Adaptive Superpixel for Active Learning in Semantic Segmentation

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Abstract

Learning semantic segmentation requires pixel-wise annotations, which can be time-consuming and expensive. To reduce the annotation cost, we propose a superpixel-based active learning (AL) framework, which collects a dominant label per superpixel instead. To be specific, it consists of adaptive superpixel and sieving mechanisms, fully dedicated to AL. At each round of AL, we adaptively merge neighboring pixels of similar learned features into superpixels. We then query a selected subset of these superpixels using an acquisition function assuming no uniform superpixel size. This approach is more efficient than existing methods, which rely only on innate features such as RGB color and assume uniform superpixel sizes. Obtaining a dominant label per superpixel drastically reduces annotators' burden as it requires fewer clicks. However, it inevitably introduces noisy annotations due to mismatches between superpixel and ground truth segmentation. To address this issue, we further devise a sieving mechanism that identifies and excludes potentially noisy annotations from learning. Our experiments on both Cityscapes and PASCAL VOC datasets demonstrate the efficacy of adaptive superpixel and sieving mechanisms.

1. Introduction

With the advent of deep learning, many computer vision tasks including semantic segmentation have dramatically evolved in recent years. Such advances are thanks to complex deep network models that can learn huge datasets. However, labeling such large datasets is prohibitively time-consuming and labor-intensive, in particular, for semantic segmentation tasks that demand a dense annotation on each pixel [8, 11]. Active learning (AL) offers an approach to alleviate the annotation cost by selectively querying only the most informative samples to annotators.

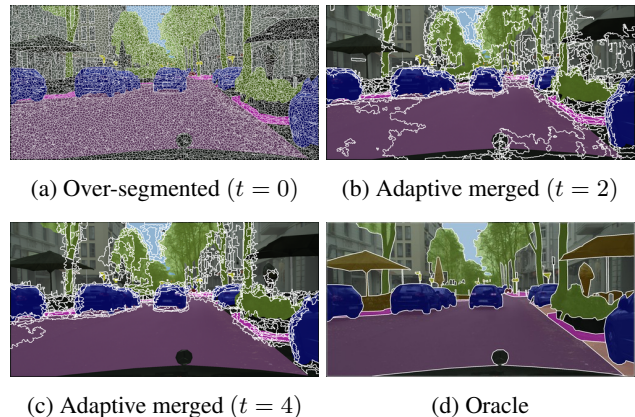Designing an effective form of annotation query is crit-

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(a) Over-segmented ($t = 0$)   (b) Adaptive merged ($t = 2$)

(c) Adaptive merged ($t = 4$)   (d) Oracle

Figure 1: *Examples of adaptive superpixels.* (a) We begin active learning with over-segmented superpixels. (b, c) In each round t, we merge superpixels in an adaptive manner using the model from the previous round. (d) As the round progresses, adaptive superpixels look similar to oracle ones.

ical in practice as it determines the actual annotation cost such as the number of clicks required and the informativeness per annotation query. For semantic segmentation, an image-wise query can be asked for a complete annotation on the semantic of every pixel in an image [9, 10, 34, 38, 40]. This is a daunting task requiring an enormous amount of clicks to indicate boundaries (using polygons or contours) for each semantic segment or to annotate semantic pixel-wisely, while the diversity of contexts which we can observe in a single image is restricted. Alternatively, one can design a *region-based* query enquiring only about the dominant label of a small region such as rectangle patch [5, 27, 37] or superpixel [4, 33]. This is known to be simple yet effective as it requires only a single click per query while enabling AL to put more focus on significant regions and to avoid annotation wastes.

AL with the region-based query needs a delicate generation of candidate regions to be queried. A small region size dilutes the budget efficiency, whereas the dominant labeling even by a perfect annotator is prone to give noisy labels
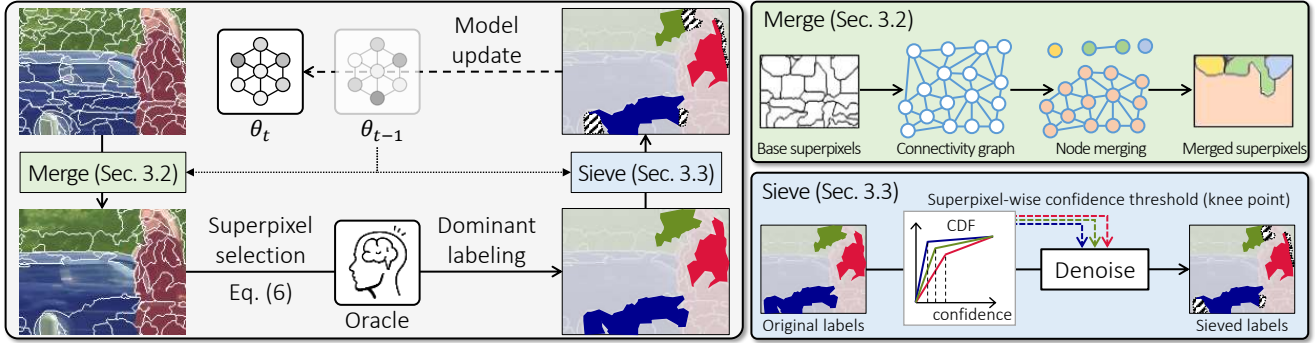
Figure 2: *An overview of the proposed framework.* In each round t, we merge superpixels with a graph using the latest model, and obtain dominant labels for selected superpixels. The dominant labels are selectively propagated to pixels with confidence above the detected knee point, resulting in the creation of a sieved dataset. Finally, we train a model with the sieved one.

when regions are too large to be consisting of pixels with a single class. However, the previous works [5, 27, 33] rely on a fixed candidate set of regions of uniform size, while we could adjust the size and shape of candidate regions as we train the semantic segmentation model over rounds of AL. This limitation remains even in recent work [4] with superpixel candidates providing less risk of noisy labels than rectangle ones since the superpixels are produced, only at the beginning, by a conventional superpixel algorithm, where conventional superpixel algorithms [1, 32, 35] cluster adjacent pixels of similar innate features (*e.g.*, color) with implicit or explicit regularization to make similar sizes or shapes of superpixels, *i.e.*, limited freedom of query region.

In this paper, to fully enjoy the benefit in terms of annotation cost while suppressing the risk of noisy labels, we devise an AL framework, illustrated in Figure 2, consisting of adaptive merging and sieving methods. The adaptive merging method repeatedly evolves the candidate superpixels for dominant labeling at every round with the latest model and no explicit regularization on the size and shape of superpixels. This indeed enables the continual improvement of the superpixels' ability to accurately capture the boundaries of semantic objects (Figure 1b and 1c), and a proper variation in the sizes and shapes of superpixels, *i.e.*, larger superpixels being attached to larger semantic objects (*e.g.*, road and building) and smaller ones to smaller objects (*e.g.*, human and vehicle) as shown in the ideal ones (Figure 1d).

Given the adaptive superpixels, we establish a corresponding acquisition function being aware of irregular superpixel sizes. It prioritizes uncertain superpixels of rare classes in order to query the most informative superpixels while balancing class distributions in the entire annotations. In addition, to alleviate the inevitable noise in the dominant labeling, we propose a sieving technique that excludes labeled pixels of high potential risks of being different classes than the dominant one. To be specific, we identify such pixels of potentially noisy labels by per-superpixel sieving with

distinct thresholds over superpixels. This provides stabler denoising than uniform sieving with a constant threshold, which might aggravate class imbalance in the sieved annotations.

Through the integration of adaptive merging and sieving into an AL framework, we achieve improved accuracy and budget-efficiency over a baseline method. Notably, the merging demonstrates effectiveness under small-sized superpixels, while the sieving plays a critical role given large-sized superpixels. Moreover, we show a consistent improvement over existing methods in various settings. We provide a thorough justification of the proposed method using various quantitative measures, where we introduce a new evaluation metric for superpixel algorithms that assesses both (achievable) accuracy and recall, where the recall is overlooked in the existing one, the achievable segmentation accuracy (ASA) [22] but important in the context of AL. This may give new insights into developing superpixel algorithms.

Our main contributions are summarized as follows:

- We propose an adaptive merging algorithm where superpixels are updated at each round (Section 3.2), and show the effectiveness of adaptive merging rather than only merging once (Section 4.2).

- We alleviate the side effect of noisy labels via a sieving technique (Section 3.3), and demonstrate especially efficient under large superpixels (Section 4.2).

- In various realistic experiments, we demonstrate the consistent improvement of the proposed AL framework, consisting of the adaptive merging and sieving methods with the dedicated acquisition function, over existing ones (Section 4.2).

- We provide an insightful analysis on proper superpixels for AL with the new evaluation metric of superpixel algorithms being aware of usage in AL (Section 5.1).

2. Related work

Active learning for segmentation. To reduce the labeling cost of semantic segmentation, active learning for segmentation selectively collects labels among unlabeled samples, and they utilize different predefined labeling units. Early approaches [34, 40] perform image-wise selection and mask labeling. Patch-based methods [5, 7, 16, 25, 37] divide images into rectangular patches and provide mask label [5, 16, 37] or polygon overlay of an object [7, 25] within the selected patch. Recently, superpixel-based approaches [4, 33] split images to perceptually meaningful regions called superpixel by running an off-the-shelf over-segmentation algorithm [1, 28, 35]. Each superpixel is labeled with a single dominant class, and thus it can be obtained efficiently [4], while a label noise may occur depending on the quality of the superpixel. We present a new efficient labeling unit, that is initialized with the superpixel but its quality continuously improves by the proposed merging algorithm. To the best of our knowledge, the proposed method is the first approach to improve the labeling units during active learning for segmentation.

Learning from noisy labels for segmentation. Considering the difficulty in acquiring high-quality labels [8], semantic segmentation often suffers from noisy annotations. Previous studies address the label noise by using gradient similarity to the clean label [41], structural constraints [2, 21], and noise-aware loss [26, 39]. A recent approach captures the moment when different classes memorize noisy labels [23]. Most of these methods [21, 26, 39] utilize a single confidence threshold to detect label noise within data. Unlike previous approaches, we propose to detect an adaptive confidence threshold per every superpixel queried, using the Kneedle algorithm [30] (Section 3.3). Filtering with the sample-adaptive threshold prevents superpixels with low overall confidence or superpixels containing minor classes from being ignored.

Superpixel mechanisms and their evaluation metric. Numerous studies segment an image into superpixels to reduce the computation burden of pixels. Cut-based approaches [22, 32, 36, 42] create superpixels by adding multiple minimum cuts into a graph with pixel nodes. Other methods evolve homogeneous clusters from the initial set of points [1, 20]. For real-time applications, a simple hill-climbing optimization is utilized to enforce color similarity [35]. Most of methods aim at generating superpixels of predefined size or shape, and the generated superpixels are evaluated by achievable segmentation accuracy and boundary recall compared with ground truth [22, 35] or by examining the regularity in superpixel shape [15, 24, 31]. To save labeling costs in active learning, it is more important to obtain superpixels as close to the ground-truth segments as possible without such constraints on the shape or size of

superpixels. To this end, we propose the merging method (Section 3.2), and a new evaluation metric of superpixel mechanism, that also takes account of the size of ground-truth segments (Section 5.1). The proposed metric not only highlights the difference of the ideal superpixel required in active learning than that in the previous context, but also gives a guideline to develop superpixel algorithms for active learning.

3. Proposed framework

Given an unlabeled image set $\mathcal{I}$, we consider an active learning scenario with dominant labeling, where a query asks an oracle annotator for the dominant class label $D(s) \in \mathcal{C} := \{1, 2, ..., C\}$ of an associated superpixel s, and we issue a batch $\mathcal{B}_t$ of B queries for each round t. Once we enquire the batch $\mathcal{B}_t$, we train a model θ_t based on the annotations obtained so far. Recalling a superpixel s is a cluster of neighboring pixels, the dominant labeling demands much less annotation effort than the pixel-wise labeling on every individual pixel x in the same superpixel s or manual segmentation to indicate boundaries separating semantics. The benefit becomes greater with larger superpixels. Meanwhile, it is prone to noisy labeling as superpixels can be blunt, *i.e.*, including pixels of different semantics.

In order to fully enjoy the benefit in terms of annotation cost while suppressing the risk of noisy labels, our framework begins with a warm-up round ($t = 0$; Section 3.1; line 1-2 in Algorithm 1) to prepare an initial model from random querying and iterates subsequent rounds ($t = 1, 2, \dots$) with the adaptive merging (Section 3.2; line 4-5 in Algorithm 1) and sieving (Section 3.3; line 6-7 in Algorithm 1) methods to evolve superpixels for dominant labeling round by round and filter out annotations with the high risk of noisy labels given the latest model. The overall procedure is summarized in Figure 2 and Algorithm 1.

3.1. Warm-up round

The adaptive merging and sieving methods demand a trained model. To obtain an initial model, we start with a canonical warm-up round, which is identical to the first round of previous work [4]. We first use an off-the-shelf superpixel algorithm, namely SEEDS [35], to partition the pixels in each image $i \in \mathcal{I}$ into a set $S_0(i)$ of superpixels, and to produce a base segmentation $\mathcal{S}_0 := \bigcup_{i \in \mathcal{I}} S_0(i)$. Querying a batch $\mathcal{B}_0$ of B superpixels randomly selected from $\mathcal{S}_0$, we then train a model θ_0 using the dominant labels for $\mathcal{B}_0$. Specifically, to obtain θ_0, we first initialize θ at a model pretrained on ImageNet, and then train it to minimize the following cross-entropy (CE) loss:

$$\hat{\mathbb{E}}_{(x,y) \sim \mathcal{D}_0}[\text{CE}(y, f_\theta(x))] \,, \tag{1}$$

where $\mathcal{D}_0 := \{(x, y) : \exists s \in \mathcal{B}_0, x \in s, y(c) = \mathbb{1}[c = D(s)]$

Algorithm 1 Proposed Framework

Require: Image set $\mathcal{I}$, batch size B, and final round T.
1: Produce base superpixels $\mathcal{S}_0 := \bigcup_{i \in \mathcal{I}} \mathcal{S}_0(i)$
2: Obtain model θ_0 training with $\mathcal{D}_0$
3: **for** $t = 1, 2, \ldots, T$ **do**
4:     Adaptively merge the base superpixels and obtain
     $\mathcal{S}_t \leftarrow \bigcup_{i \in \mathcal{I}} \text{AM}(\mathcal{S}_0(i), \theta_{t-1})$
5:     Select and query B superpixels $\mathcal{B}_t \subset \mathcal{S}_t$ with (7)
6:     Sieve $s \in \bigcup_{t'=0}^{t} \mathcal{B}_{t'}$ and obtain $\mathcal{D}_t$ in (9)
7:     Obtain model θ_t training with the sieved $\mathcal{D}_t$
8: **return** θ_T

Algorithm 2 Adaptive Merging (AM)

Require: Base superpixels S, model θ, and threshold ϵ.
1: Set $S' \leftarrow \emptyset$ and $\mathcal{G}(S) \leftarrow (S, \mathcal{E}(S))$
2: Mark s as unexplored for each $s \in S$
3: **for** $s \in S$ in descending order of $u_\theta(s)$ **do**
4:     **if** s is unexplored **then**
5:         $S' \leftarrow S' \cup \{\text{MERGE}(s, f_\theta(s); \mathcal{G}, \theta)\}$
6: **return** S'
7: **procedure** MERGE($s, f; \mathcal{G}, \theta$)
8:     Mark s as explored and set $s' \leftarrow s$
9:     **for** each neighbor n of s in $\mathcal{G}$ **do**
10:         **if** n is unexplored and $d_{\text{JS}}(f \| f_\theta(n)) < \epsilon$ **then**
11:             $s' \leftarrow s' \cup \text{MERGE}(n, f; \mathcal{G}, \theta)$
12:     **return** s'

$\forall c \in \mathcal{C}\}$ is the training data for round $t = 0$ without sieving, and $f_\theta(x) \in \mathbb{R}^{|\mathcal{C}|}$ is θ's estimate of class probability on pixel x.

We remark that we use the initial model θ_0 for round $t = 1$. In our framework, SEEDS to generate $\mathcal{S}_0$ can be replaced with any other unless $\mathcal{S}_0$ is a fair over-segmentation of semantics with a low risk of noisy labeling while partially enjoying the benefit of low annotation cost. We note that SEEDS clusters neighboring pixels of similar colors while a semantic consists of multiple colors, typically. SEEDS, ready-to-use in OpenCV [3], easily provides the desired over-segmentation [4] and a decent performance of θ_0. In addition, the warm-up round with SEEDS corresponds to that in existing work [4]. Hence, this also enables a fair comparison of our main contributions, *i.e.*, adaptive merging and sieving methods, to existing works.

3.2. Adaptive merging

In advance of dominant labeling in round $t \geq 1$, we first merge the base superpixels in $\mathcal{S}_0$ to obtain $\mathcal{S}_t$ using the model θ_{t-1} from the previous round. We then select a batch $\mathcal{B}_t$ of B superpixels from $\mathcal{S}_t$ to be annotated using an acquisition function that prioritizes uncertain superpixels of rare class labels. For simplicity, we often omit the subscript $t - 1$ and write θ for θ_{t-1}.

Adaptive merging. To obtain $\mathcal{S}_t := \bigcup_{i \in \mathcal{I}} S_t(i)$, the merging process converts base superpixels $S_0(i)$ into merged ones $S_t(i)$ for each image $i \in \mathcal{I}$. We hence focus on how we merge given base superpixels S for an image. To begin with, we convert the superpixels S into a connected graph $\mathcal{G}(S) = (S, \mathcal{E}(S))$ where S is the set of nodes, each of which corresponds to a base superpixel $s \in S$, and $\mathcal{E}(S)$ is the edge set such that $(s, n) \in \mathcal{E}(S)$ if a pair of superpixels $s, n \in S$ are adjacent. Starting from a root node $s \in S$, we then merge neighboring superpixels of similar class predictions with the root s along the breadth-first search tree. To be specific, a neighbor n is amalgamated with root s only if

$$d_{\text{JS}}\big(f_\theta(s) \| f_\theta(n)\big) < \epsilon \, , \tag{2}$$

where $f_\theta(s) := \frac{\sum_{x \in s} f_\theta(x)}{|\{x : x \in s\}|}$ is the averaged class prediction of superpixel $s \in S$, and d_{JS} is a symmetric measure of discrepancy between two distributions, namely the square root of Jensen-Shannon (JS) divergence. More formally,

$$d_{\text{JS}}(p \| q) := \sqrt{\frac{d_{\text{KL}}(p \| \frac{p+q}{2}) + d_{\text{KL}}(q \| \frac{p+q}{2})}{2}} \, , \tag{3}$$

where d_{KL} is the Kullback-Leibler divergence. Once every node has been either merged to a root or played as a root, we collect the merged superpixels into $S_t(i)$. The merging process is formally described in Algorithm 2.

Recalling (2) and the fact that d_{JS} is a distance metric, we can guarantee that any pair of superpixels s and n has the prediction discrepancy at most 2ϵ and thus similar uncertainty and predicted label if they are merged. Hence, the threshold ϵ governs the impurity of predictions in a merged superpixel. We also remark that the merging process is fully dedicated to collecting pixels of similar predictions as a part of saving the annotation budget for querying similar pixels repeatedly. Hence, the merged superpixels can have various sizes differently from existing superpixel algorithms that regularize the superpixel size to be even [15, 24, 31].

Acquisition function. From the merged superpixels $\mathcal{S}_t$, we then select a batch $\mathcal{B}_t \subset \mathcal{S}_t$ of size B to be labeled, according to an acquisition function that estimates the benefit from labeling a merged superpixel, where the benefit would be huge for uncertain superpixels of rare class labels. In what follows, we define an uncertainty measure of superpixel in (5) and a popularity estimate of class in (6), and then introduce an acquisition function in (7).

Recalling $f_\theta(x) \in \mathbb{R}^{|\mathcal{C}|}$ is the probability such that $f_\theta(c; x)$ is the estimated probability that the class c of pixel x, we adapt best-versus-second-best [17] for uncertainty

measures of pixel x and superpixel s as follows:

$$u_\theta(x) := \frac{\max_{c \in \mathcal{C} \setminus \{y_\theta(x)\}} f_\theta(c; x)}{\max_{c \in \mathcal{C}} f_\theta(c; x)} , \quad (4)$$

$$u_\theta(s) := \frac{\sum_{x \in s} u_\theta(x)}{|\{x : x \in s\}|} , \quad (5)$$

where $y_\theta(x) := \arg \max_{c \in \mathcal{C}} f_\theta(c; x)$ is the estimated dominant label of pixel x in a given model θ.

We then define a popularity estimate $p(c; \theta)$ of class $c \in \mathcal{C}$ given θ as follows:

$$p(c; \theta) := \frac{|\{x : \exists s \in \mathcal{S}_t, D_\theta(s) = c, x \in s\}|}{|\{x : \exists s \in \mathcal{S}_t, x \in s\}|} , \quad (6)$$

where $D_\theta(s) := \arg \max_{c \in \mathcal{C}} |\{x \in s : y_\theta(x) = c\}|$ is the majority of predicted labels in superpixel s. We note that low $p(c; \theta)$ implies that class c is rare in the prediction of θ. It is noteworthy that we compute the class popularity in pixel-level due to the various sizes of our merged superpixels, while the previous work [4] proposes a superpixel-wise class popularity, $\frac{|\{s : D_\theta(s) = c, s \in \mathcal{S}_t\}|}{|\{s : s \in \mathcal{S}_t\}|}$, assuming superpixels of uniform size.

Using the uncertainty $u_\theta(s)$ in (5) and the class popularity $p(c; \theta)$ in (6), we define the following acquisition function $a(s; \theta)$ prioritizing uncertain superpixels of rare classes:

$$a(s; \theta) := u_\theta(s) \exp \left(-p(D_\theta(s); \theta)\right) . \quad (7)$$

We select B superpixels of highest values of $a(s; \theta_{t-1})$ from the merged $\mathcal{S}_t$ for query batch $\mathcal{B}_t$.

Remarks. We note that it is possible to produce $\mathcal{S}_t$ from scratch rather than from base segmentation $\mathcal{S}_0$. To reduce the computational cost for the adaptive merging process, we however compose $\mathcal{S}_t$ by merging base superpixels in $\mathcal{S}_0$ from SEEDS, which is known to generate an over-segmentation of semantics. Moreover, it is computationally expensive to explore all the possible mergers and obtain $\mathcal{S}_t$ followed by the query selection. We hence conduct the merging process only for a certain portion of base superpixels with the highest values of uncertainty (c.f., line 3 in Algorithm 2) and then select $\mathcal{B}_t$ to be queried since the acquisition function would select merged superpixels of high uncertainty in the end. Further details are presented in Appendix B.

3.3. Sieving

Despite the sophisticated design of the adaptive merging, a queried superpixel can inevitably include pixels of classes different from the dominant one, in particular, as we select superpixels of which model predictions are unsure. Hence, the dominant labeling is liable to make noisy annotations. To alleviate such side effects of the dominant labeling, we propose a simple sieving technique that filter out pixels that have high potential risks of being different classes than the dominant one. We observe that for a queried superpixel s and given model θ, the risk of mismatch between the dominant label $D(s)$ and the true label of pixel $x \in s$ would be high when $f_\theta(D(s); x)$ is low. From this observation, we define

$$h(s; \theta) := \{x \in s : f_\theta(D(s); x) \geq \phi(s; \theta)\} , \quad (8)$$

where $\phi(s; \theta)$ is a knee point of the cumulative distribution function of values of $f_\theta(D(s); x)$ in superpixel s, detected by Kneedle algorithm [30]. In addition, the knee point detection allows us to have a tailored sieving threshold to each superpixel. This is important to avoid the case that the remained pixels are heavily biased to relatively easy labels after sieving. Further details are in Appendix C.

We revisit all the queried superpixel $s \in \bigcup_{t'=0}^{t} \mathcal{B}_{t'}$ and sieve them using (8) with the latest model θ_{t-1} since the model evolves round by round. We finally obtain the following sieved dataset $\mathcal{D}_t$ for round $t \geq 1$:

$$\mathcal{D}_t := \left\{ (x, y) : \begin{array}{l} \exists s \in \cup_{t'=0}^{t} \mathcal{B}_{t'}, \ x \in h(s; \theta_{t-1}), \\ y(c) = \mathbb{1}[c = D(s)] \ \forall c \in \mathcal{C} \end{array} \right\} . \quad (9)$$

Analogously to the warm-up round, initializing model θ at a model pretrained on ImageNet, we obtain θ_t trained to mainly minimize the following CE loss:

$$\hat{\mathbb{E}}_{(x,y) \sim \mathcal{D}_t}[\text{CE}(y, f_\theta(x))] . \quad (10)$$

4. Experiments

4.1. Experimental setup

Datasets. We use two semantic segmentation datasets: Cityscapes [8] and PASCAL VOC 2012 (PASCAL) [13]. Cityscapes comprises 2,975 training and 500 validation images with 19 classes, while PASCAL consists of 1,464 training and 1,449 validation images with 20 classes.

Implementation details. We adopt DeepLab-v3+ architecture with Xception-65 [6] as our segmentation backbone. During training, we use the SGD optimizer with a momentum of 0.9 and set a base learning rate to 7e-3. We decay the learning rate by polynomial decay with a power of 0.9. For Cityscapes, we resize training images to 769×769 and train a model for 60k iterations with a mini-batch size of 4. Similarly, for PASCAL, we resize training images to 513×513 and train a model for 30k iterations with a mini-batch size of 12. Unless specified, we set the value of ϵ to 0.1.

Baseline methods. We compare our algorithm to *SP* [4], the state-of-the-art superpixel-based active segmentation method. Our algorithm applies two proposed processes in each round: merging and sieving. We call our complete
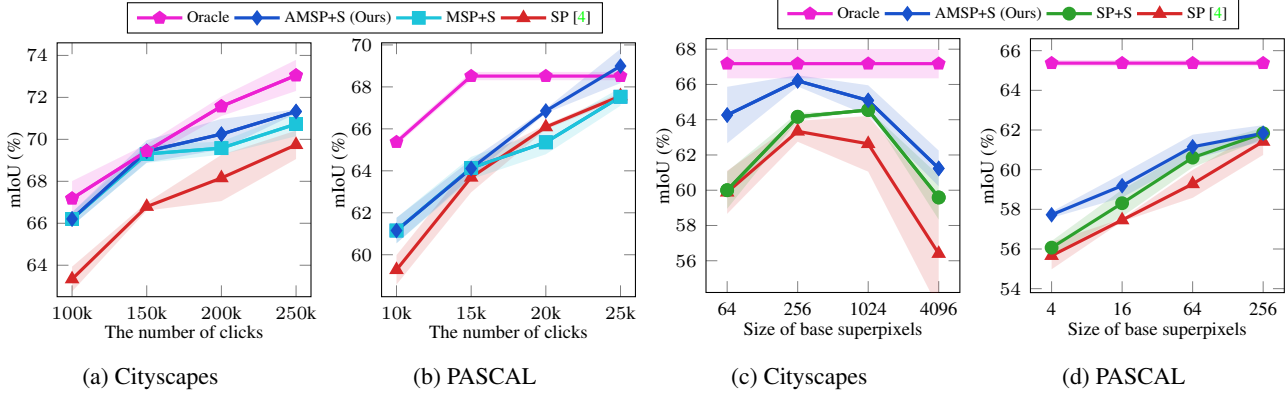
Figure 3: *Effect of adaptive superpixels.* (a, b) mIoU versus the number of clicks as budget. (c, d) mIoU versus the size of base superpixels. Each experiment is conducted with three trials and the shaded region indicates ranges.

method including adaptive merging as *AMSP+S*, while the partial version that only uses the sieving without the merging is called *SP+S*. Additionally, we evaluate the modified version of our method that performs merging only once in the second round, called *MSP+S*. Note that *AMSP+S* and *MSP+S* are identical until the second round.

Oracle baseline. The adaptive superpixel aims to merge every connected region with the same class labels. Thus, the upper bound of it is to consider each region separated by the ground truth mask as a superpixel. We refer to such ideal regions as oracle superpixels in Figure 4c. An active learning model trained using the oracle superpixels is called *Oracle*. Details are in Appendix D. As the number of oracle superpixels is limited, all of them are eventually labeled as the round progresses, and the performance of the trained model becomes equivalent to that of the pixel-wise fully supervised model. We report 100% and 90% of the *Oracle* performance for Cityscapes and PASCAL, respectively.

Evaluation protocol. We set the average size of the superpixels to 256 and 64 pixels on Cityscapes and PASCAL, respectively, for all experiments except for one where we adjust the size. Following *SP* [4], we use the number of clicks as the labeling budget. We conduct 5 rounds of data sampling, where we allocate a budget of 50k and 5k for each round on Cityscapes and PASCAL, respectively. In the first round, we randomly select superpixels to train a model, ensuring that all methods start at the same performance. We evaluate the trained model with mean Intersection-over-Union [11] on the validation images. We emphasize that the average size of superpixels containing 64 pixels is more efficient on Cityscapes, as detailed in Appendix A.

4.2. Effect of adaptive superpixels

Multi-round scenario. In Figures 3a and 3b, we compare the performance of the proposed method to *SP* [4] varying budget for both of Cityscapes and PASCAL. Note that

the performance for round 0, *i.e.*, 50K budget, is omitted as each method has the same performance at the warm-up round. The results show that our adaptive superpixel (*AMSP+S*) clearly outperforms the previous art in every budget setting on both of the datasets. In particular, the *AMSP+S* with only 150k clicks outperforms the previous art with 250k clicks in Cityscapes. In the final round, the proposed method recovers 97% and 92% of the *Oracle* performance for Cityscapes and PASCAL, respectively. To show the effectiveness of our adaptive approach, we compare *AMSP+S* to its one-shot merging version *MSP+S* in Figures 3a and 3b. On both datasets, adaptive feature of *AMSP+S* shows performance gain especially for the last two rounds. The experiments conducted for additional rounds can be found in Appendix A.

Multi-size scenario. The size of superpixels is an essential hyperparameter in superpixel-based AL, affecting both the quantity and quality of labels. In Figures 3c and 3d, we compare the proposed method to *SP* [4] varying the base superpixel size for both of Cityscapes and PASCAL, in the second round. Our adaptive superpixel (*AMSP+S*) outperforms the previous art in various superpixel sizes on both of the datasets. We also evaluate sieving only version (*SP+S*) of our method, which quantifies contribution of each components in our method. The performance improvement between *SP* and *SP+S* shows our sieving is especially helpful for large superpixels, and the performance gap between *SP+S* and *AMSP+S* shows our merging is especially effective for small superpixels. Thanks to the proposed sieving and merging, *AMSP+S* are comparably robust to the change of the superpixel size than *SP*.

Qualitative results. The quality of the proposed adaptive superpixel is illustrated in Figure 4. As shown in Figure 4a, superpixels used in the previous study [4] have uniform sizes for all areas regardless of their content. In contrast, Figure 4b demonstrates that adaptive superpixels accurately

(a) Base superpixels [35] (b) Merged superpixels (Ours) (c) Oracle superpixels
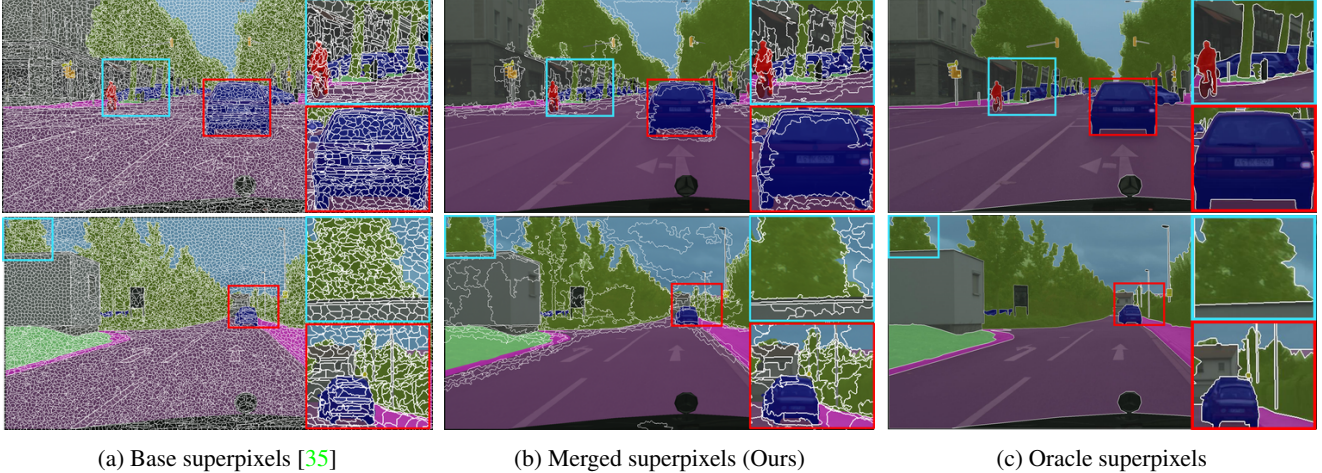
Figure 4: *Qualitative results of adaptive superpixels.* (a) Base superpixel generated by SEEDS [35] with size 256. (b) Superpixels generated with proposed adaptive merging at round 4. (c) Oracle superpixels generated from the ground truth.

reflect the actual size of the content in images, carefully capturing small object classes while efficiently covering large background classes. More examples are in Appendix F.

5. Analyses of adaptive superpixels

We propose new evaluation metrics to measure the quality of superpixel as a labeling unit for active segmentation, and utilize it to analyze our adaptive superpixels (Section 5.1). We also conduct analyses about the effect ϵ to our adaptive superpixels (Section 5.2). All analyses are conducted on Cityscapes with an average superpixel size of 256 pixels.

5.1. Achievable metrics

While various evaluation metrics for superpixel are presented [15, 22, 24, 31, 35], most of them aims to measure the quality of over-segmentation. For instance, achievable segmentation accuracy (ASA) [22] measures the segmentation accuracy when each superpixel $s \in S$ is associated with the oracle superpixel with the largest overlap. The ASA is calculated as follows:

$$\text{ASA}(S;G) := \frac{\sum_{s \in S} \max_{g \in G} |s \cap g|}{\sum_{s \in S} |s|} , \qquad (11)$$

where S and G represent the generated and oracle superpixels from the same image, respectively. As an image becomes more over-segmented, *i.e.*, the superpixel size becomes smaller, the ASA value increases. However, active learning (AL) aims to achieve the maximum benefit with the least amount of labeling effort, and therefore, the number of labels should be taken into account. In addition, the ASA is heavily biased towards classes with a large number of pixels.

In order to measure the suitability of superpixels for AL, we introduce precision and recall between generated and oracle superpixels. A generated superpixel can be viewed as positive on the inside and negative on the outside, and its precision and recall with respect to the corresponding oracle one can be calculated. For all generated superpixels, we define the achievable precision (AP) as follows:

$$\text{AP}(S;G) := \frac{1}{|S|} \sum_{s \in S} \frac{\max_{g \in G} |s \cap g|}{|s|} , \qquad (12)$$

where the summation is performed in superpixels, unlike in ASA, which implies pixel-wise precision. As we put the same weight on each superpixel, AP is less influenced by large objects than ASA. We note that AP is different to average precision [12, 29], used in object detection, which utilize the precision and recall curve. We also define the achievable recall (AR) and F1-score (AF) as:

$$\text{AR}(S;G) := \frac{1}{|S|} \sum_{s \in S} \frac{\max_{g \in G} |s \cap g|}{|g'(s;G)|} , \qquad (13)$$

$$\text{AF}(S;G) := \frac{2}{|S|} \sum_{s \in S} \frac{\max_{g \in G} |s \cap g|}{|s| + |g'(s;G)|} , \qquad (14)$$

where $g'(s;G) := \arg\max_{g \in G} |s \cap g|$ refers to the corresponding oracle superpixel. Details are in Appendix E.

All the metrics evaluate generated superpixels in comparison to oracle ones. However, the size of superpixels is also important besides their quality in AL. Therefore, it is necessary to evaluate the oracle superpixels against the generated superpixels, *i.e.*, ASA$(G;S)$, AP$(G;S)$, AR$(G;S)$ and AF$(G;S)$. We hence propose AF$(G;S)$ defined as:

$$\text{AF}(G;S) := \frac{2}{|G|} \sum_{g \in G} \frac{\max_{s \in S} |g \cap s|}{|g| + |s'(g;S)|} , \qquad (15)$$

Methods	ASA(S;G)	ASA(G;S)	AP(S;G)	AR(S;G)	AF(S;G)	AP(G;S)	AR(G;S)	AF(G;S)	mIoU
$SLIC_{4096}$	0.887	0.082	0.897	0.046	0.066	0.695	0.259	0.185	53.18
$SEEDS_{4096}$	0.909	0.082	0.900	0.050	0.070	0.665	0.309	0.221	57.61
$SLIC_{256}$	0.956	0.013	0.958	0.007	0.012	0.400	0.622	0.278	58.04
$SEEDS_{256}$	0.961	0.014	0.960	0.007	0.012	0.395	0.647	0.297	58.97
$Merged_2$	0.898	0.515	0.883	0.042	0.063	0.553	0.472	0.333	<u>60.00</u>
$Merged_4$	0.898	0.496	0.883	0.042	0.062	0.548	0.484	0.340	**61.36**
$Merged^*$	0.899	0.597	0.880	0.045	0.066	0.547	0.510	0.359	61.85
Oracle	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	70.81

Table 1: *Evaluation metrics of superpixels.* The subscript indicates the average size of the superpixel for SLIC [1] and SEEDS [35], while it indicates the round for Merged. Merged* indicates superpixel merged by a model trained with full supervision. To compute the mIoU, we train a model with 100k randomly selected superpixels.
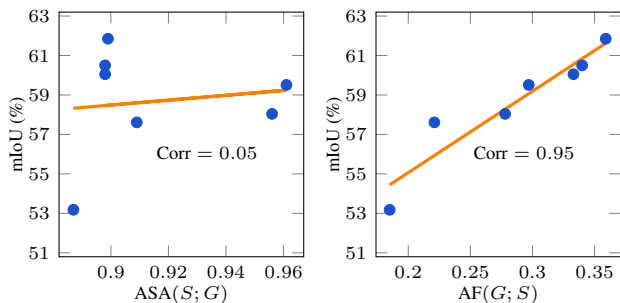

Figure 5: *Relationship between metrics and mIoU.* The correlation between ASA(S;G) and mIoU is low, while the correlation between AF(G;S) and mIoU is high. For the correlation calculation, *Oracle* in Table 1 is excluded.

where $s'(g;S) := \arg\max_{s \in S} |g \cap s|$ refers to the generated superpixel with the highest overlap, which is linked to the maximum amount of labeling we receive. Table 1 evaluates various superpixels through eight metrics. Although our merged superpixels have a relatively low ASA(S;G), they exhibit high ASA(G;S) and AF(G;S).

Correlation of metrics and mIoU. To show the proposed metric can accurately evaluate the superpixel quality for active segmentation, we measure the correlation between various evaluation metric and the performance of actively learned model in Table 1 and Figure 5. We observe that the proposed AF(G;S) shows the highest correlation to the performance of the actively learned model. We except AF(G;S) can select suitable superpixel algorithm for active learning, where the details are provided in Appendix E.

5.2. Ablation studies on epsilon

Epsilon sensitivity. In Figures 6a and 6b, we evaluate the sensitivity of our method to ϵ, which determines the amount of the merging. Proposed method show robustness to the change of ϵ, where the change of mIoU is less than 2%

for both Citycapes and PASCAL when ϵ is between 0.05 and 0.2. We observe that for every investigated ϵ values, *AMSP+S* surpasses the performance of the previous art [4].

Adaptive epsilon. We fix ϵ to 0.10 in all quantitative experiments, but there may exist an optimal ϵ for each round. In Table 2, we analyze ϵ that maximizes AF(G;S) metric for each round by assuming the existence of 10 validation images with ground truth. As the round increases, the optimal ϵ increases as well, which implies that the improvement of the model enables us to merge aggressively.

Effect of epsilon. Table 3 presents the quality of the merging algorithm under various criteria, defining correctness based on the agreement of dominant labels in paired superpixels. We merge a pair of superpixels when their ground-truth label is identical (Ground Truth), when their dominant top-1 model prediction is identical (Pseudo Label), and when the Euclidean Distance (ED) or Jensen-Shannon Divergence (JSD) of their averaged predictive probability is smaller than ϵ. Using pseudo labels leads to lower-quality merging as it ignores other minor classes. Since we utilize the predicted class probability as a feature space, JSD proves to be more effective than ED. As ϵ increases, the correct ratio decreases due to the aggressive merging of superpixels. We emphasize that ϵ can determine the trade-off between the quantity and quality of labels.

5.3. Implementation remarks for practitioners

Fast merging. The completion of the merging process for an image essentially requires a linear time complexity in the number of the base superpixels. However, to reduce this, the complete merging can be replaced with a *partial merging* that scans only a subset of base superpixels with high uncertainties as roots. This is considerable since we will eventually query only a subset of the merged superpixels according to the acquisition function (7), which prioritizes those with high uncertainties. In Table 4, we compare the complete and partial mergings in terms of the mIoU at 100k
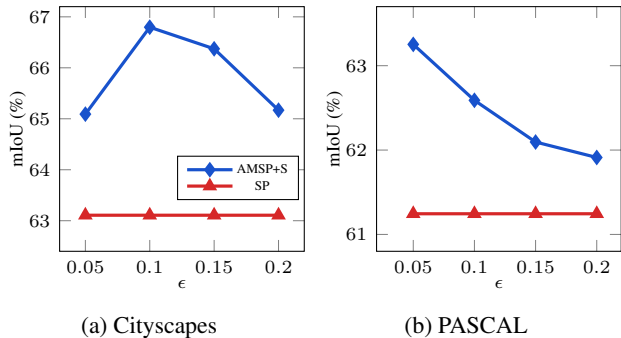
(a) Cityscapes   (b) PASCAL

Figure 6: *Epsilon sensitivity.* We experiment on superpixels with varying ϵ and demonstrate the robustness of our *AMSP+S*, while *SP* is independent of ϵ. Each experiment is conducted on the second round.

Epsilon	0.04	0.05	0.06	0.07	0.08
Merged_1	0.344	**0.346**	0.344	0.340	0.336
Merged_2	0.347	0.346	**0.348**	0.345	0.344
Merged_3	0.346	0.349	0.350	**0.351**	0.349
Merged_4	0.347	0.347	0.347	**0.348**	0.346

Table 2: *Adaptive epsilon.* $\text{AF}(G; S)$ for adaptive superpixels generated by varying ϵ is reported. The subscript indicates the round.

Method	Epsilon	Correct	Incorrect
Ground Truth	-	1.000	0.000
Pseudo Label	-	0.832	0.168
ED	0.05	0.915	0.085
	0.10	0.901	0.099
	0.15	0.891	0.109
JSD	0.05	0.934	0.066
	0.10	0.911	0.089
	0.15	0.896	0.104

Table 3: *Various merging criteria.* Using JSD performs more accurate merging than using ED. As ϵ increases, the rate of incorrect merging increases.

Methods	mIoU
SP [4]	63.77
AMSP+S (top 10%)	65.99
AMSP+S (complete 100%)	**66.53**

Table 4: *Various levels of partial merging.* Experiments are conducted under the same setting of Figure 3a with 100k clicks (Cityscapes, superpixel size of 256).

clicks. As expected, the partial merging on base superpixels with top-10% uncertainty has only a small gap to the complete merging. In addition, we find that by employing the partial merging, the time complexity is reduced significantly by a factor of 25.98 [1]. The partial merging is a useful suggestion to save computation resource for practitioners. A further investigation and discussion on the partial merging are presented in Appendix B.

Compatibility with other base superpixels. For a fair comparison to the previous study [4], we have employed the same superpixel algorithm called SEEDS [35] to generate base superpixels at the beginning. However, our merging and sieving processes can be applied on top of any other base superpixels. Indeed, in Figure 3c (and Appendix A), our method consistently shows gains over SP [4] when using base superpixels of different sizes. Furthermore, we compare SP and AMSP+S (ours) when using SLIC instead of SEEDS in the same setting of Figure 3a, where the mIoU's at 100k clicks of SP and ours have 65.97% and 67.56%, respectively, *i.e.*, the merging and sieving are also effective with SLIC as they were with SEEDS. We believe that our proposed method can work with any base superpixels even when they are from an unsupervised segmentation method [18] or a foundation model [19].

6. Conclusion

In this work, we propose an adaptive active learning framework with adaptive superpixels. Our merging and sieving methods operate adaptively every round, and the experimental results demonstrate the performance improvement of adaptive merging in various realistic situations. Furthermore, we suggest novel achievable metrics for evaluating superpixels in advance that are suitable for active learning.

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[1]The per-image runtime of the merging process (CPU-intensive) for Cityscapes is reduced from 12.42s to 0.48s on a server with two AMD EPYC 7513 32-core processors.

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