

DeepBox: Learning Objectness with Convolutional Networks

Weicheng Kuo Bharath Hariharan Jitendra Malik
 University of California, Berkeley
 {wckuo, bharath2, malik}@eecs.berkeley.edu

Abstract

Existing object proposal approaches use primarily bottom-up cues to rank proposals, while we believe that “objectness” is in fact a high level construct. We argue for a data-driven, semantic approach for ranking object proposals. Our framework, which we call DeepBox, uses convolutional neural networks (CNNs) to rerank proposals from a bottom-up method. We use a novel four-layer CNN architecture that is as good as much larger networks on the task of evaluating objectness while being much faster. We show that DeepBox significantly improves over the bottom-up ranking, achieving the same recall with 500 proposals as achieved by bottom-up methods with 2000. This improvement generalizes to categories the CNN has never seen before and leads to a 4.5-point gain in detection mAP. Our implementation achieves this performance while running at 260 ms per image.

1. Introduction

Object detection methods have moved from scanning window approaches [9] to ones based on bottom-up object proposals [11]. Bottom-up proposals [1] have two major advantages: 1) by reducing the search space, they allow the usage of more sophisticated recognition machinery, and 2) by pruning away false positives, they make detection easier. [14, 10]

Most object proposal methods rely on simple bottom-up grouping and saliency cues. The rationale for this is that this step should be reasonably fast and generally applicable to all object categories. However, we believe that there is more to objectness than bottom-up grouping or saliency. For instance, many disparate object categories might share high-level structures (such as the limbs of animals and robots) and detecting such structures might hint towards the presence of objects. A proposal method that incorporates these and other such cues is likely to perform much better.

In this paper, we argue for a *semantic, data-driven* notion of objectness. Our approach is to present a large database of images with annotated objects to a learning algorithm,

and let the algorithm figure out what low-, mid- and high-level cues are most discriminative of objects. Following recent work on a range of recognition tasks [11, 12, 18], we use convolutional networks (CNNs) [19] for this task. Concretely, we train a CNN to rerank a large pool of object proposals produced by a bottom-up proposal method (we use Edge boxes [30] for most experiments in this paper). For ease of reference, we call our approach DeepBox. Figure 1 shows our framework.

We propose a lightweight four layer network architecture that significantly improves over bottom-up proposal methods in terms of ranking (26% relative improvement on AUC over Edge boxes on VOC 2007 [8]). Our network architecture is as effective as state-of-the-art classification networks on this task while being much smaller and thus much faster. In addition, using ideas from SPP [13] and Fast R-CNN [10], our implementation runs in 260 ms per image, comparable to some of the fastest bottom-up proposal approaches like Edge Boxes (250 ms). We also provide evidence that what our network learns is category-agnostic: our improvements in performance generalize to categories that the CNN has not seen before (16% improvement over Edge boxes on COCO [20]). Our results suggest that a) there is indeed a generic, semantic notion of objectness beyond bottom-up saliency, and that b) this semantic notion of objectness can be learnt effectively by a lightweight CNN.

Object proposals are just the first step in an object detection system, and the final evaluation of a proposal system is the impact it has on detection performance. We show that the Fast R-CNN detection system [10], using 500 DeepBox proposals per image, is 4.5 points better than the same object detector using 500 Edge box proposals. Thus our high quality proposals directly lead to better object detection.

The rest of the paper is laid out as follows. In Section 2 we discuss related work. We describe our network architecture and training and testing procedures in Section 3. Section 4 describes experiments and we end with a discussion.

2. Related work

Russell et al. [26] were one of the first to suggest a category-independent method to propose putative objects.

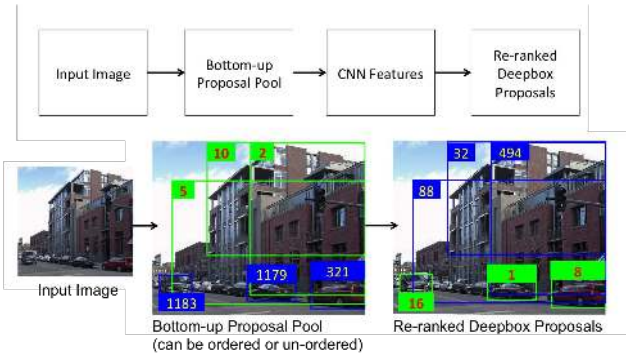


Figure 1. The DeepBox framework. Given any RGB image, we first generate bottom-up proposals and then rerank them using a CNN. High ranked boxes are shown in green and low ranked ones are blue. The number in each box is its ranking in the proposal pool. DeepBox corrects the ranking of Edge box, ranking objects higher than background.

Their method involved sampling regions from multiple segmentations of the image. More recently, Alexe et al. [1] and Endres et al. [6] propose using bottom-up object proposals as a first step in recognition. Expanding on the multiple segmentations idea, Selective search [29] uses regions from hierarchical segmentations in multiple color spaces as object proposals. CPMC [4] uses multiple graph-cut based segmentations with multiple foreground seeds and multiple foreground biases to propose objects. GOP [17] replaces graph cuts with a much faster geodesic based segmentation. MCG [2] also uses multiple hierarchical segmentations from different scales of the image, but produces proposals by combinatorially grouping regions. Edge boxes [30] uses contour information instead of segments: bounding boxes which have fewer contours straggling the boundary of the box are considered more likely to be objects.

Many object proposal methods also include a ranking of the regions. This ranking is typically based on low level region features such as saliency [1], and is sometimes learnt [2, 4]. Relatively simple ranking suffices when the goal is a few thousand proposals as in MCG [2], but to narrow the list down to a few hundred as in CPMC [4] requires more involved reasoning. DeepBox aims at such a ranking.

Multibox [7, 28] directly produces object proposals from images using a sophisticated neural network. In contemporary work, Faster R-CNN [25] uses the same large network to propose objects and classify them. DeepMask [22] also uses a very deep network to directly produce segment proposals. In comparison, our architecture is quite lightweight and can be used out of the box to rerank any bottom-up proposals.

Finally, we direct the reader to [15, 14] for a more thorough evaluation of bottom-up proposal methods.

3. Method

The pipeline consists of two steps: 1) Generate an initial pool of N bottom-up proposals. Our method is agnostic to the precise bottom-up proposal method. The main point of this step is to prune out the obviously unlikely windows so that DeepBox can focus on the hard negatives. 2) Rerank the proposals using scores obtained by the DeepBox network. We rerank each proposal by cropping out the proposal box and feeding it into a CNN, as described by Girshick et al. [11]. Because highly overlapping proposals are handled independently, this strategy is computationally wasteful and thus slow. A more sophisticated and much faster approach, using ideas from [13, 10] is described in Section 3.2.

For datasets without many small objects (e.g. PASCAL), we often only need to re-rank the top 2000 proposals to obtain good enough recall. As shown by [30], increasing the number of Edge box proposals beyond 2000 leads to only marginal increase in recall. For more challenging datasets with small objects (e.g. COCO [20]), reranking more proposals continues to provide gains in recall beyond 2000 proposals.

3.1. Network Architecture

When it comes to the network architecture, we would expect that predicting the precise category of an object is harder than predicting objectness, and so we would want a simpler network for objectness. This also makes sense from a computational standpoint, since we do not want the object proposal scoring stage to be as expensive as the detector itself.

We organized our search for a suitable network architecture by starting from the architecture of [18] and gradually ablating it while trying to preserve performance. The ablation here can be performed by reducing the number of channels in the different layers (thus reducing the number of parameters in the layer), by removing some layers, or by decreasing the input resolution so that the features computed become coarser.

The original architecture gave an AUC on PASCAL VOC of 0.76(0.62) for IoU=0.5 (0.7). First, we changed the number of outputs of *fc6* to 1024 with other things fixed and found that performance remained unchanged. Then we adjusted the input image crop from 227×227 of the network to 120×120 and observed that the AUC dropped 1.5 points for IoU=0.5 and 2.9 points for IoU=0.7 on PASCAL. With this input size, we tried removing *fc6* (drop: 2.3 points), *conv5* (drop: 2.9 points), *conv5* + *conv4* (drop: 10.6 points) and *conv5* + *conv4* + *conv3* layers (drop: 6.7 points). This last experiment meant that dropping all of *conv5*, *conv4* and *conv3* was better than just dropping *conv5* and *conv4*. This might be because *conv3*, *conv4* and *conv5* while adding to the capacity of the network are

also likely overfit to the task of image classification (as described below, the convolutional layers are initialized from a model trained on ImageNet). We stuck to this architecture (i.e., without *conv5*, *conv4* and *conv3*) and explored different input sizes for the net. For an input size of 140×140 , we obtained a competitive AUC of 0.74 (for IoU=0.5) and 0.60 (for IoU=0.7) on PASCAL, or equivalently a 4.4 point drop against the baseline.

Our final architecture can be written down as follows. Denote by $\text{conv}(k, c, s)$ a convolutional layer with kernel size k , stride s and number of output channels c . Similarly, $\text{pool}(k, s)$ denotes a pooling layer with kernel size k and stride s , and $\text{fc}(c)$ a fully connected layer with c outputs. Then, our network architecture is:
 $\text{conv}(11, 96, 4) - \text{pool}(3, 2) - \text{conv}(5, 256, 1) - \text{fc}(1024) - \text{fc}(2)$.

Each layer except the last is followed by a ReLU non-linearity. Our problem is a binary classification problem (object or not), so we only have two outputs which are passed through a softmax. Our input size is 140×140 .

While we finalized this architecture on PASCAL for Edge boxes, we show in Section 4 that the same architecture works just as well for other datasets such as COCO [20] and for other proposal methods such as Selective Search [29] or MCG [2].

3.2. Sharing computation for faster reranking

Running the CNN separately on highly overlapping boxes wastes a lot of computation. He et al. [13] pointed out that the convolutional part of the network could be shared among all the proposals. Concretely, instead of cropping out individual boxes, we pass in the entire image into the network (at a high resolution). After passing through all the convolutional and pooling layers, the result is a feature map which is some fraction of the image size. Given this feature map and a set of bounding boxes, we want to compute a fixed length vector for each box that we can then feed into the fully connected layers. To do this, note that each bounding box B in the image space corresponds to a box b in the feature space of the final convolutional layer, with the scale and aspect ratio of b being dependent on B and thus different for each box. He et al. propose to use a *fixed* spatial pyramid grid to max-pool features for each box. While the size of the grid cell varies with the box, the number of bins don't, thus resulting in a fixed feature vector for each box. From here on, each box is handled separately. However, the shared convolutional feature maps means that we have saved a lot of computation.

One issue with this approach is that all the convolutional feature maps are computed at just one image scale, which may not be appropriate for all objects. He et al. [13] suggest a multiscale version where the feature maps are computed at a few fixed scales, and for each box we pick the best scale,

which they define as the one where the area of the scaled box is closest to a predefined value. We experiment with both the single scale version and a multiscale version using three scales.

We use the implementation proposed by Girshick in Fast R-CNN [10]. Fast R-CNN implements this pooling as a layer in the CNN (the RoI Pooling layer) allowing us to train the network end-to-end.

To differentiate this version of DeepBox from the slower alternative based on cropping and warping, we call this version Fast DeepBox in the rest of the paper.

3.3. Training Procedure

3.3.1 Initialization

The first two convolutional layers were initialized using the publicly available Imagenet model [18]. This model was pretrained on 1000 Imagenet categories for the classification task. The fc layers are initialized randomly from Gaussian distribution with $\sigma = 0.01$. Our DeepBox training procedure consists of two stages. Similar to the classical notion of bootstrapping in object detection, we first train an initial model to distinguish between object boxes and randomly sampled sliding windows from the background. This teaches it the difference between objects and background. To enable it to do better at correcting the errors made by bottom-up proposal methods, we run a second training round where we train the model on bottom-up proposals from a method such as Edge boxes.

3.3.2 Training on Sliding Windows

First we generate negative windows by simple raster scanning. The sliding window step size is selected based on the box-searching strategy of Edge boxes [30]. Following Zitnick et al [30], we use α to denote the IoU threshold for neighboring sliding windows, and set it to 0.65. We generated windows in 5 aspect ratios: $(w : h) = (1 : 1), (2 : 3), (1 : 3), (3 : 2),$ and $(3 : 1)$. Negative windows which overlap with a ground truth object by more than $\beta_- = 0.5$ are discarded.

To obtain positives, we randomly perturb the corners of ground truth bounding boxes. Suppose a ground truth bounding box has coordinates $(x_{\min}, y_{\min}, x_{\max}, y_{\max})$, with the width denoted by w and the height denoted by h . Then the perturbed coordinates are distributed as:

$$x'_{\min} \sim \text{unif}(x_{\min} - \gamma w, x_{\min} + \gamma w) \quad (1)$$

$$y'_{\min} \sim \text{unif}(y_{\min} - \gamma h, y_{\min} + \gamma h) \quad (2)$$

$$x'_{\max} \sim \text{unif}(x_{\max} - \gamma w, x_{\max} + \gamma w) \quad (3)$$

$$y'_{\max} \sim \text{unif}(y_{\max} - \gamma h, y_{\max} + \gamma h) \quad (4)$$

where $\gamma = 0.2$ defines the level of noise. Larger γ introduces more robustness into positive training samples, but

might hurt localization. In practice we found that $\gamma = 0.2$ works well. In case some perturbed points go out of the image, we set them to stay on the image border. Perturbed windows that overlap with ground truth boxes by less than $\beta_+ = 0.5$ are discarded.

3.3.3 Training on Hard-negatives

Next, we trained the net on bottom-up proposals from a method such as Edge boxes [30]. Compared to sliding windows, these proposals contain more edges, texture and parts of objects, and thus form hard negatives. While sliding windows trained the net to distinguish primarily between background and objects, training on these proposals allows the net to learn the notion of complete objects and better adapt itself to the errors made by the bottom-up proposer. This is critical: without this stage, performance drops by 18% on PASCAL from 0.60 AUC at IoU=0.7 to 0.48.

The window preparation and training procedure is as described in Section 3.3.2, except that sliding windows are replaced with Edge boxes proposals. We set the overlap threshold $\beta_+ = 0.7$ slightly higher, so that the net can learn to distinguish between tight and loose bounding boxes. We set $\beta_- = 0.3$ below which the windows are labeled negative. Windows with $\text{IoU} \in [0.3, 0.7]$ are discarded lest they confuse the net.

We balanced the ratio of positive and negative windows at 1 : 3 at training time for both stages. Momentum is set to 0.9 and weight decay to 0.0005. The initial learning rate is 0.001, which we decrease by 0.1 every 20,000 iterations. We train DeepBox for 60,000 iterations with a mini-batch size of 128.

The Fast DeepBox network was trained for 120k iterations in both sliding window and hard negative training. Three scales [400, 600, 900] were used for both training and testing.

4. Experiments

All experiments except those in Section 4.7 and 4.8 were done using DeepBox. We evaluate Fast DeepBox in Section 4.7, and as a final experiment plug it into an object detection system in Section 4.8.

4.1. Learning objectness on PASCAL and COCO

In our first set of experiments, we evaluated our approach on PASCAL VOC 2007 [8] and on the newly released COCO [20] dataset. For these experiments, we used Edge boxes [30] for the initial pool of proposals. On PASCAL we reranked the top 2048 Edge box proposals, whereas on COCO we re-ranked all. We used the network architecture described in Section 3.1. For results on PASCAL VOC 2007, we trained our network on the trainval set and tested

on the test set. For results on COCO, we trained our network on the train set and evaluated on the val set.

4.2. Comparison to Edge boxes

We first compare our ranking to the ranking output by Edge boxes. Figure 2 plots Recall vs Number of Proposals in PASCAL VOC 2007 for IoU=0.7¹. We observe that DeepBox outperforms Edge boxes in all regimes, especially with a low number of proposals. The same is true for IoU=0.5 (not shown). The AUCs (Areas Under Curve) for DeepBox are 0.74(0.60) vs Edge box's 0.60(0.47) for IoU=0.5(0.7), suggesting that DeepBox proposals are 24% better at IoU=0.5 and 26% better at IoU=0.7 compared to Edge boxes. Figure 3 plots the same in COCO. The AUCs (Areas Under Curve) for DeepBox are 0.40(0.28) vs Edge boxes's 0.28(0.20) for IoU=0.5(0.7), suggesting DeepBox proposals are 40%(43%) better than Edge boxes. If we re-ranked top 2048 proposals instead, the AUCs are 0.38(0.27).

On PASCAL, we also plot the Recall vs IoU threshold curves at 1000 proposals in Figure 4. At 1000 proposals, the gain of DeepBox is not as big as at 100-500 proposals, but we still see that it is superior in all regimes of IoU.

Part of this performance gain is due to small objects, defined as objects with area less than 2000. On COCO the AUCs for DeepBox (trained on all categories) are (0.161, 0.080), while the numbers for Edge boxes are (0.061, 0.030) for IoU(0.5, 0.7). DeepBox outperforms Edge boxes by more than 160% on small objects.

Comparison to other proposal methods We can also compare our ranked set of proposals to all the other proposals in the literature. We show this comparison for IoU=0.7 in Table 1. The numbers are obtained from [30] except for MCG and DeepBox which we computed ourselves. In Table 1, the metrics are the number of proposals needed to achieve 25%, 50% and 75% recall and the maximum recall using 5000 boxes.

4.3. Visualization of DeepBox proposals

Figures 5 and 6 visualizes DeepBox and Edge box performance on PASCAL and COCO images. Figure 5 shows the ground truth boxes that are detected ("hits", shown in green, with the corresponding best overlapping proposal shown in blue) and those that are missed (shown in red) for both proposal rankings. We observe that in complicated scenes with multiple small objects or cluttered background, DeepBox significantly outperforms Edge box. The tiny boats, the cars parked by the road, the donuts and people in the shade are all correctly captured.

¹We computed recall using the code provided by [30]

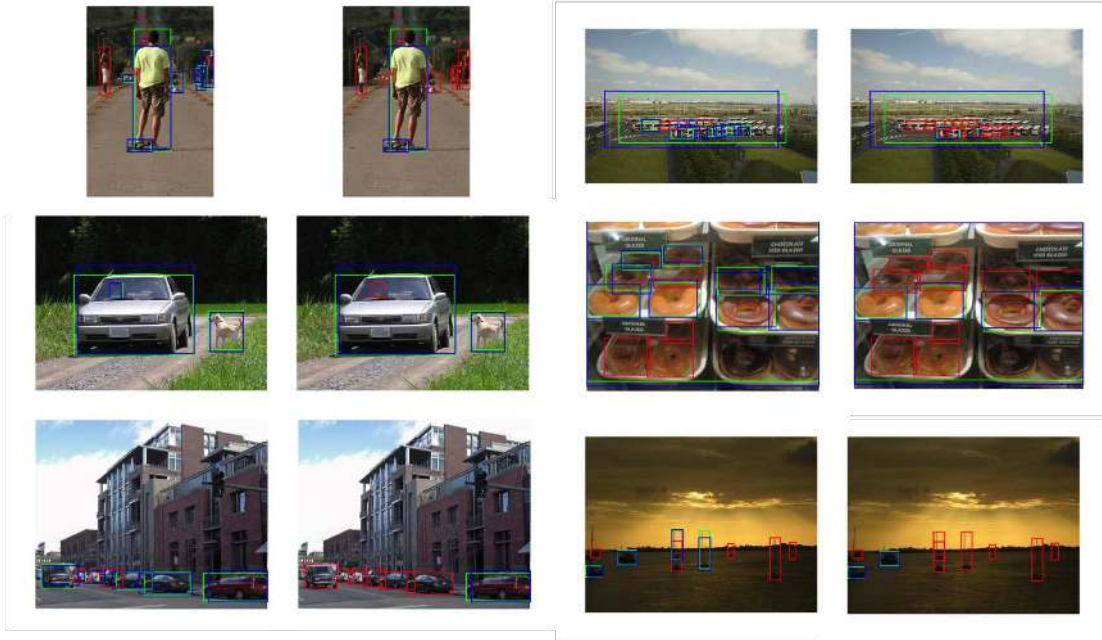


Figure 5. Visualization of hits and misses. In each image, the green boxes are ground truth boxes for which a highly overlapping proposal exists (with the corresponding proposals shown as blue boxes) and red boxes are ground truth boxes that are missed. The IoU threshold is 0.7. We evaluated 1000 proposals per image for COCO and 500 proposals per image for PASCAL. The left image in every pair shows the result of DeepBox ranking, and the right image shows the ranking from Edge boxes. In cluttered scenes, DeepBox has a higher recall. See Section 4.3 for a detailed discussion.



Figure 6. In each image we show the distribution of the proposals produced by pasting a red box for each proposal. Only the top 100 proposals are shown. For each pair of images, DeepBox is on the left and Edge boxes is the right. DeepBox proposals are more tightly concentrated on the objects. See Section 4.3 for a detailed discussion.

This is also validated by looking at the distribution of top 100 proposals (Figure 6), which is shown in red. In general, DeepBox’s bounding boxes are very densely focused on the objects of interest while Edge boxes primarily recognize contours and often spread evenly across the image in a

complicated scene.

4.4. Generalization to unseen categories

The high recall our method achieves on the PASCAL 2007 test set does not guarantee that our net is truly learning

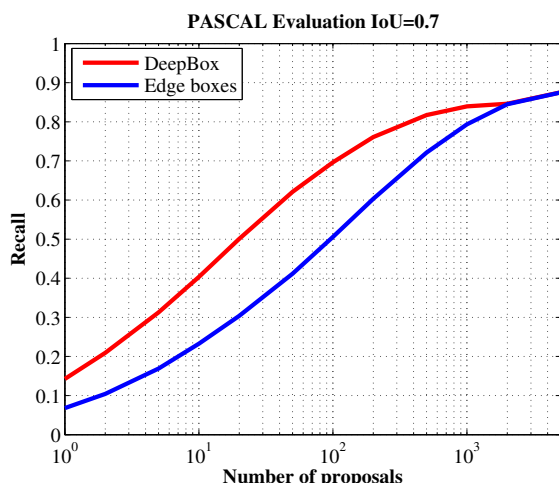


Figure 2. PASCAL Evaluation IoU=0.7. DeepBox starts off much higher than Edge boxes. The wide margin continues all the way until 500 proposals and gradually decays. The two curves join at 2048 proposals because we chose to re-rank this number of proposals.

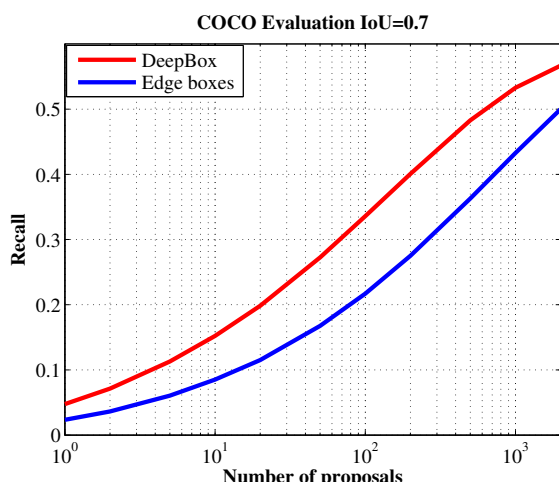


Figure 3. MS COCO Evaluation IoU=0.7. The strong gain demonstrated by DeepBox on COCO suggests that our learnt objectness is particularly helpful in a complicated dataset.

general objectness. It is possible that the net is learning just the union of 20 object categories and using that knowledge to rank proposals. To evaluate whether the net is indeed learning a more general notion of objectness that extends beyond the categories it has seen during training, we did the following experiment:

- We identified the 36 overlapping categories between Imagenet and COCO.
- We trained the net just on these overlapping categories on COCO with initialization from Imagenet. This

	AUC	25%	50%	75%	Recall (%)	Time (s)
BING[5]	0.20	292	-	-	29	0.2
Ranta[24]	0.23	184	584	-	68	10
Objectness[1]	0.27	27	-	-	39	3
Rand. P.[21]	0.35	42	349	3023	80	1
Rahtu [23]	0.37	29	307	-	70	3
SelSearch [29]	0.40	28	199	1434	87	10
CPMC [3]	0.41	15	111	-	65	250
MCG [2]	0.48	10	81	871	83	34
E.B [30]	0.47	12	108	800	87	0.25
DeepBox	0.60	3	20	183	87	2.5

Table 1. Comparison of DeepBox with existing object proposal techniques. All numbers are for an IoU threshold of 0.7. The metrics are the number of proposals needed to achieve 25%, 50% and 75% recall and the maximum recall using 5000 boxes. DeepBox outperforms in all metrics. Note that the timing numbers for DeepBox include computation on the GPU.

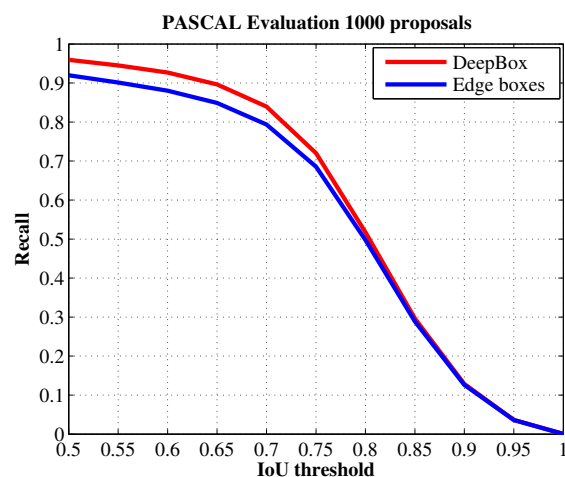


Figure 4. Variation of recall with IoU threshold at 1000 proposals. DeepBox (average recall: 57.0%) is better than Edge boxes (average recall: 54.4%) in all regimes. Comparisons to other proposal methods is shown in the supplementary.

means that during training, only boxes that overlapped highly with ground truth from the 36 overlapping categories were labeled positives, and others were labeled negatives. Also, when sampling positives, only the ground truth boxes corresponding to these overlapping categories were used to produce perturbed positives. This is equivalent to training on a dataset where all the other categories have not been labeled at all.

- We then evaluated our performance on the rest of the categories in COCO (44 in number). This means that at test time, only proposed boxes that overlapped with ground truth from the other 44 categories were considered true positives. Again, this corresponds to evaluat-

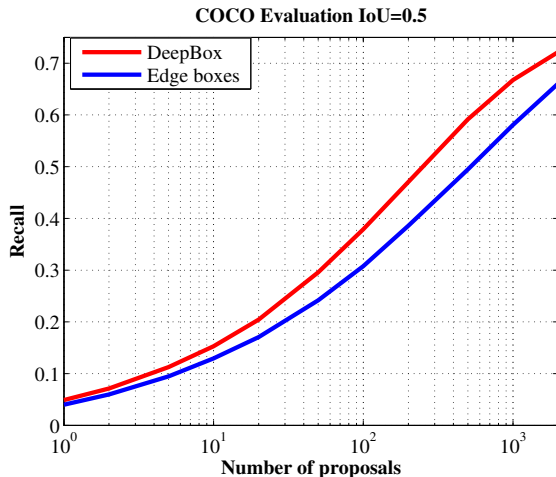


Figure 7. Evaluation on unseen categories, when ranking all proposals, at IoU=0.5.

ing on a dataset where the 36 training categories have not been labeled at all.

All other experimental settings remain the same. As before, we use Edge boxes for the initial pool of proposals which we rerank, and compare the ranking we obtain to the ranking output by edge boxes.

When reranking the top 2048 proposals, DeepBox achieved 15.7%(15.3%) AUC improvement over Edge boxes for IoU=0.5 (0.7). When reranking *all* proposals output by Edge boxes, DeepBox achieved 18.5%(16.2%) improvement over Edge boxes for IoU=0.5 (0.7) (Figure 7). In this setting, DeepBox outperforms Edge box in all regimes on unseen categories for both IoUs.

In Figure 8, we plot the ratio of the AUC obtained by DeepBox to that obtained by Edge box for all the 44 testing categories. In more than half of the testing categories, we obtain an improvement greater than 20%, suggesting that the gains provided by DeepBox are spread over multiple categories. This suggests that DeepBox is actually learning a class-agnostic notion of objectness. Note that DeepBox performs especially well for the animal super category because all animal categories have similar geometric structure and training the net on some animals helps it recognize other animals. This validates our intuition that there are high-level semantic cues that can help with objectness. In the sports super category, DeepBox performs worse than Edge boxes, perhaps because most objects of this category have salient contours that favor the Edge boxes algorithm.

These results on COCO demonstrate that our network has learnt a notion of objectness that generalizes beyond training categories.

	Vanilla	DeepBox (Trained on [30])	DeepBox (Finetuned)	Total Time (s)
Sel. Se.	0.27/0.17	0.27/0.19	0.32/0.22	12.5
MCG	0.38/0.25	0.30/0.22	0.37/0.26	36.5
Edge Box	0.28/0.20	0.38/0.27	0.38/0.27	2.5

Table 2. DeepBox on top of other proposers. For each method we show the AUC at IoU=0.5/0.7 of (left to right) the original ranking, the reranking produced by DeepBox trained on Edge boxes, and that produced after finetuning on the corresponding proposals.

4.5. DeepBox using Large Networks

We also experimented with larger networks such as “Alexnet” [18] and “VGG” [27]. Unsurprisingly, large networks capture objectness better than our small network. However, the difference is quite small: With VGG, the AUCs on PASCAL are 0.78(0.65) for IoU=0.5(0.7). The numbers for Alexnet are 0.76(0.62). In comparison our network achieves 0.74(0.60).

For evaluation on COCO, we randomly selected 5000 images and computed AUCs using the VGG and Alexnet architecture. All networks re-rank just top 2048 Edge box proposals. At IoU=0.5, VGG gets 0.43 and Alexnet gets 0.42, compared to the 0.38 obtained by our network. At IoU=0.7, VGG gets 0.31 and Alexnet gets 0.30, compared to the 0.27 obtained by our network. When re-ranking all proposals, our small net gets 0.40(0.28) for IoU=0.5(0.7).

These experiments suggest that our network architecture is sufficient to capture the semantics of objectness, while also being much more efficient to evaluate compared to the more massive VGG and Alexnet architectures.

4.6. DeepBox with Other Proposers

It is a natural question to ask whether DeepBox framework applies to other bottom-up proposers as well. We experimented with MCG and Selective Search by just reranking top 2048 proposals. (For computational reasons, we did this experiment on a smaller set of 5000 COCO images.) We experimented with two kinds of DeepBox models: a single model trained on Edge boxes, and separate models trained on each proposal method (Table 2).

A model trained on Edge boxes does not provide much gains, and indeed sometimes hurts, when run on top of Selective Search or MCG proposals. However, if we retrain DeepBox separately on each proposal method, this effect goes away. In particular, we get large gains on Selective Search for both IoU thresholds (as with Edge boxes). On MCG, DeepBox does not hurt, but does not help much either. Nevertheless, the gains we get on Edge boxes and Selective Search suggest that our approach is general and can work with any proposal method, or even ensembles of proposal methods (a possibility we leave for future work).

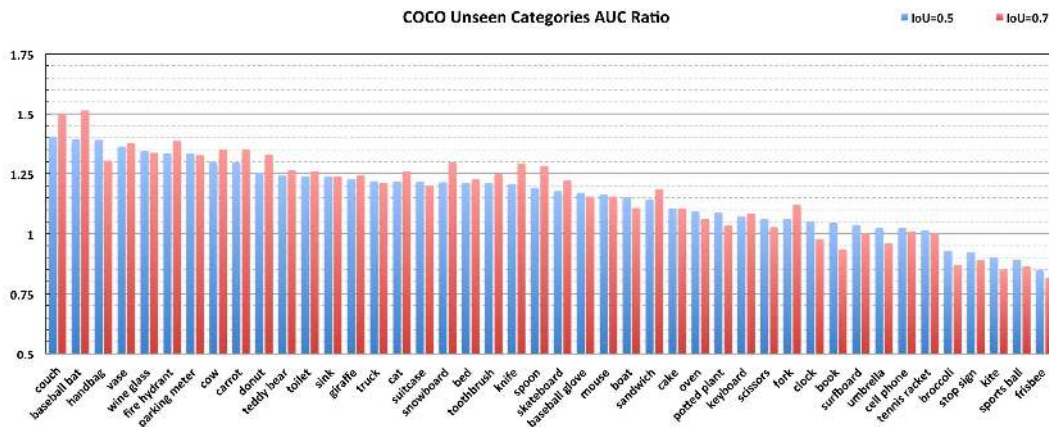


Figure 8. Evaluation on unseen categories: category-wise breakdown. This demonstrates that DeepBox network has learnt a notion of objectness that generalizes beyond training categories.

4.7. Fast DeepBox

We experimented with Fast DeepBox on COCO. The AUCs for multiscale Fast DeepBox are 0.40(0.29) vs Edge box’s 0.28(0.20) for IoU=0.5(0.7), a gain of 41%(44%) over Edge boxes. When we re-ranked top 2048 proposals instead, the AUCs are 0.37(0.27). Compared with DeepBox’s multi-thread runtime of 2.5s, Fast DeepBox (multi-scale) is an order of magnitude faster: it takes 0.26s to re-rank all proposals or 0.12s to re-rank the top-2000. This compares favorably to other bottom-up proposals. In terms of average recall with 1000 proposals, our performance (0.39) is better than GOP (0.36) [17], Selective Search (0.36) [29] and Edge boxes (0.34) [30], and is about the same as MCG (0.40) [2] while being almost 70 times faster. In contrast, Deepmask achieves 0.45 with a much deeper network at the expense of being 3 times slower (1.6 s) [22].

With a small decrease in performance, Fast DeepBox can be made much faster. With a single scale, AUC drops by about 0.005 when re-ranking top-2000 proposals and 0.01 when re-ranking all proposals. However, it only takes 0.11s to re-rank all proposals or 0.060s for the top-2000. One can also make training faster by removing the scanning-window stage and using a single scale. This speedup comes with a drop in performance of 0.015 when reranking all proposals compared to the multiscale two-stage version.

4.8. Impact on Object Detection

The final metric for any proposal method is its impact on object detection. Good proposals not only reduce the computational complexity but can also make object detection easier by reducing the number of candidates that the detector has to choose from [14, 10]. We found that this is indeed true: when using 500 DeepBox proposals, Fast-RCNN (with the VGG-16 network) gives a mAP of **37.8%**

on COCO Test at IoU=0.5, compared to only **33.3%** when using 500 Edge Box proposals. Even when using 2000 Edge Box proposals, the mAP is still lower (35.9%). For comparison, Fast R-CNN using 2000 Selective Search proposals gets a mean AP of 35.8%, indicating that with just 500 DeepBox proposals we get a 2 point jump in performance.

5. Discussion and Conclusion

We have presented an efficient CNN architecture that learns a semantic notion of objectness that generalizes to unseen categories. We conclude by discussing other applications of our objectness model.

First, as the number of object categories increases, the computational complexity of the detector increases and it becomes more and more useful to have a generic objectness system to reduce the number of locations the detector looks at. Objectness can also help take the burden of localization off the detector, which then has an easier task.

Second, AI agents navigating the world cannot expect to be trained on labeled data like COCO for every object category they see. For some categories the agent will have to collect data and build detectors on the fly. In this case, objectness allows the agent to pick a few candidate locations in a scene that look like objects and track them over time, thus collecting data for training a detector. Objectness can thus be useful for *object discovery* [16], especially when it captures semantic properties as in our approach.

6. Acknowledgement

This work is supported by a Berkeley Graduate Fellowship and a Microsoft Research Fellowship. We thank NVIDIA for giving GPUs through their academic program too.

References

- [1] B. Alexe, T. Deselaers, and V. Ferrari. Measuring the objectness of image windows. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 34(11):2189–2202, 2012. 1, 2, 6
- [2] P. Arbeláez, J. Pont-Tuset, J. Barron, F. Marques, and J. Malik. Multiscale combinatorial grouping. In *CVPR*, 2014. 2, 3, 6, 8
- [3] J. Carreira, R. Caseiro, J. Batista, and C. Sminchisescu. Semantic segmentation with second-order pooling. In *ECCV*, 2012. 6
- [4] J. Carreira and C. Sminchisescu. Cpmc: Automatic object segmentation using constrained parametric min-cuts. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 34(7):1312–1328, 2012. 2
- [5] M. Cheng, Z. Zhang, W. Lin, , and P. Torr. Bing: Binarized normed gradients for objectness estimation at 300fps. In *CVPR*, 2014. 6
- [6] I. Endres and D. Hoiem. Category independent object proposals. In *Computer Vision—ECCV 2010*, pages 575–588. Springer, 2010. 2
- [7] D. Erhan, C. Szegedy, A. Toshev, and D. Anguelov. Scalable object detection using deep neural networks. In *CVPR*, 2014. 2
- [8] M. Everingham, L. Van Gool, C. K. Williams, J. Winn, and A. Zisserman. The pascal visual object classes (voc) challenge. *International journal of computer vision*, 88(2):303–338, 2010. 1, 4
- [9] P. F. Felzenszwalb, R. B. Girshick, D. McAllester, and D. Ramanan. Object detection with discriminatively trained part-based models. *TPAMI*, 32(9), 2010. 1
- [10] R. Girshick. Fast R-CNN. In *ICCV*, 2015. 1, 2, 3, 8
- [11] R. Girshick, J. Donahue, T. Darrell, and J. Malik. Rich feature hierarchies for accurate object detection and semantic segmentation. In *CVPR*, 2014. 1, 2
- [12] B. Hariharan, P. Arbeláez, R. Girshick, and J. Malik. Simultaneous detection and segmentation. In *ECCV*, 2014. 1
- [13] K. He, X. Zhang, S. Ren, and J. Sun. Spatial pyramid pooling in deep convolutional networks for visual recognition. In *ECCV*, 2014. 1, 2, 3
- [14] J. Hosang, R. Benenson, P. Dollár, and B. Schiele. What makes for effective detection proposals? *arXiv preprint arXiv:1502.05082*, 2015. 1, 2, 8
- [15] J. Hosang, R. Benenson, and B. Schiele. How good are detection proposals, really? In *BMVC*, 2014. 2
- [16] H. Kang, M. Hebert, A. A. Efros, and T. Kanade. Connecting missing links: Object discovery from sparse observations using 5 million product images. In *ECCV*, 2012. 8
- [17] P. Krähenbühl and V. Koltun. Geodesic object proposals. In *ECCV*, 2014. 2, 8
- [18] A. Krizhevsky, I. Sutskever, and G. E. Hinton. Imagenet classification with deep convolutional neural networks. In *NIPS*, 2012. 1, 2, 3, 7
- [19] Y. LeCun, B. Boser, J. S. Denker, D. Henderson, R. E. Howard, W. Hubbard, and L. D. Jackel. Backpropagation applied to handwritten zip code recognition. *Neural computation*, 1(4):541–551, 1989. 1
- [20] T.-Y. Lin, M. Maire, S. Belongie, J. Hays, P. Perona, D. Ramanan, P. Dollr, and C. L. Zitnick. Microsoft coco: Common objects in context. In *ECCV*, 2014. 1, 2, 3, 4
- [21] S. Manen, M. Guillaumin, and L. Van Gool. Prime object proposals with randomized prim’s algorithm. In *ICCV*, 2013. 6
- [22] P. O. Pinheiro, R. Collobert, and P. Dollár. Learning to segment object candidates. In *NIPS*, 2015 (To appear). 2, 8
- [23] E. Rahtu, K. Juho, and B. Matthew. Learning a category independent object detection cascade. In *ICCV*, 2011. 6
- [24] R. E. Rantalankila P., Kannala J. Generating object segmentation proposals using global and local search. In *CVPR*, 2014. 6
- [25] S. Ren, K. He, R. B. Girshick, and J. Sun. Faster R-CNN: towards real-time object detection with region proposal networks. In *NIPS*, 2015 (To appear). 2
- [26] B. C. Russell, W. T. Freeman, A. A. Efros, J. Sivic, and A. Zisserman. Using multiple segmentations to discover objects and their extent in image collections. In *CVPR*, 2006. 1
- [27] K. Simonyan and A. Zisserman. Very deep convolutional networks for large-scale image recognition. *CoRR*, abs/1409.1556, 2014. 7
- [28] C. Szegedy, S. Reed, D. Erhan, and D. Anguelov. Scalable, high-quality object detection. *arXiv preprint arXiv:1412.1441*, 2014. 2
- [29] J. R. Uijlings, K. E. van de Sande, T. Gevers, and A. W. Smeulders. Selective search for object recognition. *IJCV*, 104(2), 2013. 2, 3, 6, 8
- [30] C. L. Zitnick and P. Dollár. Edge boxes: Locating object proposals from edges. In *ECCV*, 2014. 1, 2, 3, 4, 6, 7, 8