018). These were tuples of 3 images and a person hand-picked two images in each 3-tuple that resembled each other the most. Using the extragradient algorithm, we were able to get convergence but the results were not satisfying. We only obtained 46% accuracy on the prediction, which would compare with 17% if we had a random predictor (3 choose 2 gives 6 possibilites hence 17%). Thus, it motivated our change of dataset to obtain better results. We also moved on to the BCFW algorithm as we had not implemented it yet.

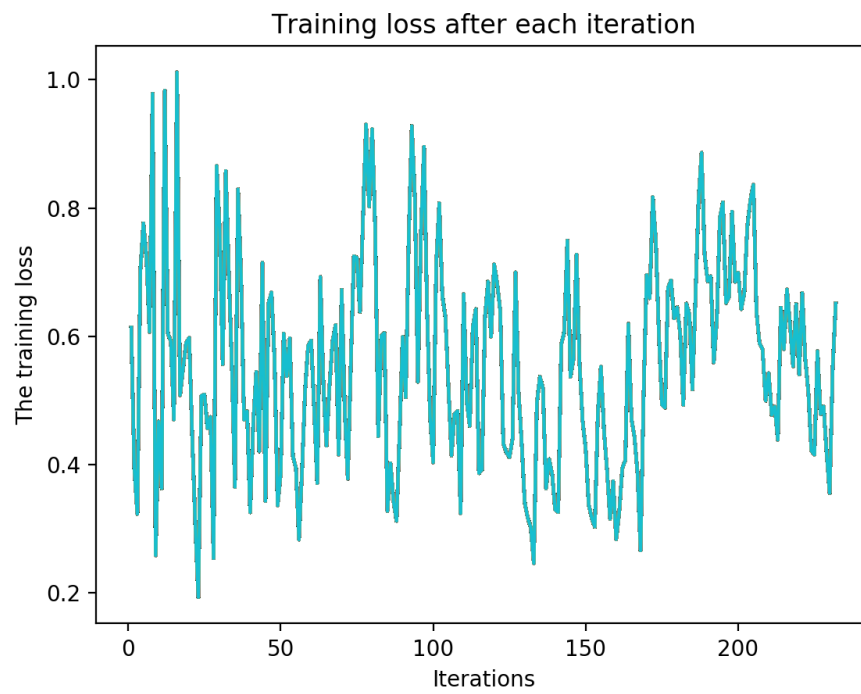


Figure 2: BCFW loss

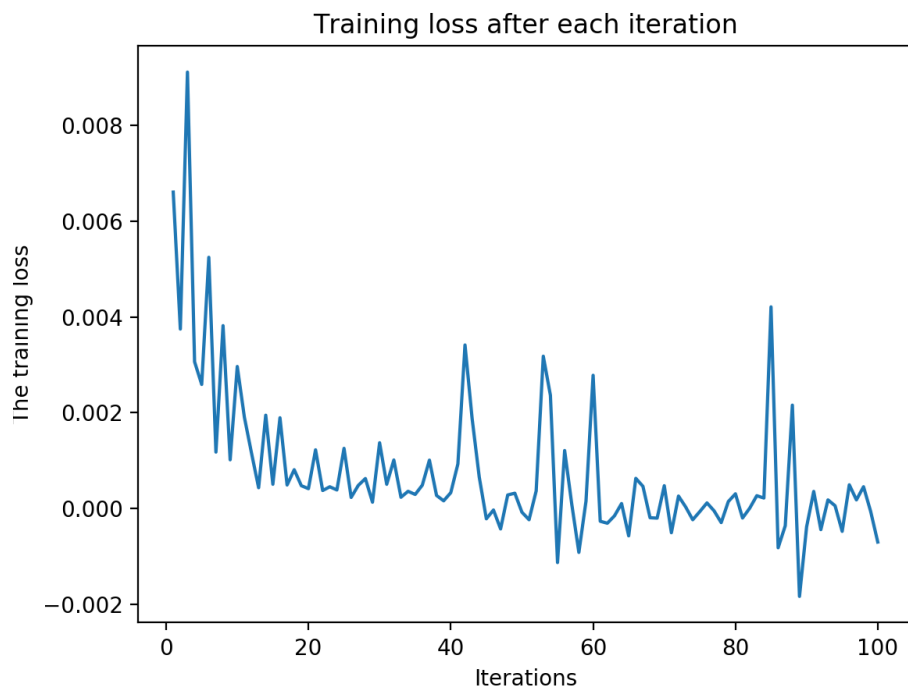


Figure 3: pystruct scene

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# Appendices

## Convex Analysis stuff

### Proximal step operator

We define the proximal step operator as follows:

$$T_\eta(\mathbf{u}, \mathbf{s}) = \max_{\mathbf{u}' \in U} \left\{ \langle \mathbf{s}, \mathbf{u}' - \mathbf{u} \rangle - \frac{1}{\eta} d(\mathbf{u}, \mathbf{u}') \leq D \right\} \quad (19)$$

The operator is useful to compute projections since when we have a strongly convex function  $h(\mathbf{u})$ , we can find its convex conjugate  $h^*(\mathbf{u}) = \max_{\mathbf{u} \in U} [\langle \mathbf{s}, \mathbf{u} \rangle - h(\mathbf{u})]$ . From the definition of a strongly convex function, we have that:

$$h(\mathbf{u}') \geq h(\mathbf{u}) + \langle \nabla h(\mathbf{u}), \mathbf{u}' - \mathbf{u} \rangle + \frac{\sigma}{2} \|\mathbf{u}' - \mathbf{u}\|^2 \quad (20)$$

where  $\sigma$  is the strong convexity parameter. Rearranging, we can define an upper bound on the squared norm of  $\mathbf{u}' - \mathbf{u}$ . This comes out as:

$$d(\mathbf{u}', \mathbf{u}) \triangleq h(\mathbf{u}') - h(\mathbf{u}) - \langle \nabla h(\mathbf{u}), \mathbf{u}' - \mathbf{u} \rangle \geq \frac{\sigma}{2} \|\mathbf{u}' - \mathbf{u}\|^2 \quad (21)$$

The distance metric  $d$  is called the Bregman divergence. The link between the Bregman divergence and the proximal step operator is that if we are given the function  $h$  inside the definition of the proximal step update, this induces the Bregman divergence, which in turn induces the update that is performed at each iteration of the extragradient algorithm. For example, if we have  $h(\mathbf{u}) = \frac{1}{2} \|\mathbf{u}\|_2^2$ , the Bregman divergence becomes  $d(\mathbf{u}', \mathbf{u}) = \frac{1}{2} \|\mathbf{u}' - \mathbf{u}\|_2^2$ . We might wonder why we care about the Bregman divergence when the definition still includes the usual norm. After all, we still optimize the term  $\langle \mathbf{s}, \mathbf{u}' - \mathbf{u} \rangle - \frac{1}{\eta} d(\mathbf{u}', \mathbf{u})$ . This is because  $h^*$  is differentiable at every point of its domain by the strong convexity of  $h$ . Thus, it is easy to compute a projection in the usual fashion: we can compute the derivative of the term inside the projection operator and set it to 0. It is impossible to do for matchings for example as the distance is not even differentiable. We provide the steps to compute a projection:

$$\mathbf{s} - \nabla_{\mathbf{u}'} d(\mathbf{u}', \mathbf{u}) = \mathbf{s} - \frac{1}{\eta} \nabla_{\mathbf{u}'} d(\mathbf{u}, \mathbf{u}') = \mathbf{s} - \frac{1}{\eta} [\nabla h(\mathbf{u}') - \nabla h(\mathbf{u})] \quad (22)$$

By setting this equation to 0, it is possible to recover the optimal  $\mathbf{y}'$  when, let's say,  $h(\mathbf{u}) = \frac{1}{2} \|\mathbf{u}'\|^2$ .



## ExtraGradient

### Convergence analysis

The restricted gap function  $\mathcal{G}_{D_w, D_z}$  is upper bounded by:

$$\mathcal{G}_{D_w, D_z}(\overline{w^\tau}, \overline{z^\tau}) \leq \frac{(D_w + D_z)L}{\tau + 1} \quad (23)$$

$$\mathcal{G}_{D_w, D_z}(w, z) = \begin{pmatrix} \sum_i F_i z_i^* \\ -F_1^T w^* \\ \vdots \\ -F_m^T w^* \end{pmatrix}^T \begin{pmatrix} w - w^* \\ z_1 - z_1^* \\ \vdots \\ z_m - z_m^* \end{pmatrix} - \begin{pmatrix} \sum_i f_i(y_i) \\ c_1 \\ \vdots \\ c_m \end{pmatrix}^T \begin{pmatrix} w - w^* \\ z_1 - z_1^* \\ \vdots \\ z_m - z_m^* \end{pmatrix}$$

We have the right tools for convergence of the algorithm. The Lipschitz constant of the operator  $Fu -$  is given by  $L$  is equal to  $\max_{u \in \mathcal{U}} \|F(u - u')\|_2 / \|u - u'\|_2 \leq \|F\|_2$ . Of course, a point  $w, z$  that satisfies  $\|w\|_2 \leq D_w$  and  $\|z\|_2 \leq D_z$  also satisfies  $\|(w, z)\|_2 \leq D$  when  $D = \sqrt{D_w^2 + D_z^2}$  since  $(w, 0) \perp (0, z)$ . It is then easy to see that  $f_D \geq \mathcal{G}_{D_w, D_z}$ . Thus, the function  $\mathcal{G}_{D_w, D_z}$  is upper bounded by the right-hand side of equation 23.