Learning Structured Set Utility Functions with Contrastive Element Representations

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Abstract

Learning utility functions over sets of elements is central to many machine learning and decision-making tasks such as feature selection, sensor placement, and content recommendation, where the goal is to evaluate and select an optimal subset of elements that provide the largest utility. These utility functions often exhibit desirable properties like monotonicity and submodularity over sets, but are typically expensive to evaluate and may lack an explicit analytical form. Moreover, the utility of a set can vary depending on certain contextual variables, further complicating the learning task. In this work, we propose a unified framework for modeling and learning contextual set functions with monotone submodular structure from data using deep networks equipped with structural regularization. Our key insight is to decompose the set function into two learnable components: (i) a context-conditioned contrastive embedding network that maps elements to a shared latent space based on performance and contextual similarity, and (ii) an aggregation network that predicts set-level utility from the sum of embeddings with a submodular norm-based regularization term encouraging the learned function to exhibit diminishing returns. This combination improves utility prediction for unseen sets and contexts and enables greedy subset selection, which admits near-optimality guarantees. We evaluate our framework on a wide variety of real-world contextual subset selection tasks such as content recommendation, document summarization, and sensor selection demonstrating consistent improvements in utility prediction compared to baselines and stronger subset selection performance under context shifts.

1 Introduction

Many tasks in machine learning and decision-making require selecting subsets of items that jointly maximize a desired utility. These tasks often arise in domains such as sensor selection Krause et al. (2008); Guestrin et al. (2005); Gottipati et al. (2019), feature acquisition Kontschieder et al. (2015); Janisch et al. (2020); Shim et al. (2018), experiment design Chaloner & Verdinelli (1995); Krause et al. (2008); Hebbal et al. (2023), resource allocation Tsitsiklis (1993); Buchgraber & Shutin (2012); Efroni et al. (2018), and recommender systems Mehrotra & Vishnoi (2023); Wang et al. (2020); Qin & Zhu (2013), where one must choose a subset of elements (e.g., sensors, features, samples) under budget or operational constraints. A common trait in these problems is that the utility of a set exhibits diminishing returns, i.e., adding an element to a smaller set provides more gain than adding it to a larger one (which is a superset of the smaller set). Such structure is naturally modeled by submodular set functions Nemhauser et al. (1978), which admit efficient approximation algorithms for subset selection via greedy strategies with near-optimality guarantees.

However, in many real-world applications, the true utility function may be unknown, may not admit a closed form analytical expression, or may be expensive to evaluate. For instance, in environmental monitoring or surveillance, the utility of a sensor configuration may depend on complex interactions between sensor specifications and environmental conditions. Moreover, the underlying utility may be contextual, varying across different deployment environments or tasks. In such cases, evaluating the true utility for all possible subsets and contexts is infeasible, motivating the need for efficient surrogate models that approximate the true utility function while preserving key structural properties like submodularity and monotonicity.

When the true utility function is not monotone submodular, optimizing it directly can be computationally challenging or infeasible. In such cases, it is beneficial to approximate the function with a monotone submodular surrogate. Recent work has shown that it is often possible to design or learn surrogate utility functions that are easier to evaluate and align well with the true objective Ross et al. (2013); Azimi et al. (2012); Das & Kempe (2018). These surrogates can then be used in greedy subset selection algorithms, enabling practical and near-optimal decision-making. However, existing approaches often require hand-crafted surrogates, rely on heuristic assumptions, or do not explicitly enforce submodular structure, limiting their ability to predict performance and reason over unseen elements or contexts.

In this work, we propose a representation-driven learning framework for contextual set functions that generalizes to unseen elements/contexts and supports efficient subset selection. Divergent from the existing work, we consider a broader class of set utility functions that are context-dependent. For example, in a sensor selection task, the utility of a sensor is influenced by environmental conditions such as terrain, weather, or ambient light. Similarly, in a recommendation task, the utility of an item depends on the preferences and characteristics of the specific user to whom it is being recommended. Our key insight is that learning contrastive element embeddings which capture performance similarity conditioned on context can enable generalization to unseen contexts, and the learnt surrogate function, which approximates the submodularity property over the set of elements, can be used for efficient subset selection and re-optimization using greedy algorithms which enjoy near-optimality guarantees.

Overview of main contributions. We introduce Select - a SEt function LEarning framework via Contrastive elemenT representations. It is an end-to-end framework consisting of two learnable components: (i) an element representation network that produces context-aware embeddings of set elements, and (ii) a set function approximation network that models the underlying contextual set function.

- First, we propose a contrastive learning framework using the triplet margin loss objective to learn element-wise contrastive embeddings $\phi(x, z)$ that map elements x and context z to a latent space based on singleton utilities obtained from an oracle. We introduce a spectral regularization into this loss function, which aims to prevent dimensional collapse of element embeddings and promotes diverse and rich representations. Under certain smoothing assumptions, we establish that this regularized loss function guarantees asymptotic convergence to a stationary point under projected gradient descent.

- Second, we propose a Deep Sets style architecture Zaheer et al. (2017) to learn (i.e., approximate) the contextual utility function using aggregated element embeddings $\hat{f}(A, z) = \rho\left(\sum_{x \in A} \phi(x, z)\right)$, where A denotes a set and z denotes a context. To ensure that the resulting (surrogate) contextual set function exhibits monotone submodular behavior, we introduce a regularization loss inspired by the LeaSuRe framework Alieva et al. (2020) for the set-level aggregator network ρ. This loss operates on synthetically constructed set quadruples to softly enforce submodularity and monotonicity.

- We evaluate our framework on a wide variety of real-world tasks, including content recommendation (using MovieLens dataset), document summarization (using Reutuers Corpus), and sensor selection in urban environments. For the sensor selection task, we use a high-fidelity simulator to gather data that captures realistic environmental variability of sensor coverage utility. Our results show that the Select framework effectively predicts utilities for unseen sets and contexts, consistently outperforming standard baselines in both prediction accuracy and subset selection quality.

2 Related Work

Submodular optimization and greedy selection. Submodular functions have been widely used in machine learning and decision-making, with applications ranging from document summarization, feature selection, experimental design, and influence maximization Leskovec et al. (2007); Bhargav et al. (2023); Lin & Bilmes (2011); Krause & Golovin (2014). The maximization of submodular functions has been studied extensively under various settings including cardinality-constrained Bhargav et al. (2024), streaming Badanidiyuru et al. (2014), and distributed environments Mirzasoleiman et al. (2015). Greedy algorithms are a core tool in this setting and are known to provide provable approximation guarantees for monotone

submodular maximization Nemhauser et al. (1978). Adaptive submodularity Golovin & Krause (2011) generalizes these guarantees to sequential decision-making and has been applied in Bayesian experimental design Chaloner & Verdinelli (1995), value of information optimization Mitrovic et al. (2019), and submodular bandits Guillory & Bilmes (2011); Yue & Guestrin (2011).

Learning submodular functions. Several works have studied learning submodular functions from data. Early work focused on learning mixtures of known submodular templates Yue & Joachims (2008); El-Arini et al. (2009), modular approximations Sipos et al. (2012), or mixtures of concave-over-modular functions Lin & Bilmes (2012). Expressive function classes such as deep submodular functions Dolhansky & Bilmes (2016) allow modeling non-linear interactions between elements while preserving submodularity; however, they are not capable of modeling all submodular functions and do not support contextual utility prediction. In a theoretical setting, the PAC learnability of general submodular functions has been studied in Balcan & Harvey (2011). In contrast to these approaches, our work uses soft regularization to encourage approximate submodularity. Since many real-world utility functions often deviate from strict submodularity, hard enforcement may result in poor approximation. Soft regularization allows the model to learn approximately submodular functions, striking a balance between flexibility and adherence to submodularity.

Learning surrogate utilities for subset selection. Several recent works have explored learning surrogate utility functions to replace expensive evaluation functions in subset selection problems Alieva et al. (2020); Azimi et al. (2012); Kim & Boukouvala (2020). These approaches allow for efficient selection when the true objective is expensive or inaccessible. The LEASURE framework Alieva et al. (2020) proposes a principled submodular regularization loss that encourages learned functions to exhibit diminishing returns. Our work builds on this foundation by integrating LEASURE-style regularization with a contrastively learned embedding framework, enabling efficient prediction over unseen sets and contexts. Furthermore, our proposed learning algorithm captures contextual dependency of the utility function, outperforming the vanilla LEASURE when the utility function varies with different contexts.

Contrastive learning for structured prediction. Contrastive learning has emerged as a powerful approach for learning representations by pulling similar instances together and pushing dissimilar ones apart Oord et al. (2018); Chen et al. (2020). It has been successfully applied in domains such as graph learning You et al. (2020), metric learning Schroff et al. (2015), and recommendation systems Liu et al. (2021). In our work, we build on existing contrastive learning frameworks to train context-conditioned element embeddings based on utility-informed similarity. By ensuring that elements with similar singleton utilities under a given context are embedded closer in the representation space, we create a utility-aware latent structure. We show that this helps in the generalization of our model to estimate utilities for unseen subsets and supports rapid re-optimization in dynamic settings.

3 Background and Problem Formulation

Let $\mathcal{V}$ be a finite ground set of elements (e.g., sensors, movies), and $\mathcal{Z}$ denote a finite set of context vectors (e.g., environmental conditions, user metadata), such that each context $z \in \mathbb{R}^p$ in the set $\mathcal{Z}$ encodes contextual information. We define a *contextual set function* as $f : 2^{\mathcal{V}} \times \mathcal{Z} \to \mathbb{R}_{\geq 0}$. In many applications, f exhibits *monotonicity* and *submodularity* over sets $S \subseteq \mathcal{V}$. Below, we formalize a new notion of contextual monotonicity and submodularity.

Definition 1 (Contextual Monotonicity)**.** *A contextual set function $f : 2^{\mathcal{V}} \times \mathcal{Z} \to \mathbb{R}_{\geq 0}$ is monotonically increasing (or non-decreasing) if for every $z \in \mathcal{Z}$ and $S_1 \subseteq S_2 \subseteq \mathcal{V}$ we have $f(S_1, z) \leq f(S_2, z)$.*

Definition 2 (Contextual Submodularity)**.** *A set function $f : 2^{\mathcal{V}} \times \mathcal{Z} \to \mathbb{R}_{\geq 0}$ exhibits contextual submodularity if it satisfies the following for every $z \in \mathcal{Z}$:*

$$f(S_1 \cup \{x\}, z) - f(S_1, z) \geq f(S_2 \cup \{x\}, z) - f(S_2, z), \quad \forall S_1 \subseteq S_2 \subseteq \mathcal{V}, x \notin S_2.$$

Our main goal is to learn a (surrogate) contextual set function $\hat{f}(S, z)$ by querying an oracle for the utilities $f(S, z)$ for set-context pairs (S, z). We wish to learn the surrogate by querying the oracle efficiently, such

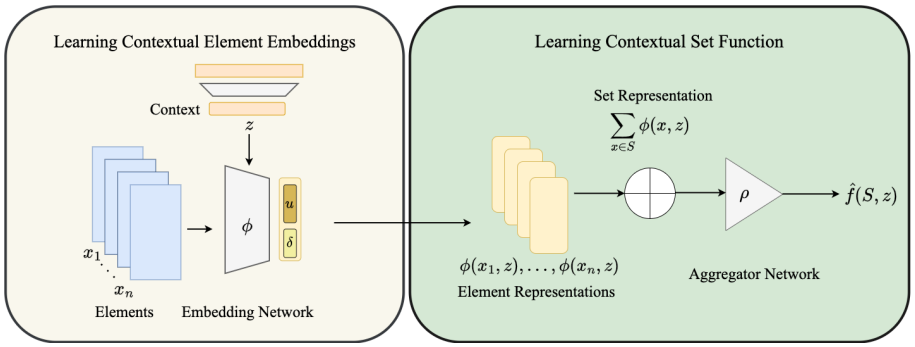


Figure 1: Architecture diagram of the SELECT framework: The first part learns contextual embeddings for elements based on their features and the given context. The second part aggregates these embeddings to represent a set and uses an aggregation network to predict contextual set utility.

that it can generalize to unseen subsets and contexts, and maintains a monotone submodular structure. Additionally, since a set function by definition does not consider the order of elements, we want the surrogate to satisfy permutation invariance Zaheer et al. (2017), as formalized below for a contextual set function.

Definition 3 (Permutation Invariance)**.** *A contextual set function $f : 2^{\mathcal{V}} \times \mathcal{Z} \to \mathbb{R}_{\geq 0}$ is permutation invariant to the order of elements in the set, i.e., for every context $z \in \mathcal{Z}$ and any permutation $\pi : [M] \to [M]$, $f(\{x_1, \ldots, x_M\}, z) = f(\{x_{\pi(1)}, \ldots, x_{\pi(M)}\}, z), x_i \in \mathcal{V}$.*

To this end, we propose a representation-driven learning framework in which the set function is modeled via a Deep Sets architecture Zaheer et al. (2017):

$$\hat{f}(S, z) = \rho\left(\sum_{x \in S} \phi(x, z)\right), \tag{1}$$

where $\phi(x, z)$ is contextual element representations, and ρ is an aggregator network.

We split the learning problem into two parts: learning the element embedding network ϕ using contrastive learning, and learning the aggregator network ρ using monotonicity and submodularity regularization over set-level utility supervision. These are discussed in the next two sections. The complete SELECT framework is shown in Figure 1.

4 Contrastive Learning of Contextual Element Embeddings

We begin by learning a contextual element embedding function $\phi : \mathcal{V} \times \mathcal{Z} \to \mathbb{R}^d$, where $\mathcal{V}$ is the finite ground set of elements (e.g., movies, sensors) and $\mathcal{Z}$ is the set of context variables (e.g., user information, environmental conditions). Each element $x \in \mathbb{R}^m$ in the ground set $\mathcal{V}$ is described by a potentially large m dimensional feature vector, which can make direct processing computationally expensive. We aim to encode this feature under a given context $z \in \mathcal{Z}$ in a shared latent space which is a compact, low-dimensional representation of high-dimensional elements tailored to specific contexts. The contrastive learning framework ensures elements with similar utility are embedded close together, while dissimilar elements are pushed farther apart. In particular, the geometry of the embedding space should reflect similarity in utility contribution, conditioned on the context.

To achieve this, we employ a contrastive learning objective based on triplet margin loss Jing et al. (2021). Each training example/sample consists of a quadruple (x_a, x_p, x_n, z), where x_a is an anchor element, x_p is a positive element (with similar utility to x_a), and x_n is a negative element (with dissimilar utility), all under the same context z. The contrastive training dataset $\mathcal{T}$ is constructed using singleton utility feedback. We denote $\mathcal{Z}_{\text{train}} \subseteq \mathcal{Z}$ to be the set of contexts used for training the network. For each context $z \in \mathcal{Z}_{\text{train}}$, we form a triplet (x_a, x_p, x_n) as follows: we sample an element (x_a) uniformly at random from $\mathcal{V}$. We query the utility oracle for $f(\{x_a\}, z)$. Then, we sample another element $x \in \mathcal{V} \setminus \{x_a\}$ uniformly at random and

denote it by x_p (*positive element*) if $|f(\{x_a\}, z) - f(\{x\}, z)| \leq \epsilon$, or denote it by x_n (*negative element*) if $|f(\{x_a\}, z) - f(\{x\}, z)| > \epsilon$, where $\epsilon > 0$ is a similarity threshold, which is a hyperparameter. We repeat this process until a predefined number of samples are gathered or a sampling budget is exhausted. For a context z, if no valid triplets (x_a, x_p, x_n) are found, we change ϵ or extend the sampling pool to ensure sufficient diversity, and repeat the process. Let $\mathcal{T}_z$ denote the set of triplets (x_a, x_p, x_n) for a context z, from which we obtain the full training set $\mathcal{T} = \bigcup_{z \in \mathcal{Z}_{\text{train}}} \mathcal{T}_z$.

We employ the triplet margin loss for training the embedding network Khosla et al. (2020). This loss encourages the embedding of x_a to be closer to that of x_p than to that of x_n by at least a margin α:

$$\mathcal{L}_{\text{contrastive}}(\phi; \mathcal{T}) = \sum_{(x_a, x_p, x_n, z) \in \mathcal{T}} \max\left(0, \text{sim}(\phi(x_a, z), \phi(x_n, z)) - \text{sim}(\phi(x_a, z), \phi(x_p, z)) + \alpha\right), \tag{2}$$

where $\text{sim}(\cdot, \cdot)$ denotes a similarity metric over the vector space, such as cosine similarity, and $\alpha > 0$ is a hyperparameter controlling the required margin between positive and negative pairs. This contrastive objective enables the model to learn a representation space in which element embeddings encode contextual utility similarity.

However, training the embedding network ϕ only with triplet loss can lead to a phenomenon known as *dimensional collapse* or *rank collapse*, where all inputs are mapped to a small subspace in the embedding space, severely limiting the model's ability to distinguish among different elements Jing et al. (2021) and the expressiveness of the learned set function. This issue has been widely observed in the contrastive learning literature, especially when the number of negatives is small or when regularization is weak Hua et al. (2021); Jiang et al. (2023). Many approaches have addressed this by introducing variance- or decorrelation-based regularization terms that promote feature diversity across dimensions. Notable methods include Barlow Twins Zbontar et al. (2021) and VICReg Bardes et al. (2022). A noteable method SimCLR Chen et al. (2020) relies on contrastive learning with large batches of negative samples and the InfoNCE loss, which encourages instance discrimination. Self-supervised learning frameworks such as BYOL Grill et al. (2020) and SimSiam Chen & He (2021) learn representations by aligning multiple views of the same input without relying on negative samples. However, both approaches rely on architectural tricks, e.g., the use of projection heads, momentum encoders or predictor networks, to avoid representational collapse. In contrast, our framework introduces an explicit regularization-based mechanism to ensure full-rank embeddings, which promotes diversity and informativeness of the learned representations. This promotes the embedding network to map each element to a distinct representation in the latent space, allowing the aggregation operator to retain information about individual elements. This distinction is crucial for learning the set function effectively, as it enables the model to account for the unique contribution of each element, even after aggregation.

Specifically, we split the output vector of the embedding network $\phi(x, z) \in \mathbb{R}^d$ into two components: $u(x, z) \in \mathbb{R}^k$, which is the contrastive component used in the triplet loss, and $\delta(x, z) \in \mathbb{R}^{d-k}$: a complementary component used to increase the diversity and volume of the full embedding space. Here k is a hyperparameter which controls the sizes of the two components. The full embedding is given by

$$\phi(x, z) = \begin{bmatrix} u(x, z) \\ \delta(x, z) \end{bmatrix}, \tag{3}$$

where the stacked vector representation reflects concatenation. We now denote the modified contrastive loss by $\mathcal{L}_{\text{triplet}}$, which is applied only on $u(x, z)$, given by

$$\mathcal{L}_{\text{triplet}}(\phi; \mathcal{T}) = \sum_{(x_a, x_p, x_n, z) \in \mathcal{T}} \max\left(0, \text{sim}(u(x_a, z), u(x_n, z)) - \text{sim}(u(x_a, z), u(x_p, z)) + \alpha\right). \tag{4}$$

We note that $\mathcal{L}_{\text{triplet}}$ is piecewise differentiable and sub-differentiable almost everywhere Khosla et al. (2020). In practice, we rely on automatic differentiation frameworks to compute gradients. A smooth surrogate such as a Huberized version of the triplet loss can be substituted for improved gradient flow Xu et al. (2016). We discuss this in detail in Section 4.1.

Next, we apply a independence regularization to the full embedding $\phi(x, z)$, encouraging the entire representation to span a high-volume region in feature space. Recall that $\mathcal{Z}_{\text{train}}$ is the set of contexts used for

training. For each $z \in \mathcal{Z}_{\text{train}}$, define the embedding matrix $U^{(z)} = [\phi(x_1, z), \ldots, \phi(x_n, z)] \in \mathbb{R}^{d \times n}$, where $\{x_1, \ldots, x_n\} = \mathcal{V}$ is the ground set of elements. To encourage the embeddings to be informative and linearly independent under each context, we introduce an independence regularization term:

$$\mathcal{L}_{\text{indep}}(\phi) = \frac{1}{|\mathcal{Z}_{\text{train}}|} \sum_{z \in \mathcal{Z}_{\text{train}}} -\log\det\left(U^{(z)\top} U^{(z)} + \varepsilon I\right), \tag{5}$$

where εI is a diagonal matrix with a small positive constant ε for numerical stability. This loss encourages the Gram matrix of the embeddings under each context to be full-rank, which geometrically corresponds to maximizing the volume of the parallelepiped spanned by the embedding vectors. This promotes the embedding network to map each element to a sufficiently distinct representation in the latent space, facilitating unique representations at the set level.

The final contrastive loss used for training the embedding network combines the modified triplet margin loss with the independence regularization:

$$\mathcal{L}_\phi = \mathcal{L}_{\text{triplet}}(\phi; \mathcal{T}) + \lambda_{\text{indep}} \mathcal{L}_{\text{indep}}(\phi), \tag{6}$$

where λ_{indep} is a tunable hyperparameter that controls the strength of the regularization term. The entire procedure is outlined in Algorithm 1.

Algorithm 1 Contrastive Learning of Contextual Element Embeddings

Require: Element set $\mathcal{V}$, context set $\mathcal{Z}$, number of samples N, utility oracle f, hyperparameters ϵ, α, k, regularization parameter λ_{indep}, epochs T, learning rate η

Initialize parameters θ_ϕ^0 for embedding network ϕ
Generate Triplet Dataset $\mathcal{T}$:
while $|\mathcal{T}| < N$ **do**
  Sample an anchor $x_a \in \mathcal{V}$ and $z \in \mathcal{Z}_{\text{train}}$ uniformly at random
  Identify $x_p \in \mathcal{V} \setminus x_a$ s.t. $|f(\{x_a\}, z) - f(\{x_p\}, z)| \leq \epsilon$ via uniform random sampling
  Identify $x_n \in \mathcal{V} \setminus x_a$ s.t. $|f(\{x_a\}, z) - f(\{x_n\}, z)| > \epsilon$ via uniform random sampling
  Add triplet $\mathcal{T} \leftarrow \mathcal{T} \cup (x_a, x_p, x_n, z)$
end while
Train ϕ **network**:
for $t = 1$ to T **do**
  Obtain embedding vectors $\phi(x_i, z), i = 1, .., n, \forall z \in \mathcal{Z}_{\text{train}}$, using the ϕ network
  Compute triplet loss $\mathcal{L}^t_{\text{triplet}}$(as in equation 4) for samples in $\mathcal{T}$ using specfied α and k
  Compute independence loss $\mathcal{L}^t_{\text{indep}}$ (as in equation 5) using embeddings $\phi(x_i, z)_{i=1}^n \forall z \in \mathcal{Z}_{\text{train}}$
  Update network parameters $\theta_\phi^{t+1} \leftarrow \theta_\phi^t - \eta \nabla \mathcal{L}_\phi^t$, where $\mathcal{L}_\phi^t = \mathcal{L}^t_{\text{triplet}} + \lambda_{\text{indep}} \mathcal{L}^t_{\text{indep}}$
end for
return Trained embedding network ϕ

4.1 Theoretical Analysis

We now present our theoretical analysis of convergence for the contrastive learning framework under projected gradient descent. We begin by formally stating the assumptions under which our results hold, followed by a few key lemmas establishing smoothness and boundedness properties of the regularized loss function. Building on these lemmas, we present the main convergence result, showing that projected gradient descent on the regularized loss asymptotically converges to a stationary point. We defer all detailed proofs to Appendix A.

Assumption 1 (Bounded Embeddings and Compact Parameter Space)**.** *For each context $z \in \mathcal{Z}_{\text{train}}$, the embedding matrix $U^z \in \mathbb{R}^{n \times d}$ is uniformly bounded: $\|U^z(\theta_\phi)\|_2 \leq R$, where $R \in \mathbb{R}_{>0}$ is some finite constant, and $\theta_\phi \in \Theta$ are the network parameters. Additionally, the parameter space $\Theta \subset \mathbb{R}^p$ is closed and compact.*

Assumption 2 (Network Regularity)**.** *The embedding network ϕ is continuously differentiable (C^1). Furthermore, $\|J^z(\theta_\phi)\| \leq K$ and $\|J^z(\theta_\phi) - J^z(\theta'_\phi)\| \leq \rho_J \|\theta_\phi - \theta'_\phi\|$ for all $\theta_\phi, \theta'_\phi \in \Theta$, where $J^z(\theta_\phi)$ denotes the Jacobian with respect to θ_ϕ, Θ is the compact parameter space, and $K, \rho_J \in \mathbb{R}$ are some finite constants.*

Assumptions 1 and 2 are commonly made in convergence analysis of gradient-based optimization methods and can be typically satisfied by projecting parameters onto a compact set, normalizing the embedding vectors and using Lipschitz activation functions (e.g., tanh) in the network Du et al. (2019).

We note that the objective/loss function (as in equation 6) consists of two parts: a triplet-margin loss and a log det regularization term. The triplet margin loss $\mathcal{L}_{\text{triplet}}$ (as in equation 4) suffers from analytical shortcomings: the hinge function $\max(0, \cdot)$ is not differentiable at zero, and its gradient is not Lipschitz continuous (Xu et al., 2016). This is an undesirable property for gradient-based optimization, as smoothness of the loss is a key requirement for convergence. To address this, we adopt a smoothed version of the triplet loss by replacing the hinge with a C^1 (continously differentiable) Huberized hinge $h_\mu(\cdot)$, controlled by a smoothing parameter $\mu > 0$. Let $\zeta(x_a, x_p, x_n) = \text{sim}(u(x_a, z), u(x_n, z)) - \text{sim}(u(x_a, z), u(x_p, z)) + \alpha$. The Huberized triplet-margin loss per triplet is defined as

$$h_\mu(\zeta) \;=\; \begin{cases} 0, & \zeta \le 0, \\ \frac{\zeta^2}{2\mu}, & 0 < \zeta < \mu, \\ \zeta - \frac{\mu}{2}, & \zeta \ge \mu, \end{cases} \tag{7}$$

where $\mu > 0$ controls the smoothing width. This is similar to the Huberized Support Vector Machine (HSVM) proposed in (Xu et al., 2016), which uses a differentiable approximation of the hinge loss function for SVMs. The resulting smoothed triplet loss is

$$\mathcal{L}^{\mu}_{\text{triplet}}(\phi, \mathcal{T}) = \sum_{(x_a, x_p, x_n) \in \mathcal{T}} h_\mu(\zeta(x_a, x_p, x_n)). \tag{8}$$

When the margin violation ζ is small ($< \mu$), the penalty is quadratic, giving smooth gradients. For large violations, the penalty grows linearly, as in the standard hinge. At the transition points 0 and μ, the function is continuously differentiable. Thus, μ acts as a smoothing parameter. Setting $\mu = 0$ recovers the standard hinge, i.e., $\max(0, \cdot)$, while larger $\mu > 0$ yields smoother behavior. The Huberized hinge function is $\mathcal{O}(1/\mu)$ gradient-Lipchitz Xu et al. (2016).

We employ a time-varying regularization parameter ε_t in equation 5 and decay it over time to balance numerical stability with representational flexibility. The overall loss function with the Huberized triplet loss as in equation 8 and the time-varying regularization parameter ε_t is given by

$$\mathcal{L}_{\phi,t} = \mathcal{L}^{\mu}_{\text{triplet}}(\phi, \mathcal{T}) + \lambda_{\text{indep}} \frac{1}{|\mathcal{Z}_{\text{train}}|} \sum_{z \in \mathcal{Z}_{\text{train}}} -\log\det(U^{(z)\top} U^{(z)} + \varepsilon_t I). \tag{9}$$

Lemma 1. *Let Assumptions 1 and 2 hold. Let $\nabla_{\theta_\phi} \mathcal{L}^{\mu}_{\text{triplet}}(\theta_\phi)$ denote the gradient of the Huberized triplet-margin loss function (as in equation 8) with respect to the network parameters θ_ϕ. For all $\theta_\phi, \theta'_\phi \in \Theta$, we have*

$$\left\| \nabla_{\theta_\phi} \mathcal{L}^{\mu}_{\text{triplet}}(\theta_\phi) - \nabla_{\theta_\phi} \mathcal{L}^{\mu}_{\text{triplet}}(\theta'_\phi) \right\| \;\le\; L^{\theta_\phi}_{\text{trip}} \, \|\theta_\phi - \theta'_\phi\|, \tag{10}$$

where

$$L^{\theta_\phi}_{\text{trip}} \;=\; \mathcal{O}\Bigg(\rho_J \; |\mathcal{Z}_{\text{train}}| \sqrt{|\bar{\mathcal{T}}_z|} \;+\; \frac{K^2}{\mu} |\mathcal{Z}_{\text{train}}| |\bar{\mathcal{T}}_z| \Bigg), \quad |\bar{\mathcal{T}}_z| = \max_{z \in \mathcal{Z}_{\text{train}}} |\mathcal{T}_z|. \tag{11}$$

Lemma 2. *Let Assumptions 1 and 2 hold. Let $g_z(\theta_\phi) = -\lambda_{\text{indep}} \log\det\big(U^z(\theta_\phi)^\top U^z(\theta_\phi) + \varepsilon I\big)$ and let $\nabla_{\theta_\phi} g_z(\theta_\phi)$ denote the gradient of $g_z(\theta_\phi)$ with respect to the network parameters θ_ϕ. For all $\theta_\phi, \theta'_\phi \in \Theta$, we have*

$$\|\nabla_{\theta_\phi} g_z(\theta_\phi) - \nabla_{\theta_\phi} g_z(\theta'_\phi)\| \;\le\; L^{\theta_\phi}_{\text{logdet}} \, \|\theta_\phi - \theta'_\phi\|, \tag{12}$$

where

$$L^{\theta_\phi}_{\text{logdet}} = \frac{2\lambda_{\text{indep}} \rho_J}{\varepsilon} \sqrt{r}\, R \;+\; K^2 \left(\frac{2\lambda_{\text{indep}}}{\varepsilon} + \frac{4\lambda_{\text{indep}} R^2}{\varepsilon^2} \right), \quad r = \min\{n, d\}. \tag{13}$$

Lemma 3. *Let Assumptions 1 and 2 hold. Let $\nabla_{\theta_\phi}\mathcal{L}_{\phi,t}(\theta_\phi)$ denote the gradient of the loss function (as in equation 9) with respect to the network parameters θ_ϕ. From Lemma 1 and Lemma 2, we have, for all $\theta_\phi, \theta'_\phi \in \Theta$,*

$$\left\|\nabla_{\theta_\phi}\mathcal{L}_{\phi,t}(\theta_\phi) - \nabla_{\theta_\phi}\mathcal{L}_{\phi,t}(\theta'_\phi)\right\| \;\le\; \alpha_t \,\|\theta_\phi - \theta'_\phi\|,$$

where

$$\alpha_t \;=\; L_{\text{trip}}^{\theta_\phi} \;+\; \frac{2\,\lambda_{\text{indep}}\,\rho_J\,\sqrt{r}\,R}{\varepsilon_t} \;+\; \frac{2\,\lambda_{\text{indep}}\,K^2}{\varepsilon_t} \;+\; \frac{4\,\lambda_{\text{indep}}\,K^2\,R^2}{\varepsilon_t^2}, \qquad r = \min\{n, d\}.$$

In other words, the loss function $\mathcal{L}_{\phi,t}$ is α_t-smooth (i.e., the gradient of $\mathcal{L}_{\phi,t}$ is α_t-Lipchitz) with $\alpha_t = \mathcal{O}\left(\frac{1}{\varepsilon_t^2}\right)$.

Lemma 4. *The loss function $\mathcal{L}_{\phi,t}$ (as in equation 9) has the following properties:*

(a) Bounded drift:

$$\left|\mathcal{L}_{t+1,\theta_\phi} - \mathcal{L}_{t,\theta_\phi}\right| \;\le\; \lambda_{\text{indep}}\, r\, \frac{|\varepsilon_{t+1} - \varepsilon_t|}{\min\{\varepsilon_{t+1}, \varepsilon_t\}}. \tag{14}$$

(b) Lower bound:

$$\mathcal{L}_{t,\theta_\phi} \;\ge\; -\,\lambda_{\text{indep}}\, r\, \log(R^2) \quad \forall\, t. \tag{15}$$

Building on Lemma 3 and Lemma 4, we now present the main convergence result for projected gradient descent applied to the time-varying loss function defined in equation 9.

Theorem 1. *Let Assumptions 1 and 2 hold. Consider the projected gradient descent (PGD) updates on the time varying loss function in equation 9 given by*

$$\theta_{\phi,t+1} = \text{Proj}_\Theta\big(\theta_{\phi,t} - \eta_t \nabla_{\theta_\phi}\mathcal{L}_t(\theta_{\phi,t})\big), \tag{16}$$

where $\nabla_{\theta_\phi}\mathcal{L}_t(\theta_{\phi,t})$ is the gradient of the loss function with respect to θ_ϕ. Let $\varepsilon_t = \varepsilon_0(t+\kappa)^{-\beta}$ with $0 < \beta < \frac{1}{2}$ and $\kappa > 1$, so that $\alpha_t = \mathcal{O}((t+\kappa)^{2\beta})$ and $\eta_t = \gamma/\alpha_t$ with $\gamma \in (0,1)$. Then

$$\lim_{t\to\infty} \|\nabla\mathcal{L}_t(\theta_t)\| = 0. \tag{17}$$

In other words, PGD on the time-varying loss function in equation 9 with a decaying regularization parameter $\varepsilon_t = \mathcal{O}((t+\kappa)^{-\beta}), 0 < \beta < \frac{1}{2}$, $\kappa > 1$, and learning rate $\eta_t = \gamma/\alpha_t$ converges to a stationary point, asymptotically.

Now, we have the following result that follows from Theorem 1.

Corollary 1. *By the asymptotic convergence in Theorem 1, there exists a limit parameter $\theta_\infty \in \Theta$ such that, for every context $z \in \mathcal{Z}_{\text{train}}$, the embedding matrix $U^z(\theta_\infty)$ is full-rank, given $d \ge n$. As a result, the set representation $\sum_{x\in S}\phi_{\theta_\infty}(x,z)$ is injective. In other words, for each context z, and for any two distinct subsets $X, Y \subseteq \mathcal{V}, X \ne Y$,*

$$\sum_{x\in X}\phi_{\theta_\infty}(x,z) \;\ne\; \sum_{y\in Y}\phi_{\theta_\infty}(y,z). \tag{18}$$

Since our framework uses a sum-based aggregator whose output feeds into the function approximation network (ρ) (see Section 5), injectivity of the set representation (as stated in Corollary 1) is essential as different sets must map to distinct embeddings to ensure that the approximation network ρ can differentiate between them.

Remark 1. *When $d < n$, injective set representations can still be achieved by assigning a dedicated coordinate in the δ subspace of the embedding of each element with unique positive values, guaranteeing uniqueness of subset sums. This construction simultaneously preserves semantic closeness in the u subspace, which continues to capture utility-based similarity among elements. While it is true that full linear independence cannot be enforced when $d < n$, this does not diminish the relevance of the log-determinant regularizer. Its role is not to impose strict independence, but to actively encourage geometric diversity by penalizing collapsed or low-rank configurations of the embeddings. This promotes spread and volume in the representation space, which is critical for stable learning and discriminative structure. In contrast, when $d \ge n$, the embedding space has sufficient degrees of freedom to naturally support linear independence and injectivity, allowing these properties to emerge as a consequence of optimization rather than through explicit structural enforcement.*

5 Learning the Surrogate Utility Function

Once the element embeddings $\phi(x, z)$ are learned, we turn our attention to learning the set-level aggregator function $\rho : \mathbb{R}^d \to \mathbb{R}$, which predicts the utility of a set given the sum of the embeddings of its elements. We construct a training dataset $\mathcal{D}_{\text{real}} = \{(S_i, z_i, y_i)\}_{i=1}^N$ consisting of set-context-utility triples. This is done by sampling set-context pairs $(S_i, z_i) \in 2^{\mathcal{V}} \times \mathcal{Z}_{\text{train}}$ uniformly at random and $y_i = f(S_i, z_i)$ is obtained by querying the utility oracle. The empirical loss for this supervised learning task is defined as:

$$\mathcal{L}_{\text{mse}}(\hat{f}, f) = \sum_{(S,z,y)\in\mathcal{D}_{\text{real}}} (\hat{f}(S, z) - y)^2. \tag{19}$$

However, simply fitting $\mathcal{L}_{\text{mse}}$ does not guarantee that the learned model is submodular. If the true function f is submodular, then this approach may capture its behavior. However, if f is only approximately submodular or not submodular at all, then minimizing $\mathcal{L}_{\text{mse}}$ will fit the network to whatever structure f has, and the learned model may not exhibit submodular/ approximate submodular structure. To address this, we need explicit regularization terms that can, in principle, bias the learning process toward submodularity and ensure that the model ρ approximates any f by its *closest approximately submodular function.*

We construct a synthetic regularization dataset $\mathcal{D}_{\text{synth}}$ (i.e., the utility oracle will not be queried/evaluated for creating this data) comprising of quadruples (X, Y, W, Z). For each $S_i, z \in \mathcal{D}_{\text{real}}$, we select sets X, Y uniformly at random such that $X \subset Y \subseteq S_i$, and let $W = X \cup \{e\}, Z = Y \cup \{e\}$ for some element $e \in \mathcal{V} \setminus Y$, also sampled uniformly at random. These quadruples are designed to expose potential violations of the diminishing returns property, which is a defining characteristic of submodular functions.

To encourage submodularity in the learned surrogate $\hat{f}(\cdot, z)$, we define the submodularity regularization loss:

$$\mathcal{L}_{\text{sub}}(\hat{f}, f) = \sum_{(X,Y,W,Z)\in\mathcal{D}_{\text{synth}}} \left[\text{ReLU}\left(\hat{f}(Z, z) - \hat{f}(Y, z) - (\hat{f}(W, z) - \hat{f}(X, z))\right)\right], \tag{20}$$

which penalizes deviations from the submodular property, i.e., $\hat{f}(Z, z) - \hat{f}(Y, z) \leq \hat{f}(W, z) - \hat{f}(X, z)$. In particular, the ReLU function ensures that the loss is non-negative and only activated when the submodularity inequality is violated. If the inequality holds (i.e., the marginal gain from adding e to the larger set Y is no greater than adding it to the smaller set X), the loss contributes zero. This selective activation makes the loss both efficient to compute and tightly focused on penalizing only true violations, without unnecessarily affecting valid examples Alieva et al. (2020). To further ensure that the learned surrogate exhibits monotonicity, we define a monotonicity regularization term:

$$\mathcal{L}_{\text{mono}}(\hat{f}, f) = \sum_{(X,W)\in\mathcal{D}_{\text{synth}}} \left[\text{ReLU}(\hat{f}(X, z) - \hat{f}(W, z))\right], \tag{21}$$

which penalizes cases where adding an element decreases the predicted utility. Again, ReLU activation ensures that only violations of monotonicity contribute to the loss, maintaining the non-negativity of the penalty. As discussed in Alieva et al. (2020), these synthetic regularization terms shape the learned function $\hat{f}$ to approximate monotone submodular behavior while requiring supervision only on small subsets. Our final training objective combines these components:

$$\mathcal{L}_\rho(\hat{f}, f) = \mathcal{L}_{\text{mse}}(\hat{f}, f) + \lambda_{\text{sub}}\mathcal{L}_{\text{sub}}(\hat{f}, f) + \lambda_{\text{mono}}\mathcal{L}_{\text{mono}}(\hat{f}, f), \tag{22}$$

where λ_{sub} and λ_{mono} are regularization parameters for the submodularity and monotonicity regularizations, respectively. We outline the surrogate learning procedure in Algorithm 2.

Algorithm 2 Learning Surrogate Utility Function $\hat{f}$

Require: Embeddings $\phi(x, z)$ for $x, z \in \mathcal{V} \times \mathcal{Z}$, dataset $\mathcal{D}_{\text{real}} = \{(S_i, z_i, f(S_i, z_i))\}_{i=1}^{N}$, regularization parameters $\lambda_{\text{sub}}, \lambda_{\text{mono}}$, epochs T, learning rate η, number of regularization samples N_s

Initialize parameters θ_ρ^0 for aggregator network ρ
Construct Synthetic Quadruples Dataset $\mathcal{D}_{\text{synth}}$:
for each $S_i \in \mathcal{D}_{\text{real}}$ until $|\mathcal{D}_{\text{synth}}| = N_s$ **do**
  Sample subsets $X \subset Y \subseteq S_i$ and element $e \notin Y$, uniformly at random
  Form quadruples $(X, Y, W = X \cup \{e\}, Z = Y \cup \{e\})$
  $\mathcal{D}_{\text{synth}} \leftarrow \mathcal{D}_{\text{synth}} \cup (X, Y, W, Z)$
end for
Train ρ **network**:
for $t = 1$ to T **do**
  Estimate loss function $\mathcal{L}_\rho^t(\hat{f}, f) = \mathcal{L}_{\text{mse}}^t(\hat{f}, f) + \lambda_{\text{sub}}\mathcal{L}_{\text{sub}}^t(\hat{f}, f) + \lambda_{\text{mono}}\mathcal{L}_{\text{mono}}^t(\hat{f}, f)$ using $\mathcal{D}_{\text{real}}$ & $\mathcal{D}_{\text{synth}}$
  Update network parameters: $\theta_\rho^{t+1} \leftarrow \theta_\rho^t - \eta \nabla \mathcal{L}_\rho^t$
end for
return Trained surrogate network ρ

6 Experiments

We evaluate our framework through a comprehensive set of experiments on content recommendation, sensor selection, and document summarization tasks designed to answer the following key questions: (i) Does the representation learning framework in Select effectively cluster similar elements while being able to discriminate between sets of elements?, (ii) Can the Select framework predict utilities of unseen sets and contextual variables accurately?, and (iii) Can the surrogate utility model learned using the Select framework drive effective downstream subset selection?

Baselines and Comparisons. We evaluate Select for its ability to predict utilities for unseen sets by varying the train to test split against the following state-of-the-art baselines: (i) Vanilla Deep Sets Zaheer et al. (2017), trained directly on set-utility pairs without monotonicity and submodularity regularization; (ii) LeaSuRe Alieva et al. (2020), where the set elements are represented as a one-hot encoding vector (as opposed to embeddings), but have the monotonicity and submodularity regularization terms. In Appendix B, we present additional details regarding datasets, model architectures, and training. We also present additional experiments with noisy oracle feedback, re-optimization under shifts, and runtime comparisons with baselines.

6.1 Content Recommendation (MovieLens Dataset).

We evaluate our framework on a movie recommendation task using the MovieLens dataset Harper & Konstan (2015). In this setup, each user is treated as a contextual variable $z \in \mathbb{R}^4$, described via demographic features such as age, gender, occupation, and zip code, while each movie is treated as a ground-set element x, encoded using its genre-based binary feature vector. For each user z, the utility of a set of movies $X \subseteq \mathcal{V}$ is $f(X, z) = \max_{x \in X} \text{rating}(x, z)/5$, which captures the user's preference for their most highly-rated movie in the set. This form models the set utility using a max-coverage-style objective aligned with user satisfaction, which is monotone-submodular Chen et al. (2017). We train Select by sampling a subset of 10 users (as contexts $\mathcal{Z}$) and 50 movies (as the ground set $\mathcal{V}$) uniformly at random along with their corresponding utility labels. This allows us to evaluate the ability of our framework to learn from user-movie interactions and test generalization to unseen movie combinations and users.

Representation Quality: We analyze the singular value spectrum of the matrix formed by stacking the embeddings $\phi(x, z)$ across elements and contexts. Specifically, we plot the logarithm of the singular values with and without the log-determinant regularization term in Figure 2a. Larger singular values correspond to a higher effective rank, indicating a richer and more diverse feature space. Our results show that log-determinant regularization significantly improves the spread of singular values, resulting in a higher-rank embedding matrix. This suggests that the regularization encourages the embeddings to span more volume.

Embedding Visualization. We apply t-SNE (t-Distributed Stochastic Neighbor Embedding van der Maaten & Hinton (2008)) technique to visualize the $d-$ dimensional element embeddings $\phi(x, z)$ in 2-D (see Figure 2b). The visualization reveals clustering patterns among items, which reflect the model's ability to encode interactions between elements and contexts based on performance similarity.

Comparison with Baselines. We compare SELECT with Vanilla Deep Sets and LEASURE and plot the test loss with varying train-test splits in Figure 2c. We observe that SELECT outperforms both Deep Sets and LEASURE frameworks, with the lowest test loss. In other words, SELECT can more accurately predict the utility of unseen sets compared to Deep Sets and LEASURE frameworks.

6.2 Sensor Selection in Urban Environments

Dataset Generation and Experimental Setup. We consider a sensor selection task where the objective is to learn the utilities of sets of camera sensors S that is defined by a coverage map of way-points under varying environmental conditions (captured by the context vector z). We note that the area coverage utility function $f(A, z)$ is monotone submodular over sets A Lin & Bilmes (2012). We use a high-fidelity photorealistic simulator in a drone detection setup built on Unreal Engine 5 as our utility oracle. In our experiments, we consider a ground set $\mathcal{V}$ of 4 camera sensors with varied characteristics. Each sensor is encoded in the feature vector x using its intrinsic parameters (e.g., FOV, range, resolution, frame rate), while each environment is encoded into vector z using meta-information such as visibility and light levels. To obtain the coverage utility of different sensor sets under varying environmental conditions, we run a YOLO-based detection pipeline Diwan et al. (2023) under distinct weather conditions (e.g., clear sky, low-light cloudy, heavy fog, etc.) for detecting drones and obtained the coverage map (i.e., number of way-points covered by sensors).

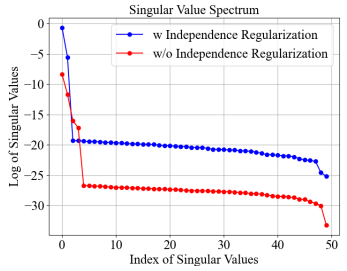
We provide further details of the experimental setup in Appendix B. We apply the proposed SELECT framework to learn contextual coverage utility of sensor sets. Using singleton feedback from drone detection coverage maps, we train a context-conditioned contrastive embedding network $\phi(x, z)$ by setting $\epsilon = 0.1$. We train the set-level surrogate $\hat{f}(A, z) = \rho\left(\sum_{x \in A} \phi(x, z)\right)$, using the supervision dataset $\mathcal{D}_{\text{real}}$, which consists of subsets $A \subseteq \mathcal{V}$ of varying sizes, with labels obtained from the simulator $y_{A,z} = f(A, z)$.

Comparison with Baselines. We compare the contextual transfer ability of SELECT with Deep Sets and LEASURE by progressively increasing the number of contexts (i.e., environment conditions) it is trained on $\mathcal{Z}_{\text{train}}$ and plot the average test loss over all sensor sets and contexts in $\mathcal{Z}_{\text{test}}$ (i.e., new environment conditions) in Figure 2d. We observe that SELECT outperforms Deep Sets and LEASURE, with lower prediction loss under the contextual shift. This shows that our framework can effectively predict utilities of sensors in new/unseen environmental conditions.

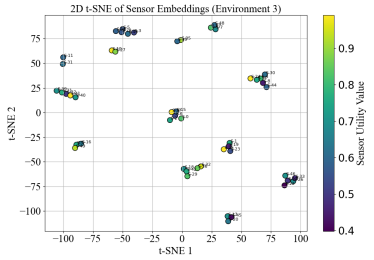
Downstream Subset Selection using Greedy. To evaluate the effectiveness of the learned surrogate utility function $\hat{f}$ in downstream tasks, we employ it as an oracle within a greedy selection framework and compare its performance against greedy selection using the true utility oracle. Specifically, we compute the ratio of the achieved utility to the optimal utility for both the surrogate-based and true-oracle-based greedy selections. This evaluation is conducted over varying ground set sizes. For each size n, we run greedy selection with subset budgets ranging from 1 to $n - 1$ and plot the average performance across these instances in Figure 2e. The results demonstrate that the surrogate function, when used with greedy selection, achieves utility values that are closely aligned with those obtained using the true utility oracle. This highlights the effectiveness of the surrogate model learning the true utility, even when trained on only 50% of subsets.

6.3 Personalized Document Summarization

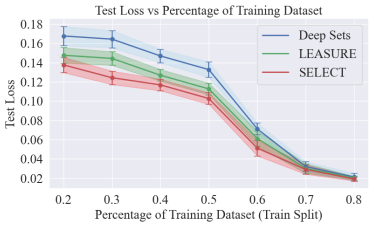
We evaluate our framework on a personalized document summarization task based on the Reuters Corpus Lewis et al. (2004). This can be seen as a contextual subset selection problem, where one has to generate a personalized summary of articles for users based on their topic importance or preference. We apply Latent Dirichlet Allocation (LDA) to the Reuters Corpus with $n_{\text{topic}} = 10$ topics. Here, the elements $x \in \mathcal{V}$ are articles and the context z corresponds to the user's topic preference vector. The utility $f(S, z)$ models the personalized coverage of set S for user z. Each article $x \in \mathcal{X}$ is associated with a topic distribution $P(i|x)$ over topics $i \in \{1, \ldots, n_{\text{topic}}\}$. A *user* is characterized by a *preference vector* $z \in \Delta^{n_{\text{topic}}}$ (a L1 normalized



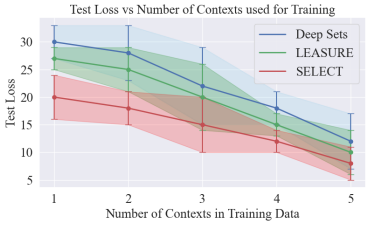
(a) Singular Value Spectrum of Embedding Space



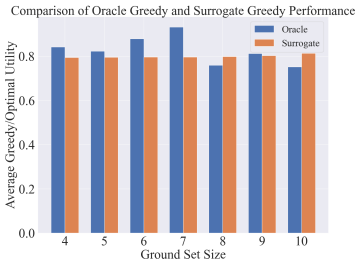
(b) Clustering of Element Embeddings based on Context and Utility



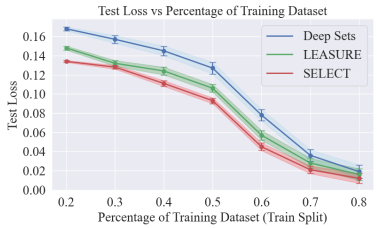
(c) Comparision of SELECT with Deep Sets and LEASURE for Movie Recommendation Task



(d) Comparision of SELECT with Deep Sets and LEASURE for Sensor Utility Prediction



(e) Performance of SELECT in Greedy Sensor Selection



(f) Comparision of SELECT with Deep Sets and LEASURE for Document Summarization Task

Figure 2: Empirical Evaluation of the SELECT Framework

weight vector), representing their affinity to different topics. We define a *contextual utility function* $f(S, z)$ over a set of articles S and user preference z as follows: $f(S, z) = \sum_{i=1}^{n_{\text{topic}}} z_i \left(1 - \prod_{x \in S}(1 - P(i|x))\right)$. This defines a *context-dependent coverage score* quantifying how well the set S covers the user's topical interests, weighted by their preferences. We note that this utility function is monotone submodular Chen et al. (2017). Our framework is trained on multiple such (S, z) pairs and evaluated on held-out users and subsets. Note that we do not aggregate utilities over users in our framework (as in Chen et al. (2017)), as our goal is to generalize to unseen contexts (i.e., new user preference vectors), not just average performance. Similar to our previous experiments, we vary the proportion of training subsets and evaluate the test loss on held-out subsets. Again, we compare the performance of SELECT against Deep Sets and LEASURE, and observe that SELECT consistently achieves lower test loss across varying training set sizes (see Figure 2f).

7 Conclusion

We proposed a framework for learning surrogates for contextual set functions with monotone submodular structure. By combining contrastive learning of element embeddings with submodular regularization on the set-level representations, our approach enables generalization to unseen sets and contexts using limited supervision samples from the true utility oracle. We present a theoretical analysis of convergence for the regularized contrastive learning framework and show that it leads to diverse element embeddings, promoting richer set representations. We show that combining this with the synthetic submodular-norm regularization, which softly enforces structure in the surrogate model, supports efficient greedy optimization. Empirical studies on content recommendation, document summarization, and sensor selection tasks demonstrate that our method generalizes effectively across contexts and outperforms baselines in utility prediction and decision quality. This framework offers a principled and scalable approach for learning surrogate set functions for structured, context-dependent decision-making problems, with limited supervision samples. Future work will focus on extending the framework to support addition of new set elements or contextual variables without requiring complete retraining or expensive fine-tuning.

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A Theoretical Proofs

A.1 Proof of Lemma 1

Proof. We first present the bound for a fixed context z and a corresponding triplet $(x_a, x_p, x_n) \in \mathcal{T}_z$. Let $u_a(\theta_\phi) = \phi_{\theta_\phi}(x_a, z)$, $u_p(\theta_\phi) = \phi_{\theta_\phi}(x_p, z)$, $u_n(\theta_\phi) = \phi_{\theta_\phi}(x_n, z)$. As a shorthand, we drop the dependence on θ_ϕ throughout the proof, e.g., u_a instead of $u_a(\theta_\phi)$. Let the Huberized triplet loss per triplet, per context, be defined as

$$\ell^{\mu}_{\text{triplet}}(\theta_\phi) \;=\; h_\mu\Big(\zeta(\theta_\phi)\Big), \quad \zeta(\theta_\phi) = \cos(u_a, u_n) - \cos(u_a, u_p) + \alpha,$$

where h_μ is as defined in equation 7. From the analysis presented in Xu et al. (2016), we have $h_\mu \in C^1$, $|h'_\mu(\zeta)| \le 1$ for all ζ, and h'_μ is $(1/\mu)$-Lipschitz (i.e., $|h'_\mu(\zeta) - h'_\mu(\zeta')| \le \frac{1}{\mu}|\zeta - \zeta'|$).

The cosine similarity between two unit norm vectors u, v, given by $\cos(u, v) = u^\top v$, is 1-Lipschitz. We have the following bounds for $\cos(\cdot)$.

$$||\cos(u, v) - \cos(u', v')|| \le \|u - u'\| + \|v - v'\|, \|\nabla_u \cos(u, v)\| \le 1, \|\nabla_v \cos(u, v)\| \le 1.$$

These follow from bilinearity and Cauchy–Schwarz inequality. By network regularity (Assumption 2), we have $\|J(\theta_\phi)\| \le K, \|J(\theta_\phi) - J(\theta'_\phi)\| \le \rho\, \|\theta_\phi - \theta'_\phi\|$. By the mean-value theorem, we have $\|\phi_{\theta_\phi}(x, z) - \phi_{\theta'_\phi}(x, z)\| \le K\|\theta_\phi - \theta'_\phi\|$.

Now, we apply the chain rule to evaluate the gradient of the Huberized triplet loss function,

$$\nabla_{\theta_\phi} \ell^{\mu}_{\text{triplet}}(\theta_\phi) = h'_\mu(\zeta(\theta_\phi))\, \nabla_{\theta_\phi} \zeta(\theta_\phi).$$

Applying the network regularity bound on the gradient of ζ, we get

$$\|\nabla_{\theta_\phi} \zeta(\theta_\phi)\| \le \|J(\theta_\phi)\|\, \|u_n - u_p\| + \|J(\theta_\phi)\|\, \|u_a\| + \|J(\theta_\phi)\|\, \|u_a\| \le 4K.$$

Now, we consider the norm-difference of the gradients, given by

$$\|\nabla_{\theta_\phi} \ell^{\mu}_{\text{triplet}}(\theta_\phi) - \nabla_{\theta_\phi} \ell^{\mu}_{\text{triplet}}(\theta'_\phi)\| \le |h'_\mu(\zeta(\theta_\phi)) - h'_\mu(\zeta(\theta'_\phi))|\, \|\nabla\zeta(\theta_\phi)\| + |h'_\mu(\zeta(\theta'_\phi))|\, \|\nabla\zeta(\theta_\phi) - \nabla\zeta(\theta'_\phi)\|.$$

Now we have

$$|\zeta(\theta_\phi) - \zeta(\theta'_\phi)| \le 4K\, \|\theta_\phi - \theta'_\phi\| \quad \Rightarrow \quad |h'_\mu(\zeta(\theta_\phi)) - h'_\mu(\zeta(\theta'_\phi))| \le \frac{4K}{\mu}\, \|\theta_\phi - \theta'_\phi\|.$$

With $\|\nabla\zeta(\theta_\phi)\| \le 4K$, this part contributes $\dfrac{16K^2}{\mu}\|\theta_\phi - \theta'_\phi\|$.

By directly applying term-by-term bounds, we have

$$\|\nabla\zeta(\theta_\phi) - \nabla\zeta(\theta'_\phi)\| \le (4\rho_J + 4K^2)\, \|\theta_\phi - \theta'_\phi\|.$$

Combining the above bounds, we have

$$\|\nabla_{\theta_\phi} \ell^{\mu}(\theta_\phi) - \nabla_{\theta_\phi} \ell^{\mu}(\theta'_\phi)\| \le \Big(\tfrac{16K^2}{\mu} + 4\rho_J + 4K^2\Big)\, \|\theta_\phi - \theta'_\phi\|.$$

Now, we will sum over these bounds for all triplets for a context z in the training data. For $\mathcal{L}^{\mu}_{\text{triplet},z} = \sum_{(x_a, x_p, x_n) \in \mathcal{T}_z} \ell^{\mu}$, the *size* of the gradient across triplets typically accumulates in Frobenius norm because each triplet selects only three rows of the embedding matrix (Petersen et al. (2008))

$$\|\nabla_{\theta_\phi} \mathcal{L}^{\mu}_{\text{triplet},z}(\theta_\phi)\| \;\le\; G^{\phi}_z \quad \text{with} \quad G^{\phi}_z = O\big(\sqrt{|\mathcal{T}_z|}\big).$$

Next, the *Lipschitz constant* across the sum adds the per-triplet constants, giving

$$\|\nabla_{\theta_\phi}\mathcal{L}^{\mu}_{\text{triplet},z}(\theta_\phi) - \nabla_{\theta_\phi}\mathcal{L}^{\mu}_{\text{triplet},z}(\theta'_\phi)\| \;\le\; L^{\phi}_{z}\,\|\theta_\phi - \theta'_\phi\|, \qquad L^{\phi}_{z} = O\Big(\frac{|\mathcal{T}_z|}{\mu}\Big)$$

Combining the above terms, we get

$$\big\|\nabla_{\theta_\phi}\mathcal{L}^{\mu}_{\text{triplet},z}(\theta_\phi) - \nabla_{\theta_\phi}\mathcal{L}^{\mu}_{\text{triplet},z}(\theta'_\phi)\big\| \;\le\; \Big(\rho_J\, G^{\phi}_{z} + K^2 L^{\phi}_{z}\Big)\,\|\theta_\phi - \theta'_\phi\|,$$

with $G^{\phi}_{z} = O(\sqrt{|\mathcal{T}_z|})$ and $L^{\phi}_{z} = O(|\mathcal{T}_z|/\mu)$ as stated above.

Without loss of generality, we replace $|\mathcal{T}_z|$ with $|\bar{\mathcal{T}}_z| = \max_{z\in\mathcal{Z}_{\text{train}}}|\mathcal{T}_z|$. Finally, multiplying by number of contexts in the training data $|\mathcal{Z}_{\text{train}}|$, we obtain the stated bound. □

A.2 Proof of Lemma 2

Proof. In this proof, we use standard results from Matrix Calculus for Positive Definite matrices which can be found in Petersen et al. (2008). We use the following shorthands throughout the proof: $\lambda = \lambda_{\text{indep}}$, $U = U^z(\theta_\phi)$ and $V = U^z(\theta'_\phi)$.

We have $g_z(\theta_\phi) = -\,\lambda_{\text{indep}}\log\det\big(U^z(\theta_\phi)^\top U^z(\theta_\phi) + \varepsilon I\big)$. For $\varepsilon > 0$, we have that $U^z(\theta_\phi)^\top U^z(\theta_\phi) + \varepsilon I \succ 0$, i.e., is Positive Definite. By applying chain rule and standard matrix calculus Petersen et al. (2008), the derivative of this $\log\det$ term is given by

$$\nabla_{\theta_\phi} g_z(\theta_\phi) = J^z(\theta_\phi)^\top\big[-\,2\lambda\, U^z(\theta_\phi)\,(U^z(\theta_\phi)^\top U^z(\theta_\phi) + \varepsilon I)^{-1}\big],$$

where $J^z(\theta_\phi)$ is the Jacobian of $U^z(\theta_\phi)$ w.r.t. θ_ϕ.

For any U, $\|\nabla g(U)\|_F \le \frac{2\lambda}{\varepsilon}\,\|U\|_F$. Now, using $\|U^z(\theta_\phi)\|_F \le \sqrt{r}R$, we obtain $\|\nabla_{\theta_\phi} g_z(\theta_\phi)\| \;\le\; \frac{2\lambda K}{\varepsilon}\sqrt{r}\,R$.

For any $\theta_\phi, \theta'_\phi \in \Theta$, we have

$$\begin{aligned}\|\nabla_{\theta_\phi} g_z(\theta_\phi) - \nabla_{\theta_\phi} g_z(\theta'_\phi)\| \le{}& \|J^z(\theta_\phi) - J^z(\theta'_\phi)\|\,\|\nabla g(U^z(\theta_\phi))\|_F \\ &+ \|J^z(\theta'_\phi)\|\,\|\nabla g(U^z(\theta_\phi)) - \nabla g(U^z(\theta'_\phi))\|_F.\end{aligned}$$

The first term is bounded by

$$\rho_J\|\theta_\phi - \theta'_\phi\| \cdot \frac{2\lambda}{\varepsilon}\sqrt{r}\,R.$$

.

To bound the second term, we use the following standard results directly (see Petersen et al. (2008); Boyd & Vandenberghe (2004)) for $A = U^\top U + \varepsilon I$: $\|A^{-1}\| \le 1/\varepsilon$ and $A^{-1} - B^{-1} = A^{-1}(B - A)B^{-1}$, where $B = V^\top V + \varepsilon I$. Combining the two bounds, we obtain

$$\|\nabla_U g(U) - \nabla_U g(V)\|_F \le \Big(\frac{2\lambda}{\varepsilon} + \frac{4\lambda R^2}{\varepsilon^2}\Big)\,\|U - V\|_F \quad \text{whenever } \|U\|_2, \|V\|_2 \le R.$$

We have $\|U^z(\theta_\phi) - U^z(\theta'_\phi)\|_F \le K\|\theta_\phi - \theta'_\phi\|$. Thus, the second term is bounded by

$$K^2\Big(\tfrac{2\lambda}{\varepsilon} + \tfrac{4\lambda R^2}{\varepsilon^2}\Big)\,\|\theta_\phi - \theta'_\phi\|.$$

Adding both bounds yields the stated Lipschitz constant $L^{\theta_\phi}_{\text{logdet}}$, given by

$$L^{\theta_\phi}_{\text{logdet}} = \frac{2\lambda_{\text{indep}}\rho_J}{\varepsilon}\sqrt{r}\,R \;+\; K^2\left(\frac{2\lambda_{\text{indep}}}{\varepsilon} + \frac{4\lambda_{\text{indep}}R^2}{\varepsilon^2}\right), \quad r = \min\{n, d\}.$$

□

A.3 Proof of Lemma 3

Proof. This follows directly by applying triangle inequality and then combining the bounds from Lemma 1 and Lemma 2. □

A.4 Proof of Lemma 4

Proof. (a) In this drift bound, we evaluate the maximum difference between the loss functions under the same network parameters θ_ϕ, but between two time steps t and $t+1$. The first terms remains unchanged since it only depends on the network parameters. It now remains to analyze the difference in the second term. Let $A_z = U^{z\top}U^z \succeq 0$ and define $h_z(\varepsilon) = -\log\det(A_z + \varepsilon I)$. By the mean value theorem,

$$|h_z(\varepsilon_{t+1}) - h_z(\varepsilon_t)| = |h_z'(\varepsilon')|\,|\varepsilon_{t+1} - \varepsilon_t|$$

for some ε' between ε_t and ε_{t+1}. Since $h_z'(\varepsilon) = -\mathrm{tr}((A_z + \varepsilon I)^{-1}) \leq r_z/\varepsilon$, we obtain

$$|h_z(\varepsilon_{t+1}) - h_z(\varepsilon_t)| \leq \frac{r}{\min\{\varepsilon_{t+1}, \varepsilon_t\}}\,|\varepsilon_{t+1} - \varepsilon_t|,$$

where $r = \min(n, d)$. Averaging over z and multiplying by λ_{indep}, we obtain the stated bound.

Note: For the schedule $\varepsilon_t = \varepsilon_0(t+\kappa)^{-\beta}$, $|\varepsilon_{t+1} - \varepsilon_t| = \mathcal{O}((t+\kappa)^{-\beta-1})$ and $\min\{\varepsilon_{t+1}, \varepsilon_t\} = \Theta((t+\kappa)^{-\beta})$, so the bound is $\mathcal{O}(1/(t+\kappa)^\beta)$.

(b) The first term, i.e., the Huberized triplet loss, is nonnegative (≥ 0). We only need to examine the regularization term to establish a lower bound.

$$\mathcal{L}_{t,\theta_\phi} \;\geq\; \lambda_{\text{indep}} \frac{1}{|\mathcal{Z}_{\text{train}}|} \sum_z -\log\det(U^{z\top}U^z + \varepsilon_t I).$$

Since $\|U^z\|_2 \leq R$, we have $U^{z\top}U^z \preceq R^2 I$. Thus

$$-\log\det(U^{z\top}U^z + \varepsilon_t I) \geq -r\log(R^2 + \varepsilon_t) \geq -r\log(R^2).$$

Averaging over z, we obtained the stated finite lower bound. □

A.5 Proof of Theorem 1

Proof. The proof is based on a standard argument using the *Descent Lemma* for α_t-smooth functions. We first establish a one–step decrease inequality for the time-varying loss, then control the drift induced by the changing ε_t using the learning rate η_t, and finally apply a telescoping sum argument. Comparing the growth rates of the descent and drift terms leads to the conclusion that the projected gradient descent iterates converge to a stationary point.

We denote $\mathcal{L}_{t,\theta_{\phi,t}}$ by $\mathcal{L}_t(\theta_{\phi,t})$. The *Descent Lemma* for α_t-smooth functions with learning rate η_t is given by

$$\mathcal{L}_t(\theta_{\phi,t+1}) \;\leq\; \mathcal{L}_t(\theta_{\phi,t}) - \eta_t\left(1 - \frac{\eta_t\alpha_t}{2}\right)\|\nabla\mathcal{L}_t(\theta_{\phi,t})\|^2.$$

By applying the *Projected Gradient Descent* update as in equation 16 with learning rate $\eta_t = \gamma/\alpha_t$,

$$\mathcal{L}_t(\theta_{\phi,t+1}) \;\leq\; \mathcal{L}_t(\theta_{\phi,t}) - \frac{c_\gamma}{\alpha_t}\|\nabla\mathcal{L}_t(\theta_{\phi,t})\|^2,$$

where $c_\gamma = \gamma(1 - \gamma/2) > 0$.

From Lemma 4, we have

$$\mathcal{L}_{t+1}(\theta_{\phi,t+1}) \;\leq\; \mathcal{L}_t(\theta_{\phi,t+1}) + \frac{C}{t+\kappa},$$

where $C > 0$ is some universal constant. Combining this, we get

$$\mathcal{L}_{t+1}(\theta_{\phi,t+1}) \;\le\; \mathcal{L}_t(\theta_{\phi,t}) - \frac{c_\gamma}{\alpha_t}\|\nabla\mathcal{L}_t(\theta_{\phi,t})\|^2 + \frac{C}{t+\kappa}.$$

Summing from $t = 0$ to $T-1$ and using $\mathcal{L}_t \ge L_{\min}$ (where $L_{\min}$ is the lower-bound which characterized in Lemma 4 (b)),

$$c_\gamma \sum_{t=0}^{T-1} \frac{1}{\alpha_t}\|\nabla\mathcal{L}_t(\theta_{\phi,t})\|^2 \;\le\; \mathcal{L}_0(\theta_{\phi,0}) - L_{\min} + C\log(T+\kappa). \tag{23}$$

With $\varepsilon_t = \varepsilon_0(t+\kappa)^{-\beta}$, we have $\alpha_t = \Theta((t+\kappa)^{2\beta})$. Therefore

$$\sum_{t=0}^{T-1} \frac{1}{\alpha_t} = \mathcal{O}(T+\kappa)^{1-2\beta}.$$

For $0 < \beta < \frac{1}{2}$, this grows polynomially in T, much faster than the $\log(T)$ growth on the right-hand side of equation 23. Now suppose, for contradiction, that there exists $\epsilon > 0$ such that $\|\nabla\mathcal{L}_t(\theta_{\phi,t})\| \ge \epsilon$ for infinitely many t. Then the left-hand side of equation 23 would be bounded below by $c_\gamma\epsilon^2 \sum_{t\in I,\, t<T} \frac{1}{\alpha_t}$, where I is the infinite set of indices where the gradient is large. This sum diverges at rate $(T+\kappa)^{1-2\beta}$, contradicting the logarithmic growth on the right-hand side. This means that the gradients cannot remain bounded away from zero infinitely.

In other words, the choice of learning rate η_t and ε_t schedule is such that it balances the growth of α_t in a way that ensures that the asymptotic sum of gradients remains finite.

As a result, we have

$$\lim_{t\to\infty} \|\nabla\mathcal{L}_t(\theta_{\phi,t})\| = 0,$$

which proves convergence to stationary points, asymptotically. □

A.6 Proof of Corollary 1

Proof. By Theorem 1, the projected gradient descent iterates satisfy $\lim_{t\to\infty}\|\nabla\mathcal{L}_t(\theta_{\phi,t})\| \to 0$, so there exists a limit point $\theta_\infty \in \Theta$. Fix $z \in \mathcal{Z}_{\text{train}}$ and let $A^z(\theta) = U^z(\theta)^\top U^z(\theta) \succeq 0$ with eigenvalues $\{\lambda_i^z(\theta)\}_{i=1}^d$. Then the independence term is

$$-\log\det\big(A^z(\theta) + \varepsilon_t I\big) \;=\; -\sum_{i=1}^{d} \log\big(\lambda_i^z(\theta) + \varepsilon_t\big).$$

Its gradient with respect to U^z is $\nabla_{U^z}\big(-\log\det(A^z + \varepsilon_t I)\big) \;=\; -2\,U^z(\theta)\,(A^z(\theta) + \varepsilon_t I)^{-1}$, whose operator norm scales like $\max_i 1/(\lambda_i^z(\theta) + \varepsilon_t)$.

By Theorem 1, we have $\theta_{\phi,t} \to \theta_\infty$ and $\|\nabla\mathcal{L}_t(\theta_{\phi,t})\| \to 0$ while $\varepsilon_t \to 0$. If, for contradiction, some $\lambda_i^z(\theta_\infty) = 0$, then by continuity $\lambda_i^z(\theta_{\phi,t}) + \varepsilon_t \to 0$, which makes $\|(A^z(\theta_{\phi,t}) + \varepsilon_t I)^{-1}\| \to \infty$ and forces the gradient contribution from the log-det term to blow up, contradicting $\|\nabla\mathcal{L}_t(\theta_{\phi,t})\| \to 0$. Hence, for all i, $\lambda_i^z(\theta_\infty) > 0$. As a result, we have $U^z(\theta_\infty)$ is full rank for all $z \in \mathcal{Z}_{\text{train}}$.

Full rank of $U^z(\theta_\infty)$ when $d \ge n$ implies linear independence of the embedding vectors $\{\phi_{\theta_\infty}(x,z)\}$; therefore the set-sum map $S \mapsto \sum_{x\in S}\phi_{\theta_\infty}(x,z)$ is injective, i.e., for $X \ne Y$ one has $\sum_{x\in X}\phi_{\theta_\infty}(x,z) \ne \sum_{y\in Y}\phi_{\theta_\infty}(y,z)$. □

B Additional Experimental Details

B.1 Experimental Setup for MovieLens Recommendation Task

In this section, we provide experimental evaluation details for the content recommendation task using the MovieLens 1M dataset Harper & Konstan (2015) as a benchmark.

B.1.1 Data Extraction and Preprocessing

The dataset contains user-movie ratings along with user demographic metadata and movie genres.

User Feature Extraction (z): Each user is represented by a contextual vector $z \in \mathbb{R}^4$, constructed as follows:

- **Age**: Integer bucket encoded as one of {1, 18, 25, 35, 45, 50, 56}
- **Gender**: Binary value $\in \{0, 1\}$
- **Occupation**: Integer value between 0–20 (21 unique values)
- **Zip code**: First digit (regional code), converted to integer $\in \{0, \ldots, 9\}$

We sample a subset of 10 users uniformly at random to form the context set $\mathcal{Z}$.

Movie Feature Extraction (x): Each movie is represented by a binary genre vector $x \in \{0, 1\}^{19}$, indicating whether the movie belongs to each of the 19 possible genres in the dataset. We uniformly sample 50 movies from the dataset to serve as the ground set $\mathcal{V}$.

Utility Label Generation ($f(X, z)$): Given a user z and a subset of movies $X \subseteq \mathcal{V}$, the utility is computed as:

$$f(X, z) = \max_{x \in X} \frac{\text{rating}(x, z)}{5},$$

where $\text{rating}(x, z)$ denotes the user's rating for movie x, if available. Ratings are normalized by 5 to lie in $[0, 1]$. Sets with no known ratings are excluded from training.

Triplet Generation: For contrastive embedding training, we construct triplets (x_a, x_p, x_n) for each user z such that:

- x_a is a movie rated above threshold (> 3.5)
- x_p is another movie rated similarly high by the same user (≥ 2.5)
- x_n is a movie rated significantly lower (< 2.5)

These triplets are used to train the embedding network via triplet loss and independence regularization.

Set Utility Dataset: We generate utility values for 1000 subsets X of size 2 to 5 for each user context z, using their actual ratings, to train the surrogate submodular model.

B.1.2 Network Architectures and Hyperparameters

Training Details: The contrastive embedding model is trained first using triplet and independence losses. The resulting embeddings are frozen and fed into the submodular surrogate model, which is trained to minimize MSE along with regularizers enforcing submodularity and monotonicity. The training and evaluation pipeline is repeated across varying train/test splits (e.g., 70/30, 80/20).

Table 1: Hyperparameters and Network Architecture for Contrastive Learning of Embeddings (ϕ)

Component	**Details**
Embedding Model Architecture	
Input Dimension	23 (19 movie genres + 4 user metadata)
Intermediate Layers	Dense(32)
Output Dimension	$d = 8$ (softplus activation)
Embedding Split	$k = 6$ (utility), $d - k = 2$ (independence)
Training Hyperparameters	
Learning Rate	10^{-4}
Batch Size	32
Number of Epochs	50
Triplet Margin	$\delta_{\text{margin}} = 0.1$
Independence Loss Weight	$\lambda_{\text{indep}} = 0.5$
Optimizer	Adam Optimizer

Table 2: Hyperparameters and Network Architecture for Surrogate Set Function (ρ)

Component	**Details**
Set Function Model Architecture	
Input Dimension	Embedding Size = 8
Hidden Layers	Dense(128, activation=ReLU), Dense(64)
Output Layer	Dense(1, activation=sigmoid)
Training Hyperparameters	
Learning Rate	Initial 10^{-3}, Exponential Decay
Decay Steps	10
Decay Rate	0.2
Number of Epochs	50
Loss Weights	$\lambda_{\text{mono}} = 0.1$, $\lambda_{\text{sub}} = 0.5$
Optimizer	Adam Optimizer with Learning Rate Schedule

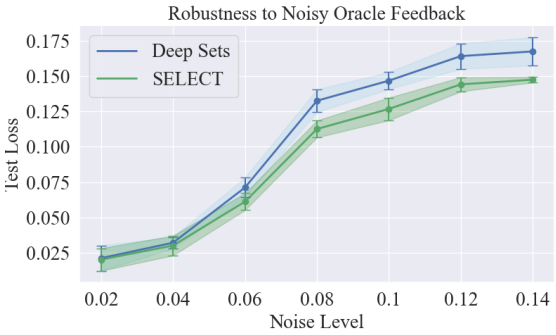
B.1.3 Additional Experiments

We evaluate our framework for its robustness to noisy oracle feedback, its performance on downstream re-optimization tasks, and present runtime comparisons with respect to baselines. We perform the following experiments on the MovieLens dataset.

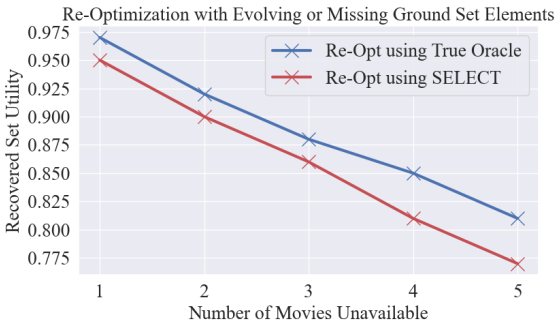
Robustness to Noisy Feedback. To assess the robustness of our framework against noisy feedback, we inject Gaussian noise $\mathcal{N}(0, \sigma^2)$ into the utility oracle f and evaluate its impact on test performance. We compare Select with the Deep Sets framework by varying σ incrementally from 0.02 to 0.14 in steps of 0.02. For each noise level, we perform a 70/30 train-test split and measure the test loss over the evaluation dataset.

We plot the test loss vs. noise level in Figure 3a. It clearly demonstrates that Select consistently achieves lower test loss across all noise levels compared to Deep Sets. This highlights the effectiveness of our method in maintaining robust generalization performance even under perturbations in the training data.

Re-optimization under Shifts. To test the robustness of our learned item embeddings, we simulate partial failure/unavailability scenarios during movie recommendation. We start by selecting 8 movies from a



(a) Evaluation of SELECT under Noisy Oracle



(b) Comparision of SELECT for

Figure 3: Evaluation of SELECT for Robustness against Noise and Failures

pool of 15 using a greedy algorithm guided by the true oracle. Then, we remove up to 6 highly rated movies from this set.

To recover from these unavailable movies which were selected for recommendation, we compare two strategies:

- **Oracle Re-optimization**, where we re-run the greedy algorithm with the true oracle to pick replacements, and
- **Embedding-based Recovery**, where we replace unavailable movies by selecting the most similar ones (as measured by cosine similarity of their embeddings) using our learned embeddings, without retraining or querying the oracle.

We measure how much utility each recovered set retains compared to the re-optimization using the true oracle. By varying number of unavailable movies, we find that the embedding-based approach preserves a high fraction of the utility and performs close to the oracle re-optimization. This shows that our model supports fast, effective recovery using embedding similarity alone, without having to perform expensive re-optimization from scratch.

Runtime Comparison. We report a runtime comparison based on the time required for the training loss to reach a threshold of 0.1 (see Table 3). This provides a consistent criterion for assessing the convergence speed across models.

Table 3: Runtime comparison of SELECT with Deep Sets and LEASURE

Model	**Time to reach training loss ≤ 0.1 (in min)**
Deep Sets	5.5 ± 0.3
SELECT	6.1 ± 0.1
LEASURE	7.2 ± 0.2

As shown in Table 3, SELECT requires slightly more time to converge compared to Deep Sets, which we attribute to the additional log-determinant regularization. However, this slower convergence comes with the advantage of consistently achieving lower validation losses, highlighting a trade-off between computation time and generalization performance.

B.2 Estimating Sensor Utilities in Urban Environments

In this section, we describe the experimental setup for evaluating our framework for a sensor utility prediction and subset selection task in urban environments using data from a high-fidelity photorealistic simulator.

B.2.1 Simulator Overview

We utilize SYGARD (Synthetic Data Generator for Automatic Target Recognition, Identification, and Detection), a high-fidelity simulation platform developed in Unreal Engine 5, designed to support large-scale image data generation for training and evaluating object detection algorithms. SYGARD integrates the Colosseum API (AirSim) for UAV flight control and Cesium for real-world terrain reconstruction, enabling the simulation of various UAV scenarios within photorealistic urban and rural environments. The platform outputs synchronized RGB imagery, object masks, and ground truth metadata (including location, orientation, and object class) from the camera at configurable frame rates, poses, and image resolutions. The system provides fine-grained control over environmental variables, allowing users to configure weather and lighting conditions to simulate diverse sensing scenarios. This includes the ability to introduce sensor noise effects such as rain, fog, and dust, enabling the generation of data under both ideal and degraded visibility conditions.

This flexible architecture allows researchers to simulate a wide range of operational contexts and generate varied datasets tailored to recognition, detection, and tracking tasks. By automating data collection workflows and standardizing annotation outputs, SYGARD provides a practical tool for generating controlled, high-diversity datasets to support aerial perception research.

B.2.2 Data Generation and Detection Evaluation

To begin the data generation, we discretize the area of interest into a uniform grid and generate a set of UAV waypoints that collectively span the full region. These waypoints are used to define the UAV's trajectory, ensuring systematic coverage of the urban environment. Once the trajectory is set, fixed ground-based cameras are configured by specifying their field of view, resolution, and pose. Environmental and lighting conditions are then applied using the parameterized weather control system.

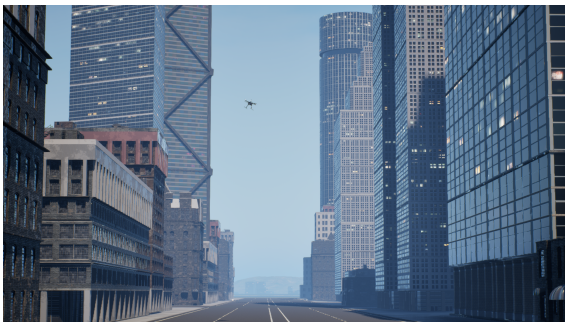
During simulation, data is captured at each waypoint the UAV reaches. For every frame, the system records RGB images from each camera, along with the corresponding ground truth metadata, including object class, location, and orientation.

After simulation, the collected metadata is postprocessed to generate bounding box annotations in YOLO format. We then run inference using the *YOLOv11m* model, which was pre-trained on the dataset provided by *Real World Object Detection Dataset for Quadcopter Unmanned Aerial Vehicle Detection*. The model's predictions are compared against the ground truth annotations to assess detection performance.

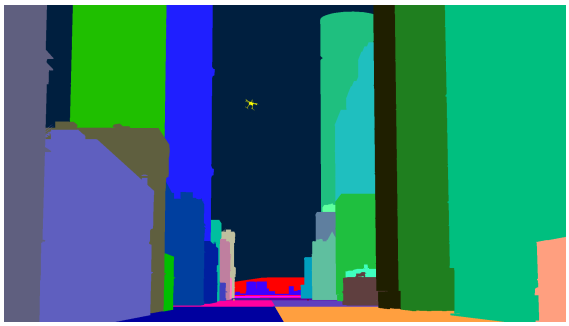
To visualize and analyze detection outcomes, we map the correctly predicted bounding box centers to spatial coordinates within the scene. This enables evaluation of how well the protected airspace was covered under the given camera and environment configuration. Figure 4 shows the full pipeline from data capture to detection mapping.

B.2.3 Urban Environment Details

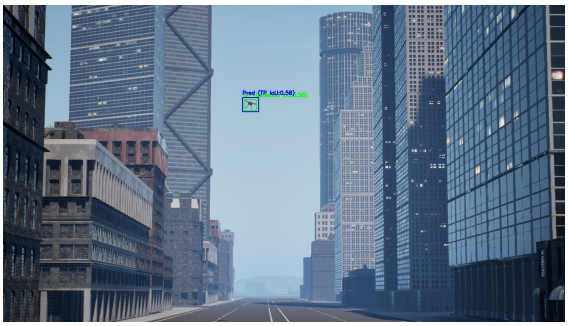
For the experimental setting, we used an urban environment constructed with a third-party plugin — *Brushify Urban Buildings Pack* — in Unreal Engine. This environment includes modular street layouts, 3D building assets, and infrastructure commonly found in cityscapes, enabling realistic simulation of urban aerial monitoring scenarios. We focus on two orthogonal streets forming a cross-shaped intersection. Each street spans approximately 650 meters in length and 53 meters in width, covering a combined area of roughly $66{,}332\,\mathrm{m}^2$, including the overlapping intersection. This configuration is used to study UAV coverage and visibility from fixed ground-based cameras deployed for drone surveillance and detection in urban environments. It provides a testbed for evaluating perception models under realistic occlusions caused by buildings and street geometry.



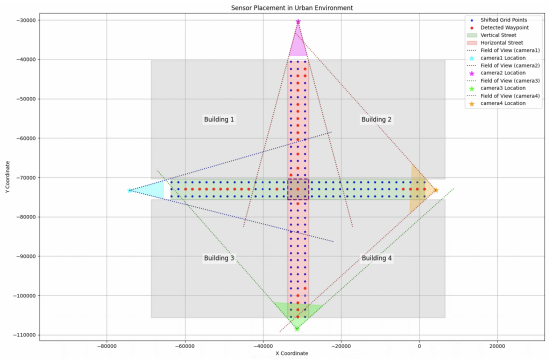
(a) RGB image



(b) Ground truth - object mask



(c) Prediction



(d) Detection map

Figure 4: Detection pipeline visualization: (a) RGB image captured during simulation, (b) generated ground truth object mask used for automatic labeling, (c) prediction from YOLOv11m, and (d) spatial map of correctly detected UAV locations.

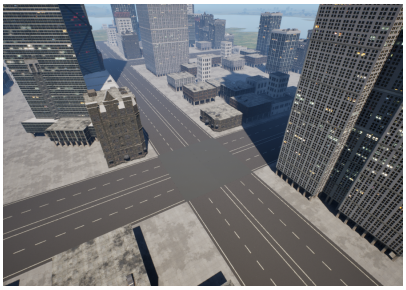


Figure 5: A top-down view of the simulated urban city environment used in our experiments, constructed using the *Brushify Urban Buildings Pack* in Unreal Engine. The environment includes modular streets and building assets suitable for simulating UAV detection scenarios.

B.2.4 Camera Configuration and Coverage Strategy

Four synchronized camera sensors are deployed to maximize coverage of the intersection area:

- **Long-range cameras** (30° field of view), positioned at opposite corners of the intersection to provide high-resolution distant views.
- **Short-range (wide-angle) cameras** (90° field of view), mounted closer to the center of the intersection for broad coverage and minimal blind spots.

The cameras capture full-HD (1920×1080) or QHD (2560×1440) imagery, with mounting positions and orientations manually specified in the simulation configuration. To evaluate the impact of sensor layout on detection performance, we permute the camera placements across trials—interchanging long-range and short-range sensor positions to produce alternate coverage configurations.

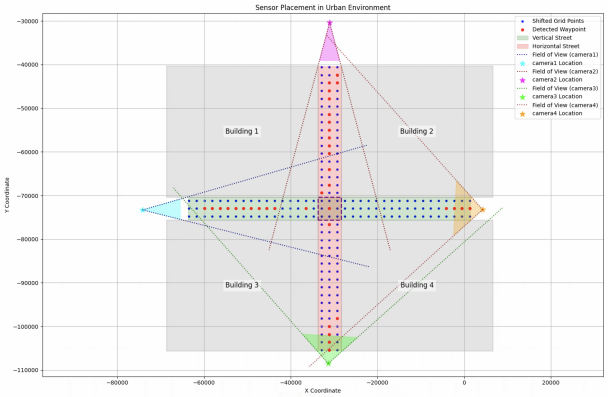


Figure 6: Camera placement and field of view (FOV) visualization over the simulated intersection area. Cameras are positioned at fixed ground-level locations around the cross-shaped intersection, with each frustum representing the approximate coverage area used for drone detection. This configuration simulates an urban surveillance setup for aerial threat monitoring.

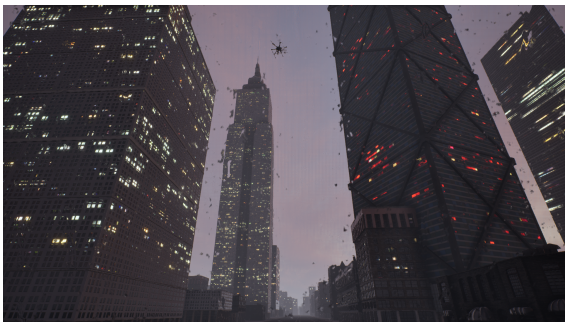
B.2.5 Environmental and Weather Control

To simulate varying visibility, occlusion, and sensor noise conditions, we configured the environment's weather and lighting settings through a structured JSON file. These parameters affect environmental factors such as fog density, cloud coverage, and material wetness, enabling realistic degradation in visual input. This is crucial for evaluating the robustness of aerial perception models under non-ideal conditions, such as limited visibility or lens obstruction.

The key parameters controlling the scene conditions include:

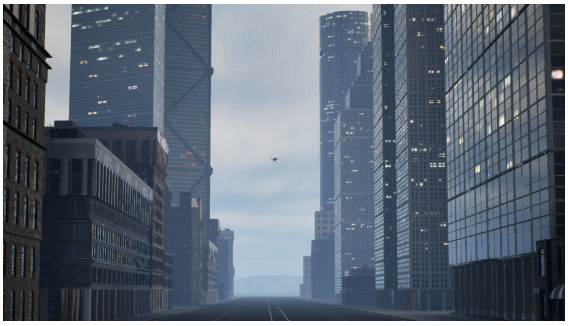
- **Time of day**: Determines sun position and lighting angle, affecting shadows, brightness, and ambient illumination.
- **Cloud coverage**: Controls the density of cloud layers, influencing overall light diffusion and scene contrast.
- **Rain**: Simulates precipitation and visual distortion due to water droplets on the camera lens.
- **Fog**: Introduces atmospheric occlusion, reducing scene visibility and simulating low-contrast environments.

These parameters are parsed and applied at runtime, allowing fine-grained control over environmental conditions in each data capture session. Figure 7 shows a representative sample of scenes under different configurations, illustrating the variability introduced by our weather simulation.



(a) Heavy rain

(b) Fog



(c) Cloudy

(d) Dust

Figure 7: Example views of the simulated environment under different weather conditions captured from different camera sensors. Each condition introduces unique visibility and sensor challenges for aerial perception.

The complete dataset contains camera specifications with location encoded in x, environment conditions in z and the number of way-points covered (in red) as measured by drone detections for each x, z pair, which is the utility value $f(x, z)$. Additionally, we also have access to utility values for set-context pairs $f(X, z)$, which will be used to train the surrogate network.

B.2.6 Training

We train the embedding network $\phi(x, z)$ using singleton utilities $f(x, z)$ obtained from the oracle using contrastive loss with log-determinant regularization, and the surrogate ρ using mean squared error on $\mathcal{D}_{\text{real}}$ and submodularity + monotonicity regularization on $\mathcal{D}_{\text{synth}}$. Both networks are optimized using Adam with learning rate scheduling and early stopping.

B.3 Experimental Details for Personalized Document Summarization

In this section, we describe the experimental setup for evaluating our framework on a personalized document summarization task based on the Reuters Corpus Lewis et al. (2004). This task is formulated as a contextual subset selection problem, where the goal is to select a set of articles that best summarizes user-specific topical preferences.

B.3.1 Data Extraction and Preprocessing

The Reuters Corpus consists of newswire articles annotated with multiple topics. We preprocess the dataset using Latent Dirichlet Allocation (LDA) with $n_{\text{topic}} = 10$ topics. Each article $x \in \mathcal{X}$ is then represented by a topic distribution vector

$$P(i|x), \qquad i \in \{1, \ldots, n_{\text{topic}}\},$$

where $P(i|x)$ denotes the probability that article x is associated with topic i.

Table 4: Hyperparameters and Network Architecture for Contrastive Learning of Embeddings (ϕ)

Component	**Details**
Embedding Model Architecture	
Input Dimension	12 (8 sensor features + 4 environmental factors)
Intermediate Layers	Dense(64, activation=ReLU)
Output Dimension	$d = 8$ (softplus activation)
Embedding Split	$k = 6$ (utility), $d - k = 2$ (independence)
Training Hyperparameters	
Learning Rate	10^{-3}
Batch Size	32
Number of Epochs	30
Triplet Margin	$\delta_{\text{margin}} = 0.1$
Independence Loss Weight	$\lambda_{\text{indep}} = 1$
Optimizer	Adam Optimizer

Table 5: Hyperparameters and Network Architecture for Surrogate Set Function (ρ)

Component	**Details**
Set Function Model Architecture	
Input Dimension	Embedding Size = 8
Hidden Layers	Dense(256, activation=ReLU), Dense(128, activation=ReLU)
Output Layer	Dense(1, activation=sigmoid)
Training Hyperparameters	
Learning Rate	Initial 10^{-4}, Exponential Decay
Decay Steps	10
Decay Rate	0.2
Number of Epochs	30
Loss Weights	$\lambda_{\text{mono}} = 0.1$, $\lambda_{\text{sub}} = 0.1$
Optimizer	Adam Optimizer with Learning Rate Schedule

User Feature Extraction (z): A user is represented by a topic preference vector $z \in \Delta^{n_{\text{topic}}}$, i.e., a probability simplex over topics. This vector models the user's affinity towards different topics. We sample 10 points on this simplex uniformly at random to form the context set (i.e., set of users) $\mathcal{Z}$.

Article Feature Extraction (x): Each article is represented by its 10-dimensional topic distribution $P(\cdot|x) \in [0, 1]^{10}$ obtained from LDA. We randomly sample 200 articles from the corpus to form the ground set $\mathcal{V}$.

Utility Label Generation ($f(S, z)$): For a user z and subset of articles $S \subseteq \mathcal{V}$, the personalized coverage utility is defined as

$$f(S, z) = \sum_{i=1}^{n_{\text{topic}}} z_i \left(1 - \prod_{x \in S} (1 - P(i|x))\right).$$

This is a monotone submodular function measuring how well S covers the user's topical preferences.

Triplet Generation: For training the embedding network, we construct triplets (x_a, x_p, x_n) relative to a user z:

- x_a: an article aligned with one of the user's top-3 preferred topics,
- x_p: an article aligned with one of the user's top-5 preferred topics,
- x_n: an article aligned with one of the user's least 2 preferred topics.

Set Utility Dataset: For each user z, we generate 1000 subsets S with size 3–7, and compute utilities $f(S, z)$. These serve as training and evaluation data for the surrogate set function model.

B.3.2 Network Architectures and Hyperparameters

Table 6: Hyperparameters and Network Architecture for Contrastive Learning of Embeddings (ϕ)

Component	**Details**
Embedding Model Architecture	
Input Dimension	20 (10 topics + 10 user preference weights)
Intermediate Layers	Dense(64, activation=ReLU)
Output Dimension	$d = 8$ (softplus activation)
Embedding Split	$k = 6$ (utility), $d - k = 2$ (independence)
Training Hyperparameters	
Learning Rate	10^{-3}
Batch Size	32
Number of Epochs	50
Triplet Margin	$\delta_{\text{margin}} = 0.1$
Independence Loss Weight	$\lambda_{\text{indep}} = 1$
Optimizer	Adam Optimizer

Table 7: Hyperparameters and Network Architecture for Surrogate Set Function (ρ)

Component	**Details**
Set Function Model Architecture	
Input Dimension	Embedding Size = 8
Hidden Layers	Dense(128, activation=ReLU), Dense(64, activation=ReLU)
Output Layer	Dense(1, activation=sigmoid)
Training Hyperparameters	
Learning Rate	Initial 10^{-5}, Exponential Decay
Decay Steps	10
Decay Rate	0.2
Number of Epochs	50
Loss Weights	$\lambda_{\text{mono}} = 0.5$, $\lambda_{\text{sub}} = 0.5$
Optimizer	Adam Optimizer with Learning Rate Schedule

Training Details: The embedding network is first trained with the triplet and independence losses. The learned embeddings are then frozen and provided to the surrogate set function model, which is trained to minimize MSE loss with additional regularizers enforcing submodularity and monotonicity. Experiments are repeated with varying train/test splits (70/30, 80/20), and we report generalization performance compared against DeepSets and LeaSuRe. Our framework consistently yields lower test loss across different training sizes.