

# Improved Retrieval of Novel Keywords for Sponsored Search

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## ABSTRACT

Sponsored search involves matching user queries to advertiser keywords to display relevant ads. A major challenge is retrieving novel keywords that have limited or no click history. We propose IRENE, a method to obtain better representations for such novel keywords by enriching their text embedding with classifiers of similar seen keywords. Specifically, IRENE represents a keyword via a learned combiner function that takes as input the keyword's text embedding and classifiers of its nearest seen keyword neighbors. This allows incorporating collaborative signals beyond just text similarity. We demonstrate IRENE's effectiveness through extensive experiments on a proprietary sponsored search dataset, where it improves ranking accuracy over state-of-the-art dense retrievers by 4% in terms of R@100. Additional gains are shown on public extreme classification benchmarks for product search and Wikipedia document tagging. IRENE adds minimal computational overhead, encodes novel keywords in under 1 ms, and seamlessly incorporates streaming keywords. The improved representations directly translate to significant online metric gains including 4.2% higher click-through rate when deployed on a commercial search engine. The code for IRENE will be released publicly upon paper acceptance.

## KEYWORDS

dense retrieval; large-scale learning; sponsored search; zero shot learning; few shot learning; extreme classification

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## 1 INTRODUCTION

**Sponsored Search:** Sponsored search is essentially a match-making system between users and advertisers with the objective to optimize user experience while searching for knowledge and help advertisers reach the right set of users who might be interested in their product/service [1]. Users encode their intent in short pieces of text called queries. Similarly, advertisers also bid on short pieces of text, relevant to their ads. One critical component of the sponsored search pipeline is the task of matching user queries to these advertiser bid keywords. Most search engines currently follow different semantics to do this matching called match-types[6]. Matching user queries to advertiser keywords is a nuanced and challenging problem as maintaining the semantics of the match-type is essential

to advertisers who often bid differently on different match-types for the same keyword[34]. Further, since this matching task sits towards the head of the ads retrieval pipeline, any accuracy gains in this application can have super-linear gains for the downstream component [40].

This work defines a "novel keyword" as a keyword that has not received any clicks till now or has been clicked just once. Note that these settings correspond to the keyword being zero-shot and one-shot respectively. The clicks received by keywords generally follow a power-law distribution with exponentially more keywords having gotten  $m$  clicks than  $m + 1$  clicks [46]. Therefore, there are a lot of such novel keywords in most sponsored search systems.

**Dense Retrieval:** The task of matching user queries to advertiser keywords can also be posed as a retrieval problem. The keyword matching task can be viewed as a retrieval problem with user queries as queries and advertiser keywords as items. Dense Retrieval (DR) is the predominant technique for industry-scale search and recommendation applications [21]. The key idea in DR is to learn a language encoder so that similar items are embedded close to each other. Coupled with Approximate Nearest Neighbor Search (ANNS) algorithms, such language encoders provide accurate and scalable solutions for search and recommendation tasks where the items to be retrieved can run into billions[16, 39].

**Extreme Classification:** In its classical form, Extreme Classification (XC) refers to the task of tagging a query with the relevant subset of items from a large, albeit fixed output space [4, 12, 47, 48]. One class of XC methods train classifiers for the fixed set of items observed during training. These classifiers can then be used as the representation of seen items enabling the XC algorithm to leverage the query embedding coupled with approximate nearest neighbor search on item classifiers for efficient retrieval. XC algorithms have been shown to obtain significant accuracy gains in retrieving items (including the keyword matching problem [10, 35]) seen during training and for which classifiers have been learned. However, XC algorithms expect at least a few training queries for an item in order to train an accurate classifier for it.

**IRENE:** IRENE obtains an item's representation by enriching its text-based representation with classifiers of similar seen items. An item is represented as the non-linear combination of its textual embedding output from a language encoder with classifiers of similar seen items learned jointly with the combination function. As a result, the representation obtained has knowledge not just from the text of the item to be retrieved, but also the collaborative knowledge encoded in the classifiers of seen items similar to the item under consideration. However, the classifiers of any item can encode very diverse information compared to its text embedding obtained from a language encoder. This can be of particular value in real-world settings with billions of items where the signals learned by the two representations can complement each other fostering symbiotic learning. When deployed to applications, this symbiotic diversity of signals can help improve robustness to item

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distribution shifts. However, the way the two different kinds of information are combined can significantly affect the accuracy of the final representation. To this end, we propose to use self-attention with novel type-embeddings to introduce some prior and help the IRENE model combine the two different kinds of embeddings effectively. The proposed method, named IRENE (short for Improved REtrieval of Novel itEms) can be 4% more accurate than the next best method for keyword retrieval. The keyword retrieval accuracy is further validated by flighting the model in an A/B test and labeling by expert judges. IRENE could increase the click-through rate by 4.2% when deployed in production. On public benchmark applications, IRENE was found to be 1.5-3% more accurate than state-of-the-art DR algorithms. Additionally, IRENE can be trained by utilizing any embedding-based dense retriever, and hence can make use of advancements in teacher training, negative-mining, loss functions etc. that researchers in the DR community seek to improve.

**Contributions** The paper makes the following contributions. First, we identify that the classifier representation for an item encodes diverse signals compared to text-encoder-based representations for items. Second, we come up with a way to obtain a better representation of a novel item by combining its text embedding with classifiers of similar seen items. The combiner is built to ensure modularity - item embedding itself can come from different types of encoders and IRENE can execute the joint training of classifiers and combiner to achieve gains on new items. Third, in the scenario when some clicked query associations are revealed for a novel item, IRENE can make use of the revealed data to improve the prediction accuracy without having to fine-tune the base model. This helps to reduce latency and complexity in an online serving infrastructure. Fourth, an efficient implementation of IRENE was done to ensure that it can scale to datasets involving more than 200M training queries. This allowed the innovations proposed in the paper to be validated by conducting an A/B test on live search engine traffic.

## 2 RELATED WORKS

The popular approaches for keyword retrieval in Sponsored Search applications include DR, XC, and generative algorithms.

**Dense Retrieval:** Classical information retrieval (IR) methods including BM25 [32] make use of lexical features to return the subset of most relevant items. On the other hand, dense retrieval methods (DR) aim to learn a feature encoder that embeds relevant items close to queries as compared to irrelevant ones. DR approaches including DPR [21] and ANCE [42] have been demonstrated to comprehensively outperform BM25 on several retrieval applications including passage retrieval [9]. Recently proposed algorithms further improved over ANCE by eliminating false positives [31], introducing token-level interactions [24] and incorporating graph neural networks [45]. While more accurate, RocketQA [31], SimCSE [14], ColBERT [24], and GraphFormers [45] can also be more computationally demanding as compared to ANCE. Interestingly, DR methods can incorporate zero-shot items out-of-the-box, however, the item representations are constrained by the text which may be insufficient, especially in the case of short-text items [13]. XC algorithms present a way to learn improved item representations via classifiers as described below.

**Extreme Classification:** Classical extreme classifications algorithms focus on learning scalable and accurate classifiers for a large number of seen items [12, 13, 17, 19, 23, 27, 30, 35, 48]. XC algorithms have found applications in multiple applications including document tagging [4], product-to-product recommendation [20, 22], and sponsored search [10, 11]. Unfortunately, classical XC methods are designed to handle items that are tagged with at least a few training queries and hence miss out on novel items which constitute a large chunk of items in sponsored search applications.

However, XC methods such as Semsup-XC [2], MACLR [43], and ZestXML [18] have been proposed recently to incorporate zero-shot and few-shot items. In particular, ZestXML [18] employs a sparse transformation to embed relevant items close to the query as compared to irrelevant ones. However, ZestXML's accuracy can be lacking especially on novel labels [2]. SemSup-XC handles novel items through a hybrid matching module that matches input instances to class descriptions using a combination of semantic and lexical similarity. However, Semsup-XC employs a shortlist based on sparse bag-of-words features that can grow to be large in order to retrieve hard negatives. In addition, Semsup-XC relies on web-scraped meta-data to boost performance on unseen items. While it may be feasible to procure such meta-data at smaller scales, it often becomes a challenging task when the number of items is in the scale of millions. Furthermore, MACLR incorporates self-supervised learning tasks of Inverse Cloze Task and SimCSE for encoder pre-training. Finally, IRENE can be 2-12% more accurate than zero-shot XC methods on publicly available benchmark datasets.

**Zero/few-shot learning:** A ton of methods have been specifically proposed to incorporate novel labels, *i.e.*, labels with at most one train point. Label attributes or prototypes can be used to transfer the knowledge from seen items to novel items [33, 38, 44]. For example, ESZSL [33] assumes that attributes like "striped", "four-legged", *etc.*, that can describe both seen and unseen animal classes are provided for a task to predict animals present in an image. Hence such methods may not apply to large-scale retrieval settings like advertiser bid keyword retrieval as collecting or generating attributes for millions of items can be a daunting task in itself. NCM [29] and ADAM [49] employ centroids to compute representations of novel items with at least one training query. These methods can scale to a large number of novel items, however, their performance may be lacking on seen labels as demonstrated in the experiments section. The representation for novel items can also be learned via classifier synthesis where the classifiers of novel items are synthesized using classifiers of seen items [25, 28] or phantom items [7]. These methods attempt to synthesize classifiers over fixed features from a pre-trained model. For instance, COSTA [28] assume that item ground-truth co-occurrence of novel item to seen items can be obtained by either a web search engine or a user-provided input. However, scraping such data for a large number of novel items is infeasible in practice. Changpinyo16 learn the phantom items with the objective of aligning the classifier and text-embedding vector spaces. However, IRENE takes a different approach and tries to harmonize the diverse information present in the two vector spaces and obtain a combined representation for novel item. Moreover, these methods employ a linear combination while synthesizing classifiers. While these relaxations may help the methods in terms of scalability but miss out on potential accuracy gains provided by

**Table 1: Average number of different query prediction for a given keyword using its text-based and classifier representation, both obtained from NGAME algorithm. Values for different number of top predictions are shown**

Top-k Considered	% of different predictions
3	70.66
5	65.2
10	62.13
30	60.86
50	59.72
80	59.25
100	58.98

feature fine-tuning and a more expressive combination. In particular, IRENE employs feature fine-tuning and a novel attention-style combiner which yielded 2% more accurate item representations as compared to simpler combinations as proposed by LAF [25].

Finally, class incremental learning approaches (CIL) fine-tune the encoder based on the training data points of novel items, whenever available. However, fine-tuning to few shot labels may lead to catastrophic forgetting issues [49]. We, therefore, compare IRENE against a theoretical baseline where we pool the revealed data for novel items with the training data and retrain a DR model from scratch. Moreover, exemplar-based [3, 8] or exemplar-free [41, 50] algorithms attempt to mitigate the catastrophic forgetting, however, these may get expensive when dealing with a large number of novel items. Further, frequently fine-tuning an existing model in production can add additional latency and logistical complexities. This is further compounded by the necessity to rebuild the ANNS data structure from scratch. IRENE achieves state-of-the-art accuracy while being computationally efficient as a novel item can be encoded within 1 ms plus IRENE can utilize incremental ANNS data structure thus making it suitable for sponsored search application with millions of novel keywords.

### 3 MOTIVATION

In this section, we provide some experiments to motivate the IRENE algorithm. The Key idea in DR is to learn two embedding functions  $\mathcal{E}_q$  and  $\mathcal{E}_i$  for mapping a query,  $x$  and an item,  $y$  to some  $D$ -dimensional vector space. Specifically, that  $\mathcal{E}_q(x) \in V$  and  $\mathcal{E}_i(y) \in V$ , where  $V = \mathbb{R}^D$ . At the same time, the core problem in extreme multi-label classification is to learn a function  $f(x) \rightarrow \mathcal{Y}$  that maps the input representation  $\mathcal{E}_{xc}$  of  $x$  to the most relevant subset of labels from the label set  $\mathcal{Y}$ . State-of-the-art deep extreme classification algorithms solve this problem by learning a language encoder to map queries to some say  $d$ -dimensional vector space, i.e.  $\mathcal{E}_{xc}(x) \in \mathbb{R}^D$ . The algorithms would further train  $d$ -dimensional classifiers,  $w_l \in \mathbb{R}^D$  one per item. Given sufficient data for an item, the learned classifier, which is not solely dependent on the item text alone is able to encode collaborative signals. At prediction time, the items whose classifiers give the input query the largest score are predicted. This operation can be represented as  $\max_{j=1}^{|\mathcal{Y}|} w_j^T \mathcal{E}_{xc}(x)$ . This max- $k$  operation can be speeded up using ANNS data structures built using the appropriate distance metric. But please note

that this is essentially the pathway adopted by DR algorithms at prediction time. Hence, extreme classifiers can be thought of as dense retrievers with classifiers as item representations.

With this context in mind, we conduct an experiment to analyze the text-based embedding for an item and the classifier trained for the items in an extreme classification algorithm. We train an NGAME encoder on the KeywordPrediction-5M dataset with 5M keywords as a dense retriever. We further train NGAME classifiers on the same dataset. Please note that the NGAME algorithm freezes the encoder while training the classifiers. Therefore, for a given query at prediction time, its representation is the same whether we were to use the text-based embedding of a keyword output by the NGAME encoder or its classifier representation. As an experimental query set, we sample random 10M queries from a set of top 600M queries asked on the search engine after deduping with the queries contained in the KeywordPrediction-5M training dataset. We use the NGAME encoder to get their embeddings and build a DiskANN algorithm on them. Then, as a thought experiment, we try to solve the problem of, given a keyword from the 5M set, which top 100 queries out of these 10M, when asked on the search engine, would lead to click on it. We obtain the two sets of predictions by inferring the text-based NGAME encoder representation of the keyword and the NGAME classifier representation using the same query ANNS index. Please note that all the pieces, except the item representation, are the same between the two set of predictions. Table 1 shows the fraction of different predictions in top top- $k$  predictions from the two sets as  $k$  is varied. In particular, on average around 59% of the queries retrieved by using a classifier representation of a keyword are different from the queries retrieved using its text-based representation. This experiment shows that the text-based and classifier representations of an item can encode diverse information and their combination might potentially lead to better representation for an item.

However, it is not possible to train classifiers for zero-shot items. For one-shot items with just one supervision query revealed, it is not possible to train their classifiers accurately. IRENE tries to bridge this gap by utilizing the classifiers trained for similar items for such novel items instead. Please note that this definition can be easily extended to rare items having  $< k$  training queries, where  $k$  can vary depending on the retrieval application. However, in this work, we focus only on zero-shot and one-shot scenarios. The next section describes the algorithmic details in IRENE.

### 4 IRENE

**Notations:** Let  $\mathcal{Y}_s$  denote the set of seen items encountered during the training phase. Note that  $L = |\mathcal{Y}_s|$  remains constant. Correspondingly, let  $\mathcal{Y}_u$  be the set of novel items which are made available at inference time, i.e.,  $|\mathcal{Y}_u|$  can keep on changing over time.

**Architecture:** The IRENE architecture is comprised of three components, the feature encoder  $\mathcal{E}_\theta$ , 1-vs-all classifiers for each seen label  $\mathbf{W} = \{w_l\}_{l=1}^{|\mathcal{Y}_s|}$ , and the combiner  $C_\phi$ . Please refer to Figure 1 which illustrates IRENE's components while representing a novel item. The encoder embeds a query  $x$  (or item) in a  $D$ -dimensional space, i.e.,  $\mathcal{E}_\theta(x) \in \mathbb{R}^D$ . IRENE is a generic algorithm suitable for several real-world applications including product-to-product recommendations, document tagging, and matching user

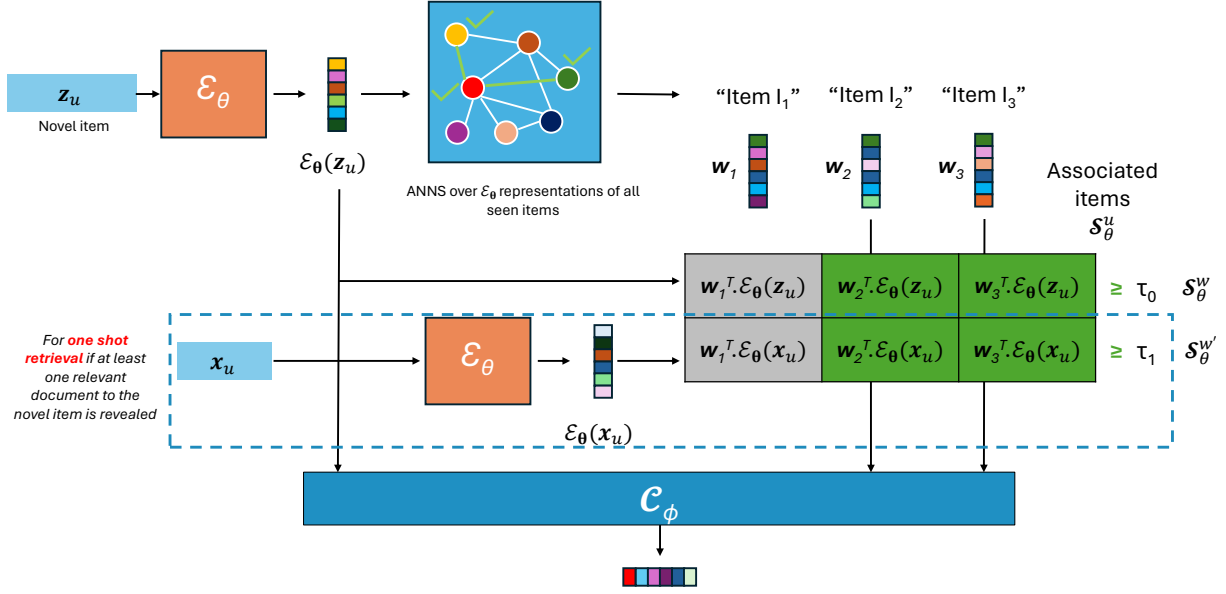


Figure 1: The representation for a novel item  $u$  with item text  $z_u$  and (optional) revealed document  $x_u$  is computed using a self-attention based combiner function  $C_\phi$ .  $C_\phi$  expects  $u$ 's encoder based embedding ( $\mathcal{E}_\theta(z_u)$ ) alongside the classifier representations of associated seen items ( $\{w_1, w_2, w_3\}$ ) as input. The associated seen items are computed on the basis of  $\mathcal{E}_\theta(z_u)$  for zero-shot novel items and  $\{\mathcal{E}_\theta(z_u), \mathcal{E}_\theta(x_u)\}$  for novel one-shot items. Please refer to text for more details. Best viewed in color.

Table 2: Performance when the associated items were (in a hypothetical scenario) revealed from the ground truth. Validation novel items were sampled from the N-Amazon-1.3M dataset to simulate these experiments. The accuracy degraded when the ground truth associations were progressively replaced by neighbors computed on the basis of similarity between the novel and seen item's encoder representations.

Configuration	P@1	P@3	P@5
Ground truth associations	33.80	22.66	17.62
Replace 1 neighbor	33.04	22.22	17.30
Replace 2 neighbors	32.30	21.73	16.93
Replace 3 neighbors	31.57	21.23	16.47
NGAME (no combiner)	30.42	19.94	15.38

queries to advertiser keywords. Thus, the feature encoder may be chosen depending on the application - the default encoder is set to a 6-layer DistilBERT [36] architecture.

#### 4.1 Item representation

Popular DR methods including ANCE use the textual description  $z_l$  of an item  $l$  using the feature encoder, i.e.,  $\mathcal{E}_\theta(z_l)$ . While novel items may be naturally incorporated in DR models, the representation may be lacking especially for short-text items comprised of just a few tokens such as keywords in Sponsored Search application. On the other hand, XC algorithms make use of a classifier-based

Algorithm 1 Getting representation for novel item in IRENE. Input: Novel item  $u$ , Output: Enriched representation  $\mathcal{E}^+(u)$

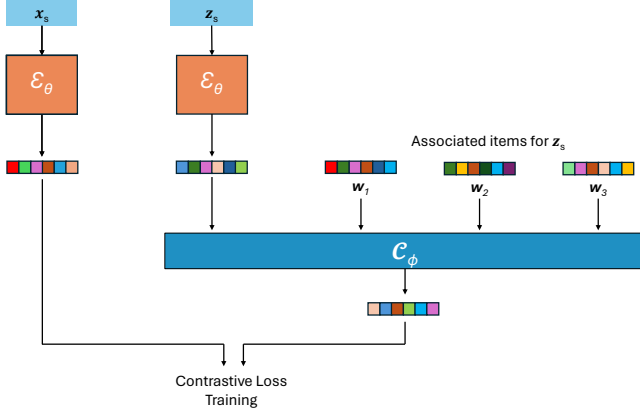
```

1:  $\mathcal{E}_\theta(u) \leftarrow \text{ENCODER}(u)$  ▷ Get embedding
2:  $S_\theta^u \leftarrow \text{ANNS}(\mathcal{E}_\theta(u), \mathcal{E}_\theta(l))$  ▷ Get shortlist
3: if zero-shot then
4:    $S_w^u \leftarrow \text{REFINE}(S_\theta^u, \mathcal{E}_\theta(u), w_l, \tau_0)$ 
5: else if one-shot then
6:    $S_w^u \leftarrow \text{REFINE}(S_\theta^u, \mathcal{E}_\theta(u), w_l, \tau_0)$ 
7:    $S_{w'}^u \leftarrow \text{REFINE}(S_\theta^u, \mathcal{E}_\theta(x_u), \tau_1)$ 
8:    $S_w^u \leftarrow \text{MAXVOTE}(S_w^u, S_{w'}^u)$ 
9: end if
10:  $\{l_1, l_2, l_3\} \leftarrow \text{TOPK}(S_w^u, 3)$ 
11:  $\{w_{l_1}, w_{l_2}, w_{l_3}\} \leftarrow \text{GETCLASSIFIERS}(\{l_1, l_2, l_3\})$ 
12:  $\mathcal{E}^+(u) \leftarrow \text{COMBINER}(\mathcal{E}_\theta(u), w_{l_1}, w_{l_2}, w_{l_3})$ 
13: return  $\mathcal{E}^+(u)$ 

```

representation, i.e.,  $w_l$ , which allows the item representation to move beyond text-based representation. However, it is challenging to learn classifiers for a novel item with no or limited data. Thus, IRENE proposes a combiner  $C_\phi$  that represents the item  $l$ , whether seen or unseen, using  $\mathcal{E}_\theta(z_l)$  and a sub-set of classifiers  $\{w_j\}_{j \in S^l}$ . Here,  $S^l$  is a set of similar seen items for item  $l$  discussed in detail in the next sections. The combiner allows IRENE to generalize better to novel items. In particular, IRENE yielded 3% accurate predictions over NGAME, ANCE, and SimCSE for predicting novel items, demonstrating the effectiveness of the proposed combiner described below.





**Figure 2: IRENE’s training pipeline. The point is embedded using the encoder  $\mathcal{E}_\theta$  and the item is embedded using the combiner  $\mathcal{C}_\phi$  and passed to a contrastive loss. Please refer to the text for more details. Best viewed in color.**

**The Combiner:** The combiner,  $\mathcal{C}_\phi$  employs a single-layer self-attention block with novel type-embeddings to represent an item. In particular, the representation for an item is obtained as  $\mathcal{E}^+(l) = \text{MLP}(\text{Self-Attention}(\mathcal{E}_\theta(z_l) + t_{enc}, w_1^l + t_{clf}, w_2^l + t_{clf}, \dots, w_{|S^l|}^l + t_{clf}))$ . Here,  $t_{enc}$  and  $t_{clf}$  are type-embeddings, one each for classifier and encoder, and are learned like positional embeddings as in BERT. MLP is a linear transformation. Also,  $\mathcal{E}_\theta(z_l)$  is the encoder representation computed on the basis of the text, and  $\{w_j^l\}_{j \in S^l}$  represent the classifiers of associated seen items for item  $l$ . The associated seen items  $S^l$  may be computed in a variety of ways depending on the class of items, viz., seen, zero-shot, and one-shot as described in the next sub-section. Please see Fig. 1 illustrating the combiner. IRENE’s representation of a novel item can be computed within 1 ms making it suitable for sponsored search application.

**Associations for seen items:** The associations for seen items are available from ground truth, i.e.,  $y_{lm}$  is observed when both  $l, m \in \mathcal{Y}_s$ . However, employing associations only on the basis of ground truth leads to misalignment between seen and novel items as such associations are not available for novel items. Moreover, ground truth may bring in some undesirable or noisy associations. For instance, in Wikipedia dataset, categories of "Academics of King’s College London" and "1878 deaths" have the article of "Johann Joseph Hoffmann" in common. However, associating "Academics of King’s College London" with "1878 deaths" may end up providing spurious signals and may not help in improving the item representation. Thus, IRENE refines the associations based on the agreement of the ground truth with encoder-based representations, for the two items  $l$  and  $m$ . In practice, at max top three associated items were selected from the ground-truth co-occurring items based on text similarity, i.e.,  $|S^l| \leq 3$ . Increasing  $|S^l|$  did not offer any substantial gains in our experiments.

**Associated seen items for novel items:** Let  $u$  denote a novel item with  $z_u$  as a textual description. Moreover, a novel item may be (optionally) tagged with a data point with textual description  $x_u$  in some scenarios. Please note that these correspond to the zero-shot and one-shot settings, respectively. A straightforward

way to compute the associations with seen items is to make use of encoder-based representation. The top- $k$  associated seen items can be computed via maximum inner product search (MIPS) as  $S_\theta^u = \arg \max_k \{\mathcal{E}_\theta(z_l)^T \mathcal{E}_\theta(z_u); l \in \mathcal{Y}_s\}$  for a novel item  $u$ . Top  $K$  items are retrieved so that  $|S_\theta^u| = K$ . The shortlist,  $S_\theta^u$ , obtained in the previous step may contain items that are textually similar based on  $\mathcal{E}_\theta$  but are not necessarily relevant to  $u$ . To address this, a refinement step is introduced with the aim of pruning away dissimilar items. Hence,  $S_\theta^u$  was further refined by pruning away irrelevant items by deploying the classifier representation of seen items to get  $S_w^u$ . Specifically, we compute  $S_w^u = \{l | w_l^T \mathcal{E}_\theta(z_u) \geq \tau_0; l \in S_\theta^u\}$ . This refinement process serves the purpose of the zero-shot setting. Additionally, in the case of a one-shot setting, where a query associated with the novel item is also available, we get another shortlist by evaluating item classifiers on the revealed query. Specifically, another shortlist can be obtained by performing the refinement step  $S_{w'}^u = \{l | w_l^T \mathcal{E}_\theta(x_u) \geq \tau_1; l \in S_\theta^u\}$ . Note this is the only step in the algorithm which uses the revealed query associated with novel item. We further do a max-voting between the two shortlists hence obtained by refining based on the label text embedding,  $S_u^w$  and based on the revealed query,  $S_u^{w'}$ .  $K$ ,  $\tau_0$ , and  $\tau_1$  are hyper-parameters of the algorithm. It should be noted that the  $|S^u| \in [0, 3]$  can vary with the item  $u$ . This procedure is explained in pseudo-code 1.

Interestingly, in some cases,  $S^u$  may be empty and the combiner reduces to a linear function applied over the item’s encoder-based representation  $\mathcal{E}_\theta(z_u)$ . The intuition here is to only pass the classifiers of seen items that are deemed relevant to the novel items based on the chosen criterion. A simulation indicated that the performance may further improve if better-associated items are provided. In particular, a small mutually exclusive validation set of novel items were sampled from the train set whose associations are available from ground truth (say  $S^*$ ).  $S$  was initialized with the associations based on item embeddings, i.e.,  $\hat{S}$ . The performance improved when neighbors in  $S$  were gradually replaced with ground truth-based associations in  $S^*$  (please refer to Table 2).

## 4.2 Training

IRENE aims to learn its model parameters  $\{\theta, \phi, W\}$  by optimizing

$$\min_{\theta, W, \phi} \mathcal{L}(\theta, W, \phi) = \sum_{i=1}^N \sum_{\substack{p \in \mathcal{Y}_s \\ y_{ip}=+1}} \sum_{n \in \mathcal{Y}_s} \ell(\mathcal{E}_\theta(x_i), C_\phi(\mathcal{E}_\theta(z_p), U^p), C_\phi(\mathcal{E}_\theta(z_n), U^n)) \quad (1)$$

where,  $i$  refers to a query,  $p$  refers to a positive item ( $y_{ip} = +1$ ),  $n$  refers to a irrelevant item ( $y_{in} = -1$ ). Moreover,  $U^p = \{w_j | j \in S_\theta^p\}$  is the set of classifier belonging to associated items for positive item  $p$ . Recall that  $S_\theta^p$  denotes the set of associated items for item  $p$ . Similarly,  $U^n$  is the set of classifier belonging to associated items for item  $n$ .  $\ell$  can be a loss function such as Triplet loss. Unfortunately, optimizing (1) induces a cost  $\mathcal{O}(NDL)$  which can be prohibitive for a large number of items. Moreover, the associated items a seen item is computed on the basis of the item’s encoder representation which will keep on changing as  $\ell$  is optimized. Thus IRENE employs a modular pipeline where the encoder is trained in the first phase

and then classifiers + combiner are learned in the second stage with a fixed encoder.

**Stage I (Learning the encoder):** Stage I treats the item embeddings as classifiers and learn  $\mathcal{E}_\theta$  in a Siamese fashion. This allows IRENE to forgo explicit dependency on  $L$  and hence it can be efficiently trained with a proper negative mining strategy. The negative mining algorithms aim to cut down the training cost by restricting the item set for each query to  $\mathcal{O}(\log L)$ . The negative mining approach based on batching similar train queries together in a mini-batch proposed by NGAME was employed for negative sampling as it has been demonstrated to yield state-of-the-art results while being computationally lightweight. It should be noted that other negative mining approaches including ANCE can be readily incorporated in IRENE. In particular,  $\theta$  is learned by optimizing

$$\min_{\theta} \mathcal{L}(\theta) = \sum_{i=1}^N \sum_{p \in \mathcal{Y}_s} \sum_{\substack{n \in \mathcal{N}_i \\ y_{ip}=+1}} [\mathcal{E}_\theta(\mathbf{x}_i)^\top \mathcal{E}_\theta(\mathbf{z}_n) - \mathcal{E}_\theta(\mathbf{x}_i)^\top \mathcal{E}_\theta(\mathbf{z}_p) + \gamma] + \quad (2)$$

where,  $\gamma$  is margin in triplet loss,  $p$  is a positive label and  $\mathcal{N}_i$  is the shortlist of negative labels for query  $i$ . IRENE employs the Adam optimizer in both stages to perform gradient descent. In practice, training of Stage I completes within a few hours for all publicly available benchmark datasets.

**Stage II (Learning the classifier and combiner):** The Stage II freezes the encoder ( $\theta$ ) and jointly learns the classifier ( $\mathbf{W}$ ) and combiner ( $\phi$ ). Freezing the encoder allows IRENE to compute the associated items  $\mathcal{S}^l$  once and then freeze them thereafter thereby improving the scalability. In principle, fine-tuning the encoder during Stage II may yield marginal gains, however, at the cost of significantly increased training time. Specifically, model parameters  $\mathbf{W}, \phi$  are learnt by optimizing

$$\begin{aligned} \min_{\mathbf{W}, \phi} \mathcal{L}(\mathbf{W}, \phi) = & \sum_{i=1}^N \sum_{p \in \mathcal{Y}_s} \sum_{\substack{n \in \mathcal{N}_i \\ y_{ip}=+1}} [\mathcal{E}_\theta(\mathbf{x}_i)^\top \mathbf{w}_n - \mathcal{E}_\theta(\mathbf{x}_i)^\top \mathbf{w}_p + \gamma_1] + \\ & + [\mathcal{E}_\theta(\mathbf{x}_i)^\top C_\phi(\mathcal{E}_\theta(\mathbf{z}_n), \mathbf{U}^n) - \mathcal{E}_\theta(\mathbf{x}_i)^\top C_\phi(\mathcal{E}_\theta(\mathbf{z}_p), \mathbf{U}^p) + \gamma_2] + \quad (3) \end{aligned}$$

where  $\gamma_1$  &  $\gamma_2$  are margin terms in triplet loss and  $\hat{\mathbf{x}}_i, \hat{\mathbf{z}}_p, \hat{\mathbf{z}}_n$  are fixed encoder based representations for  $i^{th}$  data point, positive item  $p$  and negative item  $n$ . Note that such a formulation allows IRENE to generalize better to novel items without sacrificing on seen items. As a result, IRENE could be 2% more accurate in R@100 as compared to state-of-the-art DR models in a generalized setting. Please refer to Section 5 for more details.

### 4.3 Inference

The embedding of a document  $t$  at inference time is computed as  $\mathbf{e}_t = \mathcal{E}_\theta(\mathbf{x}_t)$  where  $\mathbf{x}_t$  is the document text. An ANNS index  $A$  is built over the item representations from our model, i.e.,  $A$  is built over  $\{\mathcal{E}^+(l); l \in \mathcal{Y}_s \cup \mathcal{Y}_u\}$ . To get the most relevant items for  $t$ ,  $A$  is queried with  $\mathbf{e}_t$ . The computational complexity of IRENE's inference is  $\Omega(B + D \log(|\mathcal{Y}_s| + |\mathcal{Y}_u|))$ , where  $B$  is the cost of encoder and  $D$  is representation dimensionality. Note that the IRENE continues to integrate novel items by computing their representations

**Table 3: Results on KeywordPrediction-5M dataset. Semsup-XC-NGAME is a theoretical baseline where NGAME encoder from the table is fine-tuned on revealed query associations for one-shot items according to Semsup-XC**

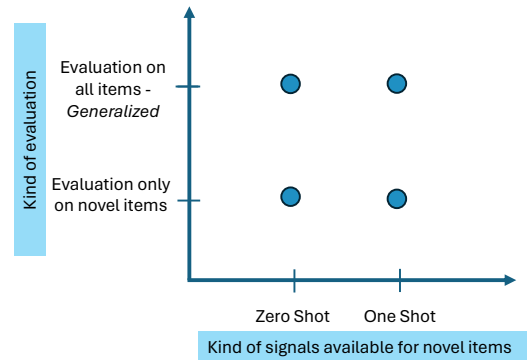
Method	R@30	R@50	R@100	P@30	P@50	P@100
Evaluation only on novel items						
IRENE-ZeroShot	34.79	49.81	77.32	78.70	71.76	60.18
NGAME encoder	33.76	48.07	74.13	76.52	69.32	57.67
SimCSE	31.37	42.87	72.45	76.3	68.40	56.32
IRENE-OneShot	35.87	50.95	78.46	79.75	72.84	61.20
NCM	32.94	46.74	71.72	74.79	67.34	55.48
Semsup-XC-NGAME	34.43	49.06	74.99	77.53	70.15	58.04
Generalized evaluation						
IRENE-ZeroShot	37.22	54.00	85.86	80.21	73.72	62.72
NGAME encoder	36.10	52.04	82.02	78.01	71.89	60.01
SimCSE	38.37	54.87	88.45	76.36	68.40	57.32
IRENE-OneShot	37.71	54.55	86.64	80.68	74.11	62.84
NCM	34.98	50.12	78.17	75.69	69.51	55.70
Semsup-XC-NGAME	36.13	51.73	80.17	77.69	70.51	58.70

**Table 4: Results on 100M zero-shot keywords on the search engine. Method Ms are anonymized in-production dense retrievers. All algorithms are provided with just the text of a keyword to get its representation**

Method	R@30	R@50	R@100	P@30	P@50	P@100
Evaluation only on novel items						
IRENE- ZeroShot	30.53	42.00	66.68	45.64	43.40	40.11
M1	28.79	39.64	62.19	44.24	41.96	38.72
M2	19.11	25.84	39.33	31.48	28.93	25.69
M3	19.93	26.49	38.99	35.72	33.11	29.63
M4	24.74	32.82	48.46	39.10	36.60	33.25

and adding them to ANNS index [37] as and when novel items appear in the system, thereby offering a promising solution for applications like sponsored search where novel items are frequently encountered and re-training the model can be expensive with large number of items.

## 5 EXPERIMENTS



**Figure 3: Four settings explored in this work based on kind of evaluation and kind of signals available for novel items**

**Table 5: Expert judges labeling results on KeywordPrediction-5M dataset**

Method	% of good quality predictions
IRENE- OneShot	77.05
IRENE- ZeroShot	73.16
NGAME Encoder	64.06

**Table 6: Latencies required to perform different steps to get IRENE representation for a novel item  $y_u$ . Steps 1, and 4 are done on a single V100 GPU, steps 2 and 3 on 96 CPU cores. All numbers are reported for batched operations.**

Step	Time (in $\mu s$ )
Calculate the embedding $\mathcal{E}_\theta$	24
Calculate encoder emb shortlist $S_u^\theta$	600
Refine the shortlist using classifiers to $S_u^\theta$	0.46
Apply the Combiner function $C_\phi$	0.3

**Table 7: Results on public datasets with different algorithms.**

Method	N-Amazon-1.3M			N-Wikipedia-500K		
	P@1	P@5	R@5	P@1	P@5	R@5
Evaluation only on novel items						
IRENE-ZeroShot	<b>31.47</b>	<b>16.41</b>	<b>31.22</b>	<b>47.01</b>	<b>15.48</b>	<b>60.19</b>
ANCE	22.38	12.02	23.32	30.67	11.92	47.71
NGAME Encoder	30.42	15.38	29.40	46.96	15.10	58.91
SemSup-XC	11.68	6.85	14.73	46.60	13.90	53.80
MACLR	21.93	11.39	21.96	39.56	15.05	58.91
ZestXML	5.58	4.22	6.35	2.62	2.62	2.32
TF-IDF	24.15	15.04	10.18	11.53	6.29	4.60
IRENE-OneShot	<b>31.92</b>	<b>16.67</b>	<b>31.68</b>	<b>47.90</b>	<b>15.79</b>	<b>61.42</b>
NGAME-OneShot (re-trained)	30.55	15.39	29.43	47.37	15.33	59.86
SemSup-XC-OneShot	13.96	6.98	15.49	46.25	13.77	53.67
NCM OneShot	26.49	48.57	28.94	40.43	13.60	53.72
ADAM OneShot	20.80	11.71	25.73	39.79	13.39	52.97
Generalized evaluation						
IRENE	<b>45.81</b>	<b>35.61</b>	<b>23.10</b>	81.79	<b>46.10</b>	<b>61.69</b>
ANCE	27.65	19.76	12.41	42.91	20.91	35.51
NGAME Encoder	45.14	34.72	22.58	<b>81.86</b>	45.38	60.96
SemSup-XC	25.13	18.37	10.59	63.92	26.59	37.22
MACLR	27.50	18.60	11.76	46.59	24.38	36.38
ZestXML	22.87	26.79	39.71	45.15	54.31	59.32
NCM	41.36	28.29	14.45	60.16	29.21	38.01
TF-IDF	16.33	7.35	16.47	15.07	6.93	11.67
IRENE-OneShot	<b>45.83</b>	<b>35.66</b>	<b>23.12</b>	81.80	<b>46.16</b>	<b>61.77</b>
NGAME OneShot (re-trained)	45.31	34.87	22.66	<b>82.22</b>	45.60	61.17
SemSup-XC OneShot	22.48	15.66	10.03	60.97	25.40	36.16
NCM OneShot	28.41	19.19	13.66	61.89	30.04	46.27
ADAM OneShot	19.13	15.26	11.50	59.54	27.77	43.46

In this section, we describe (i) datasets on which we benchmark IRENE, (ii) Baselines against which IRENE is compared, and (iii) Evaluation settings and metrics.

**Datasets:** IRENE was designed with the advertiser keyword application in mind. Therefore, we conduct both offline and online experiments for this application. Furthermore, we validate IRENE's effectiveness in acquiring enhanced representations for new items by evaluating it on public datasets. These tasks encompass similar product recommendations on Amazon and category annotation for Wikipedia articles.

**Benchmark datasets:** We create zero and one-shot datasets for evaluation on Amazon product recommendations and category annotation for Wikipedia pages by using the datasets LF-AmazonTitles-1.3M and LF-Wikipedia-500K from extreme classification repository [5]. Please refer to the supplementary material for details on dataset creation and data statistics.

**Evaluation settings and metrics:** Fig. 3 describes the four evaluation setting considered: evaluation on only novel items for zero and one-shot items; and generalized evaluation for zero and one-shot items. For a detailed description of the 4 settings please refer to the supplementary. Performance is evaluated on standard metrics including Precision@ $k$  (P@ $k$ ), and Recall@ $k$  (R@ $k$ ) at different truncation levels  $k$ . The truncation level is decided by the application. For the Keyword prediction application, an algorithm's performance depends on the fraction of good keywords in the top- $k$  keywords retrieved where large values of  $k$  are considered depending on the deployment infrastructure. Hence P@ $k$  is reported for  $k \in \{30, 50, 100\}$ .

**Baselines:** We compare IRENE with three classes of methods (i) Dense Retrieval algorithms like NGAME and ANCE. (ii) Extreme classification algorithms like MACLR, Semsup-XC, and ZestXML that are specifically designed to handle zero and few-shot scenarios and (iii) Continual learning baselines like NCM and Adam. The key idea in continual learning is to utilize new data while minimizing catastrophic forgetting. In addition, we also consider a theoretical baseline where the new data is pooled with the training data, and an NGAME dense retrieval encoder is trained on the pooled data end-to-end. Please note that generally, it is not possible to re-train a model frequently (say nightly) as new signals come in. For dense retrieval, algorithms are trained to utilize a DistilBERT model as the language encoder. The hyper-parameters of all baseline algorithms are set as suggested by their authors wherever applicable and by fine-grained validation otherwise.

**Hyper-parameters:** IRENE's tunable hyper-parameters over and above the hyper-parameters used by any DR algorithm, include the shortlist size  $K$  and the filtration thresholds for refined shortlists  $\tau_s$ . As discussed in the supplementary material, high-quality connections to seen items is essential for IRENE to obtain their high-quality representations. Hence, these metrics were set by  $k$ -fold cross validation. All other hyper-parameters were set to default values across the datasets. Refer to supplementary material for the hyper-parameter values for IRENE on different datasets.

**Advertiser bid keyword retrieval:** We discuss both offline and online results for the application.

**Online Results** IRENE was flighted on a leading search engine to perform A/B tests on live search engine traffic. However, we also do an explicit comparison of IRENE against leading proprietary and public DR algorithms in production. More specifically, we sample 100M advertiser keywords that had come into the system after the time period for which the training data scraping is done. We further take some of the top dense retrieval encoders deployed in production and compare IRENE against them for recommending keywords from this 100M set for a sampled set of queries. The algorithms' names for this comparison are anonymized for IP reasons. The results are shown in table 4. IRENE was found to be at least 4% better than the next best dense retriever in R@100. As novel items stream into the system, it might be necessary to frequently encode

the items and include them in the ANNS index. Table 6 shows that IRENE adds only minimal overhead on top of a language encoder and can get the item representation in less than one ms. Algorithms that fine-tune the trained model on revealed data such as Semsup-XC need to rebuild the ANNS index from scratch. IRENE can instead make use of updatable ANNS [37] algorithms similar to any DR algorithm. Further, as users interact with the search engine as the live A/B test is conducted, IRENE is compared against the large control ensemble of diverse algorithms. This ensemble not only contains DR algorithms but also leading generative, graph-based, and IR algorithms. Performance is measured in terms of live performance metrics. IRENE was found to increase the click-through rate (ad clicks obtained per unit query) and decrease the quick-back rate (fraction of users who didn't find the ad relevant and left the ad landing page quickly) by 4.2% and 0.9% respectively. This indicates value creation for users who were shown more relevant ads by IRENE. Additionally, IRENE could increase the keyword density (average number of keywords that survive the quality control and relevance filters) by 7.8%, which validates the quality of predictions made. IRENE could also achieve a click efficiency of 150% meaning that for every 2% increase in ad impressions, ads selected by IRENE got 3% more clicks. Further, IRENE could match queries like "granger" and "bitwarden" to advertiser keywords like "industrial supply" and "password manager" respectively. Please note that these predictions, not based on text matching, were not made by any in-production algorithm.

**Offline Results** To conduct experiments offline experiments, KeywordPrediction-5M dataset was created by mining the logs of a search engine for a specific time period. User-typed queries and the bid keyword corresponding to surfaced advertisements yielded query-keyword training pairs. The dataset, named KeywordPrediction-5M, had around 5M items and 220M training queries. Please note that we finetune the trained NGAME encoder using the methodology prescribed in the Semsup-XC work [2] to obtain the Semsup-XC-NGAME baseline. However, please note that it is not desirable to fine-tune models deployed in production as it incurs latency and complexity costs. As shown in table 3, IRENE was found to be at least 3% better in R@100 and at least 2% better in P@30 for evaluation only on zero-shot items. Similarly, when evaluation is done only on one-shot items, IRENE was found to be around 3% and 2% better in R@100 and P@30 respectively. Similar trends were observed for the generalized evaluation setting.

**Similar product recommendation on Amazon** Experiments are conducted on the N-AmazonTitles-1.3M dataset for this application. IRENE was found to be at least 2% better than the baseline algorithms in R@5 when the evaluation is done only on novel items. Similarly, IRENE outperformed algorithms that could make use of the revealed data by at least 2% in R@5. Similar trends are seen in generalized evaluation for both zero-shot and one-shot scenarios.

**Wikipedia categories prediction** Experiments are also conducted on the N-Wikipedia-500K dataset for predicting categories for a Wikipedia page. On this application, IRENE again outperforms the baseline algorithms. For zero-shot retrieval of novel articles, IRENE achieves over 6% higher recall than extreme classifiers like SemSup-XC and ZestXML. The gains are maintained in the one-shot setting where IRENE incorporates the revealed training article

**Table 8: Ablation study on Combiner Functions and Contribution of Classifier Representations to IRENE on N-Amazon-1.3M dataset**

Method	R@5	R@10	R@30	R@5	R@10	R@30
	Zero shot			One shot		
Combiner - Sum	30.36	38.13	49.29	30.74	38.71	50.36
Combiner - Weighted Sum	29.85	37.12	47.58	30.01	37.32	47.93
Combiner - Max	29.60	36.83	47.04	29.95	37.39	48.12
IRENE	31.22	39.03	50.13	31.68	39.72	51.14
IRENE with Encoder Embeddings	30.64	38.21	49.18	31.03	38.76	49.95

per novel category during inference. For a detailed evaluation of other metrics please refer to Table 11 (in the supplementary)

The consistent improvements demonstrate IRENE's ability to generalize across different use cases by learning improved representations for novel items

## 6 ABLATIONS

Experiments were conducted to understand the contributions of different components of the proposed method in IRENE.

**Utilizing Encoder vs Classifier Representations:** As discussed in sections 1 and 3, classifier representations of associated seen items in addition to encoder representation of a novel item contain useful diverse signals for encoding the novel item. Experiments were done to identify the importance of the classifier representations. Specifically, encoder representations instead of learnt classifiers were utilized for obtaining representations of associated seen items while learning the combining function  $C_\phi$ . As shown in Table 8, learning classifier representations as proposed in IRENE leads to 2% gain in R@30 over IRENE trained with encoder embeddings only on N-Amazon-1.3M dataset.

**Combining Functions** For obtaining a robust representation of a novel item, it is important to carefully *combine* the signals - encoder representation of the novel item and collaborative information from the classifier representations of associated seen items. Keeping the inputs fixed, the combiner  $C_\phi$  was changed to simpler alternatives for vector pooling suggested in previous works such as sum, max, and weighted-sum poolings. In weighted sum pooling, the weights for the different positions are learned.

As can be observed in Table 8, the self-attention with type embeddings combiner proposed in IRENE performs 2% more accurately than the best-performing sum-based combination.

**Modularization with Different Encoder** We evaluate the modularization of proposed algorithm IRENE with respect to different encoders by comparing the performance of IRENE when added to ANCE based encoder on N-Amazon-1.3M dataset. The addition of IRENE to existing ANCE encoder leads to an improvement in performance in all Recall based metrics with 2% improvement in R@30. Refer to the supplementary material for more details.



## REFERENCES

- [1] G. Aggarwal, J. Feldman, and S. Muthukrishnan. 2006. Bidding to the top: VCG and equilibria of position-based auctions. In *Approximation, Randomization, and Combinatorial Optimization. Algorithms and Techniques*.
- [2] P. Aggarwal, A. Deshpande, and K. Narasimhan. 2023. SemSup-XC: Semantic Supervision for Zero and Few-shot Extreme Classification. In *ICML*.
- [3] R. Aljundi, M. Lin, B. Goujaud, and Y. Bengio. 2019. Gradient based sample selection for online continual learning. In *NeurIPS*.
- [4] R. Babbar and B. Schölkopf. 2017. DiSMEC: Distributed Sparse Machines for Extreme Multi-label Classification. In *WSDM*.
- [5] K. Bhatia, K. Dahiya, H. Jain, P. Kar, A. Mittal, Y. Prabhu, and M. Varma. 2016. The Extreme Classification Repository: Multi-label Datasets & Code. <http://manikvarma.org/downloads/XC/XMLRepository.html>
- [6] A. Z. Broder, P. Ciccolo, M. Fontoura, E. Gabrilovich, V. Josifovski, and L. Riedel. 2008. Search Advertising Using Web Relevance Feedback. In *CIKM*.
- [7] S. Changpinyo, W.-L. Chao, B. Gong, and F. Sha. 2016. Synthesized Classifiers for Zero-Shot Learning. In *CVPR*.
- [8] A. Chaudhry, P. K. Dokania, T. Ajanthan, and P. H. S. Torr. 2018. Riemannian Walk for Incremental Learning: Understanding Forgetting and Intransigence. In *ECCV*.
- [9] N. Craswell, B. Mitra, E. Yilmaz, D. Campos, and E. M. Voorhees. 2020. Overview of the TREC 2019 deep learning track. *arXiv:2003.07820*
- [10] K. Dahiya, A. Aggarwal, D. Saini, K. Gururaj, J. Jiao, A. Singh, S. Aggarwal, P. Kar, and M. Varma. 2021. SiameseXML: Siamese Networks meet Extreme Classifiers with 100M Labels. In *ICML*.
- [11] K. Dahiya, N. Gupta, D. Saini, A. Soni, Y. Wang, K. Dave, J. Jiao, K. Gururaj, P. Dey, A. Singh, D. Hada, V. Jain, B. Paliwal, A. Mittal, S. Mehta, R. Ramjee, S. Aggarwal, P. Kar, and M. Varma. 2023. NGAME: Negative mining-aware mini-batching for extreme classification. In *WSDM*.
- [12] K. Dahiya, D. Saini, A. Mittal, A. Shaw, K. Dave, A. Soni, H. Jain, S. Aggarwal, and M. Varma. 2021. DeepXML: A Deep Extreme Multi-Label Learning Framework Applied to Short Text Documents. In *WSDM*.
- [13] K. Dahiya, S. Yadav, S. Sondhi, D. Saini, S. Mehta, J. Jiao, S. Aggarwal, P. Kar, and M. Varma. 2023. Deep encoders with auxiliary parameters for extreme classification. In *KDD*.
- [14] T. Gao, X. Yao, and D. Chen. 2021. SimCSE: Simple Contrastive Learning of Sentence Embeddings. In *EMNLP*.
- [15] Ian J Goodfellow, Mehdi Mirza, Da Xiao, Aaron Courville, and Yoshua Bengio. 2013. An empirical investigation of catastrophic forgetting in gradient-based neural networks. *arXiv preprint arXiv:1312.6211* (2013).
- [16] R. Guo, S. Kumar, K. M. Choromanski, and D. Simcha. 2016. Quantization based fast inner product search. In *Artificial Intelligence and Statistics*.
- [17] N. Gupta, P. H. Chen, H.-F. Yu, Cho-J. Hsieh, and I. S. Dhillon. 2022. ELIAS: End-to-End Learning to Index and Search in Large Output Spaces. In *NeurIPS*.
- [18] V. Gupta, R. Wadbude, N. Natarajan, H. Karnick, P. Jain, and P. Rai. 2019. Distributional Semantics Meets Multi-Label Learning. In *AAAI*.
- [19] H. Jain, V. Balasubramanian, B. Chunduri, and M. Varma. 2019. Slice: Scalable Linear Extreme Classifiers trained on 100 Million Labels for Related Searches. In *WSDM*.
- [20] T. Jiang, D. Wang, L. Sun, H. Yang, Z. Zhao, and F. Zhuang. 2021. LightXML: Transformer with Dynamic Negative Sampling for High-Performance Extreme Multi-label Text Classification. In *AAAI*.
- [21] V. Karpukhin, B. Oguz, S. Min, P. Lewis, L. Wu, S. Edunov, D. Chen, and W.-T. Yih. 2020. Dense Passage Retrieval for Open-Domain Question Answering. In *EMNLP*.
- [22] S. Khandagale, H. Xiao, and R. Babbar. 2020. Bonsai: diverse and shallow trees for extreme multi-label classification. *ML* (2020).
- [23] S. Kharbanda, A. Banerjee, E. Schultheis, and R. Babbar. 2022. CascadeXML: Rethinking Transformers for End-to-end Multi-resolution Training in Extreme Multi-label Classification. In *NeurIPS*.
- [24] O. Khattab and M. Zaharia. 2020. Colbert: Efficient and effective passage search via contextualized late interaction over bert. In *SIGIR*.
- [25] Y. Liu, X. Gao, and L. Gao, Q. Han, J. Shao. 2020. Label-activating framework for zero-shot learning. In *Neural Networks*, Vol. 121. 1–9.
- [26] Michael McCloskey and Neal J Cohen. 1989. Catastrophic interference in connectionist networks: The sequential learning problem. In *Psychology of learning and motivation* 24 (1989), 109–165.
- [27] T. K. R. Medini, Q. Huang, Y. Wang, V. Mohan, and A. Shrivastava. 2019. Extreme Classification in Log Memory using Count-Min Sketch: A Case Study of Amazon Search with 50M Products. In *NeurIPS*.
- [28] T. Mensink, E. Gavves, and C. G. M. Snoek. 2014. COSTA: Co-Occurrence Statistics for Zero-Shot Classification. In *CVPR*.
- [29] Thomas Mensink, Jakob Verbeek, Florent Perronnin, and Gabriela Csurka. 2013. Distance-Based Image Classification: Generalizing to New Classes at Near-Zero Cost. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 35, 11 (2013), 2624–2637. <https://doi.org/10.1109/TPAMI.2013.83>
- [30] A. Mittal, N. Sachdeva, S. Agrawal, S. Aggarwal, P. Kar, and M. Varma. 2021. ECLARE: Extreme Classification with Label Graph Correlations. In *WWW*.
- [31] Y. Qu, Y. Ding, J. Liu, K. Liu, R. Ren, W. X. Zhao, D. Dong, H. Wu, and H. Wang. 2021. RocketQA: An Optimized Training Approach to Dense Passage Retrieval for Open-Domain Question Answering.
- [32] S. Robertson and H. Zaragoza. 2009. The Probabilistic Relevance Framework: BM25 and Beyond. *Found. Trends Inf. Retr.* 3 (2009), 333–389.
- [33] Bernardino Romera-P. and P. Torr. 2015. An embarrassingly simple approach to zero-shot learning. In *ICML*.
- [34] P. Rusmevichientong, D. P. Williamson, and D. B. Shmoys. 2006. An optimization framework for finding revenue maximizing bid prices in keyword auctions. In *WWW*.
- [35] D. Saini, A.K. Jain, K. Dave, J. Jiao, A. Singh, R. Zhang, and M. Varma. 2021. GalaXC: Graph Neural Networks with Labelwise Attention for Extreme Classification. In *WWW*.
- [36] V. Sanh, L. Debut, J. Chaumond, and T. Wolf. 2019. DistilBERT, a distilled version of BERT: smaller, faster, cheaper and lighter. *ArXiv* (2019).
- [37] Aditi Singh, Suhas Jayaram Subramanya, Ravishankar Krishnaswamy, and Harsha Vardhan Simhadri. 2021. FreshDiskANN: A Fast and Accurate Graph-Based ANN Index for Streaming Similarity Search. *arXiv:2105.09613* [cs.IR]
- [38] J. Snell, K. Swersky, and R. S. Zemel. 2020. Prototypical Networks for Few-shot Learning. In *NeurIPS*.
- [39] S. J. Subramanya, Devvrit, R. Kadekodi, R. Krishnaswamy, and H. Simhadri. 2019. DiskANN: Fast Accurate Billion-point Nearest Neighbor Search on a Single Node. In *NeurIPS*.
- [40] Y. Wang, J. Liu, Y. Wang, C. Tai, J. Shao, J. Ma, and C. Zhai. 2015. A noise-filtered under-sampling scheme for imbalanced classification. In *Proceedings of the 24th ACM International on Conference on Information and Knowledge Management*.
- [41] Z. Wang, Z. Zhang, C.-Y. Lee, H. Zhang, R. Sun, X. Ren, G. Su, Perot V., J. Dy, and T. Pfister. 2022. Learning to Prompt for Continual Learning. *arXiv:2112.08654* [cs.LG]
- [42] L. Xiong, C. Xiong, Y. Li, K.-F. Tang, J. Liu, P. Bennett, J. Ahmed, and A. Overwijk. 2021. Approximate nearest neighbor negative contrastive learning for dense text retrieval. In *ICLR*.
- [43] Y. Xiong, W.-C. Chang, C.-J. Hsieh, H.-F. Yu, and I. Dhillon. 2021. Extreme Zero-Shot Learning for Extreme Text Classification. *arXiv:2112.08652* [cs.LG]
- [44] W. Xu, Y. Xian, J. Wang, B. Schiele, and Z. Akata. 2020. In *NeurIPS*.
- [45] J. Yang, Z. Liu, S. Xiao, C. Li, D. Lian, S. Agrawal, A. Singh, G. Sun, and X. Xie. 2021. GraphFormers: GNN-nested Transformers for Representation Learning on Textual Graph. In *NeurIPS*.
- [46] D. Yogatama, S. Y. A. An, N. A. Smith, and S. Kornblith. 2018. Bayesian optimization with a finite budget: An approximate dynamic programming approach. In *New Directions in Neural Networks: 18th International Conference on Artificial Neural Networks, ICANN 2018*.
- [47] R. You, S. Dai, Z. Zhang, H. Mamitsuka, and S. Zhu. 2019. AttentionXML: Extreme Multi-Label Text Classification with Multi-Label Attention Based Recurrent Neural Networks. In *NeurIPS*.
- [48] J. Zhang, W. C. Chang, H. F. Yu, and I. Dhillon. 2021. Fast multi-resolution transformer fine-tuning for extreme multi-label text classification. In *NeurIPS*.
- [49] D.-W. Zhou, H.-J. Ye, D.-C. Zhan, and Z. Liu. 2023. Revisiting class-incremental learning with pre-trained models: Generalizability and adaptivity are all you need.
- [50] F. Zhu, X.-Y. Zhang, C. Wang, F. Yin, and C.-L. Liu. 2021. Prototype Augmentation and Self-Supervision for Incremental Learning. In *CVPR*.

**Table 9: Dataset Statistics.**

Dataset	# Train	# novel	# Gen	# Train	# novel
	Qs	Test Qs	Test Qs	Items	Items
KeywordPrediction-5M*	220,845,427	5,022,052	5,022,052	4,999,996	5,435,443
N-AmazonTitles-1.3M	2,225,354	624,830	970,237	1,174,739	130,526
N-Wikipedia-500K	1,781,890	271,620	783,743	450,963	50,107

**Table 10: Hyper-parameters for different datasets for IRENE.**

Dataset	Encoder( $\mathcal{E}_\theta$ ) lr	Encoder( $\mathcal{E}_\phi$ ) lr	Classifiers(w) lr	# epochs for $\mathcal{E}_\theta$	# epochs for $\mathcal{E}_\phi+w$	Margin $\gamma_1, \gamma_2$	$K$	$\tau_0$
KeywordPrediction-5M	0.0001	0.0002	0.001	50	70	0.1,0.3	100	0.75
N-AmazonTitles-1.3M	0.0002	0.0002	0.001	300	120	0.1,0.3	200	0.15
N-Wikipedia-500K	0.0002	0.0002	0.001	40	120	0.1,0.3	200	0.2

**Table 11: Results on benchmark datasets with different algorithms.**

Method	N-Amazon-1.3M								N-Wikipedia-500K							
	R@3	R@5	R@10	R@30	R@100	P@1	P@3	P@5	R@3	R@5	R@10	R@30	R@100	P@1	P@3	P@5
	Evaluation only on novel items															
IRENE-ZeroShot	25.52	31.22	39.03	50.13	59.45	31.47	21.11	16.41	55.38	61.42	68.69	78.08	85.50	47.90	23.39	15.79
ANCE	18.14	23.32	30.72	43.66	57.76	22.38	15.14	12.02	40.46	47.71	58.91	75.70	87.98	30.67	16.57	11.92
NGAME Encoder	24.20	29.40	36.44	46.71	56.04	30.42	19.94	15.38	53.55	58.91	65.27	74.33	82.07	46.96	22.56	15.10
SemSup-XC	11.28	14.73	20.04	29.26	38.27	11.68	8.41	6.85	50.38	53.80	57.08	60.01	61.03	46.60	21.46	13.90
MACLR	17.59	21.96	28.59	40.35	53.38	21.93	14.50	11.39	51.02	58.91	68.53	81.30	91.70	39.56	21.37	15.05
ZestXML	5.42	6.35	6.87	7.89	8.67	5.58	4.71	4.22	6.86	9.95	14.73	21.63	25.55	2.62	2.62	2.32
TF-IDF	8.12	10.18	13.30	18.92	25.63	24.15	18.31	15.04	15.43	18.64	23.89	34.66	48.24	11.53	6.29	4.60
IRENE-OneShot	25.86	31.68	39.72	51.14	60.62	31.92	21.41	16.67	55.38	61.42	68.69	78.08	85.50	47.90	23.39	15.79
NGAME-OneShot (re-trained)	24.27	29.43	36.48	46.76	56.03	30.55	20.00	15.39	54.42	59.86	66.37	75.28	82.85	47.37	22.92	15.33
Semsup-XC-OneShot	12.55	15.49	19.76	26.93	35.27	13.96	9.07	6.98	50.21	53.67	57.04	60.04	61.02	46.25	21.24	13.77
NCM-OneShot	23.49	28.94	36.70	48.57	60.32	26.49	17.52	13.62	48.03	53.72	60.94	71.26	80.22	40.43	19.97	13.60
Adam-OneShot	20.61	25.73	33.08	44.49	55.85	20.70	14.80	11.71	47.22	52.97	60.37	70.65	79.97	39.79	19.60	13.39
	Generalized evaluation															
IRENE	17.82	23.10	31.04	44.12	57.03	45.81	40.04	35.61	52.58	61.69	70.75	80.24	87.20	81.79	60.55	46.10
ANCE	9.45	12.41	17.31	27.25	40.62	27.65	22.76	19.76	29.66	35.51	43.39	56.22	71.99	42.91	27.54	20.92
NGAME Encoder	17.45	22.58	30.25	42.72	54.81	45.14	39.15	34.72	52.24	60.96	69.58	78.67	85.50	81.86	60.13	45.38
Semsup-XC	7.76	10.59	15.21	23.41	30.87	25.13	20.93	18.37	34.22	37.22	39.37	40.72	41.10	63.92	38.84	26.59
MACLR	9.13	11.76	15.99	24.57	36.57	27.50	21.86	18.60	29.20	36.38	46.62	61.86	75.69	46.59	31.12	24.38
ZestXML	12.34	14.45	22.87	26.79	39.71	41.36	33.7	28.29	32.24	38.01	45.15	54.31	59.32	60.16	39.33	29.21
NCM	5.53	13.82	18.69	27.98	40.10	29.80	23.24	19.86	38.88	45.69	54.20	66.13	76.54	60.51	39.50	29.58
TF-IDF	13.71	16.47	20.40	27.08	34.81	16.33	9.83	7.35	9.49	11.67	14.79	20.87	30.10	15.07	9.19	6.93
IRENE-OneShot	17.83	23.12	31.06	44.17	57.14	45.83	40.07	35.66	52.64	61.77	70.84	80.37	87.37	81.80	60.61	46.16
NGAME-OneShot (re-trained)	17.52	22.66	30.33	42.78	54.88	45.31	39.33	34.87	52.44	61.17	69.82	78.96	85.81	82.22	60.46	45.60
Semsup-XC-OneShot	7.64	10.03	13.87	20.97	28.76	22.48	18.25	15.66	32.89	36.16	38.73	40.52	41.08	60.97	36.70	25.40
NCM-OneShot	10.58	13.66	18.55	28.00	40.48	28.41	22.36	19.19	39.47	46.27	54.78	66.61	76.84	61.89	40.20	30.04
Adam-OneShot	8.52	11.50	16.06	24.72	36.47	19.13	17.30	15.26	37.09	43.46	51.61	63.00	73.81	59.54	37.35	27.77

**Evaluation metrics** Evaluation was performed on Precision@ $k$  ( $P@k$ ), Recall@ $k$  ( $R@k$ ). For a query  $i$ , the predicted score vector  $\hat{y}_i \in R^L$  and ground truth vector  $y_i \in \{0, 1\}^L$ :

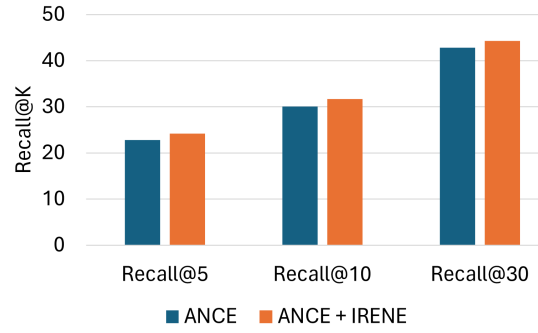
$$P@k = \frac{1}{k} \sum_{l \in \text{rank}_k(\hat{y})_d} y_{dl}$$

$$R@k = \frac{1}{\|y_i\|_0} \sum_{l \in \text{rank}_k(\hat{y})_d} y_{dl}$$

**Datasets creation details:** The results are presented on N-LF-Amazon-1.3M and N-Wikipedia-500K. These datasets were derived from LF-AmazonTitles-1.3M and LF-Wikipedia-500K available on the extreme classification repository [5]. Zero-shot and one-shot train-test splits were created in the following manner:

*Zero-Shot split:* 10% of items were randomly selected to form the novel item set. The remaining 90% of items with their associated queries formed the training corpus. The novel test set was created based on connections between test queries and novel items, while the generalized test set matched the extreme classification repository's version.

*One-shot split:* Here each novel item is provided one query, which is randomly chosen from the connections between novel item set and train queries. Note that IRENE's was found to be quite robust to the sampled query for novel items. The novel and generalized test sets are the same in both zero and one-shot settings.



**Figure 4: Plot shows the improvement in Recall for novel items over ANCE encoder with the addition of IRENE on N-Amazon-1.3M**

**Evaluation Settings** The problem setting considered in this paper can be divided on the basis of two axes. Specifically, the two axes considered are:

*What kind of signals are made available for novel items:*

- **Zero-Shot setting:** This setting focuses on the case when novel items  $\mathcal{Y}_u$  have no click signal made available. This setting assumes that the novel item which has been included for prediction has only its text available.
- **One-Shot setting:** Within this setting, we concentrate on items for which we possess exactly one associated clicked query. Unlike the zero-shot setting, where only the textual content of items is utilized for representation generation, in this setting, we assume that exactly one ground-truth query for the novel item is also revealed.

*What kind of evaluation is being done:*

- **Evaluation only on novel items:** this setting assumes that prediction has to be done only on novel items, i.e.,  $Y_s$
- **Generalized evaluation:** in this evaluation setting, the prediction set is composed of both items seen during training and novel items  $Y_s \cup Y_u$ . In this work, we explicitly consider the evaluation only on novel items because novel items are the focus of this work and sometimes, depending on the distribution of the generalized item set at prediction time, the algorithm can show accuracy gains by focusing solely on the seen items. At the same time, the phenomena of catastrophic forgetting leading to better accuracy on novel items but still, poorer accuracy on seen items is well studied [15, 26]. To guard against such a possibility, both of these 2 types of evaluations are considered.

A cartesian product of the 2 settings on the 2 axes leads us to a total of 4 settings considered in the paper.