Offline Contextual Bandits in the Presence of New Actions

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Abstract

Automated decision-making algorithms drive applications in domains such as recommendation systems and search engines. These algorithms often rely on off-policy contextual bandits or *off-policy learning* (OPL). Conventionally, OPL selects actions that maximize the expected reward within an existing action set. However, in many real-world scenarios, actions—such as news articles or video content—change continuously, and the action space evolves over time compared to when the logged data was collected. We define actions introduced after deploying the logging policy as *new actions* and focus on the problem of OPL with new actions. Existing OPL methods cannot learn and select new actions because no relevant data are logged. To address this limitation, we propose a new OPL method that leverages action features. In particular, we first introduce the Local Combination PseudoInverse (LCPI) estimator for the policy gradient, generalizing the PseudoInverse estimator initially proposed for off-policy evaluation of slate bandits. LCPI controls the trade-off between reward-modeling condition and the condition for data collection regarding the action features, capturing the interaction effects among different dimensions of action features. Furthermore, we propose a generalized algorithm called ***Policy Optimization for Effective New Actions (PONA)***, which integrates LCPI, a component specialized for new action selection, with Doubly Robust (DR), which excels at learning within existing actions. We define PONA as a weighted sum of the LCPI and DR estimators, optimizing both the selection of existing and new actions, and allowing the proportion of new action selections to be adjusted by controlling the weight parameter.

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1 Introduction

We increasingly rely on data-driven algorithms to optimize decision-makings in various domains, including recommendation systems [6, 8, 22, 23, 27], search engines [15], advertising [2], and medical treatments [11]. These problems take the form of contextual bandits, where a policy selects actions based on observed contexts, and the corresponding rewards become available. The goal in such problems is to learn a policy that maximizes the expected reward. *Off-Policy Learning* (OPL) [17, 21, 32, 35] enables learning such policies by leveraging previously collected data, eliminating the need for online deployment and avoiding the risk of negatively impacting user experiences through active exploration [14, 23]. Typically, OPL focuses on identifying the best actions within a predefined set of existing actions. However, in many real-world scenarios, the action space evolves over time as new actions emerge or existing ones are updated. For example, search systems must process new articles daily, and recommendation systems for products or videos continually welcome new items. We define these actions, introduced after the data collection phase, as ***new actions***. In this work, we rigorously address the challenges of OPL regarding the presence of such new actions for the first time in the relevant literature.

Existing OPL methods such as policy-based and regression-based approaches are effective at identifying optimal actions within the set of existing ones [23, 28]. However, the naive applications of existing methods cannot choose new actions at all, failing to give fair opportunities to them. To address this critical limitations of the typical OPL methods, we consider and formulate a scenario where actions are represented as multi-dimensional action features. There exist many real-life problems where the actions are represented with features [6, 24]. For example, in the problem of thumbnail optimization (Figure 1) like done at Netflix [1], actions correspond to thumbnails described by features such as character type (e.g., male, female, child), title position (e.g., top, middle, bottom), and title size (e.g., large, small). In particular, the left side of the figure depicts existing thumbnails in the predefined action set, while the right side illustrates new thumbnails that are not at all observed in the logged data. As in this illustration, we consider leveraging the action features to develop a new OPL method that effectively selects new actions (i.e., unobserved combinations of action features) while still achieving a competitive overall policy performance.

Merely applying existing regression-based or policy-based approaches to observable action features does not resolve the problem

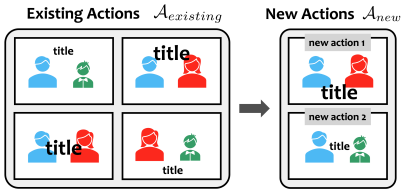


Figure 1: Examples of Existing and New Actions.
Note: There are three types of action features: **character type** (chosen as two from male, female, or child), **title position** (top, center, or bottom), and **title size** (large or small). The left side of the figure illustrates the thumbnails for existing actions, while the right side shows examples of new actions: "Male and female, title position at the bottom, large title" (**new action 1**) and "Male and child, title position at the center, small title" (**new action 2**).

of new actions. This is because the combinations of action features that represent new actions are never observed in the logged data. A possible solution might be to draw inspiration from the PseudoInverse (PI) method introduced in the slate bandit setting [12, 35, 37]. Slate bandits refer to the setting where a policy aims to optimize the selection of slates, which consist of multiple action features (which are also called sub-actions) [35]. To deal with the combinatorial slate spaces and resulting variance issues, the PI estimator relies on two conditions [35, 37]: (1) *the logging policy provides full support for each action feature independently*, and (2) *the expected reward function (q-function) is a linear combination of the intrinsic value of each feature dimension*. Under these conditions, the PI estimator can estimate the policy value or policy gradient without bias even if there are new actions. However, the linearity condition is particularly restrictive because it treats the effects of action features as completely independent, ignoring potentially significant interaction effects and thus introducing bias into the estimation [12]. Therefore, we relax the linearity condition of PI to deal with local interactions among action features and propose **Local Combinatorial Feature Interaction (LCPI)**—a generalized version of the PI estimator. LCPI enables new policies to account for interactions among different dimensions of action features, allowing a more effective selection of new actions. Although LCPI is better at identifying effective new actions, existing OPL methods, such as the policy-based approach using DR to estimate the policy gradient [4], can be more effective for learning within existing actions. This is because they do not rely on any conditions about the form of the q-function. To leverage the strengths of both approaches, we finally introduce a hybrid algorithm named ***Policy Optimization for Effective New Actions (PONA)***, which integrates LCPI and DR by weighting them through a weight parameter. This design allows PONA to optimize the overall policy performance via the effective selection of existing actions while identifying promising new actions. Furthermore, by adjusting the weight parameter, PONA can control how aggressively it selects new actions, supporting both conservative (greater focus on existing actions) and aggressive (greater focus on new actions) strategies. Results on synthetic and real-world experiments demonstrate that PONA efficiently selects new actions and achieves satisfactory overall performance, whereas existing methods fail to choose new actions severely.

2 Preliminaries: Conventional OPL

This section formulates the typical problem of OPL without new actions and introduces existing OPL methods.

First, let $x \in \mathcal{X} \subseteq \mathbb{R}^{d_x}$ represent a context vector such as user features in recommender systems. Given a context x, a possibly stochastic policy $\pi(a|x)$ selects an action $a \in \mathcal{A}$ such as products or movies. Furthermore, let $r \in \mathbb{R}_{\geq 0}$ denote a reward, such as conversion label and play duration, drawn from an unknown conditional distribution $p(r|x,a)$. In the setting of OPL, we are provided with a logged dataset $\mathcal{D} := \{(x_i, a_i, r_i)\}_{i=1}^n$ collected under a logging policy π_0 such that $(x,a,r) \sim p(x)\pi_0(a|x)p(r|x,a)$.

We define the expected reward under the deployment of a policy π (policy value) as a measure of its overall performance:

$$V(\pi) := \mathbb{E}_{p(x)\pi(a|x)p(r|x,a)}[r] = \mathbb{E}_{p(x)\pi(a|x)}[q(x,a)],$$

where $q(x,a) := \mathbb{E}[r|x,a]$ is the expected reward function or *q-function* for a given context x and action a.

The goal in OPL is to learn a new policy π_θ, parameterized by θ, using only the logged dataset $\mathcal{D}$. When learning a policy, we aim to maximize the policy value as $\theta^* = \mathrm{argmax}_{\theta\in\Theta} V(\pi_\theta)$. The following describes two typical approaches to OPL.

Firstly, the **policy-based** approach updates the policy parameter θ using iterative gradient ascent, $\theta_{t+1} \leftarrow \theta_t + \eta \nabla_\theta V(\pi_\theta)$, where

$$\nabla_\theta V(\pi_\theta) := \mathbb{E}_{p(x)}\left[\sum_{a\in\mathcal{A}} \pi_\theta(a|x) q(x,a) \nabla_\theta \log \pi_\theta(a|x)\right], \quad (1)$$

is the policy gradient (PG). Since the true PG is unknown, we need to estimate it using the logged data $\mathcal{D}$. A common approach for this estimation is to use the IPS method [19]:

$$\nabla_\theta \widehat{V}_{\mathrm{IPS}}(\pi_\theta; \mathcal{D}) := \frac{1}{n}\sum_{i=1}^n \frac{\pi_\theta(a_i|x_i)}{\pi_0(a_i|x_i)} r_i \nabla_\theta \log \pi_\theta(a_i|x_i). \quad (2)$$

where $\pi_\theta(a|x)/\pi_0(a|x)$ is called the *importance weight*. It plays a key role in ensuring the unbiasedness of IPS but often causes the issue of high variance and inefficient policy learning [28].

An improved approach to estimate the PG is using the DR estimator [4]. It leverages a q-function estimator $\hat{q}(x,a)$ to reduce the variance in the PG estimation compared to IPS as

$$\begin{aligned}\nabla_\theta \widehat{V}_{\mathrm{DR}}(\pi_\theta; \mathcal{D}) :=& \frac{1}{n}\sum_{i=1}^n \frac{\pi_\theta(a_i|x_i)}{\pi_0(a_i|x_i)} \left(r_i - \hat{q}(x_i,a_i)\right) \nabla_\theta \log \pi_\theta(a_i|x_i) \\ &+ \frac{1}{n}\sum_{i=1}^n \sum_{a\in\mathcal{A}} \pi_\theta(a|x_i)\hat{q}(x_i,a) \nabla_\theta \log \pi_\theta(a|x_i). \end{aligned} \quad (3)$$

IPS and DR are both unbiased against the true PG under the *full support* condition (**a condition to ensure sufficient data collection by the logging policy** π_0).

Condition 2.1. *(Full Support) The logging policy π_0 is said to have full support if $\pi_0(a|x) > 0, \forall x \in \mathcal{X}, \forall a \in \mathcal{A}$.*

Secondly, the **regression-based** approach estimates the q-function $q(x,a)$ using off-the-shelf supervised machine learning methods. It then transforms the estimated q-function $\hat{q}_\theta(x,a)$ into a decision-making policy, for example, by applying the softmax function. This approach may fail due to bias issues resulting from the difficulty in

accurately estimating the q-function $q(x, a)$. However, it can avoid the issue of high variance compared to the policy-based approach based on IPS and DR [9].

Existing policy-based or regression-based methods perform effectively in identifying existing actions with high expected rewards [17, 28, 32]. However, these methods cannot learn to select new actions, even if some of the new actions have high expected rewards. This is because we do not observe any data about new actions in $\mathcal{D}$, which severely violates *full support* (Condition 2.1). Therefore, we need to first relax the typical condition of full support to effectively learn policies that can choose promising new actions.

3 The Proposed Approach

The previous sections discussed the challenges associated with selecting new actions using existing OPL methods. To overcome, we propose a solution that leverages action features, which are often available in real-world decision-making problems [6, 18, 24].

3.1 Formulation of OPL with Action Features

We now represent action a by the d-dimensional action features $f(a) = (f_1(a), \ldots, f_l(a), \ldots, f_d(a))$, where $f_l(a) \in \mathcal{F}_l$ denotes the l-th dimension. In particular, we consider the setting where each action feature $f_l(a)$ is discrete and can be represented as a one-hot vector. For example, the genre feature such as 'documentary', 'romance', and 'horror' are encoded as $[1, 0, 0]$, $[0, 1, 0]$, and $[0, 0, 1]$.

In OPL with action features, we can possibly address the presence of new actions by being able to represent them as combinations of already observed factors. Figure 1 illustrates an example in the context of thumbnail selection with the 3-dimensional action features. The left side of the figure shows the existing action set, which includes thumbnails already considered by the logging policy. The right side introduces new thumbnails as new actions. For example, **new action 1** consists of "male and female characters," "title positioned at the bottom," and "large title size." We can see that we have already observed every individual feature of **new action 1** separately in the existing action set. **Despite this, existing OPL methods struggle to handle these new actions because the logged data does not include specific combinations of action features representing the new actions**. Therefore, we propose a novel method and algorithm that leverage these action features through a new estimator for the PG to identify effective new actions.

Before introducing our proposed approach, we rigorously introduce three key types of action spaces.

(1) **The space of *all* actions**: The set of all possible combinations of action features:

$$\mathcal{A} := \{a \mid a = (f_1, \ldots, f_d),\ \forall f_1 \in \mathcal{F}_1, \ldots, \forall f_d \in \mathcal{F}_d\}.$$

(2) **The space of *existing* actions**: The set of actions that have some positive probability under the logging policy:

$$\mathcal{A}_{existing} := \{a \in \mathcal{A} \mid \exists x \in \mathcal{X},\ \pi_0(a|x) > 0\}.$$

(3) **The space of *new* actions**: The set of actions that are not at all chosen under the logging policy:

$$\mathcal{A}_{new} := \{a \in \mathcal{A} \mid \forall x \in \mathcal{X},\ \pi_0(a|x) = 0\}.$$

These action spaces satisfy the following relations:

$$\mathcal{A}_{existing} \cap \mathcal{A}_{new} = \emptyset, \quad \mathcal{A}_{existing} \cup \mathcal{A}_{new} = \mathcal{A}.$$

In the typical formulation for OPL, the objective is to identify actions that maximize the expected reward from a set of *existing* actions $\mathcal{A}_{existing}$. In contrast, we consider a more general and realistic scenario, where the goal is to select actions that maximize the expected reward from $\mathcal{A}$, which includes new actions $\mathcal{A}_{new}$.

3.2 The Proposed Algorithm: PONA

To design a new algorithm for OPL with new actions, we first draw inspiration from the PI estimator initially proposed for OPE in slate bandits [35], and provide a generalization.

To introduce PI, we begin with formally defining an one-hot vector for each action feature as $\mathbb{I}_{f_l(a)} \in \mathbb{R}^{dm}$. This is a flattened vector that represents the one-hot encoding of each action feature. Using this notation, we can first extend the PI estimator [35] as an estimator for the PG as follows.

$$\nabla_\theta \widehat{V}_{\mathrm{PI}}(\pi_\theta; \mathcal{D}) = \frac{1}{n} \sum_{i=1}^{n} \left(\sum_{a \in \mathcal{A}} \pi_\theta(a|x_i) \nabla_\theta \log \pi_\theta(a|x_i) \mathbb{I}_{f_l(a)}{}^T \right) \Gamma^\dagger_{\pi_0, x_i} \mathbb{I}_{f_l(a_i)} r_i, \quad (4)$$

where $\Gamma_{\pi_0,x} := \mathbb{E}_{\pi_0(a|x)}[\mathbb{I}_{f_l(a)} \mathbb{I}^T_{f_l(a)} | x]$, and $M^\dagger$ denotes the Moore-Penrose pseudoinverse of the matrix M.

The PI estimator introduced above relies on the following conditions (3.1 and 3.2) to ensure unbiased estimation of the PG:

Condition 3.1. *(Independent Support) The logging policy π_0 ensures independent support if $\pi_0(f_l|x) > 0, \forall x \in \mathcal{X}, \forall l \in [1, ..., d], \forall f_l \in \mathcal{F}_l$. Note that $\pi_0(f_l|x) = \sum_{a \in \mathcal{A}: f_l(a) = f_l} \pi_0(a \mid x)$ is the marginal probability of observing f_l under π_0.*

This condition requires the logging policy to independently support every dimension of the action features. The condition of Independent Support is weaker than the Full Support condition (Condition 2.1), which requires the logging policy to choose every combination of action features. When new actions exist, the Full Support condition cannot hold, but the Independent Support condition may still hold even in the presence of new actions. **Due to this relaxation of the support condition, the PI estimator can learn a new policy that chooses new actions**.

The next condition of PI is with regard to the q-function.

Condition 3.2. *(Linearity) For each context $x \in \mathcal{X}$, there exists an (unknown) intrinsic reward vector $\phi_{x,l} \in \mathbb{R}^{dm}$ such that:*

$$q(x, a) = \sum_{l=1}^{d} q_l(x, f_l(a)) = \mathbb{I}^T_{f_l(a)} \phi_{x,l}.$$

The linearity condition requires that the q-function be expressed as a linear combination of latent value functions for each dimension of the feature. **This condition essentially assumes no interaction effects between different dimensions of the action feature**. While extending the PI estimator to estimate the PG is straightforward as done in Eq. (4), the linearity condition rarely holds and introduces significant bias in PG estimation [12, 37].

To overcome this critical limitation of the naive extension of PI, we first generalize Independent Support to account for local interactions of action features as follows.

Condition 3.3. *(Local Combination Support) The logging policy π_0 is said to ensure local combination support if, for the the first s dimensions of the action features, $\pi_0(f_{1:s}|x) > 0, \forall x \in \mathcal{X}, \forall f_{1:s} \in \prod_{j=1}^{s} \mathcal{F}_j$ as well as $\pi_0(f_l|x) > 0$ for the rest $s+1 \leq l \leq d$.*

Note that $f_{1:s} = (f_1, ..., f_s)$ represents the first s dimensions of the action features, where $1 \leq s \leq d$. The condition of Local Combination Support requires $f_{1:s}$ to be fully supported under the logging policy.[1] Condition 3.3 remains weaker than the original Full Support condition (Condition 2.1), because Full Support requires every dimension of the action features to be simultaneously supported (equivalent to Local Combination Support with $s = d$). When $s = 1$, Local Combination Support reduces to Condition 3.1. Along with this extension, we generalize the linearity condition for the q-function (Condition 3.2) as described below.

Condition 3.4. *(Local Linearity) Define a vector with binary values for representing the first s dimensions of the action features as $\mathbb{I}_{f_{1:s}} \in \mathbb{R}^{m^s}$. The overall action indicator $\mathbb{I}_a$ is then defined as $\mathbb{I}_a := concat[\mathbb{I}_{f_l}, \mathbb{I}_{f_{1:s}}]$. We say that the q-function meets Local Linearity, if for each context $x \in \mathcal{X}$, there exists an (unknown) intrinsic reward vector $\phi_x = concat[\phi_{x,l} \in \mathbb{R}^{dm}, \phi_{x,1:s} \in \mathbb{R}^{m^s}]$ such that:*

$$q(x,a) = \underbrace{\sum_{l=1}^{d} q_l(x, f_l(a)) + q(x, f_{1:s}(a))}_{\mathbb{I}_{f_l(a)}^T \phi_{x,l} \quad + \quad \mathbb{I}_{f_{1:s}(a)}^T \phi_{x,1:s}} = \mathbb{I}_a^T \phi_x.$$

The Local Linearity condition allows the first s dimensions of the action features to have interaction effects with each other. Therefore, this condition is milder than linearity of PI (Condition 3.2), because linearity does not allow any interaction effects across different action features. When $s = 1$, the condition of local linearity reduces to the linearity condition (Condition 3.2).

Building on these generalized conditions, we propose a new policy gradient estimator, called the Local Combination PseudoInverse (LCPI) estimator, generalizing the PI estimator [35] as below.

$$\nabla_\theta \widehat{V}_{\mathrm{LCPI}}(\pi_\theta; \mathcal{D}) = \frac{1}{n} \sum_{i=1}^{n} \left(\sum_{a \in \mathcal{A}} \pi_\theta(a|x_i) \nabla_\theta \log \pi_\theta(a|x_i) \mathbb{I}_a{}^T \right) \Gamma_{\pi_0, x_i}^{\dagger} \mathbb{I}_{a_i} r_i, \quad (5)$$

where $\Gamma_{\pi_0,x} := \mathbb{E}_{\pi_0(a|x)}[\mathbb{I}_a \mathbb{I}_a^T | x]$.

LCPI satisfies unbiasedness against the PG $\nabla_\theta V(\pi_\theta)$ under Conditions 3.3 and 3.4, i.e., $\mathbb{E}_{\mathcal{D}}[\nabla_\theta \widehat{V}_{\mathrm{LCPI}}(\pi_\theta; \mathcal{D})] = \nabla_\theta V(\pi_\theta)$. This indicates that LCPI can estimate the reward of new actions while dealing with the interaction effects among action features (the original PI estimator cannot deal with such interaction effects).

Although LCPI is effective for selecting new actions than PI by dealing with the interaction effects, traditional policy- or regression-based methods may achieve better performance within existing actions. This is because they do not rely on any condition by focusing only on existing actions. Therefore, there is an interesting tradeoff between our LCPI and traditional methods. While traditional methods focus on identifying the optimal one within existing actions, LCPI is superior in choosing new actions leverafing action features and local linearity. This interesting tradeoff leads us to finally develop the **Policy Optimization for New Actions (PONA)** algorithm, which integrates LCPI with the DR estimator as follows:

$$\nabla_\theta \widehat{V}_{\mathrm{PONA}}(\pi_\theta; \kappa, \mathcal{D}) = \kappa \cdot \nabla_\theta \hat{V}_{\mathrm{LCPI}}(\pi_\theta; \mathcal{D}) + (1-\kappa) \cdot \nabla_\theta \hat{V}_{\mathrm{DR}}(\pi_\theta; \mathcal{D}), \quad (6)$$

where $\kappa \in [0,1]$ is a hyperparameter that controls the trade-off between focusing on new actions and maximizing the overall policy value by prioritizing existing actions. A larger value of κ increases the weight of the LCPI component, which leads to greater reliance on the local linearity condition and a stronger focus on optimizing new actions. However, this approach sacrifices the effectiveness of identifying the optimal actions within the set of existing actions. In contrast, a smaller value of κ increases the weight of DR, reducing reliance on local linearity and shifting the focus toward optimizing existing actions. This results in a more conservative policy that rarely selects new actions. We can tune the value of κ in a data-driven manner using a cross-validation procedure. Multiple formulations of cross-validation can be considered for tuning κ, depending on the specific objectives. For instance, one can simply maximize the policy value $V(\pi)$ on the validation set when tuning κ. Alternatively, it is possible to impose constraints on the proportions of new actions under the learned policy, allowing control over how aggressive or conservative the new policy should be, as follows.

$$\max_{\kappa} \hat{V}(\pi_{\theta,\kappa}; \mathcal{D}) \quad \text{s.t. } \rho_L \leq \mathbb{E}_{p(x)}[\sum_{a \in \mathcal{A}_{new}} \pi_{\theta,\kappa}(a|x)] \leq \rho_U, \quad (7)$$

where ρ_L and ρ_U define the desired range for the proportion of new actions. In the next section, we will empirically demonstrate that, by performing this cross-validation procedure and changing the values of ρ_L and ρ_U, we can flexibly control the proportion between existing and new actions under the learned policy. Note that, when performing cross-validation, we can estimate the policy value $\hat{V}(\pi_{\theta,\kappa})$ of the policy induced by κ by applying off-the-shelf OPE estimators such as IPS and DR in the validation set [25].

4 Empirical Evaluation

This section empirically evaluates our proposed method, PONA, and its special case (LCPI) on synthetic and real-world datasets (**empirical results on real data can be found in Appendix D.2**).

We begin by sampling context vectors x from a normal distribution. The action features span $d = 5$ dimensions, with each feature having $m = 3$ possible values. The total number of possible actions is thus $|\mathcal{A}| = 3^5 = 243$. We then define the synthetic q-function as

$$q(x,a) = \sum_{l=1}^{d} \underbrace{q_l(x, f_l(a))}_{:= x^T M_{f_l(a)}} + \underbrace{q_{1:s}(x, f_{1:s}(a))}_{:= x^T M_{f_{1:s}(a)}} + \gamma \cdot \underbrace{q_{1:d}(x, f_{1:d}(a))}_{:= x^T M_{f_{1:d}(a)}},$$

where γ is a parameter that controls the contribution of the last term $q_{1:d}(x, f_{1:d}(a))$. M_{f_l}, $M_{f_{1:s}}$, and $M_{f_{1:d}}$ are parameter matrices sampled from a uniform distribution. The first term of the q-function, $q_l(x, f_l(a))$, represents the independent effect of each dimension of the action feature. The second term, $q_{1:s}(x, f_{1:s}(a))$, captures the interaction effects within the first s dimensions of the action feature. Most methods, including IPS, DR, and ours, can handle the first two terms because they do not involve interaction effects beyond

[1] Note that we focus on the first s dimensions just for ease of exposition, as the dimensions of the action feature can be arbitrarily reordered.

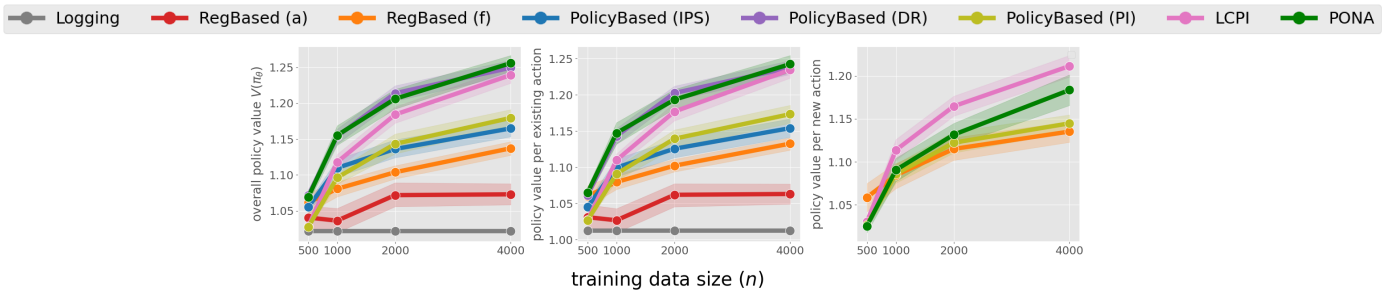


Figure 2: Comparisons of the overall policy value, policy value per existing action, and policy value per new action with varying training data sizes (n). Note that the metrics are normalized by those of the uniform random policy.

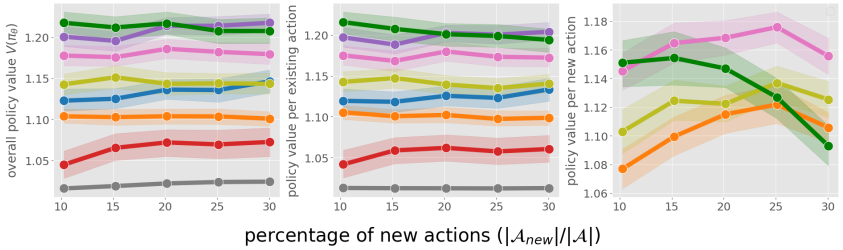


Figure 3: Comparisons of the overall policy value, policy value per existing action, and policy value per new action with varying percentages of new actions ($|\mathcal{A}_{new}|/|\mathcal{A}|$). Note that the metrics are normalized by those of the uniform random policy.

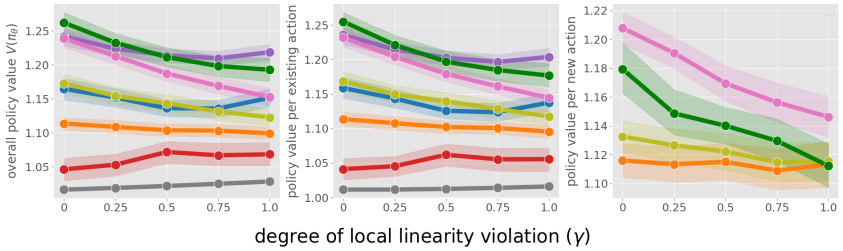


Figure 4: Comparisons of the overall policy value, policy value per existing action, and policy value per new action with varying degrees of local linearity violation (γ). Note that the metrics are normalized by those of the uniform random policy.

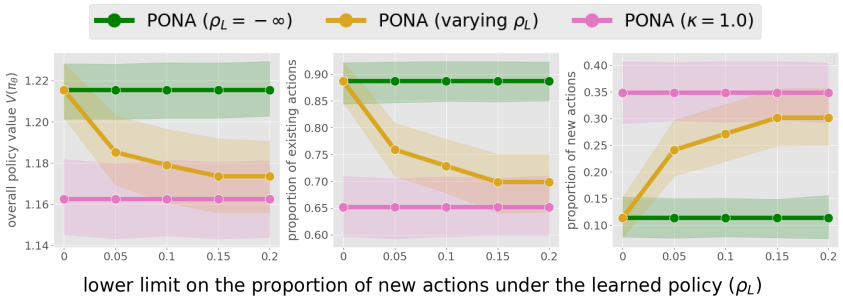


Figure 5: Comparisons of the overall policy value, proportion of existing actions, and proportion of new actions under the learned policy with varying lower limits on the proportion of new actions (ρ_L in Eq. (7)).

the first s dimensions. Only the original PI method [35] cannot estimate the second term due to its reliance on the linearity condition. The last term of the q-function, $q_{1:d}(x, f_{1:d}(a))$, accounts for the interaction effects among all dimensions of the action feature. The proposed methods cannot estimate the last term without bias due to their reliance on local linearity, while existing methods can achieve unbiased estimation of the q-function within existing actions regardless of the interaction effects. By adjusting the γ parameter, we control the degree of the condition's violation and evaluate the robustness of our methods under these violations.

Compared Methods. We compare PONA and LCPI with the logging policy π_0, the regression-based method using action index (RegBased (a)), the regression-based method using action feature (RegBased (f)), policy-based method w/ IPS (PolicyBased (IPS)), policy-based method w/ DR (PolicyBased (DR)), and policy-based

method w/ PI (PolicyBased (PI)). We report RegBased (f) as a baseline method that estimates the q-function using action features as input. It then picks the best action according to the estimated reward function $\hat{q}_\theta(x, f_{1:d}(a))$. RegBased ($f$) differs from RegBased (a) in that it may select new actions. To tune the hyperparameter κ for PONA, we perform a grid search over the range $[0, 0.25, 0.5, 0.75, 1.0]$, selecting the best value in terms of optimizing the policy value $V(\pi)$ on validation data.

Result. We report the following metrics of policies learned by each OPL method, averaged across 200 simulations.

- **overall policy value**: $\mathbb{E}[\sum_{a\in\mathcal{A}} \pi_\theta(a|x)q(x,a)]$
- **policy value per existing action**: $\frac{\mathbb{E}[\sum_{a\in\mathcal{A}_{existing}} \pi_\theta(a|x)q(x,a)]}{\mathbb{E}[\sum_{a\in\mathcal{A}_{existing}} \pi_\theta(a|x)]}$
- **policy value per new action**: $\frac{\mathbb{E}_{p(x)}[\sum_{a\in\mathcal{A}_{new}} \pi_\theta(a|x)q(x,a)]}{\mathbb{E}[\sum_{a\in\mathcal{A}_{new}} \pi_\theta(a|x)]}$

Overall policy value measures the overall effectiveness of the learned policy. **Policy value per existing action** evaluates the quality of selecting existing actions, while **policy value per new action** assesses that of selection within new actions. **Note that the logging policy π_0, RegBased (a), PolicyBased (IPS), and PolicyBased (DR) do not choose new actions at all, and thus their results do not appear in the figures of policy value per new action.**

How does PONA perform with varying sizes of training data? First, we compare the OPL methods using varying sizes of training logged data ($n \in \{500, 1000, 2000, 4000\}$), as shown in Figure 2. The figure shows that most methods, including PONA and LCPI, improve in overall policy value, policy value per existing action, and policy value per new action as the training data size increases, which aligns with expectations. Notably, LCPI performs particularly well in terms of the selection of new actions when the training data size is relatively large ($n = 2000, 4000$). However, it underperforms PolicyBased (DR) in terms of overall policy value. In contrast, PONA combines the strengths of LCPI and PolicyBased (DR), maintaining a policy value per new action comparable to RegBased (f) while matching PolicyBased (DR) in terms of overall policy value. Considering that existing methods, including PolicyBased (DR), cannot select new actions at all, it is noteworthy that **PONA not only selects new actions and gives fair opportunities to them as effectively as RegBased (f) but also achieves overall performance competitive with PolicyBased (DR).**

How does PONA perform with varying numbers of new actions? Next, Figure 3 illustrates how the OPL algorithms perform as the percentage of new actions, $100 \cdot \frac{|\mathcal{A}_{new}|}{|\mathcal{A}|}$, increases. As the percentage of new actions grows, the number of existing actions decreases. The figure shows that methods focusing exclusively on existing actions (RegBased (a), PolicyBased (IPS), PolicyBased (DR)) exhibit a slight improvement in policy value for existing actions as the percentage of new actions increases. This is because, with fewer existing actions, it becomes easier to identify the optimal action within the reduced set. Nevertheless, PONA consistently achieves the same or slightly better overall policy value compared to PolicyBased (DR), while also selecting new actions for any percentage of new actions. In comparison, PolicyBased (DR) and other traditional methods never select new actions, even as the percentage of new actions increases. PolicyBased (PI) is mostly worse than PONA and LCPI in every metric due to its reliance on linearity, which is severely violated in our experimental environment.

How does PONA perform when Condition 3.4 is violated? We next evaluate the robustness of the proposed methods against violations of their key condition, namely, local linearity. To test this, we increase the value of γ in the definition of the synthetic reward function in the x-axis of Figure 4. The figure demonstrates that as γ increases, the violations of the local linearity condition become more pronounced, leading to a gradual decrease in the overall policy value of LCPI. In contrast, existing methods that do not rely on any assumptions about the q-function exhibit little change in policy value with varying values of γ, which is reasonable. Most interestingly, PONA, which also relies on local linearity, is more robust to the condition's violation than LCPI. This occurs because its data-driven tuning process in Eq. (7) adjusts its hyperparameter κ to assign greater weight to the DR component as the violation becomes more severe. This adjustment adaptively maintains the policy value for existing actions, remaining a high overall policy value. Even in scenarios where the ability to learn new actions is at its weakest, PONA performs comparably to RegBased (f) for new actions, significantly outperforming PolicyBased (DR) and other baseline methods in selecting new actions. These results highlight PONA's ability to maintain a high policy value and effectively learn new actions, even when its key condition is severely violated

How does PONA perform when varying the constraints about the proportions of new actions during parameter tuning? In the previous experiments, we did not impose any constraints on the behavior of the learned policy when tuning the weight parameter κ of PONA (i.e., always setting $\rho_L = -\infty$ and $\rho_U = \infty$ in Eq. (7)). As a result, the tuning procedure selected the κ value that simply maximized the overall policy value in the validation data.

In Figure 5, we report the overall policy value and the proportions of existing and new actions under the learned policies for varying lower limit ρ_L in Eq. (7), while keeping $\rho_U = \infty$. Note that we include the metrics for PONA ($\rho_L = -\infty$) and PONA ($\kappa = 1.0$) as references in the figure. This experiment allows us to investigate how well PONA's behavior can be controlled through the tuning of κ. The right plot in Figure 5 demonstrates that, as the lower limit on the proportion of new actions becomes larger, the proportion of new actions under **PONA (with varying ρ_L)** increases. This result shows that we can control the behavior and aggressiveness of the learned policy by appropriately formulating the tuning process of the weight parameter κ. It is also reasonable that the overall policy value of PONA decreases with larger ρ_L, as this increases the reliance of PONA on the local linearity condition.

5 Conclusion

This work tackled the challenge of OPL with new actions. We first proposed the LCPI estimator for the policy gradient, which relaxes the restrictive conditions of PI by accounting for interactions among action features, enabling the more effective selection of new actions. To balance the strengths of LCPI for new actions and DR for existing actions, we also introduced the PONA algorithm. By integrating these estimators through a weight parameter, PONA efficiently selects new actions while maintaining strong overall performance.

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