Worst-Case Adaptive Submodular Cover

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ABSTRACT
In this paper, we study the adaptive submodular cover problem under the worst-case setting. This problem generalizes many previously studied problems, namely, the pool-based active learning and the stochastic submodular set cover. The input of our problem is a set of items (e.g., medical tests) and each item has a random state (e.g., the outcome of a medical test), whose realization is initially unknown. One must select an item at a fixed cost in order to observe its realization. There is a utility function which maps a subset of items and their states to a non-negative real number. We aim to sequentially select a group of items to achieve a “target value” while minimizing the maximum cost across realizations (a.k.a. worst-case cost). To facilitate our study, we assume that the utility function is worst-case submodular, a property that is commonly found in many machine learning applications. With this assumption, we develop a tight \((\log(Q/\eta) + 1)\)-approximation policy, where \(Q\) is the “target value” and \(\eta\) is the smallest difference between \(Q\) and any achievable utility value \(\tilde{Q} < Q\). We also study a worst-case maximum-coverage problem, a dual problem of the minimum-cost-cover problem, whose goal is to select a group of items to maximize its worst-case utility subject to a budget constraint. To solve this problem, we develop a \((1 - 1/e)/2\)-approximation solution.

KEYWORDS
Adaptive submodular maximization; Worst-case analysis; Approximation algorithms

ACM Reference Format:
Jing Yuan and Shaojie Tang. 2023. Worst-Case Adaptive Submodular Cover. In Proc. of the 22nd International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2023), London, United Kingdom, May 29 – June 2, 2023, IFAAMAS, 8 pages.

1 INTRODUCTION
In this paper, we study a fundamental problem of minimum cost adaptive submodular cover under the worst-case setting. The problem can be formulated as follows: Given a set of items, each item has a state whose value is random and unknown initially, one must select an item at a fixed cost before observing its realized state. In addition, there is a utility function that depends on both the set of selected items and their realized states. Our goal is to sequentially select a group of items based on feedback, in the form of the realized states of the selected items, to achieve a threshold function value at the minimum worst-case cost. Here the worst-case cost of a solution (a.k.a. policy) refers to the maximum incurred cost across realizations. This formulation captures many real-world applications, namely, active learning, viral marketing and sensor placement [4]. As a motivating example, consider the application of medical diagnosis. Here each item represents a medical test and the state of an item refers to the outcome from corresponding medical test. Clearly, we can not observe the outcome of a test before performing that test. We define the utility function, in terms of a set of performed tests and their outcomes, as the number of false hypotheses (e.g., diseases) ruled out by these tests. Suppose each test has a fixed cost, we aim to perform a sequence of tests (based on the outcomes from past tests) to eliminate all false hypotheses at the minimum worst-case cost.

The minimum-cost adaptive submodular cover problem has received significant attention in the literature, however, most of the existing studies focus on minimizing the expected cost of a policy [3, 4]. In particular, they often assume that there is a known prior distribution over realizations, hence, they aim to find a policy that achieves a threshold function value while minimizing the expected cost with respect to this distribution. In contrast, we focus on minimizing the worst-case cost of a policy, this is because in many real-world applications, it is often difficult or impossible to get an accurate prediction of how likely certain outcomes are. Moreover, in many time-critical diagnostic applications, such as emergency response, one must rapidly identify a cause through a series of queries. In these applications, violation of a cost-constraint (such as time-constraint) may lead to fatal consequences; therefore, it is preferable to have a policy that has a small worst-case cost.

To solve this problem, we first introduce the concept of worst-case submodularity [11], extending the classic notion of submodularity from sets to policies. We say a function is worst-case submodular if its worst-case marginal utility of an item satisfies the diminishing returns property (Definition 2.1). This property is prevalent across a diverse range of applications such as the pool-based active learning and the stochastic submodular set cover. Our main contribution is to develop a best possible \((\log(Q/\eta) + 1)\)-approximation policy for the worst-case adaptive submodular cover problem, where \(Q\) is the “target value” and \(\eta\) is the smallest difference between \(Q\) and any achievable utility value \(\tilde{Q} < Q\). In addition, we study a worst-case maximum-coverage problem, whose goal is to sequentially select a group of items to maximize its worst-case utility subject to a budget constraint. We develop a \((1 - 1/e)/2\)-approximation solution for this problem.

Additional related works. There is some work on minimizing the worst-case cost in active learning; see e.g., [1, 8]. Our results can be viewed as a generalization of their results because we can show that the utility function of pool-based active learning (or optimal decision tree design in general) is worst-case submodular. Recently, [4] introduced the concept of adaptive submodularity. Similar to our notion of worst-case submodularity, adaptive submodularity is another way of extending submodularity from sets to policies.
However, their property depends on the prior distribution of realizations, whereas there is no such dependence in defining worst-case submodularity. More importantly, our proposed notation allows for better approximation bounds in many real-world applications. In particular, [4] developed a $(1 + \log Q)$-approximation policy for the minimum-cost coverage problem under the worst-case setting if the utility function is adaptive submodular, where $p_{\text{min}}$ is the minimum probability of any realization. In contrast, our policy achieves the $(1 + \log(Q/\eta))$-approximation bound; $1/p_{\text{min}}$ can be exponentially larger than $Q$. It is also worth noting that one must know the prior distribution over realizations in order to implement [4]'s policy whereas ours does not need such information. Finally, [5, 6] studied the simultaneous learning and covering problem, whereas there is no such dependence in defining worst-case submodularity. More importantly, our proposed notation allows for better approximation bounds in many real-world applications.

There is a utility function $f : 2^E \times O^E \rightarrow \mathbb{R}_{\geq 0}$ which maps a subset of items and their states to a non-negative real number. Let $E(\pi, \phi)$ denote the subset of items selected by the policy $\pi$ under the realization $\phi$. Let $U^*$ denote the set of all realizations that have a positive probability of occurring. The worst-case utility, $f_{\text{wc}}(\pi)$, of a policy $\pi$ is defined as the minimum utility that can be achieved by $\pi$ over all possible realizations, it can be written as

$$f_{\text{wc}}(\pi) = \min_{\phi \in U^*} f(E(\pi, \phi), \phi).$$

For ease of presentation, we extend the definition of $f$ by letting $f(\psi) = \mathbb{E}_\phi[f(\text{dom}(\psi), \phi)] \mid \Phi \sim \psi]$ denote the expected utility of $\text{dom}(\psi)$ conditioned on the partial realization $\psi$. We now present the concept of worst-case marginal utility $\Delta_{\text{wc}}(e \mid \psi)$ of item $e$ when added to a partial realization $\psi$. Let $p(\phi \mid \psi) = \mathbb{P}\{\Phi = \phi \mid \Phi \sim \psi\}$ denote the conditional distribution over realizations conditioned on a partial realization $\psi$. Define

$$\Delta_{\text{wc}}(e \mid \psi) = \min_{o \in O(e, \psi)} \{f(\psi \cup \{(e, o)\}) - f(\psi),$$

where $O(e, \psi) = \{o \in O \mid \exists \phi : p(\phi \mid \psi) > 0, \phi(e) = o\}$ denotes the set of possible states that $e$ can take on, given the partial realization $\psi$.

Now we are ready to introduce the notations of worst-case submodularity and worst-case monotonicity [11].

Definition 2.1. [Worst-case Submodularity and Worst-case Monotonicity] A function $f$ is worst-case submodular if

$$\Delta_{\text{wc}}(e \mid \psi) \geq \Delta_{\text{wc}}(e \mid \psi'),$$

for any two partial realizations $\psi$ and $\psi'$ such that $\psi \subseteq \psi'$ and for any item $e \in E(\text{dom}(\psi'))$. A function $f$ is worst-case monotone if for every partial realization $\psi$ and any $e \in E \setminus \text{dom}(\psi)$, $\Delta_{\text{wc}}(e \mid \psi) \geq 0$.

Lastly, we introduce the concept of minimal dependency [2], which states that the utility of any collection of items is only dependent on the state of the items within that group.

Definition 2.2. [Minimal Dependency] We say a function $f$ is minimal dependent with respect to $p(\phi)$ if for any partial realization $\psi$ and any realization $\phi$ such that $\phi \sim \psi$, we have $f(\psi) = f(\text{dom}(\psi), \phi)$.

The properties of worst-case submodular, worst-case monotone and minimal dependent can be observed in a wide range of applications, such as pool-based active learning, stochastic submodular set cover, and adaptive influence maximization. Therefore, all results derived in this paper are applicable to these types of applications.

### 3 PROBLEM FORMULATION

Given a policy $\pi$, let $c_{\text{wc}}(\pi)$ denote the worst-case cost of $\pi$, formally $c_{\text{wc}}(\pi) = \max_{\phi \in U^*} \min_{\psi \in \Phi} c(E(\pi, \psi))$. We assume there is a “target value” $Q$ such that $f(E, \phi) = Q$ for all $\phi$. The worst-case adaptive submodular cover problem is formally defined as follows: $\min_{\pi : f(E(\pi), \phi) \leq Q} c_{\text{wc}}(\pi)$. 

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**Session 6A: Deep Learning**

**AAMAS 2023, May 29–June 2, 2023, London, United Kingdom**
For the case if \( f(E, \phi) \) varies across \( \phi \), we can define a new function \( \hat{f}(S, \phi) = \min(Q', f(S, \phi)) \), where \( Q' \) is some threshold that is no larger than \( \min_\Delta \hat{f}(E, \phi) \); that is, \( Q' \) is achievable under all realizations. Fortunately, this variation does not add additional difficulty to our problem because Lemma 3.1 shows that if \( f \) is worst-case monotone, worst-case submodular and minimal dependent with respect to \( p(\phi) \), then \( \hat{f} \) is also worst-case monotone, worst-case submodular and minimal dependent with respect to \( p(\phi) \), indicating that our results still hold if we replace the original utility function \( f \) and the “target value” \( Q \) with \( \hat{f} \) and \( Q' \), respectively.

**Lemma 3.1.** Let \( \hat{f}(S, \phi) = \min(Q', f(S, \phi)) \) for some constant \( Q' \). If \( f \) is worst-case monotone, worst-case submodular and minimal dependent with respect to \( p(\phi) \), then \( \hat{f} \) is also worst-case monotone, worst-case submodular and minimal dependent with respect to \( p(\phi) \).

**Proof:** It is trivial to show that if \( f \) is worst-case monotone and minimal dependent, then \( \hat{f} \) is also worst-case monotone and minimal dependent. We next focus on proving that if \( f \) is worst-case submodular, then \( \hat{f} \) is also worst-case submodular. We start by presenting a useful technical lemma in Lemma 3.2. Its proof is provided in appendix.

**Lemma 3.2.** Consider any five constants \( c_1, c_2, c_3, c_4 \) and \( x \) such that \( c_1 \geq c_2 \) and \( c_2 \geq c_3 \), \( c_1 - c_2 \geq c_3 - c_4 \) and \( c_2 \leq c_4 \), we have \( \min\{c_1, x\} - \min\{c_2, x\} \geq \min\{c_3, x\} - \min\{c_4, x\} \).

Consider any two partial realizations \( \psi \) and \( \psi' \) such that \( \psi \subseteq \psi' \) and any \( e \in E \backslash \text{dom}(\psi') \),

\[
\min_{o \in O(e, \psi)} \left\{ \hat{f}(\psi \cup \{(e, o)\}) - \hat{f}(\psi) \right\} - \min_{o \in O(e, \psi')} \left\{ \hat{f}(\psi' \cup \{(e, o)\}) - \hat{f}(\psi') \right\} 
\]

\[
= \min_{o \in O(e, \psi)} \left\{ \min(Q', f(\psi' \cup \{(e, o)\})) - \min(Q', f(\psi')) \right\} 
- \min_{o \in O(e, \psi')} \left\{ \min(Q', f(\psi' \cup \{(e, o)\})) - \min(Q', f(\psi')) \right\} 
\]

\[
= \left( \min_{o \in O(e, \psi)} \min(Q', f(\psi' \cup \{(e, o)\})) - \min(Q', f(\psi')) \right) 
- \left( \min_{o \in O(e, \psi')} \min(Q', f(\psi' \cup \{(e, o)\})) - \min(Q', f(\psi')) \right) .
\]

To prove the worst-case submodularity of \( \hat{f} \), it suffices to show that

\[
\left( \min_{o \in O(e, \psi)} \min(Q', f(\psi' \cup \{(e, o)\})) - \min(Q', f(\psi')) \right) - \left( \min_{o \in O(e, \psi')} \min(Q', f(\psi' \cup \{(e, o)\})) - \min(Q', f(\psi')) \right) \geq 0 .
\]

Let \( c_1 = \min_{o \in O(e, \psi)} f(\psi' \cup \{(e, o)\}) \), \( c_2 = f(\psi) \), \( c_3 \leq c_4 \), we have \( c_1 \geq c_2 \) (by worst-case monotonicity), \( c_3 \leq c_4 \) (by worst-case monotonicity), \( c_1 - c_2 \geq c_3 - c_4 \) (by worst-case submodularity) and \( c_2 \leq c_4 \) (by worst-case monotonicity). Hence, apply Lemma 3.2 with these parameters and \( x = Q' \) gives inequality (2). \( \square \)

### 4 Algorithm Design and Analysis

We first introduce a Worst-Case Density-Greedy Policy (labeled as \( \pi^9 \)) for the worst-case adaptive submodular cover problem. In each step \( t \) of \( \pi^9 \), it selects an item \( e_t \) that maximizes the worst-case “benefit-to-cost” ratio on top of the current observation, i.e.,

\[
e_t \in \arg\max_{e \in E} \frac{\Delta_{\text{wc}}(e | \psi_t-1)}{c(e)},
\]

where \( \psi_{t-1} \) denotes the partial realization observed at step \( t \). Then it updates the observation using \( \psi_t \leftarrow \psi_{t-1} \cup \{(e_t, \Phi(e_t))\} \). We follow this density-greedy rule to select items recursively until the utility of selected items achieves the quality threshold \( Q \), i.e., \( f(\psi_t) \geq Q \). With the assumption that \( f \) is minimal dependent, it is easy to verify that \( f(\psi_t) \geq Q \). A detailed description of \( \pi^9 \) is listed in Algorithm 1.

We conduct our analysis based on the concept of virtual slot, which was originally proposed in [4]. Assume after a policy \( \pi \) selects an item \( e \), it starts to "run" \( e \), and terminates after \( c(e) \) virtual slots. It is worth noting that virtual slot is only defined for analytical purposes and does not consume actual time. Based on this notation, we introduce the level-1-truncation \( \pi_l \) of a policy \( \pi \) over virtual time as follows.

**Definition 4.1 (Level-1-truncation of \( \pi \) over virtual time).** Run \( \pi \) for \( l \) virtual slots, and for every item \( e \in E \), if \( e \) has been running for \( y \) virtual slots, selecting \( e \) independently with probability \( y/c(e) \).

For example, consider a policy \( \pi \) selects three items \( e_1, e_2, e_3 \) in the end with \( c(e_1) = 2 \), \( c(e_2) = 2 \) and \( c(e_3) = 3 \). Then its level-1-truncation \( \pi_1 \) selects \( e_1 \) and \( e_2 \) with probability \( 1/3 \); its level-3-truncation \( \pi_3 \) selects \( e_1 \) deterministically, and selects \( e_2 \) with probability \( 1/2 \).

Given a realization \( \phi \) and a policy \( \pi \), for any \( l \in \mathbb{Z}^+ \), let \( \ell[l, \phi, \pi] \) denote the number of items that have a positive probability of being selected by \( \pi_l \) conditioned on \( \phi \). For convenience, we use \( \ell[l] \) to denote \( \ell[l, \phi, \pi] \) if it is clear from the context. In the previous example, we have \( \ell[3] = 2 \) because both \( e_1 \) and \( e_2 \) have a positive probability of being selected by \( \pi_3 \); we have \( \ell[5] = 3 \) because all three items have a positive probability of being selected by \( \pi_5 \).

We denote with \( h(\pi_l | \phi) \) the expected utility of \( \pi_l \) conditioned on a realization \( \phi \). Assume \( \psi_0 = \emptyset \). With the above notations and the definition of \( \pi_l \), \( h(\pi_l | \phi) \) is formally defined as follows:

\[
h(\pi_l | \phi) = f(\psi_{l-1}) + \min_{i \in \text{dom}(\psi_{l-1})} c(e_i) \frac{(f(\psi_{l-1}) - f(\psi_{l-1}))}{c(e_i)} ,
\]

where \( f(\psi_{l-1}) \) is the utility of the first \( l \)-th item, \( f(\psi_{l-1}) \) are that selected by \( \pi_l \) deterministically, the term

\[
\frac{\min_{i \in \text{dom}(\psi_{l-1})} c(e_i)}{c(e_i)}
\]

is the selection probability of the \( l \)-th item, and the term

\[
f(\psi_{l-1}) - f(\psi_{l-1})
\]

Algorithm 1 Worst-Case Density-Greedy Policy \( \pi^9 \)

1. \( t = 1; \psi_0 = \emptyset \).
2. \( \textbf{while } f(\psi_t) < Q \textbf{ do} \)
3. \( \textbf{select } e_t \in \arg\max_{e \in E} \frac{\Delta_{\text{wc}}(e | \psi_{t-1})}{c(e)} \).
4. \( \textbf{observe } \Phi(e_t) \textbf{ and update } \psi_t \leftarrow \psi_{t-1} \cup \{(e_t, \Phi(e_t))\} \).
5. \( t \leftarrow t + 1; \)
is the utility of the \( t[l] \)-th item.

Before providing the main theorem, we first present two technical results.

**Lemma 4.2.** Given any realization \( \phi \) and a policy \( \pi \), for any \( l \leq c(E(\pi, \phi)) \), we have
\[
h(\pi_1 | \phi) - h(\pi_{l-1} | \phi) = \frac{1}{c(\varepsilon[l])} \left( f(\psi_1[l]) - f(\psi_{l-1}) \right).
\]

**Proof:** Observe that if \( l \leq c(E(\pi, \phi)) \), then
\[
c(\text{dom}(\psi[l]) + c(\varepsilon[l]) = c(\text{dom}(\psi[l])) \geq l.
\]

Hence, \( \min(\|c - c(\text{dom}(\psi[l]) - c(\varepsilon[l]))) = l - c(\text{dom}(\psi[l]) - c(\varepsilon[l])) \).

It follows that (4) can be simplified to
\[
h(\pi_1 | \phi) = \frac{1}{c(\varepsilon[l])} \left( f(\psi_1[l]) - f(\psi_{l-1}) \right).
\]

To prove this lemma, we consider two cases:

- **Case 1:** We first consider the case when \( l[l] = l[l-1] \). Observe that for any \( l \leq c(E(\pi, \phi)) \), it holds that

\[
h(\pi_1 | \phi) = f(\psi_1[l]) - f(\psi_{l-1})
\]

where the first equality is from (6) and the second equality is from the assumption that \( l[l] = l[l-1] \).

- **Case 2:** We next consider the case when \( l[l] = l[l-1] + 1 \), that is, \( l[l] \) is the last virtual slot in round \( l[l-1] \) and \( l \) is the first virtual slot in round \( l[l] \). In this case, we can rewrite \( h(\pi_1 | \phi) \) as

\[
h(\pi_1 | \phi) = \frac{1}{c(\varepsilon[l])} \left( f(\psi_1[l]) - f(\psi_{l-1}) \right)
\]

where the first equality is from (6) and the observation that \( l \) is the first virtual slot in round \( l[l] \) and the second equality is by the assumption that \( l[l] = l[l-1] + 1 \). Meanwhile,

\[
h(\pi_{l-1} | \phi) = f(\psi_1[l-1]) - f(\psi_{l-1})
\]

where the second equality is because \( l-1 \) is the last virtual slot in round \( l[l-1] \), indicating that \( l - c(\text{dom}(\psi[l-1]) - c(\varepsilon[l-1])) \).

Equations 7 and 8 together imply that \( h(\pi_1 | \phi) - h(\pi_{l-1} | \phi) = \frac{1}{c(\varepsilon[l])} \left( f(\psi_1[l]) - f(\psi_{l-1}) \right) \).

Throughout the rest of this paper, let \( c* = c_w(\pi^*) \) denote the worst-case cost of the optimal solution \( \pi^* \).

**Theorem 4.3.** If the utility function \( f \) is worst-case monotone and worst-case submodular with respect to \( p(\phi) \), then for any \( L \in \mathbb{Z^+} \) and any realization \( \phi \), it holds that
\[
h(\pi^*_L | \phi) > (1 - e^{-L/c^*})Q,
\]

where \( \pi^*_L \) is the level-L-truncation of \( \pi \).

**Proof:** We first recall some notations. For each \( t \in [n] \), let \( \psi_t \) represent the partial realization of the first \( t \) items picked by \( \pi \) conditioned on \( \phi \). We use \( t[l] \) to denote the number of items that have a positive probability of being selected by \( \pi \) conditioned on \( \phi \). Hence, \( \psi_{l-1} \) represents the partial realization of the first \( l-1 \) items selected by \( \pi \) conditioned on \( \phi \).

The case when \( L > c(E(\pi, \phi)) \) is trivial: If \( L > c(E(\pi, \phi)) \), then \( t[L] = |E(\pi, \phi)| \) by the definition of \( t[L] \). It follows that \( h(\pi^{*}_L | \phi) = f(\psi_{l[L]}) = Q \), where the first equality is by the definition of \( h \) and the assumption that \( L > c(E(\pi, \phi)) \); the second equality is by the observation that \( \pi \) achieves the target value \( Q \) after selecting all \( t[L] \) items. Next we focus on the case when \( L \leq c(E(\pi, \phi)) \).

Given any \( \psi_{l-1} \), we can create a realization \( \phi^* \) in the following way. First, we make sure that \( \phi^* \) is consistent with \( \psi_{l-1} \) by defining \( \phi^* = \phi(e) \) for each \( e \in \text{dom}(\psi_{l-1}) \). For the rest of the items, we decide their states in \( \phi^* \) incrementally by simulating the execution of the optimal policy \( \pi^* \) conditioned on \( \psi_{l-1} \). Let \( \psi_t^* \) denote the partial realization after running \( \pi^* \) for \( t \) rounds. Starting with \( i = 1 \) and let \( \psi_0^* = \emptyset \), in each subsequent round \( i \), assume \( \psi_i^* \) selects \( e_i^* \) as the \( i \)-th item after observing \( \psi_{i-1}^* \); we define the state of \( e_i^* \) in \( \phi^* \) as follows:

\[
\phi^*(e_i^*) = \min_{e \in O(e_i^*)} f(\psi_{i-1}^* \cup \psi_{i-1}^* \cup \{ (e_i^*, 0) \}).
\]

The observation \( \psi_t^* \) is updated by adding new information from \( (e_i^*, \phi^*(e_i^*)) \) and the previous observation \( \psi_{t-1}^* \) and then \( \pi^* \) proceeds to the next round. This continues until \( \pi^* \) terminates, at which point the states of all items selected by \( \pi^* \) have been determined. The intuition behind creating such \( \phi^* \) is that in each round \( i \), we pick a state that is the least favorable for \( e_i^* \), in order to decrease the marginal utility of adding \( e_i^* \) to the partial realization \( \psi_{i-1}^* \cup \psi_{i-1}^* \) as much as possible. Without loss of generality, it can be assumed that \( \pi^* \) ends up choosing \( k \) items. It is possible that there are multiple realizations that fit this description, one of them is arbitrarily chosen as \( \phi^* \); in particular, \( \phi^* \) could be any realization that is consistent with \( \psi_{l-1} \cup \psi_L^* \).

To prove this theorem, it suffices to show that for all \( i \in [L] \), it holds that
\[
h(\pi^*_L | \phi) > (1 - e^{-L/c^*})Q.
\]

This is because by induction on \( L \), we have that for any \( L \in \mathbb{Z^+} \),
\[
h(\pi^*_L | \phi) = \sum_{L \in [L]} \left( h(\pi^*_L | \phi) - h(\pi^*_L | \phi) \right) > (1 - e^{-L/c^*})Q.
\]
We will concentrate on demonstrating (10) for the remainder of the proof. Let $e_i[l]$ denote the $l$-th item selected by $\pi^g$ conditioned on $\phi$, the following chain proves (10):

$$h(\pi_l | \phi) - h(\pi_{l-1} | \phi) = \frac{1}{c(e_i[l])} \left( f(\psi_{e_i[l]}(l) - f(\psi_{e_i[l]-1}) \right)$$

$$= \frac{1}{c(e_i[l])} \left( f(\psi_{e_i[l]}(l) - f(\psi_{e_i[l]-1}) \right)$$

$$\geq \min_{e \in O(e_i[l], \psi_{e_i[l]-1})} c(e_i[l])$$

$$= \max_{e \in E} \frac{1}{c(e)} \Delta_{we}(e | \psi_{e_i[l]-1}) \geq \max_{e \in E} \frac{\Delta_{we}(e_i[l] | \psi_{e_i[l]-1})}{c(e_i[l])}$$

$$\geq \sum_{e \in E} \frac{\Delta_{we}(e_i[l] | \psi_{e_i[l]-1})}{c(e_i[l])}$$

$$\geq \sum_{e \in E} \frac{\Delta_{we}(e_i[l] | \psi_{e_i[l]-1})}{c(e_i[l])}$$

$$= \frac{Q - h(\pi_{l-1} | \psi_{e_i[l]-1})}{c(e_i[l])} \geq \frac{Q - h(\pi_{l-1} | \phi)}{c(e_i[l])}.$$  

The first equality is from the assumption that $L \leq c(E(\pi^g, \phi))$ and Lemma 4.2, the third equality is by the density-greedy selection rule of $e_i[l]$, the fourth inequality is due to $\psi(e_i[l]) \in O(e_i[l], \psi_{e_i[l]-1})$, the fourth inequality is by the definition of $c^*$. The fifth inequality is due to $f^*$ being worst-case submodular, the sixth inequality is due to $f^*$ being worst-case monotone, the last inequality is because $\pi^g$ is a valid solution, indicating that $f(\psi_{e_i[l]}) = Q$, and the last inequality is by the definition of $h(\pi_{l-1} | \psi_{e_i[l]-1})$.

We next present the main theorem of this section.

**Theorem 4.4.** Suppose the utility function $f$ is worst-case monotone, worst-case submodular with respect to $\eta(\phi)$ and it satisfies the property of minimal dependency. Let $\eta$ be any value such that $f(\eta(\phi)) = Q$ and implies $f(\eta(\phi)) = Q$ for all partial realization $\phi$. Then $\pi^g$ is a feasible solution and $c_{we}(\pi^g) \leq (\ln Q + 1)c^*.$

**Proof.** Let $\phi^*$ denote the worst-case realization with respect to $\pi^g$, that is, $\phi^* \in \arg \max_{\phi \in U^*} c(E(\pi^g, \phi))$. Apply Theorem 4.3 with $L = c^* \ln (Q/\eta)$ and $\phi = \phi^*$ to give

$$h(\pi_l | \phi^*) > (1 - e^{-L/c^*})Q = (1 - \eta Q)Q = Q - \eta.$$  

(12)

Define $\pi_{\phi^*}^g$ as a policy that is identical to $\pi_{\phi^*}^g$ except that $\pi_{\phi^*}^g$ selects the $[L]$-th item deterministically. Hence,

$$h(\pi_{\phi^*}^g | \phi^*) \geq h(\pi_{\phi^*}^g | \phi) > Q - \eta.$$  

(13)

where the first inequality is because $\pi_{\phi^*}^g$ selects the $[L]$-th item deterministically while $\pi_{\phi^*}^g$ might select this item probabilistically, indicating that the utility of $\pi_{\phi^*}^g$ is no less than that of $\pi_{\phi^*}^g$; the second inequality is from (12).

By the definition of $\eta$, we have

$$h(\pi_{\phi^*}^g | \phi^*) = Q.$$  

(14)

and moreover, $\pi^g$ must select $t \{L\}$ items.

Hence, the worst-case cost of $\pi^g$ is $c(E(\pi_{\phi^*}^g, \phi^*))$. To prove this theorem, it suffices to show that $c(E(\pi_{\phi^*}^g, \phi^*))$ is upper bounded by $(\ln Q + 1)c^*$. To prove this bound, we first show that the cost of every item selected by $\pi^g$ is at most $c^*$. Consider any round $t$ of $\pi^g$, (10) and Lemma 4.2 jointly imply that

$$f(\psi_{t-1} \cup \{(e_i[l], \phi^*(e_i[l]))\}) - f(\psi_{t-1}) \geq \frac{Q - f(\psi_{t-1})}{c(e_i[l])}.$$  

(15)

where $\psi_t$ represents the partial realization of the first $t$ items picked by $\pi^g$ conditioned on $\phi^*$; $e_i[l]$ is the $t$-th item selected by $\pi^g$ conditioned on $\phi^*$.

Because $f(\psi_{t-1} \cup \{(e_i[l], \phi^*(e_i[l]))\}) \leq Q$, we have

$$f(\psi_{t-1} \cup \{(e_i[l], \phi^*(e_i[l]))\}) - f(\psi_{t-1}) \leq Q - f(\psi_{t-1})$$

This, together with (15), implies that $c(e_i[l]) \leq c^*$ for all $t$. This implies that the cost of the $[L]$-th item selected by $\pi^g$ is at most $c^*$, i.e., $c(e_{\phi^*}[L]) \leq c^*$. It follows that

$$c(E(\pi_{\phi^*}^g, \phi^*)) \leq L + c^* = c^* \ln(\eta) + c^* = (\ln Q + 1)c^*.$$  

(16)

where the first equality is from the following observation: if $L > c(E(\pi^g, \phi^*))$, then $c(E(\pi_{\phi^*}^g, \phi^*)) \leq c(E(\pi^g, \phi^*)) < L$; if

$$L \leq c(E(\pi^g, \phi^*)),$$

then $c(E(\pi_{\phi^*}^g, \phi^*)) \leq c(E(\pi^g, \phi^*)) \leq L + c(e_{\phi^*}[L]) \leq L + c^*$. □

**Tightness of Our Results:** It is easy to verify that the classic deterministic submodular cover problem [18] is a special case of our problem. Given that the best approximation ratio for the deterministic submodular cover problem is $\ln(Q/\eta) + 1$, the guarantee provided in Theorem 4.4 is the best possible.

**4.1 Pointwise submodularity is not sufficient**

A function $f$ is called pointwise submodular if $f(\cdot, \cdot): 2^{E} \rightarrow \mathbb{R}_{\geq 0}$ is submodular for all realizations $\phi \in U^*$. This property can be found in numerous applications. Unfortunately, we next construct an example to show that the ratio of $c_{we}(\pi^g)$ and $c^*$ could be arbitrarily large even if $f$ is pointwise submodular and $Q/\eta = 1$. In other words, pointwise submodularity is not sufficient to guarantee the performance bound from Theorem 4.4.

Consider a set of three items $E = \{e_1, e_2, e_3\}$ with cost $c(e_1) = e_4$ and $c(e_2) = c(e_3) = e_6$. There are two possible states $O = \{o_1, o_2\}$. Assume $U^*$ is composed of two possible realizations:

$$\phi_1 = \{(e_1, o_1), (e_2, o_1), (e_3, o_1)\}$$

and $\phi_2 = \{(e_1, o_1), (e_2, o_2), (e_3, o_1)\}$. Therefore, $e_1$ has a deterministic state $o_1$, whereas $e_2$’s state is different from $e_1$’s state. We consider a modular utility function $f$ such that $f(\phi, o) = \sum_{e \in S} v_e(\phi, o)$, where $v_e(\phi, o)$ is the value of $e$ in state $o$. We assume that $e_1$ has a deterministic value of $Q$, and $e_2$ (resp. $e_3$) has a value of $Q$ (resp. 0) in state $o_1$ and a value of 0 (resp. $Q$) in state $o_2$. Thus, $e_1$ is, $v_e_{e_1, o_1} = v_e_{e_1, o_2} = Q$ and $v_e_{e_1, o_2} = v_e_{e_1, o_1} = 0$. First, because $f$ is a linear function, it is also pointwise submodular. Moreover, it is easy to verify that $f$ is worst-case monotone and minimal dependent. Second, $Q/\eta = 1$. According to the design of $\pi^g$, it always selects $e_1$ because the worst-case “benefit-to-cost” ratio of $e_1$ (with respect
to an empty set) is \(Q/e_a > 0\), however, the worst-case "benefit-to-cost" ratios of \(e_2\) and \(e_1\) are both \(0\). By contrast, the optimal solution \(\pi^*\) always picks \(e_2\) and \(e_1\) to achieve a value of \(Q\). Hence, the worst-case cost of \(\pi^*\) is \(e_a\), whereas the optimal solution has a cost of \(2e_b\). Therefore, \(c_{we}(\pi^*) = \frac{2e_b}{2e_b} = e^*\); one can select \(e_a\) and \(e_b\) to make \(c_{we}(\pi^*)\) arbitrarily large.

5 WORST-CASE MAXIMIZATION PROBLEM

In this section, we study a dual problem of the worst-case cover problem. We call this problem the worst-case adaptive submodular problem. We call this problem the worst-case adaptive submodular problem. Our goal is to find a policy \(\pi\) to maximize the worst-case utility \(f_{we}(\pi)\) subject to a budget constraint \(B\), that is,

\[
\max_{\pi \in \pi_{we}(\pi) \leq B} f_{we}(\pi).
\]

It is worth noting that the classic problem of maximizing a monotone submodular function subject to a budget constraint [7] is a special case of our problem.

Algorithm 2 Worst-Case Density-Greedy Policy \(\pi^g\)

1: \(t = 1; \psi_0 = 0\).
2: while true do
3: \(\epsilon_t \in \arg\max_{e \in E} \Delta_{we}(e) \psi_t - 1/e(e)\);
4: \(B := B - c(e_t)\);
5: if \(B \geq 0\) then
6: select \(e_t\) and observe \(\Phi(e_t)\);
7: update \(\psi_t \leftarrow \psi_{t-1} \cup \{(e_t, \Phi(e_t))\}\);
8: else
9: break; \([\text{Replace this line using "select } e_t; \text{ break;" in the relaxed greedy policy } \pi^g]\).
10: end if
11: \(t \leftarrow t + 1\).

For simplicity, assume \(f(0) = 0\). Our solution involves two candidate policies: one is a density-greedy based policy (labeled as \(\pi^g\) by abuse of notation) and the other one selects a best singleton \(e^*\) (i.e., \(e^* \in \arg\max_{e \in E} \Delta_{we}(e | 0)\)). Our final algorithm (labeled as \(\pi^a\)) adopts the better one between these two candidates. Hence, the worst-case utility of \(\pi^a\) is \(f_{we}(\pi^a) = \max\{f_{we}(\pi^g), \Delta_{we}(e^* | 0)\}\). To complete the definition of \(\pi^a\), we next explain \(\pi^g\) in detail.

Design of \(\pi^g\). Starting with round \(t = 1\) and observation \(\psi_0 = 0\). In each subsequent round \(t\), \(\pi^g\) selects an item \(e_t\) that has the largest "benefit-to-cost" ratio, i.e.,

\[
e_t \in \arg\max_{e \in E} \Delta_{we}(e | \psi_t - 1)/c(e).
\]

Next, we update the observation using \(\psi_t \leftarrow \psi_{t-1} \cup \{(e_t, \Phi(e_t))\}\). This process iterates until the budget constraint is violated. A detailed description of \(\pi^g\) is listed in Algorithm 2.

For the purpose of proof, we introduce a relaxed version of \(\pi^g\) (labeled as \(\pi^g\)). \(\pi^g\) is identical to \(\pi^a\) except that \(\pi^g\) allows to keep the first item that violates the budget constraint. Please refer to our comments added to Line 9 in Algorithm 2 for a detailed description of this difference.

We next analyze the performance of \(\pi^g\). Before presenting the main theorem, we first provide a technical result.

Theorem 5.1. If the utility function \(f\) is worst-case monotone and worst-case submodular with respect to \(p(\phi)\), then for any \(\phi\) and any \(L \leq c(E(\pi^g, \phi))\),

\[
h(\pi^g_L | \phi | \phi) \geq (1 - e^{-L/B}) f_{we}(\pi^g)\]

(17)

where \(\pi^g\) is the optimal policy.

Proof: We first recall some notations. Let \(t[l]\) be the number of items that have a positive probability of being selected by \(\pi^g\) conditioned on \(\phi\). Let \(\psi[l]-1\) denote the partial realization of the first \(t[l] - 1\) items selected by \(\pi^g\) conditioned on \(\phi\). To prove this theorem, it suffices to show that for all \(l \in [L]\),

\[
h(\pi^g_{l} | \phi) - h(\pi^g_{l-1} | \phi) \geq f_{we}(\pi^g) - f(\psi[l]-1)\]

(18)

This is because by induction on \(l\), we have that for any \(L \leq c(E(\pi^g, \phi))\),

\[
h(\pi^g_{L} | \phi) - h(\pi^g_{L-1} | \phi) \geq f_{we}(\pi^g) - f(\psi[L]-1)\]

where the first inequality is derived from a similar proof as (10), with the only difference being that \(Q\) is replaced with \(f_{we}(\pi^g)\); the second inequality is because the worst-case cost of \(\pi^g\) is no larger than \(B\).

By the definition of \(\pi^g\), it always uses up the budget. This, together with the assumption that \(f\) is minimal dependent, implies that \(f_{we}(\pi^g) \geq h(\pi^g_{L} | \phi)\) where \(\phi^*\) is the worst-case realization of \(\pi^g\), i.e., \(\phi^* = \arg\min_{\phi \in F(\phi^g)} E(\pi^g, \phi)\). This, in combination with Theorem 5.1, leads to Corollary 5.2.

Corollary 5.2. If the utility function \(f\) is worst-case monotone, worst-case submodular with respect to \(p(\phi)\) and it satisfies the property of minimal dependency, then

\[
f_{we}(\pi^g) \geq (1 - e^{-L/B}) f_{we}(\pi^g)\]

(19)

We next present the main theorem of this section.

Theorem 5.3. If the utility function \(f\) is worst-case monotone, worst-case submodular with respect to \(p(\phi)\) and it satisfies the property of minimal dependency, then

\[
f_{we}(\pi^g) \geq 1 - e^{-1} f_{we}(\pi^g)\]

Proof: By the design of \(\pi^g\), to prove this theorem, it suffices to show that \(f_{we}(\pi^g) \geq f_{we}(\pi^g) - f(\psi)\). Suppose \(\phi^*\) is the worst-case realization of \(\pi^g\), that is,

\[
\phi^* = \arg\min_{\phi \in F(\phi^g)} E(\phi^g, \phi)\]

Let \(\psi^*\) denote the partial realization of \(E(\pi^g, \phi^*)\) conditioned on \(\phi^*\). Hence, \(E(\pi^g, \phi^*) = \text{dom}(\psi^*)\) and \(\phi^* \sim \psi^*\). Assume \(e^*\) is the
where the second equality is due to \( \phi \) of our problem. The best approximation ratio for that problem, and therefore for ours, is 1, and the fact that \( \Delta \) is minimal dependent; the worst-case real-

By the definition of \( f_{\text{wc}}(\pi^{\ast}) \) and the assumption that \( f \) is minimal dependent, we have

\[ f \left( \psi'' \cup \{ (e'', \phi^{\ast}(e'')) \} \right) \geq f_{\text{wc}}(\pi^{\ast}). \tag{21} \]

By the definition of \( \phi^{\ast}(e'') \), we have

\[ f \left( \psi'' \cup \{ (e'', \phi^{\ast}(e'')) \} \right) = f(\psi'') + \Delta_{\text{wc}}(e'' | \psi''). \tag{22} \]

It follows that

\[
\begin{align*}
&f \left( \psi'' \cup \{ (e'', \phi^{\ast}(e'')) \} \right) = f(\psi'') + \Delta_{\text{wc}}(e'' | \psi'') \\
&= f_{\text{wc}}(\pi^{\ast}) + \Delta_{\text{wc}}(e'' | \psi'') \\
&\leq f_{\text{wc}}(\pi^{\ast}) + \Delta_{\text{wc}}(e'' | \emptyset),
\end{align*}
\]

where the second equality is due to \( \phi'' \) being the worst-case realization of \( \pi^{\ast} \) and the assumption that \( f \) is minimal dependent; the inequality is due to \( f \) being worst-case submodular with respect to \( p(\phi) \) and the fact that \( \emptyset \subseteq \psi'' \).

Inequalities (21) and (23) jointly imply that

\[ f_{\text{wc}}(\pi^{\ast}) + \Delta_{\text{wc}}(e'' | \emptyset) \geq f_{\text{wc}}(\pi^{\ast}). \tag{24} \]

This, together with Corollary 5.2, implies that \( f_{\text{wc}}(\pi^{\ast}) + \Delta_{\text{wc}}(e'' | \emptyset) \geq f_{\text{wc}}(\pi^{\ast}) \geq (1 - e^{-1})f_{\text{wc}}(\pi^{\ast}). \) Hence,

\[
\max \{ f_{\text{wc}}(\pi^{\ast}), \Delta_{\text{wc}}(e'' | \emptyset) \} \geq \frac{1 - e^{-1}}{2} f_{\text{wc}}(\pi^{\ast}).
\]

\[ \Box \]

Note that the classic problem of maximizing a monotone submodular function subject to a budget constraint [7] is a special case of our problem. The best approximation ratio for that problem, and therefore for ours, is \( 1 - 1/e \).

6 PERFORMANCE EVALUATION

In this section, we conduct experiments to evaluate the performance of our proposed Worst-Case Greedy (WCG) algorithms in the context of active learning. Suppose we have a set of hypotheses \( \mathcal{H} \) and a set of unlabeled data points \( E \), where each \( e \in E \) is selected randomly from a distribution \( D \). In pool-based active learning, in order to reduce the expense of acquiring labeled data from domain experts, we select a sequence of data points to be labeled iteratively until the labels of all unlabeled examples can be inferred from the obtained labels. The version space is defined as the set of hypotheses that are consistent with the observed labels, and the cost of labeling a data point \( e \) is a fixed value \( c(e) \). Intuitively, our goal is to minimize the worst-case cost of reducing the probability mass of the version space until the target hypothesis \( h^* \) is pinpointed. Reducing the version space is achieved by eliminating false hypotheses through stochastic queries. For example, query \( e \in E \) eliminates all hypotheses that do not agree with \( h^* \) at \( e \). For the budgeted version, our objective is to minimize the probability mass of the version space within a specific budget constraint.

Our first set of experiments evaluate the performance of our algorithm as measured by the worst-case cost with respect to the changes in the size of the version space \( \mathcal{H} \), as shown in Figure 1. Each data point \( e \) is assigned a value chosen randomly from its set of possible labels. The worst-case cost is calculated as the largest cost of pinpointing the target hypothesis \( h^* \) after querying a sequence of data points. We consider three cost settings in our experiments. For the first setting, \( c(e) \) is drawn from \( (1, 20) \) uniformly at random. The result is shown in the figure with label WCG-U. For the other two settings, \( c(e) \) is drawn from \( N(\mu, \sigma^2) \) with \( \mu = 7, \sigma = 1.5 \) and \( \mu = 7, \sigma = 2.5 \), respectively. Corresponding results are labeled as WCG-N15 and WCG-N25, respectively, in the figure. To implement our algorithm, in each round we select a query with the largest conditional marginal utility over the cost until the target hypothesis is pinpointed. The conditional marginal utility is determined by the worst-case reduction in version space, given the labels from
past queries. A random algorithm is used as our baseline, which outputs a random sequence of queries until the target is pinpointed. For every set of experiments, we perform the simulation for 1,000 iterations and report the average results.

As shown in Figure 1, the x-axis refers to the size of the version space, ranging from 10 to 3000. The y-axis refers to the worst-case cost yielded by the corresponding algorithms. We evaluate our algorithm by using 20 unlabeled data points and by varying the size of the label set. Figure 1(a) shows the results where each data point has binary labels. We observe that WCG significantly outperforms the baseline in all test cases, yields a cost reduction of 30% for binary labels. Note that our algorithm considers the marginal utility as well as the cost associated with each query, leading to a lower worst-case cost of the output sequence. We also observe that for smaller version space, on average our algorithm identifies the target hypothesis with fewer queries, and WCG\_U benefits from taking more low-cost queries since the algorithm prefers a larger marginal utility to cost ratio. As the size of the version space increases, however, WCG\_U yields a much higher cost as taking low-cost queries alone is not enough to pinpoint the target and queries with potentially high cost are required to further reduce the version space.

We observe a similar structure in Figure 1(b), (c) and (d), showing the results for three-label data points, four-label data points and a hybrid case, respectively. For the hybrid case, we randomly divide our 20 unlabeled data points into three groups. The first group contains 10 binary-label data points, the second group contains 5 three-label data points, and the third group contains 5 four-label data points. We observe that our algorithm generates a lower worst-case cost when each data point has more possible labels. The reason is that queries with more possible labels tend to yield a higher marginal reduction in version space, therefore less queries are selected in the output, leading to a lower worst-case cost.

Our second set of experiments investigate how the budget affects the reduction in version space, as illustrated in Figure 2. The x-axis holds the value of the budget, and the y-axis holds the reduction in version space generated by the algorithms. We consider 3000 hypothesis with 20 unlabeled data points, and tight budget constraint is enforced. Figure 2(a), (b), (c) and (d) plot the results for binary-label data points, three-label data points, four-label data points and the hybrid case as aforementioned, respectively. As anticipated, the reduction in version space becomes greater as the budget increases. Again, for smaller budgets, WCG yields a higher reduction in version space under uniform cost model than it does under the other two cost models. As the budget goes up, more queries are included in the output sequence, and we observe that the reduction in version space among different cost models converges.

7 APPENDIX

Proof of Lemma 3.2. For the case when $c_1 \leq c_3$, this result has been proved in Lemma 2 in [12]. We next focus on the case when $c_1 > c_3$. We prove this lemma in five subcases depending on the relation between $x$ and the other four constants. Notice that when $c_1 > c_3$, $c_1 \geq c_2$, $c_3 \geq c_4$, and $c_2 \leq c_4$, we have $c_1 > c_3 \geq c_4 \geq c_2$.

- If $x \geq c_1 > c_3 \geq c_4 \geq c_2$, then $\min\{c_1, x\} = c_1$, $\min\{c_2, x\} = c_2$, $\min\{c_3, x\} = c_3$ and $\min\{c_4, x\} = c_4$. Thus, $\min\{c_1, x\} = \min\{c_2, x\} = \min\{c_3, x\} = \min\{c_4, x\} = c_4$ due to the assumption that $c_1 - c_2 \geq c_3 - c_4$.
- If $c_1 > x \geq c_3 \geq c_4 \geq c_2$, then $\min\{c_1, x\} = x$, $\min\{c_2, x\} = c_2$, $\min\{c_3, x\} = c_3$ and $\min\{c_4, x\} = c_4$. Thus, $\min\{c_1, x\} = \min\{c_2, x\} = x - c_2$ and $\min\{c_3, x\} = \min\{c_4, x\} = c_4 - c_4$. Because $x \geq c_3$ and $c_2 \leq c_4$, we have $x - c_2 \geq c_3 - c_4$. It follows that $\min\{c_1, x\} - \min\{c_2, x\} \geq \min\{c_3, x\} - \min\{c_4, x\}$.
- If $c_1 > c_3 > x \geq c_4 \geq c_2$, then $\min\{c_1, x\} = x$, $\min\{c_2, x\} = c_2$, $\min\{c_3, x\} = x$ and $\min\{c_4, x\} = c_4$. Thus, $\min\{c_1, x\} = \min\{c_2, x\} = x - c_2$ and $\min\{c_3, x\} = \min\{c_4, x\} = x - c_4$. Because $c_2 \leq c_4$, we have $x - c_2 \geq x - c_4$, thus $\min\{c_1, x\} - \min\{c_2, x\} \geq \min\{c_3, x\} - \min\{c_4, x\}$.
- If $c_1 > c_3 \geq c_4 > x \geq c_2$, then $\min\{c_1, x\} = x$, $\min\{c_2, x\} = c_2$, $\min\{c_3, x\} = x$ and $\min\{c_4, x\} = x$. Thus, $\min\{c_1, x\} = \min\{c_2, x\} = x - c_2$ and $\min\{c_3, x\} = \min\{c_4, x\} = 0$ due to the assumption that $c_1 - c_3 \geq c_4 - c_2$. Because $x \geq c_2$, we have $x - c_2 \geq 0$, thus $\min\{c_1, x\} - \min\{c_2, x\} \geq \min\{c_3, x\} - \min\{c_4, x\}$.
- If $c_1 > c_3 \geq c_4 \geq c_2 > x$, then $\min\{c_1, x\} = x$, $\min\{c_2, x\} = x$, $\min\{c_3, x\} = \min\{c_4, x\} = x - x = 0$. Thus, $\min\{c_1, x\} = \min\{c_2, x\} = \min\{c_3, x\} = \min\{c_4, x\} = 0$.

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