

Expanding Low-Density Latent Regions for Open-Set Object Detection

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Abstract

Modern object detectors have achieved impressive progress under the close-set setup. However, open-set object detection (OSOD) remains challenging since objects of unknown categories are often misclassified to existing known classes. In this work, we propose to identify unknown objects by separating high/low-density regions in the latent space, based on the consensus that unknown objects are usually distributed in low-density latent regions. As traditional threshold-based methods only maintain limited low-density regions, which cannot cover all unknown objects, we present a novel Open-set Detector (OpenDet) with expanded low-density regions. To this aim, we equip OpenDet with two learners, Contrastive Feature Learner (CFL) and Unknown Probability Learner (UPL). CFL performs instance-level contrastive learning to encourage compact features of known classes, leaving more low-density regions for unknown classes; UPL optimizes unknown probability based on the uncertainty of predictions, which further divides more low-density regions around the cluster of known classes. Thus, unknown objects in low-density regions can be easily identified with the learned unknown probability. Extensive experiments demonstrate that our method can significantly improve the OSOD performance, e.g., OpenDet reduces the Absolute Open-Set Errors by 25%-35% on six OSOD benchmarks. Code is available at: <https://github.com/csuhan/opendet2>.

1. Introduction

Although the past decade has witnessed significant progress in object detection [3, 17, 29, 37, 39, 45], modern object detectors are often developed with a close-set as-

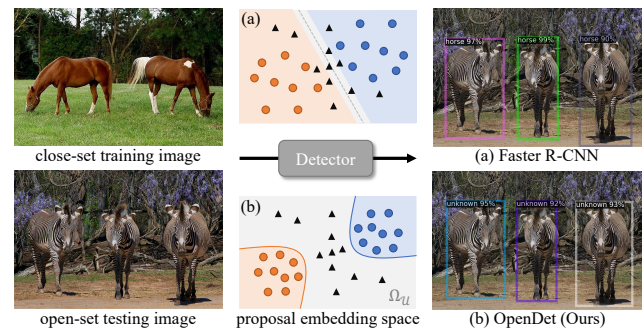


Figure 1. Trained on close-set images, **(a) threshold-based methods**, e.g., Faster R-CNN, usually misclassify unknown objects (black triangles, e.g. zebra) into known classes (colored dots, e.g. horse) due to limited low-density regions (in gray color). **(b) Our method** identifies unknown objects by expanding low-density regions. We encourage compact proposal features and learn clear separation between known and unknown classes.

sumption that the object categories appearing in the testing process are contained by the training sets, and quickly lose their efficiency when handling real-world scenarios as many objects categories have never been seen in the training. See Fig. 1 for an instance, where a representative object detector, i.e., Faster R-CNN [39] trained on PASCAL VOC [14], misclassifies zebra into horse with high confidence, as the new class zebra is not contained by PASCAL VOC. To alleviate this issue, Open-Set Object Detection (OSOD) has been recently investigated, where the detector trained on close-set datasets is asked to detect all known objects and identify unknown objects in open-set conditions.

OSOD can be seen as an extension of Open-Set Recognition (OSR) [40]. Although OSR has been extensively studied [2, 7, 16, 40, 51, 53], rare works attempted to solve the challenging OSOD. Dhamija *et al.* [12] first benchmarked the open-set performance of some representative methods [29, 37, 39], which indicates most detectors are overestimated in open-set conditions. Miller *et al.* [32, 33] adopt dropout sampling [15] to improve the robustness of

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detectors in open-set conditions. Joseph *et al.* [23] proposed an energy-based unknown identifier by fitting the energy distributions of known and unknown classes. In summary, prior works usually leverage hidden evidence (*e.g.*, the output logits) of pre-trained models as unknown indicators, with the cost of additional training step and complex post-processing. Can we train an open-set detector *with only* close-set data, and *directly* apply it to open-set environments *without* complex post-processing?

We draw inspiration from the consensus that known objects are usually clustered to form high-density regions in the latent space, while unknown objects (or novel patterns) are distributed in low-density regions [5, 18, 38]. From this perspective, proper separation of high/low-density latent regions is crucial for unknown identification. However, traditional methods, *e.g.*, hard-thresholding (Fig. 1 (a)), only maintain limited low-density regions, as higher thresholds will hinder the close-set accuracy. In this work, we propose to identify unknown objects by expanding low-density latent regions (Fig. 1 (b)). Firstly, we learn compact features of known classes, leaving more low-density regions for unknown classes. Then, we learn an unknown probability for each instance, which serves as a threshold to divide more low-density regions around the cluster of known classes. Finally, unknown objects distributed in these regions can be easily identified.

More specifically, we propose an Open-set Detector (OpenDet) with two learners, Contrastive Feature Learner (CFL) and Unknown Probability Learner (UPL), which expands low-density regions from two folds. Let us denote the latent space with $\Omega = \Omega_{\mathcal{K}} \cup \Omega_{\mathcal{U}}$, where $\Omega_{\mathcal{K}}$ and $\Omega_{\mathcal{U}}$ represent high/low-density sub-space, respectively. CFL performs instance-level contrastive learning to encourage intra-class compactness and inter-class separation of known classes, which expands $\Omega_{\mathcal{U}}$ by narrowing $\Omega_{\mathcal{K}}$. UPL learns unknown probability for each instance based on the uncertainty of predictions. As we carefully optimize UPL to maintain the close-set accuracy, the learned unknown probability can serve as a threshold to divide more $\Omega_{\mathcal{U}}$ around $\Omega_{\mathcal{K}}$. In the testing phase, we directly classify an instance into the unknown class if its unknown probability is the largest among all classes.

To demonstrate the effectiveness of our method, we take PASCAL VOC [14] for close-set training and construct several open-set settings considering both VOC and COCO [30]. Compared with previous methods, OpenDet shows significant improvements on all open-set metrics without compromising the close-set accuracy. For example, OpenDet reduces the Absolute Open-Set Errors (introduced in Sec. 4.1) by 25%-35% on six open-set settings. We also visualize the latent feature in Fig. 2, where OpenDet learns clear separation between known and unknown classes. Besides, we conduct extensive ablation experiments to analyze

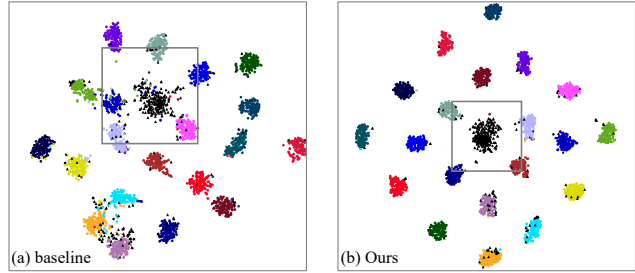


Figure 2. **t-SNE visualization of latent features.** We take VOC classes as known classes (colored dots), and non-VOC classes in COCO as unknown classes (black triangles). Our method learns a clear separation between known and unknown classes.

the effect of our main components and core design choices. Furthermore, we show that OpenDet can be easily extended to one-stage detectors and achieve satisfactory results. We summarize our contributions as:

- To our best knowledge, we are the first to solve the challenging OSOD by modeling low-density latent regions.
- We present a novel Open-set Detector (OpenDet) with two well-designed learners, CFL and UPL, which can be trained in an end-to-end manner and directly applied to open-set environments.
- We introduce a new OSOD benchmark. Compared with previous methods, OpenDet shows significant improvements on all open-set metrics, *e.g.*, OpenDet reduces the Absolute Open-Set Errors by 25%-35%.

2. Related Work

Open-Set Recognition. Early attempts on OSR [1, 22, 24, 41, 52] usually leverage traditional machine learning methods, *e.g.*, SVM [22, 41]. Bendale *et al.* [2] introduced OpenMax, the first deep learning-based OSR method, which redistributes the output probabilities of the softmax layer. Other approaches include generative adversarial network-based methods [16, 34] which generate potential open-set images to train an open-set classifier, reconstruction-based methods [35, 44, 51] which adopt auto-encoder to recover latent features and identify unknown by reconstruction errors, and prototype-based methods [6, 7] which identify open-set images by measuring the distance to learned prototypes. In addition, Zhou *et al.* [53] proposed to learn data placeholders to anticipate open-set data and classifier placeholders to distinguish known and unknown. Kong *et al.* [26] utilized an adversarially trained discriminator to detect unknown examples. Our method is more related to [53]. Differently, [53] requires close-set pre-train and calibration on validation sets, while our method is trained in an end-to-end manner, and the learned unknown probability is accurate and calibration-free.

Open-Set Object Detection is an extension of OSR in object detection. Dhamija *et al.* [12] first formalized OSOD

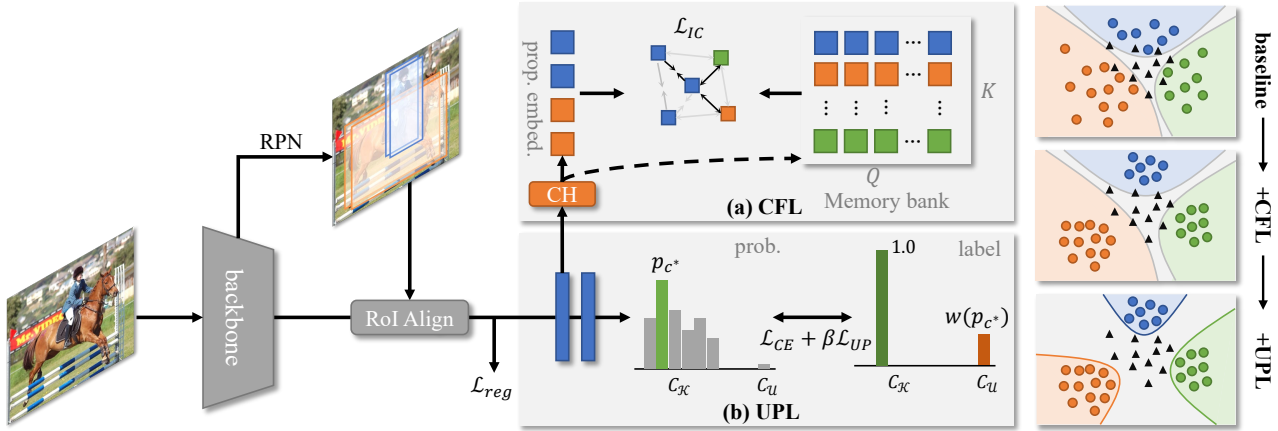


Figure 3. **Overview of our proposed method.** **Left:** OpenDet is a two-stage detector with (a) Contrastive Feature Learner (CFL) and (b) Unknown Probability Learner (UPL). CFL first encodes proposal features into low-dimensional embeddings with the Contrastive Head (CH). Then we optimize these embeddings between the mini-batch and memory bank with an Instance Contrastive Loss \mathcal{L}_{IC} . UPL learns probabilities for both known classes C_K and unknown class C_U with cross-entropy loss \mathcal{L}_{CE} and Unknown Probability Loss \mathcal{L}_{UP} . **Right:** A toy illustration of how different components work. Colored dots and triangles denote proposal features of different known and unknown classes, respectively. Our method identifies unknown by expanding low-density latent regions (in gray color).

and benchmarked some representative detectors by their classifiers. Classifiers with a background class [39] performs better than one-vs-rest [29] and objectness-based [37] classifiers in handling unknown objects. Dhaniya *et al.* [12] also show that the performance of most detectors is overestimated in open-set conditions. Miller *et al.* [32, 33] utilized dropout sampling [15] to estimate uncertainty in object detection and thus reduce open-set errors. Joseph *et al.* [23] proposed an energy-based unknown identifier by fitting the energy distributions of known and unknown classes. However, the approach in [23] requires extra open-set data of unknown classes, which violates the original definition of OSOD. In summary, previous methods leverage hidden evidence (*e.g.*, the output logits) of pre-trained models as unknown indicators. But they need additional training step and complex post-processing to estimate the unknown indicator. In contrast, OpenDet can be trained with only close-set data and directly identify unknown objects with the learned unknown probability.

Contrastive Learning is a methodology to learn representation by pulling together positive sample pairs while pushing apart negative sample pairs, which has been recently popularized for self-supervised representation learning [4, 8, 9, 13, 19, 20]. Khosla *et al.* [25] first extended self-supervised contrastive learning to the full-supervised setting and received a lot of attention from other fields, *e.g.*, long-tailed recognition [10, 47], semantic segmentation [46, 48] and few-shot object detection [43]. Our approach is also inspired by supervised contrastive learning [25]. In this work, we explore *instance-level* contrastive learning to learn compact features of object proposals.

Uncertainty Estimation. Neural networks tend to produce over-confident predictions [27]. Estimating the uncertainty

of model predictions is important for real-world applications. Currently, uncertainty estimation can be categorized into sampling-based and sampling-free methods. Sampling-based methods ensemble predictions of multiple runs [15] or multiple models [27], which are not applicable for speed-critical object detection. Sampling-free methods learn additional confidence value [11, 42] to estimate uncertainty. Our method belongs to the latter family. The learned unknown probability can reflect the uncertainty of predictions.

3. Methodology

3.1. Preliminary

We formalize OSOD based on prior works [12, 23]. Let us denote with $D = \{(x, y), x \in X, y \in Y\}$ an object detection dataset, where x is an input image and $y = \{(c_i, \mathbf{b}_i)\}_{i=1}^N$ denotes a set of objects with corresponding class label c and bounding box \mathbf{b} . We train the detector on the training set D_{tr} with K known classes $C_K = \{1, \dots, K\}$, and test it on the testing set D_{te} with objects from both known classes C_K and unknown classes C_U . The goal is to detect all known objects (objects $\in C_K$), and identify unknown objects (objects $\in C_U$) so that they will not be misclassified to C_K . As it is impossible to list infinite unknown classes, we denote them with $C_U = K+1$.

Different from OSR, OSOD has its unique challenges. In OSR, an image only belongs to C_K or C_U ; any example out of C_K is defined as unknown. In OSOD, an image may contain objects from both C_K and C_U , which is defined as mixed unknown [12]. That means unknown objects will also appear in D_{tr} , but have not been labeled yet. Besides, detectors usually keep a background class C_{bg} which is easily confused with C_U .

3.2. Baseline Setup

We setup the baseline with Faster R-CNN [39], which consists of a backbone, Region Proposal Network (RPN) and R-CNN. The standard R-CNN includes a shared fully connected (FC) layer and two separate FC layers for classification and regression. We augment R-CNN in three ways. **(a)** We replace the shared FC layer with two parallel FC layers so that the module applied to the classification branch will not affect the regression task. **(b)** Inspired by [7, 49], we use cosine similarity-based classifier to alleviate the over-confidence issue [2, 36]. Specifically, we adopt scaled cosine similarity scores as output logits: $s_{i,j} = \frac{\alpha \mathcal{F}(x)_i^\top w_j}{\|\mathcal{F}(x)_i\| \|w_j\|}$, where $s_{i,j}$ denotes the similar score between i -th proposal features $\mathcal{F}(x)_i$ and weight vector of class j . α is the scaling factor ($\alpha=20$ by default). **(c)** The box regressor is set to class-agnostic, *i.e.*, the regression branch outputs a vector of length 4 rather than $4(K+2)$. Note that our baseline does not improve the open-set performance, but it is effective for the whole framework (Fig. 3).

3.3. Contrastive Feature Learner

This section presents Contrastive Feature Learner (CFL) to encourage intra-class compactness and inter-class separation, which expands low-density latent regions by narrowing the cluster of known classes. As shown in Fig. 3 (a), CFL contains a contrastive head (CH), a memory bank, and an instance contrastive loss \mathcal{L}_{IC} . For a proposal feature $\mathcal{F}(x)_i$, we first encode it into a low-dimensional embedding with CH. Then, we optimize the embeddings from the mini-batch and memory bank with \mathcal{L}_{IC} . We give more details in the following part.

Contrastive Head. We build a contrastive head (CH) to map high-dimensional proposal feature $\mathcal{F}(x)_i$ to low-dimensional proposal embedding $\mathbf{z}_i \in \mathbf{R}^d$ ($d = 128$ by default). In detail, CH is a multilayer perceptron with sequential FC, ReLU, FC, and L2-Norm layers, which is applied to the classification branch of R-CNN in training and abandoned during inference.

Class-Balanced Memory Bank. Popular contrastive representation learning usually adopts large-size mini-batch [25] or memory bank [20] to increase the diversity of exemplars. Here we build a novel class-balanced memory bank to increase the diversity of object proposals. Specifically, for each class $c \in \mathcal{C}_{\mathcal{K}}$, we initialize a memory bank $M(c)$ of size Q . Then, we sample representative proposals from a mini-batch with two steps: **(a)** We sample proposals with Intersection of Union (IoU) $> T_m$ where T_m is an IoU threshold to ensure the proposals contain relevant semantics. **(b)** For each mini-batch, we sample q ($q \leq Q$) proposals that are least similar (*i.e.*, minimum cosine similarity) with existing exemplars in $M(c)$. This step makes our memory banks store more diverse exemplars and enable

long-term memory. Finally, we repeat (a) and (b) every iteration where the oldest proposals are out of the memory and the newest into the queue.

Instance-Level Contrastive Learning. Inspired by supervised contrastive loss [25], we propose an Instance Contrastive (IC) Loss to learn more compact features of object proposals. Assume we have a mini-batch of N proposals, IC Loss is formulated as:

$$\mathcal{L}_{IC} = \frac{1}{N} \sum_{i=1}^N \mathcal{L}_{IC}(\mathbf{z}_i), \quad (1)$$

$$\mathcal{L}_{IC}(\mathbf{z}_i) = \frac{1}{|M(\mathbf{c}_i)|} \sum_{\mathbf{z}_j \in M(\mathbf{c}_i)} \log \frac{\exp(\mathbf{z}_i \cdot \mathbf{z}_j / \tau)}{\sum_{\mathbf{z}_k \in A(\mathbf{c}_i)} \exp(\mathbf{z}_i \cdot \mathbf{z}_k / \tau)}, \quad (2)$$

where \mathbf{c}_i is the class label of i -th proposal, τ is a temperature hyper-parameter, $M(\mathbf{c}_i)$ denotes the memory bank of class \mathbf{c}_i , and $A(\mathbf{c}_i) = M \setminus M(\mathbf{c}_i)$. Note that we only optimize proposals with IoU $> T_b$ where T_b is an IoU threshold similar to T_m .

Although unknown objects are unavailable in training, the separation of known classes benefits unknown identification. Optimizing \mathcal{L}_{IC} is equivalent to pushing the cluster of known classes away from low-density latent regions. As shown in Fig. 2 (b), our method learns a clear separation between known and unknown classes with only close-set training data.

3.4. Unknown Probability Learner

As introduced in Sec. 3.3, CFL expands low-density latent regions by narrowing the cluster of known classes (*i.e.*, high-density regions). However, we still lack explicit boundaries to separate high/low-density regions. Traditional threshold-based methods with a small score threshold (*e.g.*, 0.05) only maintain limited low-density regions, which cannot cover all unknown objects. Here we present Unknown Probability Learner (UPL) to divide more low-density latent regions around the cluster of known classes.

To this aim, we first augment the K -way classifier with the $K+1$ -way classifier, where $K+1$ denotes the unknown class. Then the problem becomes: *how to optimize the unknown class with only close-set training data?* Let us consider a simple known vs. unknown classifier with available open-set data, we can directly train a good classifier by maximizing margins between classes. Now, we only have close-set data; To train such a classifier, we relax the maximum margin principle and only ensure all known objects are correctly classified, *i.e.*, maintaining the close-set accuracy. With this premise, we will introduce how to learn the unknown probability in the following section.

Review Cross-Entropy (CE) Loss. We first review softmax CE Loss, the default classification loss of Faster R-CNN. Let \mathbf{s} denote the classification logits of a proposal, the softmax probability \mathbf{p} of class c is defined as:

Method	VOC	VOC-COCO-20				VOC-COCO-40				VOC-COCO-60			
	mAP κ \uparrow	WI \downarrow	AOSE \downarrow	mAP κ \uparrow	AP u \uparrow	WI \downarrow	AOSE \downarrow	mAP κ \uparrow	AP u \uparrow	WI \downarrow	AOSE \downarrow	mAP κ \uparrow	AP u \uparrow
FR-CNN [39]	80.10	18.39	15118	58.45	0	22.74	23391	55.26	0	18.49	25472	55.83	0
FR-CNN* [39]	80.01	18.83	11941	57.91	0	23.24	18257	54.77	0	18.72	19566	55.34	0
PROSER [53]	79.68	19.16	13035	57.66	10.92	24.15	19831	54.66	7.62	19.64	21322	55.20	3.25
ORE [23]	79.80	18.18	12811	58.25	2.60	22.40	19752	55.30	1.70	18.35	21415	55.47	0.53
DS [33]	80.04	16.98	12868	58.35	5.13	20.86	19775	55.31	3.39	17.22	21921	55.77	1.25
OpenDet	80.02	14.95	11286	58.75	14.93	18.23	16800	55.83	10.58	14.24	18250	56.37	4.36

Table 1. **Comparisons with other methods on VOC and VOC-COCO-T₁**. We report close-set performance (mAP κ) on VOC, and both close-set (mAP κ) and open-set (WI, AOSE, AP u) performance of different methods on VOC-COCO-{20, 40, 60}. * means a higher score threshold (*i.e.* 0.1) for testing.

Method	VOC-COCO-0.5n				VOC-COCO-n				VOC-COCO-4n			
	WI \downarrow	AOSE \downarrow	mAP κ \uparrow	AP u \uparrow	WI \downarrow	AOSE \downarrow	mAP κ \uparrow	AP u \uparrow	WI \downarrow	AOSE \downarrow	mAP κ \uparrow	AP u \uparrow
FR-CNN [39]	9.25	6015	77.97	0	16.14	12409	74.52	0	32.89	48618	63.92	0
FR-CNN* [39]	9.01	4599	77.66	0	16.00	9477	74.17	0	33.11	37012	63.80	0
PROSER [53]	9.32	5105	77.35	7.48	16.65	10601	73.55	8.88	34.60	41569	63.09	11.15
ORE [23]	8.39	4945	77.84	1.75	15.36	10568	74.34	1.81	32.40	40865	64.59	2.14
DS [33]	8.30	4862	77.78	2.89	15.43	10136	73.67	4.11	31.79	39388	63.12	5.64
OpenDet	6.44	3944	78.61	9.05	11.70	8282	75.56	12.30	26.69	32419	65.55	16.76

Table 2. **Comparisons with other methods on VOC-COCO-T₂**. Note that we put VOC-COCO-2n in the appendix due to limited space.

$$p_c = \text{softmax}(s_c) = \frac{\exp(s_c)}{\sum_{j \in C} \exp(s_j)}, \quad (3)$$

where $C = C_{\mathcal{K} \cup \mathcal{U} \cup b_g}$ denotes all known classes $C_{\mathcal{K}}$, unknown class $C_{\mathcal{U}}$ and background C_{b_g} . Then, we formulate softmax CE Loss \mathcal{L}_{CE} as:

$$\mathcal{L}_{CE} = - \sum_{c \in C} y_c \log(p_c), \quad y_c = \begin{cases} 1, & c = c^* \\ 0, & c \neq c^* \end{cases}, \quad (4)$$

where c^* means the ground truth class, and y is the one-hot class label. For simplicity, we re-write \mathcal{L}_{CE} as:

$$\mathcal{L}_{CE} = - \log(p_{c^*}). \quad (5)$$

Learning Unknown Probability. Since there is no supervision for the unknown probability p_u , we consider a conditional probability p'_u under the ground truth probability p_{c^*} . Formally, we define p'_u as a softmax probability without the logit of ground truth class c^* :

$$p'_u = \frac{\exp(s_u)}{\sum_{j \in C, j \neq c^*} \exp(s_j)}, \quad (6)$$

where u is short for the unknown class $C_{\mathcal{U}}$. Then, similar to CE Loss, we formulate an Unknown Probability (UP) Loss \mathcal{L}_{UP} to optimize p'_u , which is defined as:

$$\mathcal{L}_{UP} = - \log(p'_u). \quad (7)$$

After that, we jointly optimize the CE Loss \mathcal{L}_{CE} and UP Loss \mathcal{L}_{UP} (illustrated in Fig. 3 (b)), where \mathcal{L}_{CE} aims to

maintain the close-set accuracy, and \mathcal{L}_{UP} learns the unknown probability. Take Fig. 3 (bottom-right) for an illustration, optimizing \mathcal{L}_{UP} is equivalent to dividing more low-density latent regions (in gray color) from known classes. Once we finished the training, the learned unknown probability serves as an indicator to identify unknown objects in these low-density regions.

Uncertainty-weighted Optimization. Although we optimize the conditional probability p'_u instead of p_u , \mathcal{L}_{UP} will still penalize the convergence of \mathcal{L}_{CE} , leading to the accuracy drop of known classes. Inspired by uncertainty estimation [11, 42], we add a weighting factor $w(\cdot)$ to \mathcal{L}_{UP} , which is defined as a function of p_{c^*} :

$$w(p_{c^*}) = (1 - p_{c^*})^\alpha p_{c^*}, \quad (8)$$

where α is a hyper-parameter ($\alpha=1$ by default). Despite many design choices of $w(\cdot)$ (shown in Tab. 6), we choose a simple yet effective one in Eq. 8. We are inspired by the popular uncertainty signal: entropy $w(\mathbf{p}) = -\mathbf{p} \log(\mathbf{p})$. Since Eq. 8 has a similar curve shape to entropy (see our appendix), it can also reflect uncertainty. But our empirical findings suggest that Eq. 8 is easier to optimize than entropy. Finally, we formulate the uncertainty-weighted UP Loss as follow:

$$\mathcal{L}_{UP} = -w(p_{c^*}) \log(p'_u). \quad (9)$$

Hard Example Mining. It is unreasonable to let all known objects learn the unknown probability as they do not belong

to the unknown class. Therefore, we present uncertainty-guided hard example mining to optimize \mathcal{L}_{UP} with high-uncertainty proposals, which may overlap with real unknown objects in the latent space. Here we consider two uncertainty-guided mining methods:

- *Max entropy.* Entropy is a popular uncertainty measure [27, 31] defined as: $H(\mathbf{p}) = -\sum_{c \in C} p_c \log(p_c)$. For a mini-batch, We sort them in descending entropy order, and select *top-k* examples.
- *Min max-probability.* Max-probability, *i.e.*, the maximum probability of all classes: $\max(\mathbf{p})$, is another uncertainty signal. We select *top-k* examples with minimum max-probability.

Furthermore, since background proposals usually overwhelm the mini-batch, we sample the same number of foreground and background proposals, enabling our model to recall unknown objects from the background class.

3.5. Overall Optimization

Our method can be trained in an end-to-end manner with the following multi-task loss:

$$\mathcal{L} = \mathcal{L}_{rpn} + \mathcal{L}_{reg} + \mathcal{L}_{CE} + \beta \mathcal{L}_{UP} + \gamma_t \mathcal{L}_{IC}, \quad (10)$$

where \mathcal{L}_{rpn} denotes the total loss of RPN, \mathcal{L}_{reg} is smooth L1 loss for box regression, β and γ_t are weighting coefficients. Note γ_t is proportional to the current iteration t so that we can gradually decrease the weight of \mathcal{L}_{IC} for better convergence of \mathcal{L}_{CE} and \mathcal{L}_{UP} .

4. Experiment

4.1. Experimental Setup

Datasets. We construct an OSOD benchmark using popular PASCAL VOC [14] and MS COCO [30]. We take the `trainval` set of VOC for close-set training. Meanwhile, we take 20 VOC classes and 60 non-VOC classes in COCO to evaluate our method under different open-set conditions. Here we define two settings: **VOC-COCO- $\{\mathbf{T}_1, \mathbf{T}_2\}$** . For setting \mathbf{T}_1 , we gradually increase open-set classes to build three joint datasets with $n=5000$ VOC testing images and $\{n, 2n, 3n\}$ COCO images **containing** $\{20, 40, 60\}$ non-VOC classes, respectively. For setting \mathbf{T}_2 , we gradually increase the Wilderness Ratio (WR)² [12] to construct four joint datasets with n VOC testing images and $\{0.5n, n, 2n, 4n\}$ COCO images **disjointing** with VOC classes. See our appendix for more details.

Evaluation Metrics. We use the **Wilderness Impact (WI)** [12] to measure the degree of unknown objects misclassified to known classes: $WI = (\frac{P_K}{P_{K \cup U}} - 1) \times 100$, where P_K and $P_{K \cup U}$ denote the precision of close-set and open-set

²Wilderness Ratio is the ratio of #images with unknown objects to #images with known objects.

CFL	UPL	WI \downarrow	AOSE \downarrow	mAP \uparrow	AP \uparrow
	baseline	19.26	16433	58.33	0
✓		17.92	15162	58.54	0
	✓	16.47	12018	57.91	14.27
✓	✓	14.95	11286	58.75	14.93

Table 3. **Effect of different components** on VOC-COCO-20.

classes, respectively. Note that we scale the original WI by 100 for convenience. Following [23], we report WI under a recall level of 0.8. Besides, we also use **Absolute Open-Set Error (AOSE)** [33] to count the number of misclassified unknown objects. Furthermore, we report the **mean Average Precision (mAP)** of known classes (mAP \mathcal{K}). Lastly, we measure the novelty discovery ability by AP \mathcal{U} (AP of the unknown class). Note WI, AOSE, and AP \mathcal{U} are open-set metrics, and mAP \mathcal{K} is a close-set metric.

Comparison Methods. We compare OpenDet with the following methods: Faster R-CNN (**FR-CNN**) [39], Dropout Sampling (**DS**) [33], **ORE** [23] and **PROSER** [53]. FR-CNN is the base detector of other methods. We also report FR-CNN*, which adopts a higher score threshold for testing. We use the official code of ORE and reimplement DS and PROSER based on the FR-CNN framework.

Implementation Details. We use ResNet-50 [21] with Feature Pyramid Network [28] as the backbone of all methods. We adopt the same learning rate schedules with Detectron2 [50]. SGD optimizer is adopted with an initial learning rate of 0.02, momentum of 0.9, and weight decay of 0.0001. All models are trained on 8 GPUs with a batch size of 16. For **CFL**, we set memory size $Q=256$ and sampling size $q=16$. We sample proposals with an IoU threshold $T_m=0.7$ for the memory bank, and $T_b=0.5$ for the mini-batch. For **UPL**, we sample $k=3$ examples for foreground and background proposals respectively. Besides, we set hyper-parameters $\alpha=1.0$ and $\beta=0.5$. We set the initial value of $\gamma_t=0.1$ and linearly decrease it to zero.

4.2. Main Results

We compare OpenDet with other methods on VOC-COCO- $\{\mathbf{T}_1, \mathbf{T}_2\}$. Tab. 1 shows results on VOC-COCO- \mathbf{T}_1 by gradually increasing unknown classes. Compared with FR-CNN, FR-CNN* with a higher score threshold (0.05 \rightarrow 0.1) does not reduce WI, but results in a decrease in mAP \mathcal{K} , where known objects with low confidence are filtered out. PROSER improves AOSE and AP \mathcal{U} to some extent, but the WI and mAP \mathcal{K} are even worse. Although ORE and DS achieve comparable mAP \mathcal{K} , the improvement on open-set metrics is limited. The proposed OpenDet outperforms other methods by a large margin. Taking VOC-COCO-20 for an example, OpenDet gains about 20%, 25%, 14.93 on WI, AOSE and AP \mathcal{U} respectively without compromising the mAP \mathcal{K} (58.75 vs. 58.45). Besides, we also report mAP \mathcal{K} on VOC, which indicates OpenDet is competitive in the traditional close-set setting (80.02 vs. 80.10).

Memory	size	WI \downarrow	mAP $\kappa\uparrow$
single-GPU mini-batch	~50	16.19	58.29
cross-GPU mini-batch	~50 \times 8	15.88	58.07
class-agnostic memory bank	5120	15.99	57.47
class-agnostic memory bank*	65536	15.49	58.90
class-balanced memory bank	256 \times 20	14.95	58.75

Table 4. **Class-balanced memory bank.** We compare our class-balanced memory bank with other variants. We keep class-agnostic memory bank the same size with ours (256 \times 20=5120). 8 and 20 are the number of GPU and VOC classes, respectively. * means a larger memory size.

	(a)	(b)	(c)	(d)	(e)	(f)
T $_b$	0.5	0.7	0.9	0.5	0.5	0.7
T $_m$	0.5	0.7	0.9	0.7	0.9	0.9
WI \downarrow	15.33	15.16	15.27	14.95	14.62	15.27
mAP $\kappa\uparrow$	58.29	58.55	58.32	58.75	58.66	58.33
(a) IoU threshold						
q	16	16	16	32	64	128
Q	128	256	512	256	256	256
WI \downarrow	15.36	14.95	14.47	15.24	15.43	14.77
mAP $\kappa\uparrow$	58.51	58.75	58.31	58.32	57.77	58.18

(b) Memory size and mini-batch sampling size

Table 5. **Sampling strategy in CFL.** We list different choices of (a) memory sampling threshold T $_m$ and mini-batch sampling threshold T $_b$, (b) memory size Q and sampling size q.

We also compare OpenDet with other methods by increasing the WR, where the results in Tab. 2 draws similar conclusions with Tab. 1. Our method performs better as the WR increases. For example, the mAP κ gains on VOC-COCO- $\{0.5n, n, 4n\}$ are $\{0.64, 1.04, 1.63\}$, indicating that our method actually separates known and unknown classes.

4.3. Ablation Studies

In this section, we conduct ablation experiments on VOC-COCO-20 to analyze the effect of our main components and core design choices.

Overall Analysis. We first analyze the contribution of different components. As shown in Tab. 3, our two modules, CFL and UPL, show substantial improvement compared with the baseline. The combination of CFL and UPL further boosts the performance. We also visualize the latent features in Fig. 2, where our method learns clear separation between known and unknown classes.

Contrastive Feature Learner. We carefully study the design choices of the memory bank and example sampling strategy in CFL. As \mathcal{L}_{IC} is optimized between the current mini-batch and the memory bank, we investigate different **designs of memory** in Tab. 4. Compared with the mini-batch (*i.e.*, short-term memory), the settings with a memory bank perform better on WI. However, imbalanced training data makes the class-agnostic memory bank filled with high-frequency classes, leading to a drop in

	$w(\cdot)$	WI \downarrow	AOSE \downarrow	mAP $\kappa\uparrow$	AP $\mathcal{U}\uparrow$
	baseline	19.26	16433	58.33	0
(a)	identity	10.50	12185	56.42	11.33
(b)	$-p_{c^*} \log(p_{c^*})$	14.70	11384	58.13	13.71
(c)	$(1 - p_{c^*})^\alpha p_{c^*}$	14.95	11286	58.75	14.93
(d)	$(1 - p_m)^\alpha p_m$	14.86	11296	58.03	14.15
(e)	$H(\mathbf{p})/\log(C)$	14.29	11690	57.75	14.65

Table 6. **Different designs of $w(\cdot)$ in \mathcal{L}_{UP} .** p_m is the maximum probability of all classes: $p_m = \max(\mathbf{p})$. (e) denotes normalized entropy where $H(\mathbf{p}) = -\sum_c p_c \log(p_c)$ and C is the number of known classes.

Setting	WI \downarrow	AOSE \downarrow	mAP $\kappa\uparrow$	AP $\mathcal{U}\uparrow$
OpenDet (w/ HEM)	14.95	11286	58.75	14.93
(a) w/o HEM	18.33	13733	57.41	13.91
(b) w/o bg.	13.02	12230	56.53	13.49
(c) top-k:				
1	14.46	12826	58.42	14.54
3	14.95	11286	58.75	14.93
5	14.66	10412	58.50	14.55
10	15.15	10358	58.25	14.86
all	18.40	11779	56.55	13.89
(d) metric:				
random	17.01	13065	56.99	15.58
max entropy	14.29	11514	58.27	15.46
min max-probability	14.95	11286	58.75	14.93

Table 7. **Hard example mining (HEM) in UPL.** (a) without HEM. (b) without background: we only sample foreground proposals. (c) varying *top-k*. the setting *all* means all foreground and equal number of background proposals. (d) mining methods.

mAP κ (58.76 \rightarrow 57.47). Enlarging the memory bank size (5120 \rightarrow 65536) can alleviate this issue, but it requires more computation. The proposed class-balanced memory bank can store more diverse examples with a small memory size, outperforming other variants.

We further study the design choices of **example sampling strategies**. For a mini-batch, we consider the IoU threshold T $_b$; for the memory bank, we consider the IoU threshold T $_m$, memory size Q and mini-batch sampling size q. As shown in Tab. 5a, the settings (d) and (e) achieve the best result in mAP κ and WI, respectively, while (a)-(c) are worse than (d)-(e) in WI. This indicates that the mini-batch requires a loose constraint to gather more diverse examples, while the memory bank needs high-quality examples to represent the class centers. In Tab. 5b, (b) and (c) perform better than other settings, which demonstrates that long-term memory (*i.e.*, larger Q/q) is a good choice for CFL.

Unknown Probability Learner. We first explore **different variants of $w(\cdot)$** . Compared with the baseline, Tab. 6 (a) significantly reduces WI and AOSE, but leads to mAP κ drop, which indicates the learned unknown probability is overestimated. The formula of (b) is similar to entropy, and (c) is our default setting. As discussed in Sec. 3.4, both (b) and (c) achieve satisfactory results in WI and AOSE, but (c) is outperforms (b) in mAP κ and

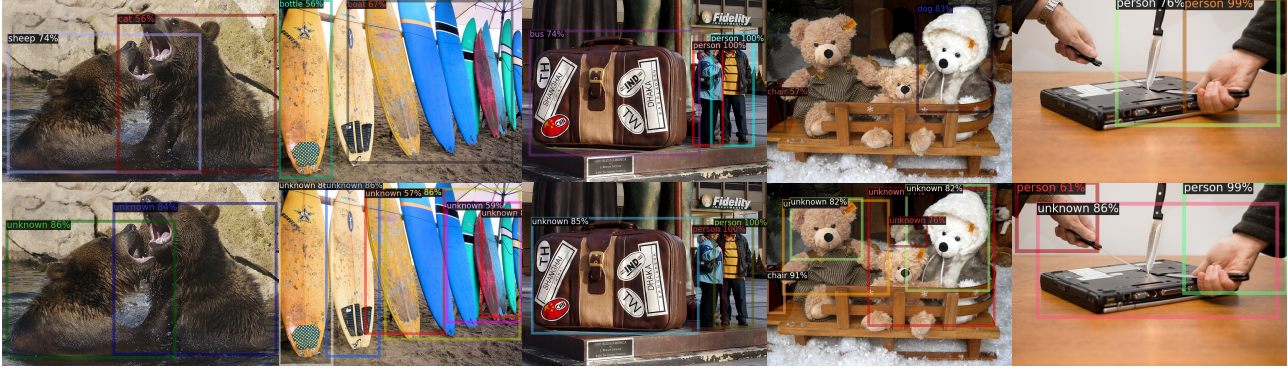


Figure 4. **Qualitative comparisons** between the baseline (top) and OpenDet (bottom). We train both models on VOC and visualize the detection results on COCO. Note that we apply NMS between known classes and the unknown class for better visualization.

AP_U . (d) and (e) are two variants of $w(\cdot)$ based on max-probability and entropy, respectively. They obtain comparable performance on open-set metrics, but the mAP_K is lower than (c).

We also analyze the effect of **Hard example mining (HEM)** in Tab. 7. Comparing Tab. 7 (a) (without HEM) with our default setting (with HEM), we show HEM is crucial for UPL. Tab. 7 (b) indicates background proposals are also necessary for unknown probability learning, *e.g.*, OpenDet without background leads to 2.22 and 1.44 drop in mAP_K and AP_U . Besides, we varying the hyper-parameter *top-k* in Tab. 7 (c) where HEM works in a wide range of k (≤ 10), while optimizing all examples is not applicable. Tab. 7 (d) demonstrates the effectiveness of two mining methods, *i.e.*, max entropy and min max-probability. **Qualitative Comparisons.** Fig. 4 compares the qualitative results of baseline and OpenDet. OpenDet gives an unknown label to unknown objects (bottom row), while the baseline method classifies them to known classes or the background (top row). See our appendix for more qualitative results.

4.4. Extend to One-Stage Detector

Although OpenDet is based on a two-stage detector, it can be easily extended to other architectures, *e.g.*, a representative one-stage detector RetinaNet [29]. RetinaNet has a backbone and two parallel sub-networks for classification and regression, respectively. Different from FR-CNN, RetinaNet adopts Focal Loss [29] for dense classification. Here we show how to extend OpenDet to RetinaNet (denote with Open-RetinaNet). For CFL, we append the contrastive head to the second-last layer of the classification sub-network. We adopt the same sampling strategies in CFL and optimize \mathcal{L}_{IC} with pixel-wise features. For UPL, we only sample hard foreground examples as RetinaNet does not preserve a background class. Then \mathcal{L}_{UP} is jointly optimized with Focal Loss. Tab. 8 reports the results on VOC-COCO-20, where Open-RetinaNet shows significant improvements

Method	WI $_{\downarrow}$	AOSE $_{\downarrow}$	mAP_K $_{\uparrow}$	AP_U $_{\uparrow}$
RetinaNet	14.58	38071	57.44	0
Open-RetinaNet	10.84	16815	57.25	11.02

Table 8. **Performance of Open-RetinaNet** on VOC-COCO-20.

on all open-set metrics and achieves comparable close-set mAP_K . For example, Open-RetinaNet gains 23.7%, 55.8%, and 11.02 in WI, AOSE, and AP_U , respectively.

5. Conclusions

This paper proposes a novel Open-set Detector (OpenDet) to solve the challenging OSOD task by expanding low-density latent regions. OpenDet consists of two well-designed learners, CFL and UPL, where CFL performs *instance-level* contrastive learning to learn more compact features and UPL learns the unknown probability that serves as a threshold to further separate known and unknown classes. We also build an OSOD benchmark and conduct extensive experiments to demonstrate the effectiveness of our method. Compared with other methods, OpenDet shows significant improvements on all metrics.

Limitations. We notice that some low-quality proposals belonging to known classes are given the unknown label during inference, and cannot be filtered out by per-class non-maximum suppression. Although these proposals do not hurt the close-set mAP_K , it raises a new question about reducing false unknown predictions, which is also a direction for our future work.

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