

REWARD DROPOUT IMPROVES CONTROL: BI-OBJECTIVE PERSPECTIVE ON REINFORCED LM

Changhun Lee & Chiehyeon Lim

Graduate School of Artificial Intelligence, UNIST

ABSTRACT

We study the theoretical aspects of Reinforced Language Models (RLMs) from a bi-objective optimization perspective. Specifically, we consider the RLMs as a Pareto optimization problem that maximizes the two conflicting objectives, i.e., reward objective and likelihood objectives, simultaneously. Our main contribution consists of three parts. First, we establish the theoretical foundations of RLM as a Pareto optimization problem by presenting Reward Upper BOund (RUBO) and Pareto optimality. Our theoretical outcomes are supported by not only deductive proofs but also empirical results. Second, we propose Reward Dropout, a simple yet powerful method that guarantees to improve a bi-objective optimization of RLM. Lastly, we demonstrate that the Reward Dropout is consistently effective across five benchmark datasets and four benchmark LLMs, meaning that the Reward Dropout significantly improves the optimization performance of RLMs.

1 INTRODUCTION

The emergence of ChatGPT has sparked public interest in language models (LMs), resulting in a surge of LM research in both academia and industry. In particular, the use of reinforcement learning (RL) to control LMs has emerged as a significant research topic. In fact, leveraging RL to fine-tune LMs, or reinforced language models (RLMs) (Stiennon et al., 2020; Korbak et al., 2022; Ouyang et al., 2022; Bai et al., 2022), has long been studied as one of the general approaches to building controllable language models (CLMs) (Hu et al., 2017; Liu et al., 2022; Zhang et al., 2022a; Liu et al., 2023), where the goal is to generate sequences of intended attributes. The sequences here include texts (Yu et al., 2017; Li et al., 2017b; Ziegler et al., 2019; Liu et al., 2020a; Ouyang et al., 2022), melodies (Jaques et al., 2017; Jiang et al., 2020), molecules (Guimaraes et al., 2017; Olivercrona et al., 2017; Popova et al., 2018), menu lists (Chen et al., 2015; Lee et al., 2021; Mårtensson, 2021), purchase behaviors (Zhao et al., 2017; Bai et al., 2019; Zou et al., 2019; Shin et al., 2022), etc. Despite its long history and recent popularity, however, there is still a lack of theoretical understanding of how RLM works, under what conditions it succeeds or fails, and whether it can be guaranteed to improve control performance.

In this work, we study the theoretical aspects of RLMs through the lens of a Pareto optimization problem. Specifically, in Section 2, we consider the objective function of RLM as the off-policy RL problem (see Eq (4)) and in Section 3, we recast the RLM from a bi-objective problem that has the nature of a Pareto optimization (see Eq (6)). Section 4 presents theoretical and empirical evidence that the RLM is indeed a Pareto optimization problem. Based on this evidence, we propose Reward Dropout, a simple yet powerful method that guarantees to improve the bi-objective optimization of RLM. Finally, in Section 5, we evaluate the performance of Reward Dropout on five RLM benchmark datasets. Reward Dropout, which has its theoretical origins in Theorem 4.3, showed significant performance improvements on all RLM benchmark datasets. Our contributions are summarized as follows:

- Show that RLMs can be analyzed from a bi-objective perspective, which has the nature of Pareto optimization.
- Propose a simple yet powerful method named Reward Dropout that guarantees to improve the bi-objective optimization of RLMs.
- Demonstrate the effect of Reward Dropout is consistent across five benchmark datasets and four benchmark LLMs.

2 PRELIMINARIES

2.1 CONTROLLABLE LANGUAGE MODELS

Controllable language models (CLMs) are the models designed to address a controlled text generation (Hu et al., 2017; Liu et al., 2022; 2023; Zhang et al., 2022a). That is, the CLM aims to inject a specific control code c into a language model (LM) so that the sequence (trajectory) $\tau = [x_1, x_2, \dots, x_T]$ is generated as intended. Current approaches for modeling CLMs include the class conditional language model (CCLM) (Ficler & Goldberg, 2017; Dai et al., 2019; Keskar et al., 2019; Sudhakar et al., 2019), Bayesian controllable language model (BCLM) (Dathathri et al., 2019; Krause et al., 2020; Yang & Klein, 2021; Lu et al., 2021; Li et al., 2022), and reinforced language model (RLM) (Bian et al., 2019; Yu et al., 2017; Xu et al., 2018; Luo et al., 2019; Liu et al., 2020c; Stiennon et al., 2020; Korbak et al., 2022; Ouyang et al., 2022; Bai et al., 2022).

In CCLM approach, we prepend a code c to the sequence, i.e., $\text{concat}(c, \tau)$, so that the language model parameters θ_{lm} are directly updated on c ,

$$\ln p_{\text{clm}}(\tau|c) := \sum_{t=1}^T \ln p_{\text{lm}}(x_t|x_{<t}, c). \quad (1)$$

Note that a target code c' is fed to $p_{\text{clm}}(\hat{\tau}|c')$ to intend a specific control during inference. On the other hand, in BCLM approach, we separate the control part from the language model using Bayes' theorem by defining a distinctive classifier $p_{\text{cls}}(c|\tau)$,

$$\ln p_{\text{clm}}(\tau|c) = \ln \frac{p(\tau)p(c|\tau)}{p(c)} \propto \ln p_{\text{lm}}(\tau) + \ln p_{\text{cls}}(c|\tau). \quad (2)$$

Similar to CCLM, a target code c' is fed to $p_{\text{cls}}(c'|\hat{\tau})$ during inference. The differences is that c is given as a label of $p_{\text{cls}}(\cdot|\tau)$ rather than a conditional variable of $p_{\text{lm}}(x_t|x_{<t}, \cdot)$. The parameters of $p_{\text{lm}}(\tau)$ and $p_{\text{cls}}(c|\tau)$ are separately pre-trained (i.e., θ_{lm} is not updated on c), and the decoding process is controlled online by summing up the log-likelihoods of on-the-fly sequences $\hat{\tau}$ and target codes c' (i.e., sampling $\hat{\tau}$ that maximizes $\ln p_{\text{lm}}(\hat{\tau}) + \ln p_{\text{cls}}(c'|\hat{\tau})$).

2.2 REINFORCED LANGUAGE MODEL

Reinforced Language Models (RLM) is somewhere in the middle of CCLM and BCLM. Analogous to BCLM, the RLM separates the control part as a reward model $R(\tau) := p_{\text{cls}}(c|\tau)$, but like CCLM, θ_{lm} is updated on c through $R(\tau)$,

$$\ln p_{\text{clm}}(\tau|c) \approx \ln p_{\text{lm}}(\tau|\theta_{\text{clm}}) \quad \text{where} \quad \theta_{\text{clm}} = \arg \max_{\theta_{\text{lm}}} \mathbb{E}_{\tau \sim p_{\text{lm}}(\hat{\tau}|\theta_{\text{lm}})} [R(\tau)]. \quad (3)$$

In general, RLM studies (Stiennon et al., 2020; Korbak et al., 2022; Ouyang et al., 2022; Bai et al., 2022) focuses on maximizing the objective function defined as:

$$\arg \max_{\theta} \mathbb{E}_{\tau \sim \pi_{\theta}^{\text{RL}}} [R(\tau)] - \text{KL}[\pi_{\theta}^{\text{RL}}(\tau) || \pi_{\theta}^{\text{SL}}(\tau)] \iff \arg \min_{\theta} \text{KL} [\pi_{\theta}^{\text{RL}}(\tau) || \pi_{\theta}^{\text{SL}}(\tau) e^{R(\tau)}] \quad (4)$$

where π_{θ}^{SL} is a behavior model pre-trained on a supervision dataset, $R(\cdot)$ is a reward function, and π_{θ}^{RL} is a target model optimized for π_{θ}^{SL} and $R(\cdot)$ simultaneously. This suggests that RLM is not only a bi-objective problem, but also an off-policy RL problem where the behavior model π_{θ}^{SL} determines the sampling distribution of sentences $\tau \sim \pi_{\theta}^{\text{RL}}$. Note that $R(\cdot)$ is commonly defined as a reward model R_{ϕ} parameterized by ϕ , i.e., a pre-trained classifier that predicts how likely the given sentence τ contains the code of intended attributes.

3 PROBLEM STATEMENT

3.1 OPTIMIZING RLM AS BI-OBJECTIVES PROBLEM

Given an off-policy RL can be viewed as a probabilistic inference (Kappen et al., 2012; Rawlik et al., 2012; Levine, 2018), Eq (4) indicates that RLM can be addressed by the probabilistic inference framework. This framework allows us an approximate inference that estimates the target trajectory

$\tau \sim \pi \in \mathcal{T}_\pi$ under the behavior trajectory $\tau \sim \beta \in \mathcal{T}_\beta$, by minimizing Kullback-Leibler Divergence (KLD):

$$\text{KL} \left[\pi(\tau) \middle\| \beta(\tau) e^{R(\tau)} \right] = \sum_{\tau} \pi(\tau) \ln \frac{\pi(\tau)}{\beta(\tau) e^{R(\tau)}}, \quad (5)$$

where $\beta(\tau)$ is a behavior policy and $\pi(\tau)$ is a target policy. Treating RLM as a probabilistic inference implies that a control variable is defined as an entire trajectory τ , rather than an action x_t as is in traditional RL frameworks. Consequently, we can optimize RLM by minimizing Eq (5), and an optimal solution $\pi^*(\tau)$ is obtained as a composite of the reward objective $R(\cdot)$ and the (behavior policy's) likelihood objective $\beta(\cdot)$:

$$\pi^*(\tau) = \frac{\beta(\tau) e^{R(\tau)}}{\sum_{\tau} \beta(\tau) e^{R(\tau)}} = \beta(\tau) e^{R(\tau)} \quad \left(\because \sum_{\tau} \beta(\tau) e^{R(\tau)} = 1 \right), \quad (6)$$

which confirms that optimizing RLMs is the bi-objectives problem. Note that $\sum_{\tau} \beta(\tau) e^{R(\tau)} = 1$ is a necessary condition for Eq (5) to have a minimum value.

3.2 PARETO OPTIMIZATION PROBLEM

There are two cases of the bi-objectives problem: when the two objectives are in conflict or not. The former case is referred to as a Pareto optimization problem (Ngatchou et al., 2005; Kyriakis & Deshmukh, 2022; Lin et al., 2019; 2022) that entails the following concepts:

Definition 3.1 (Pareto Dominance). *Assume arbitrary policies $\pi^a, \pi^b \in \Theta_\pi$. π^a is said to dominate π^b , denoted as $\pi^b \prec \pi^a$, if and only if $\mathbb{E}_{\tau \sim \pi^b} [R(\tau)] \leq \mathbb{E}_{\tau \sim \pi^a} [R(\tau)]$ and $\mathbb{E}_{\tau \sim \pi^b} [\beta(\tau)] \leq \mathbb{E}_{\tau \sim \pi^a} [\beta(\tau)]$ for all τ .*

Definition 3.2 (Pareto Improvement). *If $\pi^b \prec \pi^a$, the move from π^b to π^a is a Pareto improvement. Let $\hat{\pi}, \pi^* \in \Theta_\pi$ be non-optimal and optimal policies, respectively. A Pareto improvement always occurs for $\hat{\pi}$.*

Definition 3.3 (Pareto Optimality). *A policy $\pi^* \in \Theta_\pi$ is Pareto optimal if there is no $\hat{\pi} \in \Theta_\pi$ such that $\pi^* \prec \hat{\pi}$, and a trajectory $\tau^* \in \mathcal{T}_{\pi^*}$ is said to be a Pareto optimal point.*

Definition 3.4 (Pareto Set / Frontier). *A Pareto set is a set of Pareto optimal points, and its image in the objective space is the Pareto frontier.*

Simply put, the target policy $\pi(\tau)$ is called Pareto optimal when policy improvement is no longer possible. Note that an optimal policy $\pi^*(\tau)$ is the Pareto solution, a trajectory sampled from it is the Pareto optimal point $\tau^* \sim \pi^*$, and a line connecting all optimal points is called the Pareto frontier. In Section 4, we show that optimizing an RLM is the Pareto optimization problem where the reward objective $R(\cdot)$ and the likelihood objective $\beta(\cdot)$ are in a trade-off.

3.3 TERMS & NOTATIONS

Given that RLMs integrate both RL and LM contexts, some readers may find the context-specific terminology confusing. Therefore, in this paper, we aim to use consistent terminology across these contexts to eliminate potential confusion. In the subsequent paragraph, we define some interchangeable terms and notations used in our study

In the RL context, τ is a trajectory consisting of total T actions, where each t -th action a_t is sampled from the behavior policy $\beta(\tau)$. In the LM context, τ is a text sequence $x = [x_1, \dots, x_T]$ consisting of total T words sampled from the behavior LM $\beta_\theta(\tau)$. Actions (words) are tokenized by zero or natural numbers, so the trajectory (sequence) space \mathcal{T} is defined over non-negative integer space, $\tau \in \mathcal{T} \subseteq \mathbb{Z}_0$. From RLM perspectives, the two contexts have the same training goal: “*to optimize the target policy $\pi(\tau)$ or target LM $\pi_\theta(\tau)$ w.r.t. the reward objective $R(\tau)$, but adhere to the likelihood objective (i.e., behavior policy or behavior LM) $\beta(\tau)$.*” The parameters of the behavior and target LMs are denoted as $\bar{\theta}$ and θ , respectively. $\bar{\theta}$ is a pre-defined (pre-trained) fixed parameter and θ is a parameter that is initialized to $\bar{\theta}$ and fine-tuned during a training process. In this paper, we use the terms “policy” and “LM” interchangeably. Therefore, let us focus on whether a given policy (or LM) is either behavior or target one. Finally, we refer to $\beta(\tau)$ as the behavior policy or likelihood objective. The former name comes from the off-policy RL perspective, while the latter comes from

the Pareto optimization perspective. Note that $\pi(\tau)$ and $\beta(\tau)$ are the probability density functions, i.e., $\pi(\tau), \beta(\tau) \in [0, 1]$, $\sum_{\tau} \pi(\tau) = \sum_{\tau} \beta(\tau) = 1$. Similarly, $R(\tau) \in [0, 1]$ was considered to have values between 0 and 1.

4 THEORETICAL ANALYSIS, METHODOLOGY, AND VALIDATION

In this section, we prove that RLM can theoretically be considered a Pareto optimization problem. First, we show that reward is upper-bounded (see Theorem 4.1), and that the Pareto optimality is achieved by the reward upper bound such that the reward objective $R(\tau)$ is negatively logarithmic to the likelihood objective $\beta(\tau)$ (see Theorem 4.2). Furthermore, we present that the negation of the reward upper bound yields a Pareto improvement condition (see Theorem 4.3) and propose a simple yet powerful method, called Reward Dropout, that guarantees to improve the bi-objective optimization of RLM. Finally, we empirically verify the theoretical results and validate whether Reward Dropout is effective.

4.1 REWARD UPPER BOUND, PARETO OPTIMALITY & IMPROVEMENT

The essence of Pareto optimality lies in that both objectives have a trade-off at the optimal points, or in other words, both objectives, $R(\tau)$ and $\beta(\tau)$, must be better off simultaneously up to the optimal points. This implies one objective can be improved only up to “a certain level” without sacrificing the other; here, that level represents “an optimal state.” Accordingly, if the optimal state is specified, the reward objective $R(\tau)$ should be upper-bounded by the likelihood objective $\beta(\tau)$. In this regard, we present Theorem 4.1 that provides a Reward Upper BOund (RUBO). RUBO provides us with an interesting intuition: *“the larger the KL divergence between $\pi(\tau)$ and $\beta(\tau)$, the higher the expected reward $\mathbb{E}_{\tau \sim \pi}[R(\tau)]$.* In other words, reward maximization requires π to deviate as far away from β as possible. The proof is given in Appendix B.1.

Theorem 4.1 (Reward Upper Bound). *If $\sum_{\tau} \pi(\tau) = 1$ and $\pi(\tau) = \beta(\tau)e^{R(\tau)}$ hold, then $\mathbb{E}_{\tau \sim \pi}[R(\tau)] \leq \text{KL}[\pi(\tau) || \beta(\tau)]$ holds.*

Proof sketch. Show that Eq (5), i.e., $\text{KL}[\pi(\tau) || \beta(\tau)e^{R(\tau)}]$, is non-negative and yields an inequality. Then, we can rewrite the inequality such that the reward is upper-bounded. \square

According to Definitions 3.1 through 3.4, Pareto optimality requires that the likelihood $\beta(\tau)$ and reward $R(\tau)$ objectives should be negatively related for all the optimal points $\tau^* \sim \pi^*$, and the Pareto frontier should be drawn as a rightward sloping line accordingly. That is, the optimal policy $\pi^*(\tau)$ must yield a result that the two objectives are negatively related. In this regard, we present Theorem 4.2. Theorem 4.2 states that as long as RUBO holds, $\beta(\tau)$ and $R(\tau)$ have a negative logarithmic relationship for all optimal solutions, i.e., $\forall \tau^* \sim \pi^*$ where π^* is given by Eq (6), i.e., $\pi^*(\tau) = \beta(\tau)e^{R(\tau)}$. This clarifies that optimizing RLM is a Pareto optimization problem. The proof is given in Appendix B.2.

Theorem 4.2 (Pareto Optimality). *If $\mathbb{E}_{\tau \sim \pi}[R(\tau)] \leq \text{KL}[\pi(\tau) || \beta(\tau)]$ holds, then $\forall \tau^* \sim \pi^*$, $R(\tau) = -\ln \beta(\tau)$ holds.*

Proof sketch. Show that when the expected reward is maximized, i.e., $\max \mathbb{E}_{\tau \sim \pi}[R(\tau)]$, the inequality by reward upper bound, i.e., $\mathbb{E}_{\tau \sim \pi}[R(\tau)] \leq \text{KL}[\pi(\tau) || \beta(\tau)]$, becomes equality, and that $R(\tau)$ and $\beta(\tau)$ are negatively related in this equality. \square

In a Pareto optimization problem, any policy that is not Pareto optimal always has room for Pareto improvement. By Theorems 4.1 and 4.2, we confirmed that Eq (6), i.e., $\pi(\tau) = \beta(\tau)e^{R(\tau)}$, is a Pareto optimal, and thus, by Definition 3.2, $\pi(\tau) \neq \beta(\tau)e^{R(\tau)}$ always results in the Pareto improvement. That is, satisfying a condition for $\pi(\tau) \neq \beta(\tau)e^{R(\tau)}$ guarantees to improve the optimization of RLM. We derive this condition through *reductio ad absurdum*, i.e., the proof by contradiction, in Theorem 4.3. Specifically, Theorem 4.3 shows that the negation of Theorem 4.1, i.e., $\mathbb{E}_{\tau \sim \pi}[R(\tau)] > \text{KL}[\pi(\tau) || \beta(\tau)]$, leads to the negation of Eq (6), i.e., $\pi(\tau) \neq \beta(\tau)e^{R(\tau)}$, and the Pareto improvement holds accordingly. As shown by the proof in Appendix B.3, $\mathbb{E}_{\tau \sim \pi}[R(\tau)] > \text{KL}[\pi(\tau) || \beta(\tau)]$ is equivalent to $\mathbb{E}_{\tau \sim \pi_{\theta}}[R(\tau)] + \mathbb{E}_{\tau \sim \pi_{\theta}}[\ln \beta(\tau)] > 0$, and thus updating θ to satisfy $\mathbb{E}_{\tau \sim \pi_{\theta}}[R(\tau)] + \mathbb{E}_{\tau \sim \pi_{\theta}}[\ln \beta(\tau)] > 0$ guarantees policy improvement. In short, we can better optimize θ by manipulating $R(\cdot)$ or $\beta(\cdot)$ such that $\mathbb{E}_{\tau \sim \pi}[R(\tau)] + \mathbb{E}_{\tau \sim \pi}[\ln \beta(\tau)] > 0$ is always satisfied.

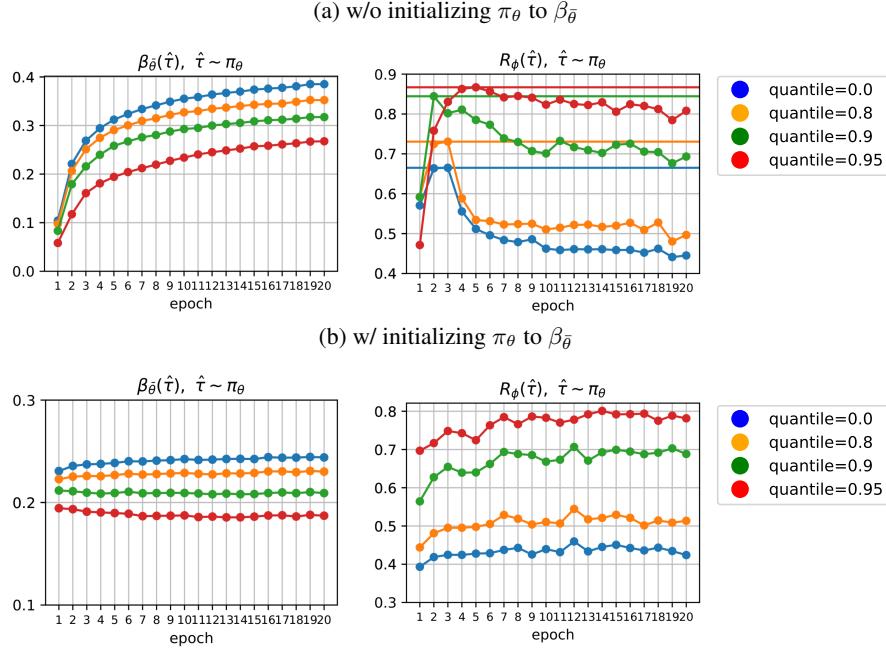


Figure 1: Presenting the bi-objectivity and trade-off in Eq (5), and illustrating the Reward Dropout effect according to different quantiles and scenarios. The red, green, orange, and blue horizontal lines represent the Reward Upper Bound (RUBO). It is worth noting that Reward Dropout works consistently in both scenarios (a) and (b).

Theorem 4.3 (Pareto Improvement Condition). *For $\pi(\tau) \neq \beta(\tau)e^{R(\tau)}$ to hold, $\mathbb{E}_{\tau \sim \pi}[R(\tau)] > KL[\pi(\tau) || \beta(\tau)]$, or equivalently Eq (7), must hold.*

$$\mathbb{E}_{\tau \sim \pi}[R(\tau)] + \mathbb{E}_{\tau \sim \pi}[\ln \beta(\tau)] > 0 \quad (7)$$

Proof sketch. Show that the contraposition of RUBO, i.e., $\mathbb{E}_{\tau \sim \pi}[R(\tau)] > KL[\pi(\tau) || \beta(\tau)]$, yields the Pareto improvement, i.e., $\pi(\tau) \neq \beta(\tau)e^{R(\tau)}$. For this, we can use “*the proof by contradiction*” method: $p \rightarrow q \Rightarrow \neg q \rightarrow \neg p$. \square

4.2 REWARD DROPOUT

According to Theorem 4.3, the target policy is guaranteed to improve both $R(\tau)$ and $\beta(\tau)$ simultaneously as long as Eq (7) holds. The message behind it is simple: “*all you need is to manipulate either or both $R(\cdot)$ and $\beta(\cdot)$ so that $\mathbb{E}_{\tau \sim \pi}[R(\tau)] + \mathbb{E}_{\tau \sim \pi}[\ln \beta(\tau)] > 0$ is achieved for all τ .*” However, in an off-policy RL context, $\beta(\tau)$ is either a pre-defined policy or a pre-trained LM, whose distribution or parameter should be fixed. Accordingly, it is only $R(\tau)$ that can be manipulated, and “*we need to manipulate $R(\tau)$ such that only a few high rewards are considered.*” The reason why “only a few high rewards” should be considered is that $\mathbb{E}_{\tau \sim \pi}[R(\tau)]$ refers to the average reward \tilde{r} , and the average is sensitive to bias caused by outliers. Extremely saying, a single high reward is more effective at satisfying Eq (7) than many average rewards. As a practical implementation of reward manipulation, we proposed Reward Dropout, a technique that leaves only a few high rewards and sets the rest to zero. Specifically, it sorts rewards in ascending order, divides them into equal intervals, and then sets rewards that fall below a certain quartile to zero. Reward Dropout is an example of an RL technique that leverages quantized reward intervals (Dabney et al., 2018; Lu et al., 2022), and is therefore applicable to any models or algorithms that deal with RL problems.

4.3 BI-OBJECTIVITY, TRADE-OFF, AND THE EFFECT OF REWARD DROPOUT

In this section, we present empirical evidence that optimizing RLM is a Pareto optimization problem where “*the two conflicting objectives are optimized simultaneously.*” Also, we show that satisfying Eq (7), or Reward Dropout, is indeed effective for improving the optimization of RLM. Lastly, we experiment with how the initialization of the target policy affects the optimization performance.

To evaluate the performance, we visualized a trend of likelihood and reward objectives. Both objectives were represented by behavior model $\beta_{\bar{\theta}}$ and reward model R_{ϕ} , respectively. For the behavior model we used a benchmark LLM (e.g., OpenAI GPT-2) without fine-tuning, while for the reward model, we implemented a Transformer-based classifier by ourselves and pre-trained it on the relevant dataset according to control attributes (e.g., sentiment, topic, etc.). In this experiment, we used AG_News (Zhang et al., 2015) dataset, and the reward model was trained to predict how likely the given sentence belongs to a sports topic. Figure 1 shows the result in two different scenarios: (a) π_{θ} was initialized with random parameters, and (b) π_{θ} was initialized with behavior parameters $\bar{\theta}$.

Figure 1a illustrates a result of scenario (a) and demonstrates that both objectives are maximized simultaneously (i.e., bi-objectives optimization) until the RUBO is touched, after which we can observe that $R(\cdot)$ continues to fall while $\beta(\cdot)$ continues to rise (i.e., trade-offs between $\beta(\cdot)$ and $R(\cdot)$). This supports Theorems 4.1 and 4.2 that (1) the reward is upper-bounded (2) $\beta(\cdot)$ and $R(\cdot)$ are log-negatively related, and provides evidence that RLM is a Pareto optimization problem. On the other hand, Figure 1b illustrates a result of scenario (b). In general, RLM researchers prefer to follow this scenario (so do we) because if we initialize the target policy π_{θ} to the pre-trained LLM $\beta_{\bar{\theta}}$, we do not need to optimize our model for the likelihood objective but only for the reward objective; the large parameter space of LLM is robust enough to withstand parameter degeneracy due to reward optimization. For training practicality and stability, all experiments in this paper were designed to follow scenario (b).

The key takeaway from Figure 1 is that Reward Dropout drives performance improvement in both scenarios (a) and (b). It is also noteworthy that as the quantile increases, i.e., as the model learns rewards that are biased toward the top few outliers, performance improves more significantly. This is exactly what we intended for Reward Dropout, as described in Section 4.2. Most importantly, the sum of the likelihood and reward values always increases with Reward Dropout, which is evidence that Reward Dropout is definitely achieving Pareto Improvement.

5 BENCHMARK EXPERIMENTS

In this section, we evaluate the performance of Reward Dropout on five benchmark datasets and test whether the effect of Reward Dropout maintains regardless of the capacity of behavior LMs.

Datasets To validate the effectiveness of Reward Dropout, we conducted performance experiments on five RLM benchmark datasets, aiming to control the generation of text with specific attributes. Each dataset covers different attributes of sentences including sentiment (negative, positive), politeness (polite, non-polite), toxicity (toxic, non-toxic), emotion (anger, disgust, fear, happiness, sadness, surprise), and topic (world, sports, business, sci/tech). For the sentiment, toxicity, emotion, and topic datasets, we collected publicly accessible sources such as Yelp (Zhang et al., 2015), Jigsaw (Dataset, 2017), DailyDialog (Li et al., 2017a), and AG_News (Zhang et al., 2015), respectively. The politeness dataset was downloaded from the GitHub repository released by Madaan et al. (2020).¹

Models & Algorithms. To build the behavior LM $\beta_{\bar{\theta}}$, we used OpenAI GPT-2 (Radford et al., 2019), the pre-trained LLM released by HuggingFace transformers library.² The target LM π_{θ} were initialized to the parameters of $\beta_{\bar{\theta}}$, and the target parameters θ were updated by fine-tuning them w.r.t the rewards predicted by a pre-trained reward model R_{ϕ} . For update algorithms, we utilized three policy-based RL algorithms: deterministic policy gradient (DPG) (Silver et al., 2014), stochastic policy gradient (SPG) (Williams, 1992; Sutton et al., 1999), and top-k policy gradient (KPG). They were all implemented in an off-policy gradient fashion (Degris et al., 2012; Liu et al., 2020b) (see Algorithm 1). In the LM context, we can implement DPG and SPG with greedy decoding and stochastic decoding, respectively. Similarly, the KPG was implemented based on top-k decoding strategy, expecting an intermediate performance between DPG and SPG. See Appendix C.1 for more information on how to implement DPG, SPG, and KPG in the LM context.

Random Dropout and Dropout Rate To clarify what we are dropping out affects the performance of Reward Dropout, we introduced a random Reward Dropout inspired by Srivastava et al. (2014). Random Dropout randomly sets some rewards to zero according to the dropout rate. In

¹<https://github.com/tag-and-generate/politeness-dataset>

²<https://huggingface.co/gpt2>

Decoding (Policy Gradient)	Reward Dropout	γ	Dataset				
			sentiment	politeness	toxicity	emotion	topic
<i>greedy</i> <i>(DPG)</i>	<i>no dropout</i>	–	0.506	0.602	0.505	0.023	0.277
		<i>random</i>	0.80 0.90 0.95	0.512 0.513 0.514	0.641 0.652 0.663	0.513 0.513 0.512	0.024 0.026 0.024
		<i>quantile</i>	0.80 0.90 0.95	0.735 0.780 0.778	0.715 0.834 0.883	0.521 0.529 0.562	0.049 0.062 0.067
	<i>stochastic</i> <i>(SPG)</i>	<i>no dropout</i>	–	0.660	0.896	0.706	0.103
			<i>random</i>	0.80 0.90 0.95	0.652 0.662 0.654	0.891 0.894 0.903	0.719 0.700 0.707
			<i>quantile</i>	0.80 0.90 0.95	0.821 0.852 0.854	0.933 0.950 0.971	0.741 0.759 0.785
	<i>top-k</i> <i>(KPG)</i>	<i>no dropout</i>	–	0.677	0.864	0.671	0.089
			<i>random</i>	0.80 0.90 0.95	0.669 0.672 0.668	0.877 0.876 0.875	0.665 0.704 0.687
			<i>quantile</i>	0.80 0.90 0.95	0.833 0.861 0.858	0.892 0.930 0.963	0.703 0.722 0.741
		<i>negative</i>	The chicken-crap, which is the worst thing I've ever seen.				
		<i>positive</i>	The chicken is so delicious , it's a big one.				
		<i>world</i>	The issue focused on the fact that Iran is not a state of war , and it has been unable to defend its people .				
		<i>sci/tech</i>	The issue focused on the development of a new system for computing and networking is that it takes more than two seconds to develop.				

Table 1: The numbers in the table denote the average rewards at the end of training. The underlined, **red-colored**, and **bolded** numbers represent the highest performance cases across the dropout, decoding, and dataset options, respectively. Note that γ is the dropout rate.

Dataset	Control attribute	Generated text
<i>sentiment</i>	<i>negative</i>	The chicken-crap, which is the worst thing I've ever seen.
	<i>positive</i>	The chicken is so delicious , it's a big one.
<i>topic</i>	<i>world</i>	The issue focused on the fact that Iran is not a state of war , and it has been unable to defend its people .
	<i>sci/tech</i>	The issue focused on the development of a new system for computing and networking is that it takes more than two seconds to develop.

Table 2: Above texts were generated by the target LM trained with stochastic decoding and quantile dropout ($\gamma = 0.95$). The underlined phrase refers to a given prefix, and the **red-colored words** highlight controlled parts. More examples are provided in Appendix F

addition, to evaluate how performance changes with the dropout rate, we introduced γ as a hyperparameter that denotes the percentage of zero rewards per training batch. Three dropout rates $\gamma \in \{0.80, 0.90, 0.95\}$ were tested.

Implementation Details In order for the behavior LM to generate a sentence, we need to provide the behavior LM with an initial state to start the generation process. To do this, we provided the behavior LM with a prefix that is an incomplete sentence as an initial state. Refer to Appendix C for implementation details (e.g., pseudo algorithm, hyperparameters, initialization setting, etc.).

Evaluation The performance of Reward Dropout was evaluated in three ways. First, we compared the average rewards of target LM at the end of training (see Table 1). This summarizes the expected

rewards achieved at the Pareto optimal state. Second, we visualized the reward growth of the target LM over training epochs. This describes the Pareto improvement effect (see Appendix E) driven by Reward Dropouts. Third, the controlled texts were evaluated by humans to ensure if they are reliable. For fairness, we grouped the evaluators to represent as different genders and races as possible (see Appendix G). Lastly, we tested if the larger behavior LM, the weaker the effect of Reward Dropout. The first and second evaluations were conducted with different dropout, decoding, and hyperparameter settings, while the third and last evaluation was conducted with the best setting.

6 RESULTS

Table 1 shows the results for our first evaluation: Reward Dropout improves the control performance for all decodings and datasets. In particular, it is likely that the higher γ (i.e., the more dropout), the better performance. Also, we can observe that the quantile dropout is much more effective than the random dropout, which is evidence that reward manipulation leads to Pareto improvement. Table 2 presents some examples of generated text that was controlled to have a specific sentiment or topic. These examples show that stochastic decoding with quantile dropout successfully controls the target LM to generate text as intended.

Figure 2 is a case result related to the second evaluation, showing that the average reward of the target LM increases throughout training. This suggests that quantile dropout is undoubtedly effective. We provide the full results in Appendix E due to page limit. To summarize the full results, 1) greedy decoding is the worst decoding strategy while stochastic decoding is the best one, 2) random dropout improves control performance better than no dropout at least with greedy decoding, and 3) there is no outstanding trend of reward growth in the emotion dataset. The last point is probably due to the unbalanced labels and lack of samples in the emotion dataset (see Appendix D), which also explains the small figures at emotion column in Table 1.

The third evaluation was conducted through a survey. We prepared 55 items designed to ask three types of questions: 1) distinguish between real and generated text, 2) select the more human-like text, and 3) label appropriate control attributes (i.e., control codes) to the generated text. Due to the page limit, we provide the survey form and results in Appendix G. The survey results show that respondents confused real texts and generated texts, and believed that generated text is more human-like. At the same time, it showed that the control performance met humans' reliability standards. In conclusion, training a target LM with stochastic decoding and quantile dropout can produce reliable texts with human-level control.

Figure 3 illustrates how the parameter size of LLMs affects the performance of Reward Dropout. We compared four models in total, with the models and parameter sizes as follows:

- OpenAI GPT2 (117 million parameters)
- Meta OPT (350 million (Zhang et al., 2022b))
- Meta XGLM (564 million (Lin et al., 2021))
- MIT GPT2 (774 million)

This shows that the effect of Reward Dropouts is always valid regardless of the parameter size. Reward Dropout always outperformed the non-dropout case ($q=0.0$). The effect between dropout rates was almost consistent. In 7 out of the 8 cases, higher dropout rates led to better performance. The only exception was XGLM with the Topic - Sci/Tech dataset, where the effect between dropout rates was reversed. Also, we can see that the parameter size of the LLM has a positive impact on the RLM optimization, in particular, the larger the model capacity, the higher the average reward. The exception was once again XGLM and one possible explanation for this is that XGLM was pre-trained on a multilingual translation dataset. Given that our experiment was conducted with English sentences only, the large number of languages the model had to learn with its limited parameter

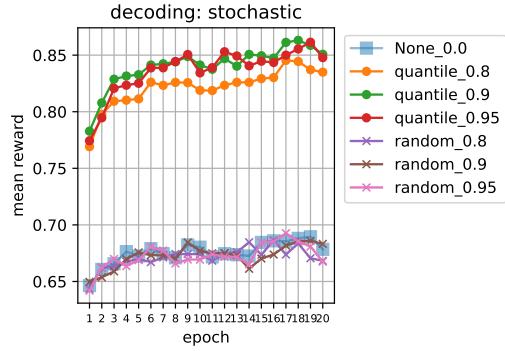
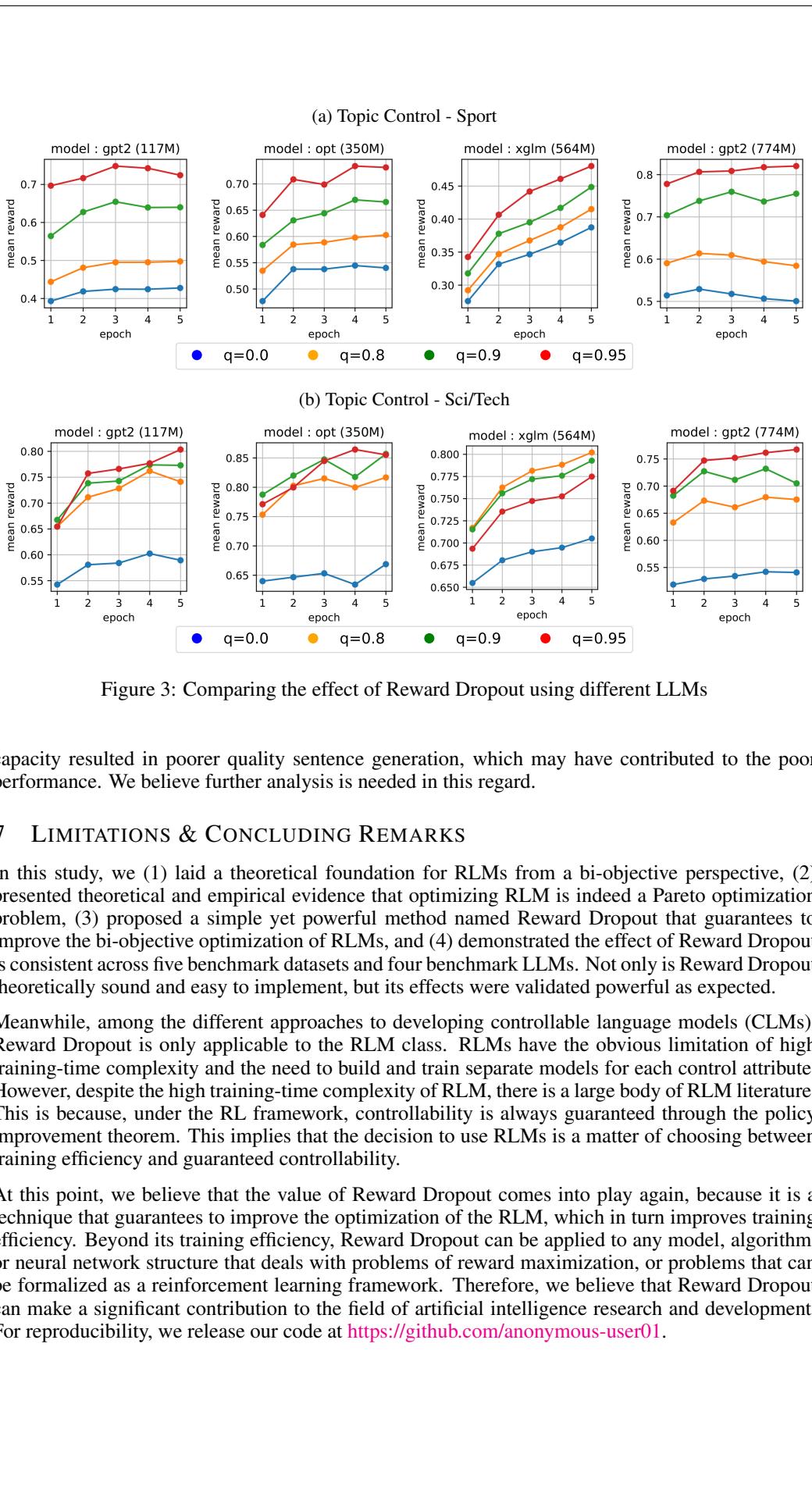


Figure 2: Sentiment Control - Negative



REFERENCES

- Xueying Bai, Jian Guan, and Hongning Wang. A model-based reinforcement learning with adversarial training for online recommendation. *Advances in Neural Information Processing Systems*, 32, 2019.
- Yuntao Bai, Andy Jones, Kamal Ndousse, Amanda Askell, Anna Chen, Nova DasSarma, Dawn Drain, Stanislav Fort, Deep Ganguli, Tom Henighan, et al. Training a helpful and harmless assistant with reinforcement learning from human feedback. *arXiv preprint arXiv:2204.05862*, 2022.
- Junyi Bian, Baojun Lin, Ke Zhang, Zhaohui Yan, Hong Tang, and Yonghe Zhang. Controllable length control neural encoder-decoder via reinforcement learning. *arXiv preprint arXiv:1909.09492*, 2019.
- John Burkardt. The truncated normal distribution. *Department of Scientific Computing Website, Florida State University*, 1:35, 2014.
- Xiuli Chen, Gilles Bailly, Duncan P Brumby, Antti Oulasvirta, and Andrew Howes. The emergence of interactive behavior: A model of rational menu search. In *Proceedings of the 33rd annual ACM conference on human factors in computing systems*, pp. 4217–4226, 2015.
- Will Dabney, Mark Rowland, Marc Bellemare, and Rémi Munos. Distributional reinforcement learning with quantile regression. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 32, 2018.
- Ning Dai, Jianze Liang, Xipeng Qiu, and Xuanjing Huang. Style transformer: Unpaired text style transfer without disentangled latent representation. *arXiv preprint arXiv:1905.05621*, 2019.
- Dataset. Kaggle Detoxification Challenge, 2017. URL <https://www.kaggle.com/c/jigsaw-toxic-comment-classification-challenge/data>. Published by Jig-Saw and Google.
- Sumanth Dathathri, Andrea Madotto, Janice Lan, Jane Hung, Eric Frank, Piero Molino, Jason Yosinski, and Rosanne Liu. Plug and play language models: A simple approach to controlled text generation. *arXiv preprint arXiv:1912.02164*, 2019.
- Thomas Degris, Martha White, and Richard S Sutton. Off-policy actor-critic. *arXiv preprint arXiv:1205.4839*, 2012.
- Jessica Ficler and Yoav Goldberg. Controlling linguistic style aspects in neural language generation. In *Proceedings of the Workshop on Stylistic Variation*, pp. 94–104, Copenhagen, Denmark, September 2017. Association for Computational Linguistics. doi: 10.18653/v1/W17-4912. URL <https://aclanthology.org/W17-4912>.
- Gabriel Lima Guimaraes, Benjamin Sanchez-Lengeling, Carlos Outeiral, Pedro Luis Cunha Farias, and Alán Aspuru-Guzik. Objective-reinforced generative adversarial networks (organ) for sequence generation models. *arXiv preprint arXiv:1705.10843*, 2017.
- Zhitong Hu, Zichao Yang, Xiaodan Liang, Ruslan Salakhutdinov, and Eric P Xing. Toward controlled generation of text. In *International conference on machine learning*, pp. 1587–1596. PMLR, 2017.
- Ehsan Imani, Eric Graves, and Martha White. An off-policy policy gradient theorem using emphatic weightings. *Advances in Neural Information Processing Systems*, 31, 2018.
- Riashat Islam, Komal K Teru, Deepak Sharma, and Joelle Pineau. Off-policy policy gradient algorithms by constraining the state distribution shift. *arXiv preprint arXiv:1911.06970*, 2019.
- Natasha Jaques, Shixiang Gu, Dzmitry Bahdanau, José Miguel Hernández-Lobato, Richard E Turner, and Douglas Eck. Sequence tutor: Conservative fine-tuning of sequence generation models with kl-control. In *International Conference on Machine Learning*, pp. 1645–1654. PMLR, 2017.

-
- Nan Jiang, Sheng Jin, Zhiyao Duan, and Changshui Zhang. RL-duet: Online music accompaniment generation using deep reinforcement learning. In *Proceedings of the AAAI conference on artificial intelligence*, volume 34, pp. 710–718, 2020.
- Hilbert J Kappen, Vicenç Gómez, and Manfred Opper. Optimal control as a graphical model inference problem. *Machine learning*, 87:159–182, 2012.
- Nitish Shirish Keskar, Bryan McCann, Lav R Varshney, Caiming Xiong, and Richard Socher. Ctrl: A conditional transformer language model for controllable generation. *arXiv preprint arXiv:1909.05858*, 2019.
- Tomasz Korbak, Ethan Perez, and Christopher Buckley. RL with kl penalties is better viewed as bayesian inference. In *Findings of the Association for Computational Linguistics: EMNLP 2022*, pp. 1083–1091, 2022.
- Ben Krause, Akhilesh Deepak Gotmare, Bryan McCann, Nitish Shirish Keskar, Shafiq Joty, Richard Socher, and Nazneen Fatema Rajani. Gedi: Generative discriminator guided sequence generation. *arXiv preprint arXiv:2009.06367*, 2020.
- Panagiotis Kyriakis and Jyotirmoy Deshmukh. Pareto policy adaptation. In *International Conference on Learning Representations*, volume 2022, 2022.
- Changhun Lee, Soohyeok Kim, Chiehyeon Lim, Jayun Kim, Yeji Kim, and Minyoung Jung. Diet planning with machine learning: teacher-forced reinforce for composition compliance with nutrition enhancement. In *Proceedings of the 27th ACM SIGKDD Conference on Knowledge Discovery & Data Mining*, pp. 3150–3160, 2021.
- Sergey Levine. Reinforcement learning and control as probabilistic inference: Tutorial and review. *arXiv preprint arXiv:1805.00909*, 2018.
- Xiang Li, John Thickstun, Ishaan Gulrajani, Percy S Liang, and Tatsunori B Hashimoto. Diffusion-lm improves controllable text generation. *Advances in Neural Information Processing Systems*, 35:4328–4343, 2022.
- Yanran Li, Hui Su, Xiaoyu Shen, Wenjie Li, Ziqiang Cao, and Shuzi Niu. Dailydialog: A manually labelled multi-turn dialogue dataset. In *Proceedings of The 8th International Joint Conference on Natural Language Processing (IJCNLP 2017)*, 2017a.
- Zichao Li, Xin Jiang, Lifeng Shang, and Hang Li. Paraphrase generation with deep reinforcement learning. *arXiv preprint arXiv:1711.00279*, 2017b.
- Timothy P Lillicrap, Jonathan J Hunt, Alexander Pritzel, Nicolas Heess, Tom Erez, Yuval Tassa, David Silver, and Daan Wierstra. Continuous control with deep reinforcement learning. *arXiv preprint arXiv:1509.02971*, 2015.
- Xi Lin, Hui-Ling Zhen, Zhenhua Li, Qing-Fu Zhang, and Sam Kwong. Pareto multi-task learning. *Advances in neural information processing systems*, 32, 2019.
- Xi Lin, Zhiyuan Yang, Xiaoyuan Zhang, and Qingfu Zhang. Pareto set learning for expensive multi-objective optimization. *Advances in Neural Information Processing Systems*, 35:19231–19247, 2022.
- Xi Victoria Lin, Todor Mihaylov, Mikel Artetxe, Tianlu Wang, Shuohui Chen, Daniel Simig, Myle Ott, Naman Goyal, Shruti Bhosale, Jingfei Du, et al. Few-shot learning with multilingual language models. *arXiv preprint arXiv:2112.10668*, 2021.
- Han Liu, Bingning Wang, Ting Yao, Haijin Liang, Jianjin Xu, and Xiaolin Hu. Bridging the gap between training and inference of bayesian controllable language models. *arXiv preprint arXiv:2206.05519*, 2022.
- Pengfei Liu, Weizhe Yuan, Jinlan Fu, Zhengbao Jiang, Hiroaki Hayashi, and Graham Neubig. Pre-train, prompt, and predict: A systematic survey of prompting methods in natural language processing. *ACM Computing Surveys*, 55(9):1–35, 2023.

-
- Ruibo Liu, Guangxuan Xu, Chenyan Jia, Weicheng Ma, Lili Wang, and Soroush Vosoughi. Data boost: Text data augmentation through reinforcement learning guided conditional generation. *arXiv preprint arXiv:2012.02952*, 2020a.
- Yao Liu, Adith Swaminathan, Alekh Agarwal, and Emma Brunskill. Off-policy policy gradient with stationary distribution correction. In *Uncertainty in Artificial Intelligence*, pp. 1180–1190. PMLR, 2020b.
- Yixin Liu, Graham Neubig, and John Wieting. On learning text style transfer with direct rewards. *arXiv preprint arXiv:2010.12771*, 2020c.
- Ximing Lu, Sean Welleck, Peter West, Liwei Jiang, Jungo Kasai, Daniel Khashabi, Ronan Le Bras, Lianhui Qin, Youngjae Yu, Rowan Zellers, et al. Neurologic a* esque decoding: Constrained text generation with lookahead heuristics. *arXiv preprint arXiv:2112.08726*, 2021.
- Ximing Lu, Sean Welleck, Jack Hessel, Liwei Jiang, Lianhui Qin, Peter West, Prithviraj Ammanabrolu, and Yejin Choi. Quark: Controllable text generation with reinforced unlearning. *Advances in neural information processing systems*, 35:27591–27609, 2022.
- Fuli Luo, Peng Li, Jie Zhou, Pengcheng Yang, Baobao Chang, Zhifang Sui, and Xu Sun. A dual reinforcement learning framework for unsupervised text style transfer. *arXiv preprint arXiv:1905.10060*, 2019.
- Aman Madaan, Amrith Setlur, Tanmay Parekh, Barnabas Poczos, Graham Neubig, Yiming Yang, Ruslan Salakhutdinov, Alan W Black, and Shrimai Prabhumoye. Politeness transfer: A tag and generate approach. In *Proceedings of the 58th Annual Meeting of the Association for Computational Linguistics*, pp. 1869–1881, Online, July 2020. Association for Computational Linguistics. doi: 10.18653/v1/2020.acl-main.169. URL <https://aclanthology.org/2020.acl-main.169>.
- Victor Mårtensson. Ai-driven meal planning in the foodtech industry: A reinforcement learning approach. *Master's Theses in Mathematical Sciences*, 2021.
- Patrick Ngatchou, Anahita Zarei, and A El-Sharkawi. Pareto multi objective optimization. In *Proceedings of the 13th international conference on intelligent systems application to power systems*, pp. 84–91. IEEE, 2005.
- Marcus Olivecrona, Thomas Blaschke, Ola Engkvist, and Hongming Chen. Molecular de-novo design through deep reinforcement learning. *Journal of cheminformatics*, 9(1):1–14, 2017.
- Long Ouyang, Jeffrey Wu, Xu Jiang, Diogo Almeida, Carroll Wainwright, Pamela Mishkin, Chong Zhang, Sandhini Agarwal, Katarina Slama, Alex Ray, et al. Training language models to follow instructions with human feedback. *Advances in Neural Information Processing Systems*, 35: 27730–27744, 2022.
- Mariya Popova, Olexandr Isayev, and Alexander Tropsha. Deep reinforcement learning for de novo drug design. *Science advances*, 4(7):eaap7885, 2018.
- Alec Radford, Jeffrey Wu, Rewon Child, David Luan, Dario Amodei, Ilya Sutskever, et al. Language models are unsupervised multitask learners. *OpenAI blog*, 1(8):9, 2019.
- Konrad Rawlik, Marc Toussaint, and Sethu Vijayakumar. On stochastic optimal control and reinforcement learning by approximate inference. *Proceedings of Robotics: Science and Systems VIII*, 2012.
- Jongkyung Shin, Changhun Lee, Chiehyeon Lim, Yunmo Shin, and Junseok Lim. Recommendation in offline stores: A gamification approach for learning the spatiotemporal representation of indoor shopping. In *Proceedings of the 28th ACM SIGKDD Conference on Knowledge Discovery and Data Mining*, pp. 3878–3888, 2022.
- David Silver, Guy Lever, Nicolas Heess, Thomas Degris, Daan Wierstra, and Martin Riedmiller. Deterministic policy gradient algorithms. In *International conference on machine learning*, pp. 387–395. Pmlr, 2014.

-
- Nitish Srivastava, Geoffrey Hinton, Alex Krizhevsky, Ilya Sutskever, and Ruslan Salakhutdinov. Dropout: a simple way to prevent neural networks from overfitting. *The journal of machine learning research*, 15(1):1929–1958, 2014.
- Nisan Stiennon, Long Ouyang, Jeffrey Wu, Daniel Ziegler, Ryan Lowe, Chelsea Voss, Alec Radford, Dario Amodei, and Paul F Christiano. Learning to summarize with human feedback. *Advances in Neural Information Processing Systems*, 33:3008–3021, 2020.
- Akhilesh Sudhakar, Bhargav Upadhyay, and Arjun Maheswaran. Transforming delete, retrieve, generate approach for controlled text style transfer. *arXiv preprint arXiv:1908.09368*, 2019.
- Richard S Sutton and Andrew G Barto. *Reinforcement learning: An introduction*. MIT press, 2018.
- Richard S Sutton, David McAllester, Satinder Singh, and Yishay Mansour. Policy gradient methods for reinforcement learning with function approximation. *Advances in neural information processing systems*, 12, 1999.
- Ronald J Williams. Simple statistical gradient-following algorithms for connectionist reinforcement learning. *Machine learning*, 8:229–256, 1992.
- Jingjing Xu, Xu Sun, Qi Zeng, Xuancheng Ren, Xiaodong Zhang, Houfeng Wang, and Wenjie Li. Unpaired sentiment-to-sentiment translation: A cycled reinforcement learning approach. *arXiv preprint arXiv:1805.05181*, 2018.
- Kevin Yang and Dan Klein. Fudge: Controlled text generation with future discriminators. *arXiv preprint arXiv:2104.05218*, 2021.
- Lantao Yu, Weinan Zhang, Jun Wang, and Yong Yu. Seqgan: Sequence generative adversarial nets with policy gradient. In *Proceedings of the AAAI conference on artificial intelligence*, volume 31, 2017.
- Hanqing Zhang, Haolin Song, Shaoyu Li, Ming Zhou, and Dawei Song. A survey of controllable text generation using transformer-based pre-trained language models. *arXiv preprint arXiv:2201.05337*, 2022a.
- Susan Zhang, Stephen Roller, Naman Goyal, Mikel Artetxe, Moya Chen, Shuhui Chen, Christopher Dewan, Mona Diab, Xian Li, Xi Victoria Lin, et al. Opt: Open pre-trained transformer language models. *arXiv preprint arXiv:2205.01068*, 2022b.
- Xiang Zhang, Junbo Jake Zhao, and Yann LeCun. Character-level convolutional networks for text classification. In *NIPS*, 2015.
- Xiangyu Zhao, Liang Zhang, Long Xia, Zhuoye Ding, Dawei Yin, and Jiliang Tang. Deep reinforcement learning for list-wise recommendations. *arXiv preprint arXiv:1801.00209*, 2017.
- Daniel M Ziegler, Nisan Stiennon, Jeffrey Wu, Tom B Brown, Alec Radford, Dario Amodei, Paul Christiano, and Geoffrey Irving. Fine-tuning language models from human preferences. *arXiv preprint arXiv:1909.08593*, 2019.
- Lixin Zou, Long Xia, Zhuoye Ding, Jiaxing Song, Weidong Liu, and Dawei Yin. Reinforcement learning to optimize long-term user engagement in recommender systems. In *Proceedings of the 25th ACM SIGKDD International Conference on Knowledge Discovery & Data Mining*, pp. 2810–2818, 2019.

A DERIVATIONS

A.1 DERIVATION OF EQUATION (6)

From a probabilistic inference perspective, the off-policy RL can be addressed as a problem of minimizing the following Kullback-Leibler Divergence (KLD) (Kappen et al., 2012; Levine, 2018):

$$\text{KL} [\pi(\tau) \parallel \beta(\tau)e^{R(\tau)}] = \sum_{\tau} \pi(\tau) \ln \frac{\pi(\tau)}{\beta(\tau)e^{R(\tau)}} = -\mathbb{E}_{\tau \sim \pi} [R(\tau) + \ln \beta(\tau)] - \mathcal{H}[\pi]. \quad (8)$$

Here, $R(\tau)$ is the reward function defined by the control objective, which is set to increase the reward signal exponentially. From RL perspectives, minimizing Eq (8) can be converted into a maximization problem,

$$\arg \max_{\pi} \mathbb{E}_{\tau \sim \pi} [R(\tau) + \ln \beta(\tau)] + \mathcal{H}[\pi] \quad \text{s.t.} \quad \sum_{\tau} \pi(\tau) = 1,$$

where $\sum \pi(\tau) = 1$ is the constraint that the total probability of the sampled trajectories must be 1, and, by the Lagrangian method, the objective function is written as

$$\mathcal{L}(\pi) = \mathbb{E}_{\tau \sim \pi} [R(\tau) + \ln \beta(\tau)] + \mathcal{H}[\pi] + \lambda \left(\sum_{\tau} \pi(\tau) - 1 \right). \quad (9)$$

By optimizing Eq (9), the optimal policy π^* is given such that both the reward and the likelihood of behavior policy are maximized w.r.t. a sampled trajectory from target policy $\tau \sim \pi(\tau)$,

$$\pi^*(\tau) = \beta(\tau)e^{R(\tau)} \times e^{-(1-\lambda)} = \frac{\beta(\tau)e^{R(\tau)}}{e^{1-\lambda}} = \frac{\beta(\tau)e^{R(\tau)}}{\sum_{\tau} \beta(\tau)e^{R(\tau)}}. \quad (10)$$

Note that $e^{1-\lambda}$ is a normalization constant (partition function) defined by the probability condition $\sum_{\tau} \pi(\tau) = 1$. This implies that if the Lagrange multiplier is equal to 1, i.e., $\lambda = 1$, the optimal target policy $\pi^*(\tau)$ follows $\beta(\tau)e^{R(\tau)}$ because $\pi^*(\tau) = \beta(\tau)e^{R(\tau)}/e^0 = \beta(\tau)e^{R(\tau)}$, and the trajectory sampling $\tau \sim \pi(\tau)$ is determined by $\beta(\tau)e^{R(\tau)}$.

B PROOFS

B.1 PROOF OF THEOREM 4.1

Theorem 4.1 *If $\sum_{\tau} \pi(\tau) = 1$ and $\pi(\tau) = \beta(\tau)e^{R(\tau)}$ hold, then $\mathbb{E}_{\tau \sim \pi} [R(\tau)] \leq \text{KL} [\pi(\tau) \parallel \beta(\tau)e^{R(\tau)}]$ holds.*

Proof. Given $\sum_{\tau} \pi(\tau) = 1$ and $\pi(\tau) = \beta(\tau)e^{R(\tau)}$, it is obvious that $\sum_{\tau} \pi(\tau) = \sum_{\tau} \beta(\tau)e^{R(\tau)} = 1$ holds. Then, we can obtain the non-negativity of $\text{KL} [\pi(\tau) \parallel \beta(\tau)e^{R(\tau)}]$.

$$\begin{aligned} \text{KL} [\pi(\tau) \parallel \beta(\tau)e^{R(\tau)}] &= \sum_{\tau} \pi(\tau) \ln \frac{\pi(\tau)}{\beta(\tau)e^{R(\tau)}} = -\sum_{\tau} \pi(\tau) \ln \frac{\beta(\tau)e^{R(\tau)}}{\pi(\tau)} \\ &\geq -\ln \sum_{\tau} \pi(\tau) \frac{\beta(\tau)e^{R(\tau)}}{\pi(\tau)} \quad (\because \text{Jensen Inequality}) \\ &= -\ln \sum_{\tau} \beta(\tau)e^{R(\tau)} = 0 \quad \left(\because \sum_{\tau} \beta(\tau)e^{R(\tau)} = 1 \right) \end{aligned}$$

As a result, $\text{KL} [\pi(\tau) \parallel \beta(\tau)e^{R(\tau)}] \geq 0$ holds, which leads to $\mathbb{E}_{\tau \sim \pi} [R(\tau)] \leq \text{KL} [\pi(\tau) \parallel \beta(\tau)e^{R(\tau)}]$, or equivalently, $\mathbb{E}_{\tau \sim \pi} [\ln \beta(\tau)] \leq \mathbb{E}_{\tau \sim \pi} [\pi(\tau) \parallel e^{R(\tau)}]$. \square

B.2 PROOF OF THEOREM 4.2

Theorem 4.2 *If $\mathbb{E}_{\tau \sim \pi}[R(\tau)] \leq \text{KL}[\pi(\tau) \parallel \beta(\tau)]$ holds, then $\forall \tau^* \sim \pi^*, R(\tau) = -\ln \beta(\tau)$ holds.*

Proof. Suppose the reward upper bound is given by $\mathbb{E}_{\tau \sim \pi}[R(\tau)] \leq \text{KL}[\pi(\tau) \parallel \beta(\tau)]$. Then, we can expand the upper bound by $-\mathbb{E}_{\tau \sim \pi}[\ln \beta(\tau)]$ as below.

$$\mathbb{E}_{\tau \sim \pi}[R(\tau)] \leq \text{KL}[\pi(\tau) \parallel \beta(\tau)] = -\mathbb{E}_{\tau \sim \pi}[\ln \beta(\tau)] - \underbrace{\mathcal{H}[\pi]}_{\geq 0} \leq -\mathbb{E}_{\tau \sim \pi}[\ln \beta(\tau)]$$

This implies $\text{KL}[\pi(\tau) \parallel \beta(\tau)] = -\mathbb{E}_{\tau \sim \pi}[\ln \beta(\tau)]$ holds iff $\mathcal{H}[\pi] = 0$. At the optimal points $\tau^* \sim \pi^*$, trivially $\mathcal{H}[\pi]$ goes to zero because the target policy converges to a specific distribution without uncertainty, which yields the maximal expected reward, i.e., $\mathbb{E}_{\tau^* \sim \pi^*}[R(\tau)] = \max \mathbb{E}_{\tau \sim \pi}[R(\tau)]$. As a result, the following identity is obtained:

$$\mathbb{E}_{\tau^* \sim \pi^*}[R(\tau)] = -\mathbb{E}_{\tau^* \sim \pi^*}[\ln \beta(\tau)], \quad (11)$$

implying $\forall \tau^* \sim \pi^*, R(\tau) = -\ln \beta(\tau)$ holds. \square

Proof. Here we provide another way of proving Theorem 4.2. This is more intuitive and simpler way. Let us take a partial derivative of $\text{KL}[\pi(\tau) \parallel \beta(\tau)e^{\tau}]$ w.r.t $\pi(\tau)$ and set it to zero.

$$\frac{\partial \text{KL}[\pi(\tau) \parallel \beta(\tau)e^{\tau}]}{\partial \pi(\tau)} = \ln \pi(\tau) + 1 - \ln \beta(\tau) - R(\tau) \stackrel{\text{set}}{=} 0. \quad (12)$$

The above equation describes an implicit function of $\pi(\tau)$, $\beta(\tau)$, and $R(\tau)$, which implies the optimal state of target policy, $\pi^*(\tau)$. Now, we can arrange this in the form of an explicit function whose $R(\tau)$ is the dependent variable and the others are independent variables. Then, the result shows that $R(\tau)$ is negative logarithmic to $\beta(\tau)$,

$$R(\tau) = \ln \pi(\tau) + 1 - \ln \beta(\tau) \implies R(\tau) = -\ln \beta(\tau), \quad (13)$$

where $\ln \pi(\tau)$ and $+1$ can be ignored because they are irrelevant to interpreting the relationship between $R(\tau)$ and $\beta(\tau)$. We know that Eq (13) was derived from Eq (12) and thus implies an optimal state of target policy by itself. In other words, Eq (13) describes the condition under which Pareto optimality is achieved, and that condition is that $R(\tau)$ and $\beta(\tau)$ must be negatively related for all τ . \square

B.3 PROOF OF THEOREM 4.3

Theorem 4.3 *For $\pi(\tau) \neq \beta(\tau)e^{R(\tau)}$ to hold, $\mathbb{E}_{\tau \sim \pi}[R(\tau)] > \text{KL}[\pi(\tau) \parallel \beta(\tau)]$, or equivalently Eq (14), must hold.*

$$\mathbb{E}_{\tau \sim \pi}[R(\tau)] + \mathbb{E}_{\tau \sim \pi}[\ln \beta(\tau)] > 0 \quad (14)$$

Proof. By Theorem 4.1, we know that $\pi(\tau) = \beta(\tau)e^{R(\tau)}$ is a necessary condition for the reward upper bound to hold ($p \rightarrow q$). By Definition 3.2, we also know that $\pi(\tau) \neq \beta(\tau)e^{R(\tau)}$ indicates the Pareto improvement. As a corollary, if the negation of the reward upper bound yields $\pi(\tau) \neq \beta(\tau)e^{R(\tau)}$ ($\neg q \rightarrow \neg p$), then we can assume that negation leads to the Pareto improvement.

Suppose the reward upper bound is given by $\mathbb{E}_{\tau \sim \pi}[R(\tau)] \leq \text{KL}[\pi(\tau) \parallel \beta(\tau)]$. We can rewrite it in the form of inequality as below:

$$\begin{aligned} 0 &\geq \mathbb{E}_{\tau \sim \pi}[R(\tau)] - \text{KL}[\pi(\tau) \parallel \beta(\tau)] = \mathbb{E}_{\tau \sim \pi}[R(\tau)] - \underbrace{\mathbb{E}_{\tau \sim \pi}[\ln \pi(\tau)]}_{= -\mathcal{H}[\pi]} + \underbrace{\mathbb{E}_{\tau \sim \pi}[\ln \beta(\tau)]}_{\geq 0} \\ &\geq \mathbb{E}_{\tau \sim \pi}[R(\tau)] + \mathbb{E}_{\tau \sim \pi}[\ln \beta(\tau)] \end{aligned} \quad (15)$$

The above inequality shows that $\mathbb{E}_{\tau \sim \pi}[R(\tau)] + \mathbb{E}_{\tau \sim \pi}[\ln \beta(\tau)]$ cannot be larger than zero as long as $\mathbb{E}_{\tau \sim \pi}[R(\tau)] \leq \text{KL}[\pi(\tau) \parallel \beta(\tau)]$ holds. But assume $\mathbb{E}_{\tau \sim \pi}[R(\tau)] + \mathbb{E}_{\tau \sim \pi}[\ln \beta(\tau)]$ is larger than

zero, i.e., $\mathbb{E}_{\tau \sim \pi} [R(\tau)] + \mathbb{E}_{\tau \sim \pi} [\ln \beta(\tau)] > 0$, which is equivalent to the negation of Eq (15). Then, we can see that a contradiction arises in the necessary condition $\pi(\tau) = \beta(\tau)e^{R(\tau)}$ as follows:

$$\begin{aligned}\pi(\tau) = \beta(\tau)e^{R(\tau)} &\implies \ln \pi(\tau) = R(\tau) + \ln \beta(\tau) && \text{(Logarithm on both sides.)} \\ &\implies \underbrace{\mathbb{E}_{\tau \sim \pi} [\ln \pi(\tau)]}_{= -\mathcal{H}[\pi] \leq 0} = \underbrace{\mathbb{E}_{\tau \sim \pi} [R(\tau)] + \mathbb{E}_{\tau \sim \pi} [\ln \beta(\tau)]}_{\text{is assumed to be } > 0} && \text{(Expectation on both sides.)} \\ &\implies -\mathcal{H}[\pi] \neq \mathbb{E}_{\tau \sim \pi} [R(\tau)] + \mathbb{E}_{\tau \sim \pi} [\ln \beta(\tau)] && \text{(Equality does not hold.)}\end{aligned}$$

where $-\mathcal{H}[\pi] \leq 0$ and $\mathbb{E}_{\tau \sim \pi} [R(\tau)] + \mathbb{E}_{\tau \sim \pi} [\ln \beta(\tau)] > 0$ conflict. This contradiction means $\pi(\tau) \neq \beta(\tau)e^{R(\tau)}$. Since $\pi(\tau) \neq \beta(\tau)e^{R(\tau)}$ indicates the Pareto improvement, we can conclude that $\mathbb{E}_{\tau \sim \pi} [R(\tau)] + \mathbb{E}_{\tau \sim \pi} [\ln \beta(\tau)] > 0$ guarantees policy improvement. \square

C IMPLEMENTATION DETAILS

C.1 OFF-POLICY DPG, SPG, AND KPG IN THE LM CONTEXT

Off-policy policy gradient is an off-policy extension of the policy gradient method (Sutton & Barto, 2018; Sutton et al., 1999), and began to attract attention from Degris et al. (2012). Since then, further studies have been established to improve training efficiency (Lillicrap et al., 2015; Silver et al., 2014), correct the distribution mismatch between the behavior and target policies (Islam et al., 2019; Liu et al., 2020b), or address the sub-optimality issue of the behavior policy (Imani et al., 2018).

According to Silver et al. (2014), we can implement the off-policy DPG as below:

$$\nabla_{\theta} J_{\beta_{\bar{\theta}}}(\pi_{\theta}) \approx \sum_{s \in \mathcal{S}} \rho^{\beta_{\bar{\theta}}}(s) \nabla_{\theta} \pi_{\theta}(a|s) Q^{\pi_{\theta}}(s, a) ds = \mathbb{E}_{s \sim \rho^{\beta_{\bar{\theta}}}} [\nabla_{\theta} \pi_{\theta}(s) \nabla_a Q^{\pi_{\theta}}(s, a)|_{a=\pi_{\theta}(s)}] \quad (16)$$

where $\rho^{\beta_{\bar{\theta}}}(s)$ is the state visitation history of the behavior policy $\beta_{\bar{\theta}}$, and $Q^{\pi_{\theta}}(s, a)$ is the state-action value function. In the LM context, we can define the t -th action as the t -th token and the t -th state as the partial sentence observed up to the t -th token. On the other hand, since a sentence has meaning as a whole, we cannot define the reward of the t -th token, but only the reward of the entire sentence. That is, the off-policy policy gradient cannot be established without integrating the state s and action a in the LM context. Therefore, we can rewrite the off-policy DPG, or Eq (16) w.r.t τ as follows:

$$\nabla_{\theta} J_{\beta_{\bar{\theta}}}(\pi_{\theta}) = \mathbb{E}_{\tau \sim \beta_{\bar{\theta}}} [\nabla_{\theta} \pi_{\theta}(\tau) R_{\phi}(\tau)] \quad s.t. \quad \tau = \arg \max_{\tau} \beta_{\bar{\theta}}(\tau). \quad (17)$$

Note that s and a were integrated into τ , meaning that we considered the entire trajectory τ instead of intermediate actions and states, and excluded the intervention of the target policy π_{θ} within the trajectory.³ As a result, 1) the state-action value function $Q^{\pi_{\theta}}(s, a)$ was replaced by the reward model $R_{\phi}(\tau)$, 2) the action derivative ∇_a was removed, 3) the state visitation history of the behavior policy $s \sim \rho^{\beta_{\bar{\theta}}}$ was replaced the behavior trajectory $\tau \sim \beta_{\bar{\theta}}(\tau)$, and lastly, 4) the deterministic target policy $a = \pi_{\theta}(s)$ was removed, and the argmax constraint $\tau = \arg \max_{\tau} \beta_{\bar{\theta}}(\tau)$ was introduced instead. Given $\arg \max_{\tau} \beta_{\bar{\theta}}(\tau)$ represents greedy decoding, Eq (17) implies that we can implement the off-policy DPG by running the greedy decoding strategy. In other words, we can also implement the off-policy SPG and KPG simply by removing the argmax constraint from Eq (17) and running the appropriate decoding strategies (e.g., stochastic/top-k decoding).

C.2 PREFIX INITIALIZATION

For the behavior LM to generate trajectories, an initial state must be provided so that the behavior LM can begin its generative process. Each trajectory represents a respective text sentence, and therefore every trajectory must be initialized with a different initial state. In light of this, we fed the behavior LM with sequences that were initialized with prefixes. Specifically, the first p words of each text, $x_{1:p}$, were given as the initial state of the trajectory from which the behavior LM starts decoding (generative) process.

³If the intermediate actions a_t and states s_t are not considered but only the trajectory τ , then we need to remove π_{θ} 's influence on τ (e.g., $Q^{\pi_{\theta}}(s, a)$ and $a = \pi_{\theta}(s)$) because τ should be determined only by $\beta_{\bar{\theta}}$ in an off-policy setup.

C.3 HYPERPARAMETERS

To fine-tune the target LM, we set the batch size, training epoch, learning rate α , prefix length p , and total generation length T to 256, 20, 5e-04, 2, and 15, respectively. Note that for computational efficiency, we randomly sampled around 50k samples from each dataset rather than using the full samples.

C.4 PSEUDO ALGORITHM

Algorithm 1 Off-policy policy gradient with reward dropout

```

1: Input: sequence data  $x$ , label data  $y$ , prefix length  $p$ , total length  $T$ , learning rate  $\alpha$ , dropout  $\in \{\text{random, quantile}\}$ , dropout rate  $\gamma \in [0, 1)$ 
2: Load pre-trained LLM as a behavior policy  $\beta(\cdot)$  with parameter  $\bar{\theta}$ 
3: Initialize target policy  $\pi(\cdot)$  with parameter  $\theta = \bar{\theta}$ 
4: Load pre-trained classifier as a reward model  $R(\cdot)$  with parameter  $\phi$  and fine-tune it on labels  $y$ 
5: for epoch do
6:    $\tau \sim \beta_{\bar{\theta}}(\hat{x}_{p+1:T} | x_{1:p})$                                  $\triangleright$  generate trajectories from the prefix of  $p$  length
7:    $\hat{r} = R_{\phi}(\tau)$                                                $\triangleright$  calculate rewards of generated trajectories
8:   if dropout = random then
9:      $\hat{r}_{\text{dropout}} = \text{Random\_Dropout}(\hat{r}, \gamma)$        $\triangleright$  dropout  $\gamma\%$  of rewards by random per batch
10:  else if dropout = quantile then
11:     $\hat{r}_{\text{dropout}} = \text{Quantile\_Dropout}(\hat{r}, \gamma)$        $\triangleright$  dropout bottom  $\gamma\%$  of rewards per batch
12:  else
13:     $\hat{r}_{\text{dropout}} \leftarrow \hat{r}$                                       $\triangleright$  no dropout
14:  end if
15:   $\nabla_{\theta} J_{\beta_{\bar{\theta}}}(\pi_{\theta}) = \mathbb{E}_{\tau \sim \beta_{\bar{\theta}}} [\nabla_{\theta} \pi_{\theta}(\tau) \times \hat{r}_{\text{dropout}}]$    $\triangleright$  calculate gradients of the target policy
16:   $\theta_{\text{new}} \leftarrow \theta + \alpha \nabla_{\theta} J_{\beta_{\bar{\theta}}}(\pi_{\theta})$            $\triangleright$  update parameters of the target policy
17: end for
18: return optimal target policy parameters  $\theta^*$ 

```

D DATASET SUMMARY

Dataset		<i>sentiment</i> (Zhang et al., 2015)	<i>politeness</i> (Madaan et al., 2020)	<i>toxicity</i> (Dataset, 2017)	<i>emotion</i> (Li et al., 2017a)	<i>topic</i> (Zhang et al., 2015)
Data size (# of samples)		560,000	1,121,980	159,571	76,052	120,000
# of labels (# of codes)		2	10 (2)	2	7 (6)	4
Per label size	<i>label 0</i>	280,000	78,843	144,277	62,357	30,000
	<i>label 1</i>	280,000	120,104	15,294	691	30,000
	<i>label 2</i>		123,942		247	30,000
	<i>label 3</i>		95,333		123	30,000
	<i>label 4</i>		83,860		10,253	
	<i>label 5</i>		82,429		877	
	<i>label 6</i>		88,274		1,504	
	<i>label 7</i>		100,103			
	<i>label 8</i>		129,603			
	<i>label 9</i>		219,489			

Table 3: **(Descriptive Statistics)** The table shows the total number of samples, labels, and samples per label for each dataset. Note that the numbers in parentheses indicate the number of labels we used in training. For example, we dichotomized the 10 politeness labels by relabeling labels 0 to 8 as “non-polite”, and we removed label 0 which denotes “no emotion” from the emotion dataset. Note that the gray cell highlights the severe imbalance in emotion labels.

E VISUALIZATION OF REWARD GROWTH

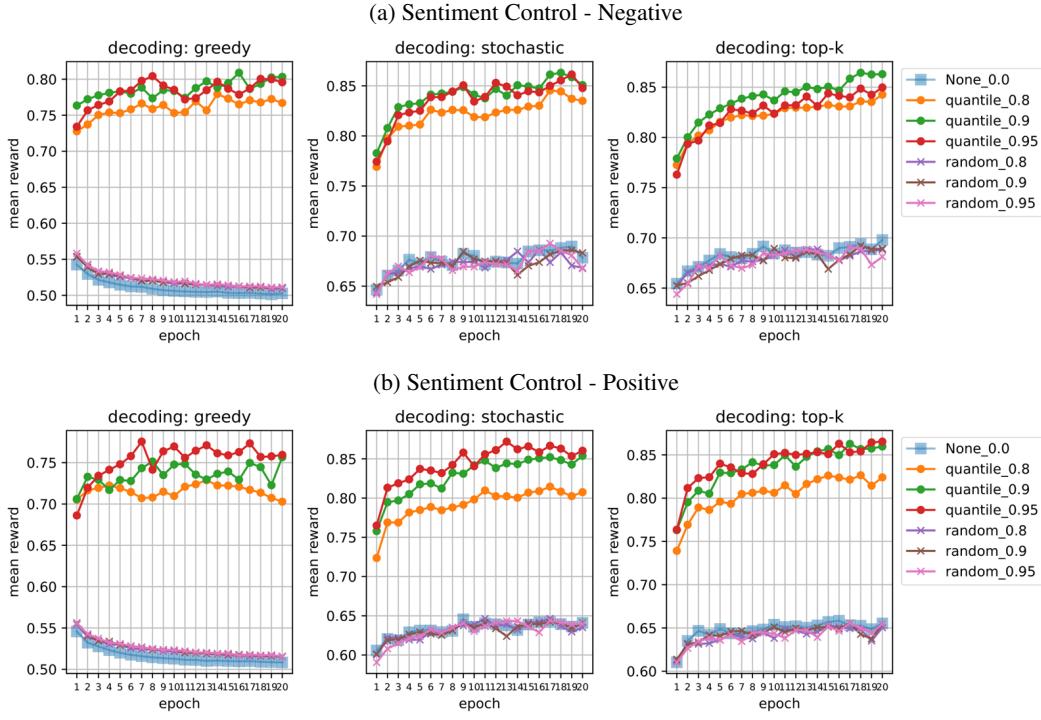


Figure 4: Sentiment Dataset

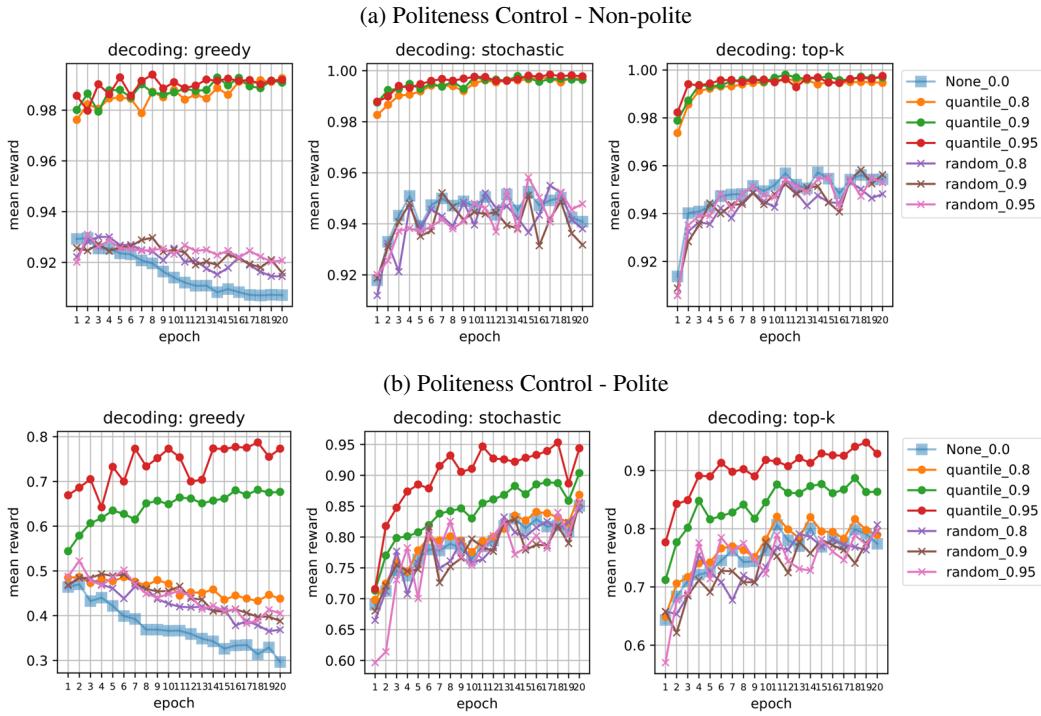


Figure 5: Politeness Dataset

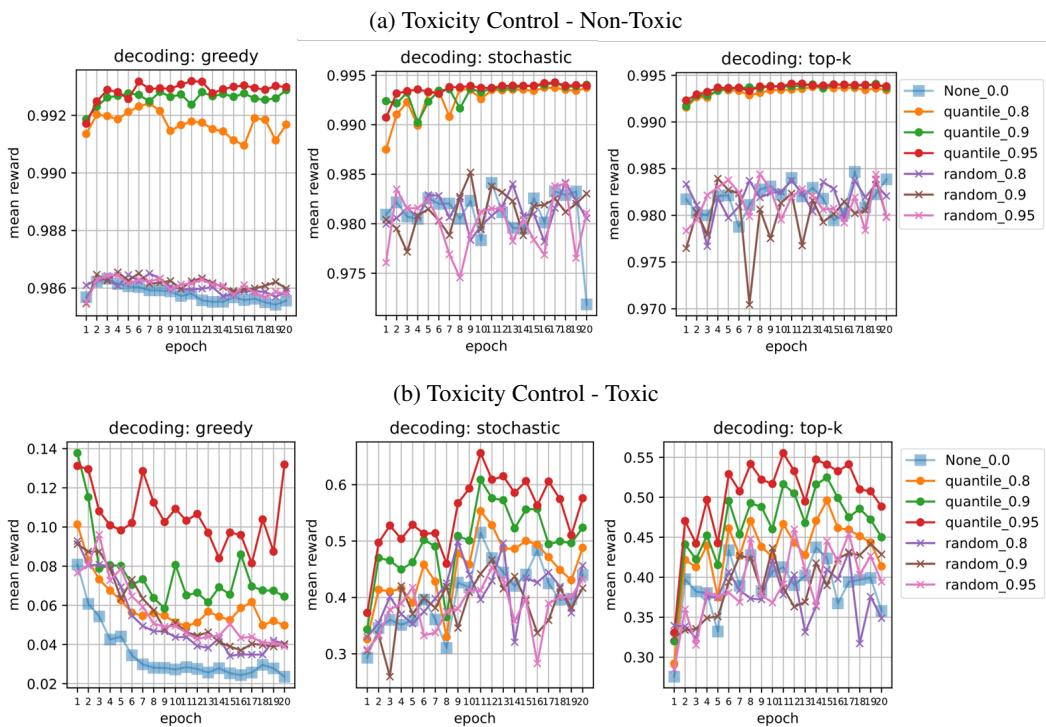


Figure 6: Toxicity Dataset

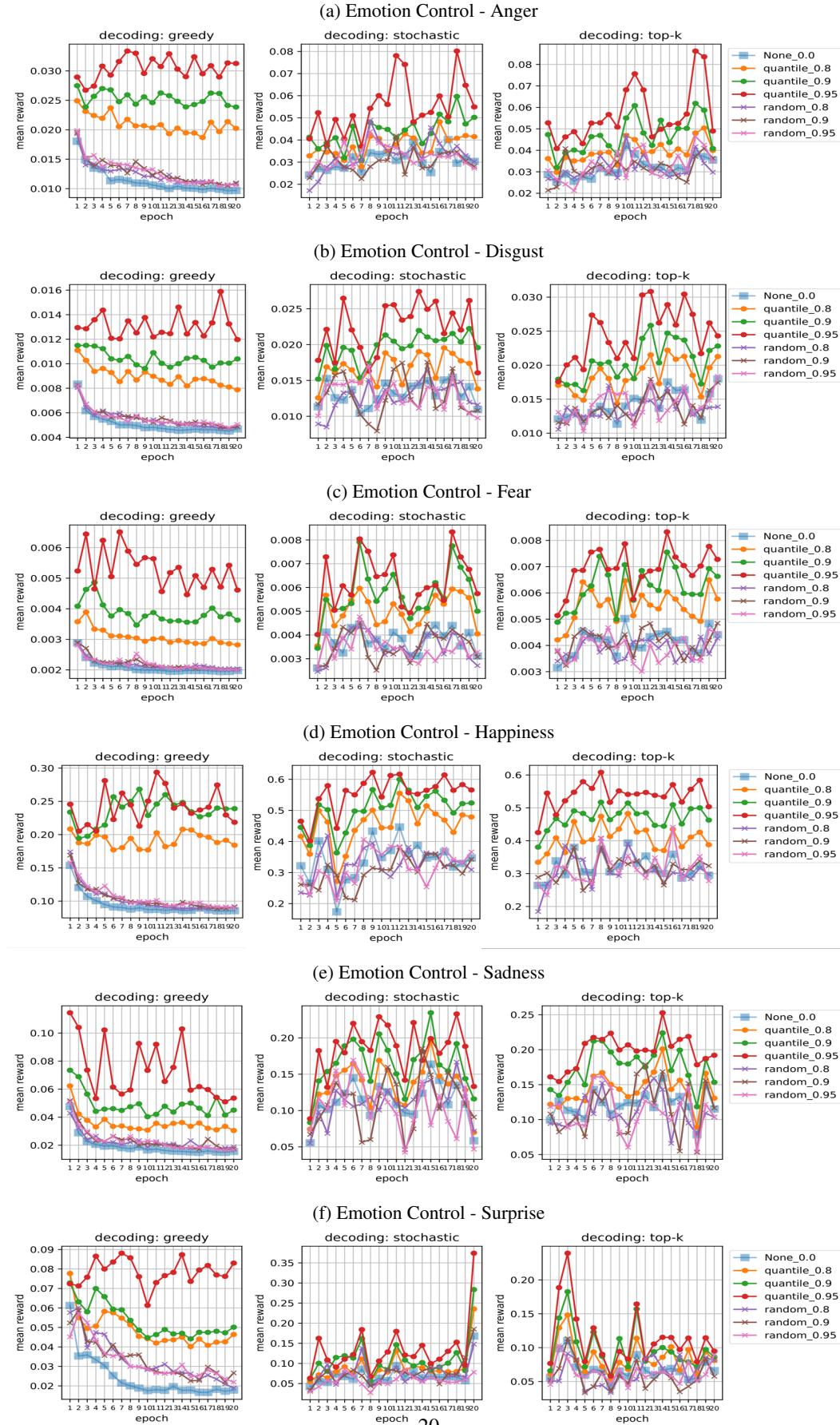


Figure 7: Emotion Dataset

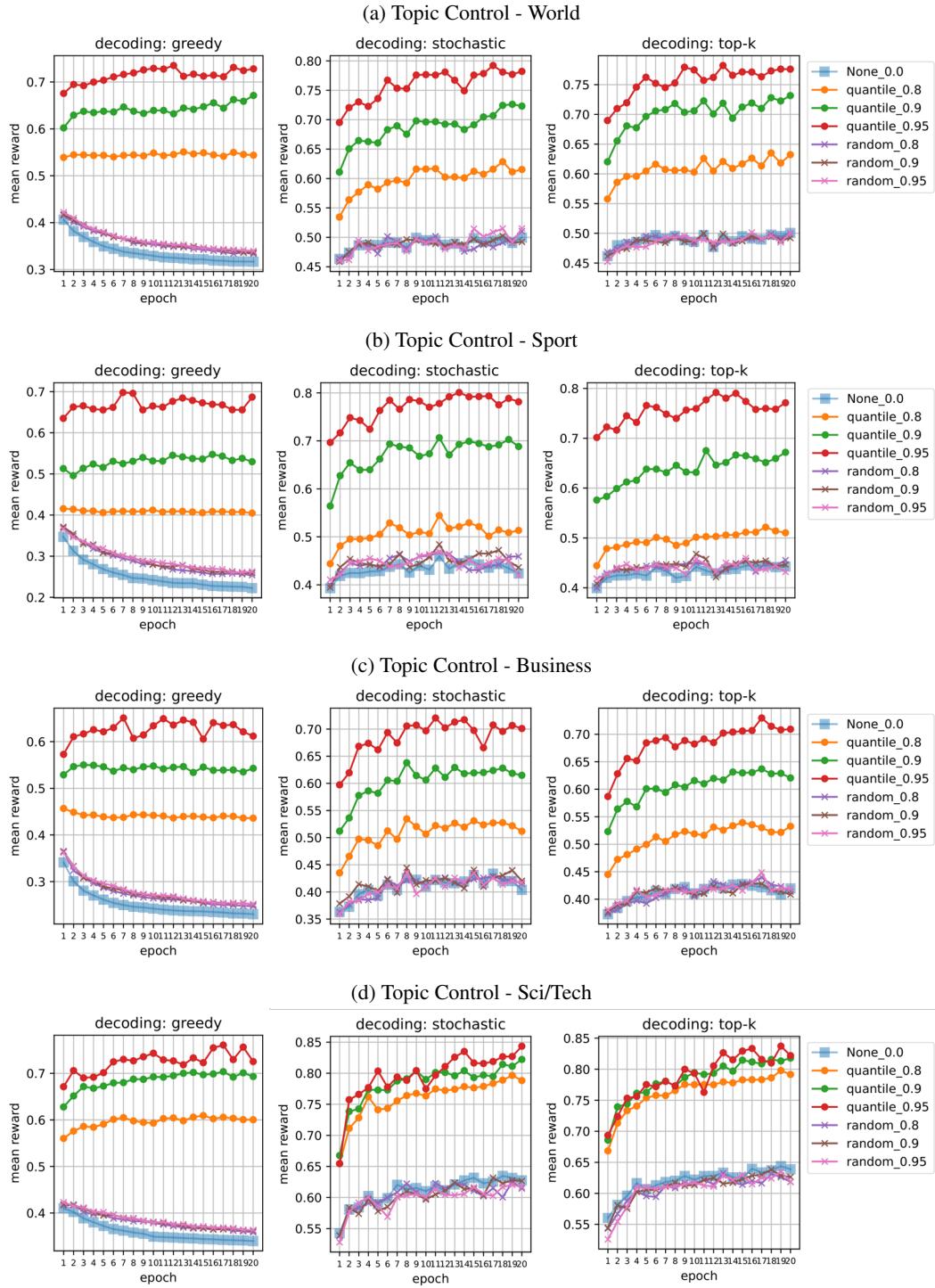


Figure 8: Topic Dataset

F GENERATED TEXT WITH INTENDED ATTRIBUTES

Dataset	Control attribute	Generated text
<i>sentiment</i>	<i>negative</i>	<u>The painting</u> of the World, by Paul Thomas Woodford.
		<u>The chicken</u> -crap, which is the worst thing I've ever seen.
		<u>The country</u> 's leaders have been accused of being using "toxic"
	<i>positive</i>	<u>The painting</u> is a beautiful, unique and unique collection of antique pieces from the British period.
		<u>The chicken</u> is so delicious, it's a big one.
		<u>The country</u> is so amazing, I'm going to do it!"
<i>politeness</i>	<i>non-polite</i>	<u>I do not know</u> that the same thing happened to Mr.
	<i>polite</i>	<u>I do not know</u> if you would like to see more of the new music.
<i>toxicity</i>	<i>non-toxic</i>	<u>What</u> is the most important thing that I've written?
	<i>toxic</i>	<u>What</u> the hell is wrong with that?
<i>emotion</i>	<i>anger</i>	<u>When I hear that news</u> , it's not like you're going to do this.
	<i>disgust</i>	<u>When I hear that news</u> , my wife's head was spinning.
	<i>fear</i>	<u>When I hear that news</u> , it's a shame.
	<i>happiness</i>	<u>When I hear that news</u> , it's a lot of fun.
	<i>sadness</i>	<u>When I hear that news</u> , it's a bit of an odd feeling.
	<i>surprise</i>	<u>When I hear that news</u> , it's a little bit strange.
<i>topic</i>	<i>world</i>	<u>The issue focused</u> on the fact that Iran is not a state of war, and it has been unable to defend its people.
	<i>sport</i>	<u>The issue focused</u> on the defense, which is a big part of what we have seen in recent years.
	<i>business</i>	<u>The issue focused</u> on the economy, but it also includes a number of other factors that have contributed to growth in GDP growth.
	<i>sci/tech</i>	<u>The issue focused</u> on the development of a new system for computing and networking is that it takes more than two seconds to develop.

Table 4: **(Examples of Controlled Text)** The table shows examples of generated text that was controlled to have a specific attribute. During generation, the target LM was executed using top-k decoding ($k = 10$) and temperature sampling (temperature = 0.3). Note that underlined texts indicate the initialized prefixes. Some of the prefixes (e.g., "The painting", "The chicken", "The country", and "The issue focused on") are borrowed from existing literature (Dathathri et al., 2019), while the others are our own curation.

G HUMAN EVALUATION

Survey Design. We planned a survey for human evaluation as shown in Figure 9. The survey was designed to include three types of questions. The first type includes questions that require participants to distinguish between real text and AI-generated text. This type was designed to measure how acceptable the generated texts are to humans. Similarly, the second type requires participants to distinguish if a text is real or generated. The only difference is that participants contrast real and generated texts (but which one is real is unknown to participants), then selects one that is likely to be written by a human. This type was designed to measure human-likeness of the generated text. Lastly, the third type requires participants to label appropriate control attributes (control codes) to the generated texts. This type was designed to test whether the improvement in control performance quantified in Table 1 and Appendix E meets human standards.

(a) Survey Question Type 1

Please make a decision if a below text is real or AI-generated.

Below items provide the sentences that are either real or fake (AI-generated). Click the checkbox where you think the sentence belongs.

Please do not rely on typos, grammatical errors, misspellings, or incomplete sentences to distinguish the real from the fake. The benchmark datasets we used are all real data, and real data contains many of the above problems.

Also, the sources of our dataset are very diverse, from news articles to online reviews. This means that the samples below contain a wide range of writing styles, so be careful not to rely on a particular writing format to distinguish between sentences.

I've been coming here for over a year. *

Real
 AI-generated

(b) Survey Question Type 2

Please make a decision which sentence is more human-like.

Below items compare two similar sentences. Click the checkbox on the sentence you think is more human.

Click the sentence that is more human-like. *

Islamabad backs Kofi Annan ISLAMABAD: Pakistan has lent its full support to United Nations Secretary ...
 Islamabad backs Kofi Annan

(c) Survey Question Type 3-1 (Sentiment Labeling)

Please make a decision whether a given text is negative or positive.

Below items show some sentences and candidate classes. Click the checkbox on the class you think each sentence belongs to.

Note that the sentences are all AI-generated with the intended attributes. The focus of this section is to evaluate whether the generated sentences clearly reveal the intended attributes.

Worst place in the entire country to live. I'm a big fan of this show and I have been thinking about it for years, but now we're going through a lot more than that was expected for me when he got started out there.

negative
 positive

(d) Survey Question Type 3-2 (Politeness Labeling)

Please make a decision whether a given text is polite or not.

Below items show some sentences and candidate classes. Click the checkbox on the class you think each sentence belongs to.

Note that the sentences are all AI-generated with the intended attributes. The focus of this section is to evaluate whether the generated sentences clearly reveal the intended attributes.

the company has been able to find out more about the project. I think it's a great opportunity * for us, and we're really excited that there is an open source of information on how much needed in our community.

non-polite
 polite

(e) Survey Question Type 3-3 (Topic Labeling)

Please make a decision which topic a given text belongs to.

Below items show some sentences and candidate classes. Click the checkbox on the class you think each sentence belongs to.

Note that the sentences are all AI-generated with the intended attributes. The focus of this section is to evaluate whether the generated sentences clearly reveal the intended attributes.

Report: Pinochet's new home in the city of Oakland, Calif. (Photo courtesy John Deutch) *

world
 sport
 business
 sci/tech

Figure 9: (**Survey Form**.) A total of 55 items were presented to participants where each item is categorized into one of three question types. As of the third type, we experimented only with *sentiment*, *politeness*, and *topic* datasets.

Survey Analysis. The percentage of correct answers by question type is summarized in the figure below. According to this figure, less than half of the respondents who answered Type 1 and 2 questions correctly. Considering that Type 1 and 2 questions ask participants if they can distinguish between real and generated texts, this result suggests that the controllable language model with reward dropout can generate reliable sentences. Meanwhile, more than half of the respondents replied with the correct answer on Type 3 question. Especially, over 70% of the respondents correctly labeled the sentiment and topic-control texts. This means that the performance improvements driven by reward dropouts reached human standards to some extent. Taking these all together, we can conclude that a target LM trained with SPG and reward dropout is able to generate reliable sentences while achieving a control performance in line with human standards. This implies that target LMs are unlikely to sacrifice likelihood objectives for reward improvements, i.e., it is likely to maximize the likelihood and reward objectives simultaneously.

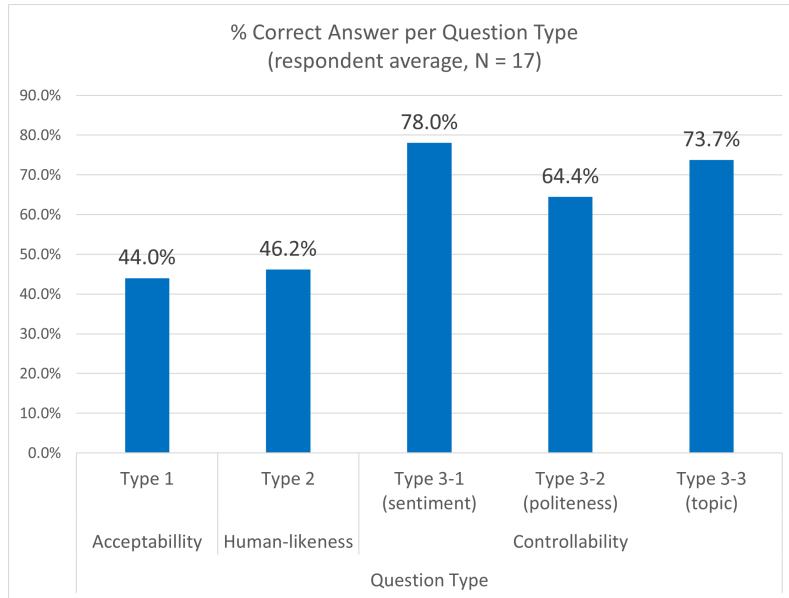


Figure 10: (**Survey Result.**) The survey was conducted with a total of 17 respondents. The respondent group was organized to include as diverse ethnicities (i.e., White, Hispanic, Mixed, East and Central Asian), genders (i.e., male and female), and ages (i.e., from 20 to 58) as possible.

H ADDITIONAL THEORETICAL ANALYSIS

In Pareto optimization, it is common that objectives are introduced as deterministic functions. However, in the context of RLM, a likelihood objective is represented by the behavior LM, and several pre-trained LMs can optionally be used; that is, different behavior policies (different likelihood objectives) can be considered. Accordingly, it would be useful to analyze how changes in behavior policy affect the optimal policy. To this end, we analyze two types of behavior policies here: high-informative behavior policy and ill-defined behavior policy, whose properties are described by Propositions H.1 and H.2, respectively:

Proposition H.1 (Auxiliary Condition). *If $\mathbb{E}_{\tau^* \sim \pi^*} [R(\tau)] = -\mathbb{E}_{\tau^* \sim \pi^*} [\ln \beta(\tau)]$ holds, then $\mathbb{E}_{\tau^* \sim \pi^*} [R(\tau)] = \mathcal{H}[\beta(\tau)]$ holds proportionally.*

Proposition H.2 (Violation Condition). *If $\mathbb{E}_{\tau \sim \pi} [R(\tau)] \leq \text{KL}[\pi(\tau) || \beta(\tau)]$ and $\forall \tau \sim \pi, \beta(\tau) = 0$ hold, then the optimal policy $\pi^*(\tau)$ becomes a uniform policy.*

Proposition H.1 describes an auxiliary condition that leads to a further Pareto improvement: the higher the entropy of the behavior policy, the higher the maximal expected reward. Since entropy means information, it trivially states that “*a highly informative behavior policy increases the maximal level of expected reward.*” That is, Proposition H.1 refers to a condition that improves the Pareto optimality itself, which is different from Theorem 4.3 that refers to a condition for an improved solution under the given Pareto optimality. The proof is provided in Appendix H.1.

On the other hand, Proposition H.2 implies that “*if the behavior policy is ill-defined, the optimal state of the target policy collapses into a completely random state.*” When we say a behavior policy is ill-defined, it means that the optimal policy does not exist with that behavior policy. In other words, if a behavior policy violates Eq (6) under a certain condition, that condition is a violation condition and yields an ill-defined behavior policy. In Appendix H.2, we prove that the violation condition is given by $\forall \tau \sim \pi, \beta(\tau) = 0$, in which case the optimal policy will be a uniform policy.

H.1 PROOF OF PROPOSITION H.1

Proposition I.1 *If $\mathbb{E}_{\tau^* \sim \pi^*} [R(\tau)] = -\mathbb{E}_{\tau^* \sim \pi^*} [\ln \beta(\tau)]$ holds, then $\mathbb{E}_{\tau^* \sim \pi^*} [R(\tau)] = \mathcal{H}[\beta(\tau)]$ holds proportionally.*

Proof. Suppose the Pareto optimality is given by $\mathbb{E}_{\tau^* \sim \pi^*} [R(\tau)] = -\mathbb{E}_{\tau^* \sim \pi^*} [\ln \beta(\tau)]$. At the optimal points $\tau^* \sim \pi^*$, trivially, $\pi^*(\tau) = \beta(\tau)e^{R(\tau)}$ holds and $R(\tau)$ has maximal values for all τ . Let k be the maximal value of $R(\tau)$. Then, we can replace $\pi^*(\tau)$ by $\beta(\tau)e^k$ and arrange the right-hand side of Eq (11) by

$$-\mathbb{E}_{\tau^* \sim \pi^*} [\ln \beta(\tau)] = -\mathbb{E}_{\tau \sim \beta} [e^k \ln \beta(\tau)] = \alpha \mathcal{H}[\beta(\tau)] \propto \mathcal{H}[\beta(\tau)],$$

where $\alpha = e^k$ is a proportionality constant (e.g., if $k = 1$ then $e^k \approx 2.718$) and can be ignored. As a result, $\mathbb{E}_{\tau^* \sim \pi^*} [R(\tau)] = \mathcal{H}[\beta(\tau)]$ holds proportionally. \square

H.2 PROOF OF PROPOSITION H.2

Proposition I.2 *If $\mathbb{E}_{\tau \sim \pi} [R(\tau)] \leq \text{KL}[\pi(\tau) || \beta(\tau)]$ and $\forall \tau \sim \pi, \beta(\tau) = 0$ hold, then the optimal policy $\pi^*(\tau)$ becomes a uniform policy.*

Proof. Let a target policy have a positive range $\pi(\tau) \in (0, 1]$, or equivalently, $0 < \pi(\tau) \leq 1$. This condition is stricter but reasonable since we are only dealing with sampled (feasible) trajectories $\tau \sim \pi$, and the sampled trajectories represent non-zero probabilities. Next, let us consider the optimal state $\pi(\tau) = \beta(\tau)e^{R(\tau)}$. Considering the optimal state is required not only because it is a necessary condition for the reward upper bound $\mathbb{E}_{\tau \sim \pi} [R(\tau)] \leq \text{KL}[\pi(\tau) || \beta(\tau)]$, but also because it states the existence of an optimal solution.

Considering $\pi(\tau) \in (0, 1]$ and $\pi(\tau) = \beta(\tau)e^{R(\tau)}$ together, the domain of target policy $\tau \in \mathcal{T}_\pi$ is defined by which $\beta(\tau)e^{R(\tau)} \in (0, 1]$ is satisfied. This implies that the behavior policy $\beta(\tau)$ and the reward objective $R(\tau)$ are well-defined only in that domain, having a support set given by

$\{\exists \tau \in \mathcal{T}_\pi \mid 0 < \beta(\tau)e^{R(\tau)} \leq 1\}$. Conversely, out of that domain, e.g., $\beta(\tau)e^{R(\tau)} = 0$,⁴ a support set is given by $\{\forall \tau \in \mathcal{T}_\pi \mid \beta(\tau)e^{R(\tau)} = 0\}$, implying that either $\beta(\tau)$ or $R(\tau)$ is ill-defined. Since $e^{R(\tau)}$ is positive for all $R(\tau) \in [0, 1]$, trivially $\beta(\tau)e^{R(\tau)} = 0$ holds if and only if $\beta(\tau)$ is zero for all τ , i.e., $\forall \tau, \beta(\tau) = 0$.

Now, suppose $\mathbb{E}_{\tau \sim \pi} [R(\tau)] \leq \text{KL}[\pi(\tau) \parallel \beta(\tau)]$ and $\forall \tau \sim \pi, \beta(\tau) = 0$ holds. Then, the reward changes to the entropic reward, and the reward upper bound disappears as $-\ln \beta(\tau) \rightarrow +\infty$ at $\beta(\tau) = 0$.

$$\underbrace{\mathbb{E}_{\tau \sim \pi} [R(\tau)] \leq -\underbrace{\mathbb{E}_{\tau \sim \pi} [\ln \beta(\tau)] - \mathcal{H}[\pi]}_{= \text{Reward Upper Bound}}}_{\text{= Entropic Reward}} \iff \underbrace{\mathbb{E}_{\tau \sim \pi} [R(\tau)] + \mathcal{H}[\pi] \leq -\underbrace{\mathbb{E}_{\tau \sim \pi} [\ln \beta(\tau)]}_{= +\infty \text{ s.t. } \beta(\tau) = 0}}$$

As a result, the bounded reward maximization turns into an unbounded entropic reward maximization, and thus the optimal policy becomes a uniform policy as it has the highest entropy. \square

H.3 BEHAVIOR POLICY IN 10-TURN POSITIONING GAME

In the 10-turn position game, we implemented the behavior policy (a policy of the behavior agent) based on the truncated normal distribution according to Burkardt (2014). Note that a support set of the normal distribution is defined on a real-value domain, but the action space (and thus position space) must be an integer domain. Accordingly, we integerized it by rounding up if the sampled action is greater than the average and rounding down if it is less. For example, assume μ and σ of the behavior policy are 3 and 0.5, respectively, and suppose one sampled action by the behavior policy is 3.71. In this case, we round up 3.71 by 4, and thus the next visiting state is set to 4. Similarly, if a sampled action is 3.12, then the next visiting state is set to 3.

H.4 EMPIRICAL VALIDATION OF PROPOSITIONS

This section provides an empirical analysis that demonstrates all theoretical results presented in the previous section. To this end, we devised a simulation experiment called a 10-turn positioning game. The goal of this experiment is to confirm the theoretical results and analyze them in the RLM context.

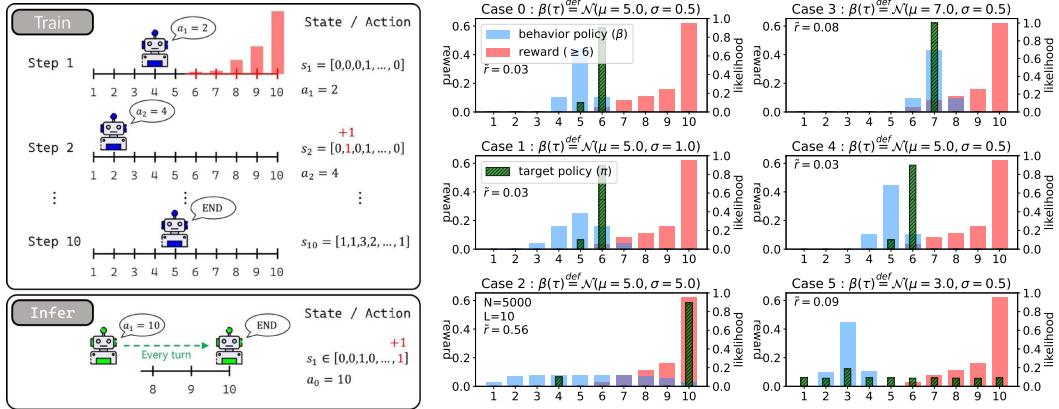
10-turn Positioning Game. Figure 11a describes the 10-turn positioning game. In this game, an agent changes its position over 10 turns. Each turn is indexed by $t = 1, \dots, 10$. Two agents participate in this game: the **behavior agent** and the **target agent**. Each agent selects one of 10 actions $a_t \in [1, 2, \dots, 10]$ in each t -th turn and moves to a corresponding position $i \in [1, 2, \dots, 10]$. The history of an agent's position is a trajectory τ . The **behavior agent** changes its positions based on a **normal distribution policy**, $a_t \sim \mathcal{N}(\mu, \sigma^2)$ for $t = 1, \dots, 10$ and collects rewards if the occupied position is rewarded.⁵ The **target agent** observes a trajectory of the behavior agent and learns from it in an off-policy manner. For simplicity, we set a **reward distribution** to have an **exponential shape** only at $i \in [6, 10]$. Note that agent's state s_t is defined as a vector, which describes a cumulative visit frequency to each position, $\forall t, s_t = [s_1, \dots, s_i, \dots, s_{10}]$, and $\forall i, s_i \in \mathbb{Z}_0^{10}$; here, $s_i \in \mathbb{Z}_0^{10}$ indicates that the value of s_i is defined by integer numbers between 0 and 10. The state vector is initialized to a random position at the first turn.

Simulation Results & Interpretations. Figure 11b shows the simulation results. A total of 5000 trajectories were simulated ($N = 5000$) where each trajectory has a length of 10 ($L = 10$) and reward values were normalized by the softmax function. The rewards were distributed to each position in ascending order from smallest to largest. That is, the largest reward is 1.0 at position 10, implying the expected reward of the target agent, i.e., $\mathbb{E}_{\tau \sim \pi} [R(\tau)] = \frac{1}{N \times L} \sum_{n=1}^N \sum_{t=1}^L R(s_t^n, a_t^n) \triangleq \tilde{r}$, can be up to 1.0 at maximum.

The first and second columns in Figure 11b demonstrate Propositions H.1 and H.2, respectively. The first column shows that the more uniform the behavior agent's policy, the higher the target agent's expected reward (Cases 0, 1 and 2). This result is consistent with Proposition H.1. On the

⁴We do not consider $\beta(\tau)e^{R(\tau)} > 1$ for the out-of-domain because there are infinitely many combinations of $\beta(\tau) \in [0, 1]$ and $R(\tau) \in [0, 1]$ that satisfy $\beta(\tau)e^{R(\tau)} > 1$.

⁵Refer to Appendix H.3 for the details.



(a) **Concept Illustration:** The horizontal bar shows available positions and actions agents' visit frequency to corresponding positions. The red bar together. Red positions indicate a reward indicates a reward distribution defined over $i \in [6, 10]$. \tilde{r} is the zone. Blue/green agents refer to behavior/target agents, respectively. Note that 10 converges to only a few actions that maximize reward. (2) In case turns (steps) make up a single trajectory.

(b) **Results:** The blue and green bars represent the behavior/target bar shows available positions and actions agents' visit frequency to corresponding positions. The red bar together. Red positions indicate a reward indicates a reward distribution defined over $i \in [6, 10]$. \tilde{r} is the zone. Blue/green agents refer to behavior/target agents, respectively. Note that 10 converges to only a few actions that maximize reward. (1) In cases 0-4, π expected reward achieved by a target agent. (1) In cases 0-4, π converges to only a few actions that maximize reward. (2) In case 5, $\pi(\tau)$ collapses into a uniform policy because $\beta(\tau)$ is ill-defined.

Figure 11: (10-turn Positioning Game.) Concepts and Results

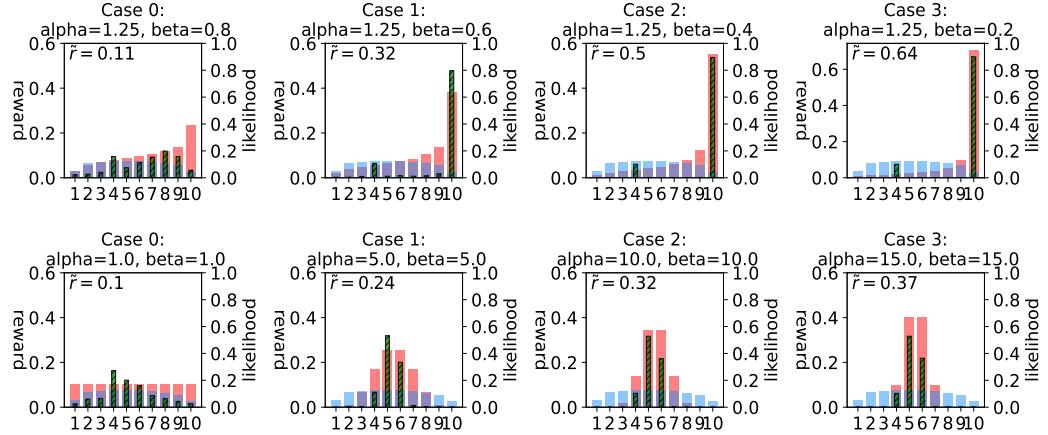


Figure 12: (Reward Manipulation & Pareto Improvement.) The behavior and target agents' policies are represented by the blue and green bars, respectively. The behavior policy was set to a normal distribution whose parameters are $\mu = 5.0$ and $\sigma = 5.0$, and each manipulated reward distribution was defined over full positions $i \in [1, 10]$ and set to a beta distribution for different shape parameters alpha and beta. Other conditions were set the same as before (e.g., $N = 5000$, $L = 10$).

other hand, the second column shows that the farther the behavior agent's policy is defined from the reward distribution, the less reward the target agent collects (Cases 3 and 4). Furthermore, if the behavior agent's policy is ill-defined (i.e., if the behavior agent cannot enter the reward zone, or the behavior agent samples no actions between 6 and 10.), then the target agent receives no rewards from the behavior agent. As a result, the target agent's policy converges to a uniform policy, maximizing entropic rewards (Case 5). This result is consistent with Proposition H.2.

We can also interpret Figure 11b from the RLM perspective. The first column highlights that target LMs will be better controlled if behavior LMs can cover as large a token space (a dictionary) as possible. This is because the large token space is more likely to create opportunities for exploring higher-reward sentences. Therefore, it is recommended to use large language models (LLMs) when building RLMs. The second column emphasizes the importance of preparing the training dataset

correctly. For example, let us say we need to control the target LM so that sentences are generated with negative sentiment. If the behavior LM is pre-trained on a dataset consisting only of positive sentences (i.e., the behavior policy is ill-defined), then the behavior LM cannot provide negative candidate sentences. Consequently, the target LM cannot experience any rewards and therefore never be controlled.

H.5 NON-NORMAL BEHAVIOR POLICY

In this subsection, we provide additional results when a behavior policy is non-normal.

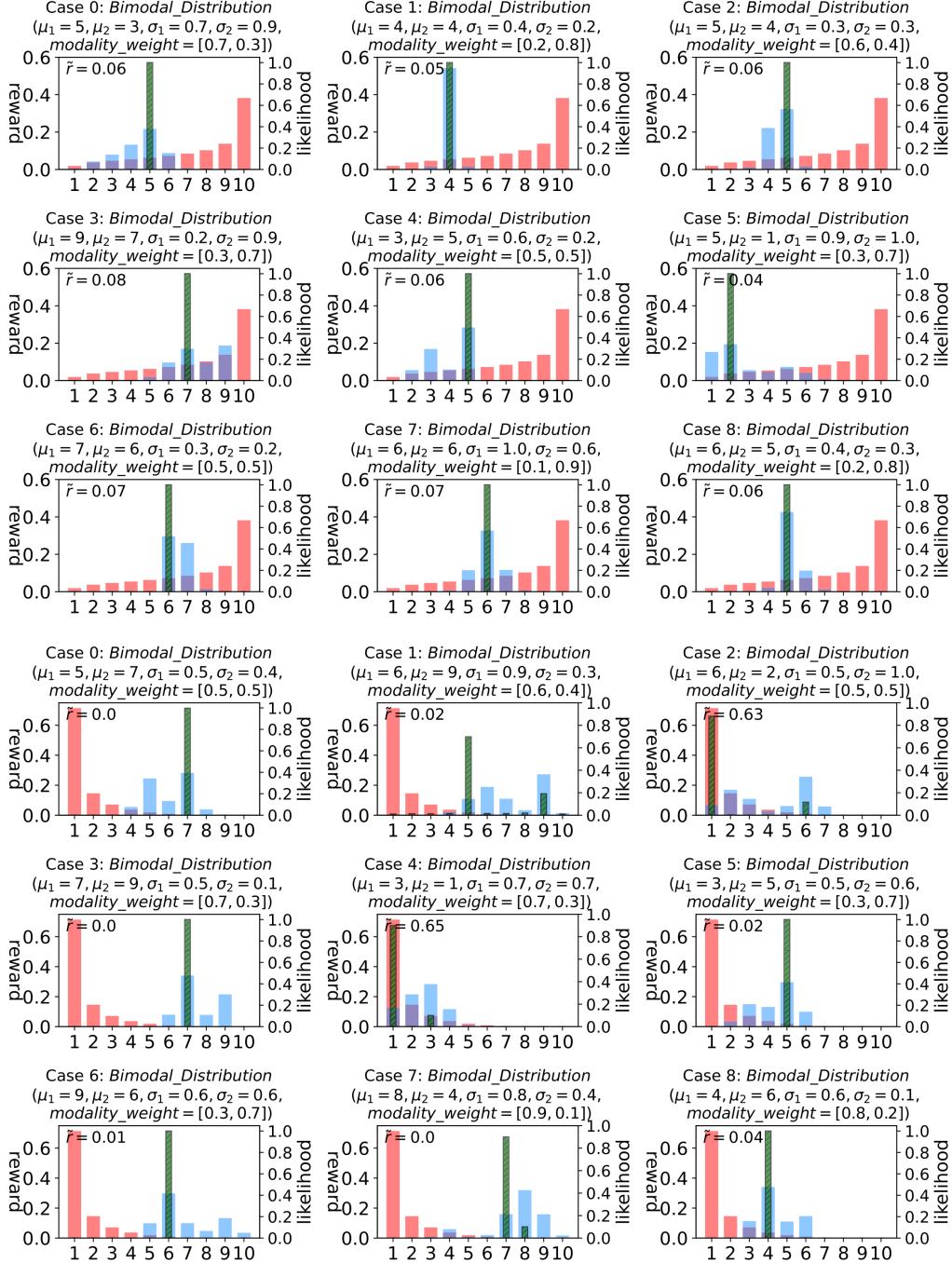


Figure 13: Additional results with non-normal behavioral policies and different reward distributions.