Non-Stationary Contextual Pricing with Safety Constraints

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Abstract

In a contextual pricing problem, a seller aims at maximizing the revenue over a sequence of sales sessions (described by feature vectors) using binary-censored feedback of "sold" or "not sold". Existing methods often overlook two practical challenges (1) the best pricing strategy could change over time; (2) the prices and pricing policies must conform to hard constraints due to safety, ethical or legal restrictions. We address both challenges by solving a more general problem of *universal dynamic regret* minimization in *proper* online learning with exp-concave losses — an open problem posed by Baby & Wang (2021) that we partially resolve in this paper, with attention restricted to loss functions coming from a generalized linear model. Here "dynamic regret" measures the performance relative to a non-stationary sequence of policies, and "proper" means that the learner must choose *feasible* strategies within a pre-defined convex set, which we use to model the safety constraints. In this work, we consider a linear noisy valuation model for the customers. With the market noises drawn from a *known strictly log-concave* distribution, our algorithm achieves $\tilde{O}(d^3T^{1/3}C_T^{2/3} \vee d^3)$ dynamic regret in comparison with the optimal policy series, where T, d and C_T stand for the time horizon, the feature dimension and the total variation (characterizing non-stationarity) respectively. This regret is near-optimal with respect to T (within $O(\log T)$ gaps) and C_T, and our algorithm is adaptable to *unknown* C_T and remains *feasible* throughout. However, the dependence on d is suboptimal and the minimax rate is still open.

1 Introduction

Feature-based dynamic pricing, or *contextual* pricing, is a problem where the seller sets prices for different products based on their features and aims to maximize revenue. In general, a customer will make her decision based on a comparison between the price and her own valuation of the product. Formally, many existing works (e.g., Cohen et al., 2020; Javanmard & Nazerzadeh, 2019; Xu & Wang, 2021; Luo et al., 2021) adopt the following linear-feature valuation model:

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Contextual pricing. For $t = 1, 2, ..., T$:

1. A context $x_t \in \mathbb{R}^d$ is revealed that describes a sales session (product, customer and context).
2. The customer valuates the product as $y_t = x_t^\top \theta_t^* + N_t$ using x_t.
3. The seller proposes a price $v_t > 0$ concurrently (according to x_t and historical sales records).
4. The transaction is successful if $v_t \leq y_t$, i.e., the seller gets a reward (payment) of $r_t = v_t \cdot \mathbb{1}(v_t \leq y_t)$.

Here T is the unknown time horizon, x_t's are adversarial features (which can be stochastic or non-stochastic series), θ_t^*'s are *hidden parameters* mapping features to valuations linearly, and N_t's are i.i.d. noises drawn from a known distribution $\mathbb{D}$. Denote $\mathbb{1}_t := \mathbb{1}(v_t \leq y_t)$ as the *Boolean-censored* feedback that equals 1 if $v_t \leq y_t$ and 0 otherwise, and we only observe $\mathbb{1}_t$ instead of the realized y_t at each round. Our goal is to maximize the cumulative expected reward, and the *regret* is defined as the difference of expected rewards between v_t and the best price at each round.

Time-variant Behavior and Dynamic Regret. Comparing with existing linear contextual pricing problem settings (e.g., Cohen et al., 2020; Javanmard & Nazerzadeh, 2019; Xu & Wang, 2021) where the linear valuation parameter θ_t^* is fixed as the same θ^* over all t, in this work we allow moderate changing of customers' valuations: i.e. θ_t^*'s can vary over time, and the *total variation* $\sum_{t=1}^{T-1} \|\theta_t^* - \theta_{t+1}^*\|_1$ is upper bounded by some C_T (which could be unknown to the seller). Here we adopt the L_1-norm bound because it is a reasonable metric for capturing the non-stationarity of the valuation mechanism: For instance, suppose each element of x_t indicates the amount of one component of this product, and therefore each element of θ_t^* indicates the unit price of this component. In this example, $\|\theta_t^* - \theta_{t+1}^*\|_1$ reflects the general price fluctuations on the market, i.e., the sum of market-wise price changes over all components. To characterize the performance of a pricing scheme under this non-stationary setting, we adopt the concept of *dynamic regret*. In this notion, we compare the performance of v_t we propose with that of the optimal pricing policy that knows the sequence of θ_t^* in advance. A rigorous definition of this dynamic regret will be presented in Section 2.3.

Proper Learning. Usually, the actions/strategies we are allowed to adopt are restricted in some specific *safe domains*. Taking any action/strategy outside this domain would probably cause risky, illegal or inconsistent outcomes. Our algorithm works by maintaining an estimate, θ_t, for the true valuation parameter θ_t^* at each round t, and we in turn take θ_t as a *parametric strategy* for proposing the price v_t according to a greedy policy (see Section 2.3 for more details). In this work, we require that the estimate θ_t must fall in a specific convex and closed domain $\mathcal{D}_t$ at each round t. Here $\mathcal{D}_t$ can be chosen adversarially with the constraint imposed by Assumption 1. As will be explained in Section 2.4, this is to address the fact that pricing strategies must conform to hard constraints due to safety restrictions.

Universal Dynamic Regret and Proper OCO with co-variates. Next, we take a digression and describe a general Online Convex Optimization (OCO) setting which will play a pivotal role in solving the contextual pricing problem.

Proper OCO with co-variates. For $t = 1, 2, ..., T$:

1. Adversary reveals a co-variate $x_t \in \mathbb{R}^d$.
2. Learner makes a decision $\hat{\theta}_t$ in a convex domain $\mathcal{D}_t \subset \mathbb{R}^d$.
3. Adversary reveals a convex loss function $\ell_t(\theta) = g_t(\theta^T x_t)$.

This setting embodies OCO under a wide range of loss functions from the generalized linear model (GLM) family for appropriate choices of g_t. The co-variates x_t can be thought of as a feature that encodes valuable information about the context in round t which can be used by the learner to make its predictions. Examples of this setting include (but are not limited to) linear regression and logistic regression.

The goal of the learner is to control its universal dynamic regret:

$$R(w_{1:T}) := \sum_{t=1}^{T} \ell_t(\hat{\theta}_t) - \ell_t(w_t), \tag{1}$$

where $w_{1:T} = \{w_1, w_2, \ldots, w_T\}$ is *any* comparator sequence satisfying $w_t \in \mathcal{D}_t$ for all $t \in [T]$. This is known to be a good metric in characterizing the performance of a learner in non-stationary environments (Zinkevich, 2003). Dynamic regret bounds are usually expressed in literature as functions of the time horizon T and a path length that captures the smoothness of the comparator sequence such as $C_T = \sum_{t=1}^{T-1} \|w_t - w_{t+1}\|_1$.

1.1 Summary of Contributions

Our main contributions are given below.

1. We present an algorithm ProDR (Algorithm 1) that attains an *optimal* $\tilde{O}(d^3(T^{\frac{1}{3}}C_T^{\frac{2}{3}} \vee 1))$ dynamic regret (modulo dependencies in d and $\log T$) for the setting of proper OCO with co-variates under exp-concave losses (see Section 3.1).

2. We construct an algorithm PDRP (Algorithm 2) with a base learner ProDR, which solves the non-stationary contextual pricing problem with strictly log-concave noise. We define the dynamic regret of contextual pricing as Eq.(3) and show that PDRP achieves a $\tilde{O}(d^3(T^{\frac{1}{3}}C_T^{\frac{2}{3}} \vee 1))$ dynamic regret guarantee (see Section 3.2).

3. We show that any algorithm must incur a dynamic regret of $\Omega(T^{\frac{1}{3}}C_T^{\frac{2}{3}} \vee 1)$ in the contextual pricing problem, which says that PDRP is minimax optimal up to d and $\log T$ factors (see Section 3.3).

Novelty. Owing to the reduction of Xu & Wang (2021), the non-stationary contextual pricing problem can be reduced to an OCO problem with co-variates and exp-concave losses. The key subroutine we developed — ProDR — is the first to achieve an *optimal* universal dynamic regret with *exp-concave* losses in the *proper OCO with covariate* setting. ProDR makes considerable progress towards addressing the open problem posed by Baby & Wang (2021) on the more general version of the above problem with *general exp-concave* losses (rather than GLM with known covariates) . The only existing attempt to this open problem requires the decision set to be an L_∞ ball (Baby & Wang, 2022b), which cannot be used to handle arbitrary convex decision sets as we do.

Summary of techniques. The key technique in deriving ProDR is a novel "transfer theorem" which takes the algorithm of Baby & Wang (2022b) (L_∞ ball decision set) and converts it to an optimal algorithm for the setting of proper OCO with co-variates under *arbitrary convex decision sets*. This idea is similar in spirit to the improper-proper reduction in the work of Cutkosky & Orabona (2018) where they consider general convex losses. However, a direct application of their reduction scheme cannot give fast rates for exp-concave losses. To circumvent this issue, we propose new reduction schemes that carefully take the curvature of the losses into account thereby allowing us to derive fast and optimal dynamic regret rates under exp-concave losses (see Section 3.1 for a list of technical challenges). Such a "transfer theorem" could be of independent interest and impactful in the general context of non-stationary online learning. That the non-stationary dynamic pricing problem can be optimally solved using ProDR is a testament to this fact.

1.2 Related Works

Here we discuss how our work relates to the existing literature on dynamic pricing and dynamic regret.

Dynamic Pricing Dynamic pricing has been extensively studied under the single product (non-contextual) setting (e.g. Kleinberg & Leighton, 2003; Besbes & Zeevi, 2015; Wang et al., 2021), where the goal is to find and approach the best fixed price that maximizes the expected revenue. The problem is later generalized to *contextual pricing* where a feature x_t occurs at each time t and the customer's valuation is dependent on x_t. A widely adopted model is the *linear valuation* (e.g., Cohen et al., 2020; Javanmard & Nazerzadeh, 2019; Xu & Wang, 2021), where they assume all customers' valuations are a fixed feature-to-valuation mapping (i.e., θ_t^* is fixed, $\forall t$) adding i.i.d. noises drawn from a known distribution. As a result, the best price varies on different features occurring over time, and the goal turns to approach the best price in every round. However, the optimal pricing policy is static and the regret definition is a comparison of performance between our proposed price and the optimal policy that knows θ^* and the noise distribution in advance. In this work, we adopt this linear valuation setting and further generalize to non-stationary cases where the linear mapping θ_t^* is changeable over time. As a result, the best pricing policy also changes according to θ_t^*, and we have to analyze the algorithmic performance in the scale of *dynamic regret*. Leme et al. (2021) also studies non-stationary

pricing problems and adopts the dynamic regret metric. However, their loss function and constraints are defined on *realized* valuations, different from our regret function defined on the *expected* valuations. Also, they adopt a non-contextual problem setting and assume individual variation bounds on each pair of adjacent valuations like $|v_{t+1} - v_t| \leq \epsilon_t$ for some $\epsilon_t > 0, t = 1, 2, \ldots, T$. Under their assumptions, they achieve an $\tilde{O}(T^{\frac{1}{2}} C_T^{\frac{1}{2}})$ optimal regret with a matching lower bound[1]. Given those differences in problem settings, their regret bounds are not applicable to our problem.

Some existing works on stationary pricing problems adopt contextual bandits to achieve sub-linear static regrets (Luo et al., 2021; Xu & Wang, 2022). Therefore, it is also possible to reduce our non-stationary pricing problem to a non-stationary bandit problem (Chen et al., 2019; Cheung et al., 2022; Zhao et al., 2020a). However, similarly to what Amin et al. (2014) indicates in stationary contextual pricing, a direct application of non-stationary bandit algorithms to our known-noise-distribution setting might cause sub-optimality in dynamic regret. Such a reduction might be optimal without the knowledge of noise distribution, but it is beyond the scope of this work.

Besides, a recent stream of works study the pricing problems under constraints on inventory (Chen & Gallego, 2022), reserve-price (Niu et al., 2020), fairness (Cohen et al., 2021; 2022; Xu et al., 2023; Chen et al., 2023) and budget (Salehi & Mirmohammadi, 2023), etc. Our work also contributes to this series as we enforce safety constraints and adaptively measure the impact of those constraints on the dynamic regret.

Dynamic Regret. There is a rich body of literature aimed in minimizing the universal dynamic regret (Eq.(1)) in OCO setting where the earliest works can be traced back to Zinkevich (2003). When the revealed losses are convex, Zhang et al. (2018) proposes algorithms to attain an optimal dynamic regret rate of $O(\sqrt{T(1+P_T)})$ where $P_T = \sum_{t=1}^{T-1} \|w_t - w_{t+1}\|_2$. When the loss functions are gradient Lipschitz, problem dependent regret bounds have been developed in the work of Zhao et al. (2020b). In addition to gradient Lipschitzness, if the losses have extra curvature properties such as exp-concavity, Baby & Wang (2021) proposes algorithms that attain a near optimal dynamic regret of $\tilde{O}^*(T^{1/3}C_T^{2/3} \vee 1)$ ($\tilde{O}^*$ hides dependencies on dimensions and factors of $\log T$). The work of Baby & Wang (2022b) shows similar rates for non-smooth and exp-concave losses in a proper learning setting when the decision set is an L_∞ ball. In contrast, our work is able to attain near optimal rates for arbitrary convex decision sets for a large family of exp-concave losses. Further Baby & Wang (2022b) also shows optimal rates for arbitrary bounded convex decision sets when the losses are strongly convex.

If we take all the comparators w_t in Eq.(1) to be same, one recovers the notion of static regret. There are works that aim in controlling the static regret in any time window which makes them suitable for learning in non-stationary environments. These algorithms fall into the category of adaptive / strongly adaptive regret minimization algorithms. Examples of such methods include Hazan & Seshadhri (2007); Daniely et al. (2015); Adamskiy et al. (2016); Jun et al. (2017); Cutkosky (2020); Baby et al. (2021); Zhang et al. (2021). We refer the readers to Baby & Wang (2021) and references therein for a more inclusive survey on dynamic regret and strongly adaptive algorithms.

There has also been recent advances (e.g. Zhao et al., 2022; Baby & Wang, 2022a) in applying online learning techniques to design controllers. In particular, Baby & Wang (2022a) uses a reduction from Linear Quadratic Regulator (LQR) problem to online (mini-batch) linear regression problem due to the work of Foster & Simchowitz (2020). They employ a black-box reduction technique to convert the algorithm of Baby & Wang (2022b) to one that attains optimal dynamic regret for online linear regression under the setting of proper learning. This is facilitated by exploiting the constant hessian property of linear regression losses. However, this property will not be satisfied for exp-concave losses in general. As such it is unclear that the black-box reduction techniques of Baby & Wang (2022a) are generalisable beyond linear regression. Hence the results in this paper are not directly implied by their results. We direct the readers to Baby & Wang (2022b) for an elaborate discussion about the literature on online learning and control.

[1]Here we reduce their loss bound to our notations.

2 Notations and Problem Setup

In this section, we specify necessary mathematical symbols and notations, and define functions for algorithm design and regret analysis. We also present three examples to illustrate the concept of proper learning in contextual pricing.

2.1 Symbols and Notations.

The pricing process consists of T rounds. $x_t, \theta_t^* \in \mathbb{R}^d$, $y_t \in \mathbb{R}$, $v_t \in \mathbb{R}_+$ and $N_t \in \mathbb{R}$ denote the feature vector, the linear valuation parameter, the customer's valuation, the seller's price and the noise at time t, sequentially. At each round, we receive a payoff (reward) $r_t = v_t \cdot \mathbb{1}_t$, where the binary variable $\mathbb{1}_t$ indicates the *customer's decision*, i.e., $\mathbb{1}_t = \mathbf{1}(v_t \leq y_t)$.

2.2 Technical Assumptions

Denote a norm-bounded domain family $\mathcal{D}_p^B = \{\theta \in \mathbb{R}^d, \|\theta\|_p \leq B\}$. We firstly present assumptions on domain constraints of x_t and θ_t^*:

Assumption 1 (Domain Constraints)**.** Assume $x_t \in \mathcal{D}_x$ where $\mathcal{D}_x \subseteq \mathcal{D}_2^1$ is convex and closed, and $\theta_t^* \in \mathcal{D}_t$ where every $\mathcal{D}_t \subseteq \mathcal{D}_2^B \subset \mathcal{D}_\infty^B$ is also convex and closed. Each $\mathcal{D}_t$ can be chosen adversarially and is known to the learner before time t.

Here we want the customers' valuations to be bounded. Equivalently, we may also assume that $\mathcal{D}_x \subseteq \mathcal{D}_2^{B_1}$ and $\mathcal{D}_t \subseteq \mathcal{D}_2^{B/B_1}$ for any $B_1 > 0$. With these assumptions, we know that $|x_t^\top \theta| \leq B, \forall \theta \in \mathcal{D}_2^B, t = 1, 2, \ldots, T$. Next, we make a reasonable assumption on customers' expected valuations:

Assumption 2 (Non-Negative Expected Valuation)**.** For a customer's valuation $y_t = x_t^\top \theta_t^*$, we assume the *expected valuation* $x_t^\top \theta_t^* \geq 0, t = 1, 2, \ldots, T$.

Now we make assumptions on the distribution of noise N_t. According to Prékopa (1973), we firstly present the definitions of *log-concavity* and *strict log-concavity* on 1-dimension distributions.

Definition 2.1 (Log-concavity and strict log-concavity)**.** A probability measure P defined on $\mathbb{R}$ is said to be *log-concave* if and only if for any pair $A, B \subset \mathbb{R}$ of intervals, it holds that

$$P(\lambda A + (1-\lambda)B) \geq \{P(A)\}^\lambda \{P(B)\}^{1-\lambda}, \forall \lambda \in (0,1).$$

Here "+" denotes Minkowski addition. Also, P is *strictly log-concave* if and only if for any pair $A, B \subset \mathbb{R}$ of intervals, $A \neq B$, it holds that

$$P(\lambda A + (1-\lambda)B) > \{P(A)\}^\lambda \{P(B)\}^{1-\lambda}, \forall \lambda \in (0,1).$$

Then we make the following assumption:

Assumption 3 (Valuation noise distribution)**.** At each time $t = 1, 2, \ldots, T$, the noise N_t is independently and identically sampled from a fixed *strictly log-concave* distribution $\mathbb{D}$ with a twice continuously differentiable cumulative distribution function (CDF) F. Furthermore, the first and second derivatives of the CDF, denoted as f and f', respectively are bounded by two finite constants $B_f := \sup_{\omega \in \mathbb{R}} f(\omega)$ and $B_{f'} := \sup_{\omega \in \mathbb{R}} |f'(\omega)|$.

According to Definition 2.1, let (i) $A = (-\infty, x], B = (-\infty, y]$ and (ii) $A = (x, +\infty), B = (y, +\infty)$ respectively, and we have F and $(1-F)$ are both strictly log-concave functions. Existing works on contextual pricing also adopt log-concavity assumptions (see Javanmard & Nazerzadeh, 2019). For a detailed discussion on log-concave distributions, we kindly refer the audience to Bagnoli & Bergstrom (2006).

All of those three assumptions are supposed to hold throughout the paper.

2.3 Functions and Key Quantities

Greedily Pricing. Here we adopt two functions defined by Xu & Wang (2021) and also make use of their properties. Firstly, we introduce an *expected reward* function $g(v, u) := \mathbb{E}[r_t | v_t = v, x_t^\top \theta^* = u] = v \cdot (1 - F(v - u))$ that is unimodal w.r.t. v. Secondly, we introduce a *greedily pricing* function $J(u) := \text{argmax}_{v \in \mathbb{R}} g(v, u)$. $J(u)$ has two important properties: On the one hand, $J(u)$ is strictly monotonically

increasing, with $J'(u) \in (0,1)$. Therefore, $J(u)$ and $J^{-1}(v)$ are bijections, $\forall u \in \mathbb{R}, v > 0$. On the other hand, we have $\|\nabla_\theta J(x^\top \theta)\|_2 = |J'(x^\top \theta)| \cdot \|x\|_2 \leq 1$, which guarantees a low price-changing rate while modifying parameter θ.

Restrictions on Actions/Parametric Strategies. When we take an action by presenting a price v_t, there always exists an $\theta_t \in \mathbb{R}^d$ such that $x_t^\top \theta_t = J^{-1}(v_t)$. Therefore, for any price $v_t > 0$, it is equivalent to firstly propose a corresponding *parametric strategy* θ_t (satisfying $x_t^\top \theta_t = J^{-1}(v_t)$) and then set the price as $J(x_t^\top \theta_t)$. Since we are approaching the optimal price (which is $J(x_t^\top \theta^*)$) and that $\theta_t^* \in \mathcal{D}_t$, we may restrict the strategy θ_t to be taken within $\mathcal{D}_t$ at each time t. We will explain more on the motivation of the restrictions in Section 2.4.

Negative Log-likelihood. We define

$$\ell_t(\theta) = -\mathbb{1}_t \cdot \log\left(1 - F(v_t - x_t^\top \theta)\right) - (1 - \mathbb{1}_t) \log\left(F(v_t - x_t^\top \theta)\right) \tag{2}$$

as a negative log-likelihood function at round t. Also, we define an expected log-likelihood function $L_t := \mathbb{E}_{N_t}[\ell_t(\theta)|x_t, \theta_t^*]$. For the simplicity of notations in the following sections, we denote $h_t(\theta) := \frac{\partial \ell_t(\theta)}{\partial x_t^\top \theta} \in \mathbb{R}$, and we show a property of $h_t(\theta)$:

Lemma 2.2. *For $\theta \in \mathcal{D}_2^B$, there exist constants $0 < h_{\min} \leq h_{\max} < +\infty$ such that*

$$h_{\max} = \sup_{\theta \in \mathcal{D}_2^B} |h_t(\theta)|, h_{\min} = \inf_{\theta \in \mathcal{D}_2^B} |h_t(\theta)|, \forall t = 1, 2, \ldots, T.$$

We prove this by noticing that $h(\theta)$ is continuous and $\mathcal{D}_2^B$ is closed, and the details are in Appendix B.1. With this lemma, we may know that $\ell_t(\theta)$ is Lipschitz (see Lemma 3.8).

Dynamic Regret. Finally, we define the cumulative *dynamic regret*:

$$\mathbf{Reg}_T = \sum_{t=1}^{T} g(J(x_t^\top \theta_t^*), x_t^\top \theta_t^*) - g(v_t, x_t^\top \theta_t^*). \tag{3}$$

We usually measure the regret as a function of T, d and the total variation $C_T := \sum_{t=1}^{T-1} \|\theta_t^* - \theta_{t+1}^*\|_1$.

2.4 Examples

Here we present three examples where the nature requires the strategies to lie in a "safe domain", regarding risk-taking, legal or consistency concerns.

Risk Control Adopting strategies outside a pre-defined and protected decision set can be very risky in general. Concerning our contextual pricing problem, an extremely low price would lead to significant loss of profit. Therefore, we have to set a lower pricing bar for each item. At each time t, suppose the lower bar is $c_t > 0$, and therefore our parametric strategy θ_t should satisfy $c_t \leq J(x_t^\top \theta_t)$. Since $J(u)$ is monotonically increasing, we have $x_t^\top \theta_t \geq J^{-1}(c_t)$. By intersecting $\{\theta \in \mathbb{R}^d | x_t^\top \theta \geq J^{-1}(c_t)\}$ with the L_2-norm ball $\mathcal{D}_2^B$, we get a convex and compact set $\mathcal{D}_t$, in which any parametric strategy θ satisfies the norm bound and will lead to a price not less than c_t given the $J(x_t^\top \theta)$ greedy pricing policy.

Legal Concern There exist laws or regulations regarding the highest price of some specific products. For each item with feature x_t, suppose that we cannot set a price exceeding $c_t > 0$. Equivalently, the parametric strategy θ_t we take must satisfy $v_t = J(x_t^\top \theta_t) \leq c_t$. Since $J(u)$ is monotonically increasing, this is further equivalent to $x_t^\top \theta_t \leq J^{-1}(c_t)$. Therefore, the restricted strategy space $\mathcal{D}_t$ is the intersection of $\{\theta | x_t^\top \theta \leq J^{-1}(c_t)\}$ with the L_2-norm ball $\mathcal{D}_2^B$, which is a convex and compact set. Any parametric strategy falling out of $\mathcal{D}_t$ would lead to either $v_t > c_t$ or $\|\theta\| > B$.

Price Consistency It is important for the seller to be consistent on setting prices, or otherwise it might cause pricing discrimination. Specifically, if two identical items with feature x occur at time t and $t+1$, then their prices must be close to each other. In other words, we require $|J(x^\top \theta_t) - J(x^\top \theta_{t+1})| \leq C, \forall x \in \mathcal{D}_x \subset \mathcal{D}_2^1$ for some constant $C > 0$. For each $x \in \mathcal{D}_x$, we may solve it and get

Algorithm 1 Proper Dynamic Regret minimization (ProDR)

1: **Input:** Base algorithm $\mathcal{A}$, barrier multiplier $G' > 0$, exp-concavity factor β.
2: **for** $t = 1, 2, \ldots, T$: **do**
3: Get iterate $\tilde{\theta}_t$ from $\mathcal{A}$.
4: Feature x_t and proper domain $\mathcal{D}_t$ are revealed
5: Output $\hat{\theta}_t = \text{argmin}_{\theta \in \mathcal{D}_t} |x_t^\top (\theta - \tilde{\theta}_t)|$.
6: Loss ℓ_t is revealed.
7: Construct $\hat{\ell}_t(\theta)$ as in Eq.(4) and set

$$f_t(\theta) = \hat{\ell}_t(\theta) + G' \cdot S_t(\theta),$$

where $S_t(\theta) = \min_{\eta \in \mathcal{D}_t} |\nabla \hat{\ell}_t(\hat{\theta}_t)^\top (\eta - \theta)|$;
8: Send $f_t(\theta)$ to $\mathcal{A}$ as loss at time t.
9: **end for**

$$J^{-1}(J(x^\top \theta_t) - C) \leq x^\top \theta_{t+1} \leq J^{-1}(C + J(x^\top \theta_t)).$$

Denote this set as $\mathcal{S}_t(x)$, and we have $\mathcal{D}_{t+1} \subseteq \cap_{x \in \mathcal{D}_x} \mathcal{S}_t(x)$. Since $\theta_t \in \mathcal{S}_t(x), \forall x$, the intersection is non-empty.

3 Main Results

In this section, we present and analyse our algorithms. In Section 3.1, we first study the more general problem of universal dynamic regret (Eq.(1)) minimization in a proper OCO setting. Results of Section 3.1 will be applied in Section 3.2 to derive an optimal algorithm for the non-stationary pricing problem. All omitted proofs in this section are deferred to Appendix B.

3.1 Dynamic Regret of ProDR

In this section, we study the **Pro**per **D**ynamic **R**egret minimization (ProDR) algorithm (Algorithm 1). We consider the protocol of proper OCO with co-variates introduced in Section 1.

The goal of this section is to control the universal dynamic regret as defined in Eq.(1). We start by listing out the assumptions we made for the OCO problem.

Assumption 4. A constant $B > 0$ is known such that $\max_{\theta \in \mathcal{D}_t} \|\theta\|_\infty \leq B$ for all $t \in [n]$.

Assumption 5. The losses ℓ_t obey $\|\nabla \ell_t(\theta)\|_2 \leq G$ for all $t \in [n]$ and $\theta \in \mathcal{D}_t$ (recall that $\mathcal{D}_t \subseteq \mathcal{D}_2^B$ from Section 2.2).

Assumption 6. The losses are α exp-concave. i.e $\ell_t(y) \geq \ell_t(x) + \nabla \ell_t(x)^\top (y - x) + \frac{\alpha}{2} \left(\ell_t(x)^\top (y - x)\right)^2$, for $\alpha > 0$ and for all $x, y \in \mathcal{D}_2^B$.

Assumption 4 puts a relatively mild constraint that a box enclosing all the decision sets is known ahead of time. Lipschitzness assumptions like Assumption 5 are standard in online learning. Assumption 6 states that the loss ℓ_t exhibits a strong curvature in the direction of its gradients (see Hazan et al., 2007, as an example). We will exploit this curvature to derive fast regret rates.

Qualitative description of ProDR. The base algorithm $\mathcal{A}$ in ProDR is expected to optimally control the dynamic regret under exp-concave losses and when the decision set is a box: $\mathcal{D}_\infty^B = \{x \in \mathbb{R}^d : \|x\|_\infty \leq B\}$, where B is as in Assumption 4. The idea is to perform a black-box reduction that can convert the base algorithm $\mathcal{A}$ to an algorithm that attains good dynamic regret guarantee on the domains $\mathcal{D}_t$. Though similar ideas have been already explored in the work of Cutkosky & Orabona (2018), our way of constructing such reductions for the current problem is new and interesting in its own right in the context of exp-concave online learning. Next, we expand upon this matter highlighting the differences from Cutkosky & Orabona (2018). We construct losses f_t in Line 7 of ProDR where the $S_t(\theta)$ term acts as a regularizer that penalizes $\mathcal{A}$ for

predicting points outside $\mathcal{D}_t$. We would like the losses f_t to be exp-concave as the base algorithm $\mathcal{A}$ expects. However, a direct application of the techniques of Cutkosky & Orabona (2018) does not satisfy this property. We address this issue by carefully constructing f_t as in Line 7 of Algorithm 1 such that: 1) gradients of both $\hat{\ell}_t(\theta)$ and $S_t(\theta)$ lie in the span of co-variate x_t and 2) $\hat{\ell}_t(\theta)$ is exp-concave, meaning that it exhibits strong curvature along the direction of x_t. Now, 1 and 2 together implies that the surrogate losses f_t still remains exp-concave as it exhibits strong curvature along the direction of its gradient (which is spanned by x_t). The particular choice of $\hat{\ell}_t(\theta)$ is found to be crucial in preventing the exp-concavity factor of losses f_t from collapsing to zero. We will show that the dynamic regret of ProDR w.r.t. losses $\hat{\ell}_t$ is upper bounded by the dynamic regret of the base algorithm $\mathcal{A}$ wrt losses f_t which is well controlled.

We next describe the dynamic regret guarantees of Algorithm 1. We inherit all the notations used in the algorithm description.

Theorem 3.1. *Let $\beta = \min\{\alpha/2, 1/(8GB\sqrt{d})\}$ and $\gamma = \frac{1}{4\left(2GB\sqrt{d\beta}+1/(2\sqrt{\beta})\right)^2}$ and $G' = 1 + 2GB\beta\sqrt{d}$. Let $\mathcal{A}$ in ProDR algorithm be FLH-ONS (Fig.1 in Appendix A) instantiated with parameters $\zeta = 2\gamma/25$, $\mathcal{G} = GG'$ and $\phi = B$. Then ProDR (Algorithm 1) satisfes*

$$\sum_{t=1}^{T} \ell_t(\hat{\theta}_t) - \ell_t(w_t) = \tilde{O}\left((d^3\gamma + \frac{d^2}{\gamma})(T^{1/3}C_T^{2/3} \vee 1)\right),$$

where $C_T := \sum_{t=2}^{T} \|w_t - w_{t-1}\|_1$ with $w_t \in \mathcal{D}_t$. $a \vee b := \max\{a, b\}$ and $\tilde{O}$ hides dependence of constants G, B, α and poly-logarithmic factors of T.

Remark 3.2 (Adaptivity to C_T). In light of the $\Omega(dB^2 \log T \vee d^{1/3}T^{1/3}C_T^{2/3}B^{4/3})$ lower bound (see Baby & Wang, 2021, Proposition 11), we see that the ProDR algorithm adapts optimally to the path variation C_T of the comparator sequence, which may not be known ahead of time.

Proof. Due to the α exp-concavity of losses ℓ_t over the domain $\mathcal{D}_2^B$ and $\beta \leq \frac{\alpha}{2}$ we have that:

$$\ell_t(\theta) \ \geq \ell_t(\hat{\theta}_t) + \nabla \ell_t(\hat{\theta}_t)^\top(\theta - \hat{\theta}_t) + \beta\left(\nabla \ell_t(\hat{\theta}_t))^\top(\theta - \hat{\theta}_t)\right)^2,$$

for any $\theta \in \mathcal{D}_2^B$. Hence following Hazan et al. (2007), we consider the linear-regression-type surrogate losses:

$$\hat{\ell}_t(\theta) := \left(\nabla \ell_t(\hat{\theta}_t)^\top(\theta - \hat{\theta}_t)\sqrt{\beta} + \frac{1}{2\sqrt{\beta}}\right)^2. \tag{4}$$

Hence for any $\theta \in \mathcal{D}_2^B$ we have that

$$\ell_t(\hat{\theta}_t) - \ell_t(\theta) \leq \frac{1}{4\beta} - \hat{\ell}_t(\theta) = \hat{\ell}_t(\hat{\theta}_t) - \hat{\ell}_t(\theta). \tag{5}$$

where we used the fact that $\hat{\ell}_t(\hat{\theta}_t) = \frac{1}{4\beta}$.

Given that $S_t(\theta_t^*) = S_t(\hat{\theta}_t) = 0$ since $\theta_t^*, \hat{\theta}_t \in \mathcal{D}_t$, we have

$$f_t(\theta_t^*) = \hat{\ell}_t(\theta_t^*), f_t(\hat{\theta}_t) = \hat{\ell}_t(\hat{\theta}_t). \tag{6}$$

Let us denote $\nabla \ell_t(\theta) = h_t(\theta) x_t$ where $h_t(\theta) = g_t'(x_t^\top \theta)$. Now, according to the definition of $S_t(\theta)$ and $\hat{\theta}_t$, we have:

$$\begin{aligned} f_t(\tilde{\theta}_t) =& \hat{\ell}_t(\tilde{\theta}_t) + G' \cdot S_t(\tilde{\theta}_t) \\ =& \hat{\ell}_t(\tilde{\theta}_t) + G' \cdot \min_{\eta \in \mathcal{D}_t} |\nabla \ell_t(\hat{\theta}_t)^\top (\eta - \tilde{\theta}_t)| \\ =& \hat{\ell}_t(\tilde{\theta}_t) + G' \cdot \min_{\eta \in \mathcal{D}_t} |h_t(\hat{\theta}_t)||x_t^\top (\eta - \tilde{\theta}_t)| \\ =& \hat{\ell}_t(\tilde{\theta}_t) + G' \cdot |h_t(\hat{\theta}_t)||x_t^\top (\hat{\theta}_t - \tilde{\theta}_t)| \\ =& \hat{\ell}_t(\tilde{\theta}_t) + G' \cdot |\nabla \ell_t(\hat{\theta}_t)^\top (\hat{\theta}_t - \tilde{\theta}_t)|. \end{aligned}$$

Next we proceed to upper bound the regret w.r.t. losses $\hat{\ell}_t$ by the regret w.r.t. losses f_t. We need the following lemma.

Lemma 3.3. *Under the assumptions of Theorem 3.1, we have that*

$$|\hat{\ell}_t(\theta) - \hat{\ell}_t(\hat{\theta}_t)| \leq G' |\nabla \ell_t(\hat{\theta}_t)^\top (\theta - \hat{\theta}_t)|,$$

for any $\theta \in \mathcal{D}_\infty^B$ where $G' := (1 + 2GB\beta\sqrt{d})$.

The proof is shown in Appendix B.2. With this lemma, we have

$$\hat{\ell}_t(\hat{\theta}_t) \leq \hat{\ell}_t(\tilde{\theta}_t) + G' \cdot |\nabla \ell_t(\hat{\theta}_t)^\top (\hat{\theta}_t - \tilde{\theta}_t)| = f_t(\tilde{\theta}_t).$$

Combining the above inequality with Eq.(6) we obtain

$$\hat{\ell}_t(\hat{\theta}_t) - \hat{\ell}_t(\theta_t^*) \leq f_t(\tilde{\theta}_t) - f_t(\theta_t^*).$$

Now using Eq.(5) along with the previous relation yields that

$$\sum_{t=1}^T \ell_t(\hat{\theta}_t) - \ell_t(\theta_t^*) \leq \sum_{t=1}^T f_t(\tilde{\theta}_t) - f_t(\theta_t^*).$$

The following lemma specifies how to compute the sub-gradient of the regularizer term $S_t(\theta)$ in Line 7 of Algorithm 1. Further it highlights an important property that a sub-gradient of $S_t(\theta)$ lies in the span of covariate x_t (recall that $\nabla \ell_t(\theta) = h(\theta) x_t$). This is also useful for proving the joint exp-concavity of the losses f_t.

Lemma 3.4. *The function $S_t(\theta)$ is convex across $\mathbb{R}^d$. Denote $\eta_t(\theta) := \operatorname{argmin}_\eta |x_t^\top (\eta - \theta)|$. When $\nabla \ell_t(\hat{\theta}_t)^\top (\eta_t(\theta) - \theta) \neq 0$, we have:*

$$\nabla S_t(\theta) = \begin{cases} \nabla \ell_t(\hat{\theta}_t), & \text{if} \quad \nabla \ell_t(\hat{\theta}_t)^\top (\eta_t(\theta) - \theta) < 0 \\ -\nabla \ell_t(\hat{\theta}_t), & \text{if} \quad \nabla \ell_t(\hat{\theta}_t)^\top (\eta_t(\theta) - \theta) > 0. \end{cases}$$

When $\nabla \ell_t(\hat{\theta}_t)^\top (\eta_t(\theta) - \theta) = 0$, we have $\mathbf{0} \in \partial S_t(\theta)$.

The proof of Lemma 3.4 is in Appendix B.3. In the next lemma, we show that the losses f_t remain exp-concave with appropriate exp-concavity factor **bounded away** from zero. This is the key lemma that helps to control the regret of ProDR.

Lemma 3.5. *Define $\gamma := \frac{1}{4\left(2GB\sqrt{d\beta} + 1/(2\sqrt{\beta})\right)^2}$. We have that the surrogate losses f_t are $2\gamma/25$ exp-concave and $2GG'$ Lipschitz in L_2 norm across $\mathcal{D}_\infty^B$.*

Algorithm 2 Proper Dynamic Regret Pricing (PDRP)

Input: Noise distribution $\mathbb{D}$ (including its CDF F and PDF f).
ProDR algorithm $\mathcal{A}$ instantiated as in Theorem 3.1.
for $t = 1, 2, \ldots, T$: **do**
  Feature x_t and proper domain $\mathcal{D}_t$ are revealed and sent to $\mathcal{A}$.
  Get $\hat{\theta}_t \in \mathcal{D}_t$ from $\mathcal{A}$.
  Seller proposes $v_t = J(x_t^\top \hat{\theta}_t)$ and receive $\mathbb{1}_t$.
  Send loss $\ell_t(\theta)$ defined in Eq.(2) to $\mathcal{A}$.
end for

As is stated earlier in this section, the intuition of this lemma comes from two facts: (1) both $\nabla\hat{\ell}_t(\theta)$ and $\nabla S_t(\theta)$ are in the span of x_t, and (2) $\hat{\ell}_t(\theta)$ is exp-concave. As a result, the strong curvature of $\hat{\ell}_t(\theta)$ along the x_t direction "absorbs" the plain convexity of $S_t(\theta)$ and therefore guarantees the exp-concavity of $f_t(\theta)$. We defer the detailed proof to Appendix B.4. Hence from Baby & Wang (2022b, Theorem 10) , FLH-ONS algorithm (Fig.1 in Appendix A) run with parameters $\zeta = 2\gamma/25$, $\mathcal{G} = GG'$ and $\phi = B$ can be used to control

$$\begin{aligned}\sum_{t=1}^{T} f_t(\tilde{\theta}_t) - f_t(\theta_t^*) =& \tilde{O}\left(d^2(G^2(G')^2B^2\gamma d + G^2(G')^2B^2 + \frac{1}{\gamma})(T^{1/3}C_T^{2/3} \vee 1)\right) \\ =& \tilde{O}\left(d^3(T^{1/3}C_T^{2/3} \vee 1)\right),\end{aligned}$$

where the last line is got by plugging in the values of γ and G' and upper bounding further. ■

3.2 Dynamic regret of PDRP

In this section, we present our main algorithm for controlling the dynamic regret on contextual pricing problem, the **P**roper **D**ynamic **R**egret **P**ricing (PDRP) (Algorithm 2).

Qualitative description of PDRP. Xu & Wang (2021) observes that the pricing problem can be reduced to the setting of proper OCO with co-variates and exp-concave losses. This observation, armed with the ProDR algorithm, naturally lends itself to the algorithm PDRP for controlling dynamic regret of the pricing problem.

We are now ready to present regret guarantees for the non-stationary pricing problem.

Theorem 3.6. *Consider the linear noisy contextual pricing problem defined in Section 1. Assume that we know the noise distribution $\mathbb{D}$ exactly. By properly initializing β, γ and G' with pre-knowledge, PDRP (Algorithm 2) obeys $\mathbf{Reg}_T = \tilde{O}(d^3(T^{\frac{1}{3}}C_T^{\frac{2}{3}} \vee 1))$, where $\mathbf{Reg}_T$ is as defined in Eq.(3), $\tilde{O}$ hides poly-logarithmic factors of T and $(a \vee b) = \max\{a, b\}$.*

Proof. We start with the lemmas that help us leverage the OCO framework of Section 3.1.

Lemma 3.7. *(Xu & Wang, 2021, Lemma 5 and 6) Under the assumptions in Theorem 3.6, for $\theta \in \mathcal{D}_2^B$, we have:*

$$g(J(x_t^\top\theta_t^*), x_t^\top\theta_t^*) - g(J(x_t^\top\theta), x_t^\top\theta_t^*) \leq \frac{2C}{C_{down}}\left(E[\ell_t(\theta) - \ell_t(\theta_t^*)]\right),$$

where ℓ_t is defined in Eq.(2), $C = 2B_f + (B + J(0))B_{f'}$ and

$$C_{down} := \inf_{\omega\in[-B,B+J(0)]} \min\left\{\frac{d^2\log(1-F(\omega))}{d\omega^2}, \frac{d^2\log(F(\omega))}{d\omega^2}\right\} > 0.$$

So we have

$$\mathbf{Reg}_T \leq \frac{2C}{C_{down}}\mathbb{E}[\ell_t(\hat{\theta}_t) - \ell_t(\theta_t^*)]. \tag{7}$$

Next, we record the curvature and smoothness properties of losses ℓ_t.

Lemma 3.8. *Let $G = h_{\max}$ defined in Lemma 2.2. Under the assumptions in Theorem 3.6, for $\theta \in \mathcal{D}_t$, we have: (1) $\ell_t(\theta)$ is G-Lipschitz in $\|\cdot\|_2$ norm, and (2) $\ell_t(\theta)$ $\frac{C_{down}}{C_{exp}}$-exp-concave. Here $C_{exp} := \sup_{\omega\in[-B,B+J(0)]} \max\left\{\frac{f(\omega)^2}{F(\omega)^2}, \frac{f(\omega)^2}{(1-F(\omega))^2}\right\}$ and C_{down} is defined in Lemma 3.7 .*

This lemma is derived from Xu & Wang (2021) Lemma 7, and we defer the proof to Appendix B.5. The lemma above implies that the losses satisfy Assumption 5 in Section 3.1. Further they satisfy Assumption 6 with exp-concavity factor of C_{down}/C_{exp}. So we can use the ProDR algorithm (Algorithm 1) to control the dynamic regret wrt losses ℓ_t. Let $\beta = \min\{C_{down}/(2C_{exp}), 1/(8GB\sqrt{d})\}$ and $\gamma = \frac{1}{4\left(2GB\sqrt{d\beta}+1/(2\sqrt{\beta})\right)^2}$ and $G' = 1 + GB\sqrt{d}C_{down}/C_{exp}$. Hence continuing from Eq.(7), we apply Theorem 3.1 to obtain

$$\mathbf{Reg}_T \leq \tilde{O}\left(d^3(T^{1/3}C_T^{2/3} \vee 1)\right).$$

This completes the proof of the theorem. ■

Remark 3.9. Although noise distributions are known as we assumed, the coefficient of our regret upper bound depends highly on the distribution. As is indicated by Xu & Wang (2021), when the noise N_t is an i.i.d. Gaussian noise with zero mean and σ standard deviation, this coefficient is exponentially large w.r.t. $\frac{1}{\sigma}$ as σ approaches 0, which is counter-intuitive.

3.3 Lower Bound on Dynamic Pricing Regret

So far, we have developed a ProDR algorithm that is suitable for domain-constraint optimization of generalized linear model, and have constructed a PDRP algorithm to solve the linear contextual pricing problem where PDRP achieves a $\tilde{O}(d^3(T^{\frac{1}{3}}C_T^{\frac{2}{3}} \vee 1))$ dynamic regret. This upper regret bound is optimal for online exp-concave optimization as is shown by Baby & Wang (2021), but is it still optimal for our feature-based dynamic pricing setting in specific? The answer is Yes. This dynamic regret is near-optimal up to d and $\log T$ factors, and here we present the following theorem.

Theorem 3.10 (Lower dynamic regret bound)**.** *Let $d = 1$ in the contextual pricing problem we consider. For any algorithm $\mathcal{A}$, there exists a specific problem setting where $\mathcal{A}$ has to suffer an $\Omega(T^{\frac{1}{3}}C_T^{\frac{2}{3}} \vee 1)$ expected dynamic regret.*

With this theorem, we may claim that our PDRP algorithm is near-optimal. We here show a proof sketch and defer the full proof to Appendix B.6.

Proof Sketch. The proof is developed in three steps: Firstly, we construct a hypothesis set $\mathbf{\Theta}$ in which there are N different $\{\theta_t^*\}_{t=1}^T$ series whose total variations are upper bounded by C_T. For any pair of two different series $\{\theta_t^*\}_{t=1}^T$'s in $\mathbf{\Theta}$, they are identical for $T/3$ out of T rounds in total, and are different by some small δ for the rest $2T/3$ rounds. Secondly, we show that their corresponding feedback distributions are also "similar" to each other under the metric of KL-divergence. Therefore, according to Fano's Inequality, any algorithm can hardly distinguish among these distributions. Finally, we show that a failure of correctly distinguish the underlying distribution (i.e., the real $\{\theta_t^*\}_{t=1}^T$ series) will result in an $\Omega(T^{\frac{1}{3}}C_T^{\frac{2}{3}} \vee 1)$ regret. ■

4 Conclusion

In this work, we studied the non-stationary contextual pricing problem under safety constraints. We first presented the ProDR algorithm for minimizing universal dynamic regret in the framework of proper OCO with co-variates and exp-concave losses. This contribution could be of independent interest in the context of non-stationary online learning. As a concrete application, we constructed our pricing algorithm, PDRP, by making use of ProDR as the base learner. We showed that PDRP attains a $\tilde{O}(d^3(T^{\frac{1}{3}}C_T^{\frac{2}{3}} \vee 1))$ dynamic regret in our pricing problem setting. Finally, we proved that this rate is information-theoretically optimal (modulo dependencies on d and $\log T$).

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References

Dmitry Adamskiy, Wouter M Koolen, Alexey Chernov, and Vladimir Vovk. A closer look at adaptive regret. *The Journal of Machine Learning Research*, 17(1):706–726, 2016.

Kareem Amin, Afshin Rostamizadeh, and Umar Syed. Repeated contextual auctions with strategic buyers. In *Advances in Neural Information Processing Systems (NIPS-14)*, pp. 622–630, 2014.

Dheeraj Baby and Yu-Xiang Wang. Optimal dynamic regret in exp-concave online learning. In *Conference on Learning Theory*, pp. 359–409. PMLR, 2021.

Dheeraj Baby and Yu-Xiang Wang. Optimal dynamic regret in LQR control. In *Advances in Neural Information Processing Systems*, 2022a.

Dheeraj Baby and Yu-Xiang Wang. Optimal dynamic regret in proper online learning with strongly convex losses and beyond. In *International Conference on Artificial Intelligence and Statistics*, pp. 1805–1845. PMLR, 2022b.

Dheeraj Baby, Xuandong Zhao, and Yu-Xiang Wang. An optimal reduction of tv-denoising to adaptive online learning. In *Proceedings of The 24th International Conference on Artificial Intelligence and Statistics*, Proceedings of Machine Learning Research, pp. 2899–2907, 2021.

Mark Bagnoli and Ted Bergstrom. Log-concave probability and its applications. In *Rationality and Equilibrium: A Symposium in Honor of Marcel K. Richter*, pp. 217–241. Springer, 2006.

Omar Besbes and Assaf Zeevi. On the (surprising) sufficiency of linear models for dynamic pricing with demand learning. *Management Science*, 61(4):723–739, 2015.

Nicolo Cesa-Bianchi and Gabor Lugosi. *Prediction, Learning, and Games*. Cambridge University Press, New York, NY, USA, 2006. ISBN 0521841089.

Ningyuan Chen and Guillermo Gallego. A primal–dual learning algorithm for personalized dynamic pricing with an inventory constraint. *Mathematics of Operations Research*, 47(4):2585–2613, 2022.

Xin Chen, Zexing Xu, Zishuo Zhao, and Yuan Zhou. Personalized pricing with group fairness constraint. In *Proceedings of the 2023 ACM Conference on Fairness, Accountability, and Transparency*, pp. 1520–1530, 2023.

Yifang Chen, Chung-Wei Lee, Haipeng Luo, and Chen-Yu Wei. A new algorithm for non-stationary contextual bandits: Efficient, optimal and parameter-free. In *Conference on Learning Theory*, pp. 696–726. PMLR, 2019.

Wang Chi Cheung, David Simchi-Levi, and Ruihao Zhu. Hedging the drift: Learning to optimize under nonstationarity. *Management Science*, 68(3):1696–1713, 2022.

Maxime C Cohen, Ilan Lobel, and Renato Paes Leme. Feature-based dynamic pricing. *Management Science*, 66(11):4921–4943, 2020.

Maxime C Cohen, Sentao Miao, and Yining Wang. Dynamic pricing with fairness constraints. *Available at SSRN 3930622*, 2021.

Maxime C Cohen, Adam N Elmachtoub, and Xiao Lei. Price discrimination with fairness constraints. *Management Science*, 68(12):8536–8552, 2022.

Ashok Cutkosky. Parameter-free, dynamic, and strongly-adaptive online learning. In *International Conference on Machine Learning*, pp. 2250–2259. PMLR, 2020.

Ashok Cutkosky and Francesco Orabona. Black-box reductions for parameter-free online learning in banach spaces. In *Thirty-First Annual Conference on Learning Theory (COLT-18)*, pp. 1493–1529. PMLR, 2018.

Amit Daniely, Alon Gonen, and Shai Shalev-Shwartz. Strongly adaptive online learning. In *International Conference on Machine Learning*, pp. 1405–1411, 2015.

Dylan Foster and Max Simchowitz. Logarithmic regret for adversarial online control. In *International Conference on Machine Learning*, pp. 3211–3221. PMLR, 2020.

Elad Hazan and Comandur Seshadhri. Adaptive algorithms for online decision problems. In *Electronic colloquium on computational complexity (ECCC)*, volume 14, 2007.

Elad Hazan, Amit Agarwal, and Satyen Kale. Logarithmic regret algorithms for online convex optimization. *Machine Learning*, 69(2-3):169–192, 2007.

Adel Javanmard and Hamid Nazerzadeh. Dynamic pricing in high-dimensions. *The Journal of Machine Learning Research*, 20(1):315–363, 2019.

Kwang-Sung Jun, Francesco Orabona, Stephen Wright, and Rebecca Willett. Improved strongly adaptive online learning using coin betting. In *Artificial Intelligence and Statistics*, pp. 943–951. PMLR, 2017.

Robert Kleinberg and Tom Leighton. The value of knowing a demand curve: Bounds on regret for online posted-price auctions. In *IEEE Symposium on Foundations of Computer Science (FOCS-03)*, pp. 594–605. IEEE, 2003.

Renato Paes Leme, Balasubramanian Sivan, Yifeng Teng, and Pratik Worah. Learning to price against a moving target. In *International Conference on Machine Learning*, pp. 6223–6232. PMLR, 2021.

Yiyun Luo, Will Wei Sun, et al. Distribution-free contextual dynamic pricing. *arXiv preprint arXiv:2109.07340*, 2021.

Chaoyue Niu, Zhenzhe Zheng, Fan Wu, Shaojie Tang, and Guihai Chen. Online pricing with reserve price constraint for personal data markets. *IEEE Transactions on Knowledge and Data Engineering*, 34(4): 1928–1943, 2020.

András Prékopa. On logarithmic concave measures and functions. *Acta Scientiarum Mathematicarum*, 34: 335–343, 1973.

Shabnam Salehi and S Hamid Mirmohammadi. A solution approach for sponsored search advertising and dynamic pricing for a perishable product and an online retailer with budget constraint. *Computers & Industrial Engineering*, 177:109086, 2023.

Yining Wang, Boxiao Chen, and David Simchi-Levi. Multimodal dynamic pricing. *Management Science*, 67 (10):6136–6152, 2021.

Jianyu Xu and Yu-Xiang Wang. Logarithmic regret in feature-based dynamic pricing. *Advances in Neural Information Processing Systems*, 34:13898–13910, 2021.

Jianyu Xu and Yu-Xiang Wang. Towards agnostic feature-based dynamic pricing: Linear policies vs linear valuation with unknown noise. In *International Conference on Artificial Intelligence and Statistics*, pp. 9643–9662. PMLR, 2022.

Jianyu Xu, Dan Qiao, and Yu-Xiang Wang. Doubly fair dynamic pricing. In *International Conference on Artificial Intelligence and Statistics*, pp. 9941–9975. PMLR, 2023.

Lijun Zhang, Shiyin Lu, and Zhi-Hua Zhou. Adaptive online learning in dynamic environments. In *Proceedings of the 32nd International Conference on Neural Information Processing Systems*, pp. 1330–1340, 2018.

Lijun Zhang, Guanghui Wang, Wei-Wei Tu, Wei Jiang, and Zhi-Hua Zhou. Dual adaptivity: A universal algorithm for minimizing the adaptive regret of convex functions. *Advances in Neural Information Processing Systems*, 34:24968–24980, 2021.

Peng Zhao, Lijun Zhang, Yuan Jiang, and Zhi-Hua Zhou. A simple approach for non-stationary linear bandits. In *International Conference on Artificial Intelligence and Statistics*, pp. 746–755. PMLR, 2020a.

Peng Zhao, Yu-Jie Zhang, Lijun Zhang, and Zhi-Hua Zhou. Dynamic regret of convex and smooth functions. *Advances in Neural Information Processing Systems*, 33:12510–12520, 2020b.

Peng Zhao, Yu-Xiang Wang, and Zhi-Hua Zhou. Non-stationary online learning with memory and non-stochastic control. In *International Conference on Artificial Intelligence and Statistics*, pp. 2101–2133. PMLR, 2022.

Martin Zinkevich. Online convex programming and generalized infinitesimal gradient ascent. In *Proceedings of the 20th international conference on machine learning (icml-03)*, pp. 928–936, 2003.

A Preliminaries

For the sake of completeness, we recall the description of the Follow-the-Leading-History (FLH) algorithm (see Hazan & Seshadhri, 2007).

FLH: inputs - Learning rate ζ, $\mathcal{G}$, $\phi > 0$ and T ONS base learners $E^1, \ldots, E^T$ initialized with parameters $G = \mathcal{G}$, $D = 2\phi\sqrt{d}$, $\alpha = \zeta$ and decision set $\mathcal{D} = \{\theta \in \mathbb{R}^d : \|\theta\|_\infty \leq \phi\}$. The learner E_t starts operating from time t.

1. For each t, $v_t = (v_t^{(1)}, \ldots, v_t^{(t)})$ is a probability vector in $\mathbb{R}^t$. Initialize $v_1^{(1)} = 1$.
2. In round t, set $\forall j \leq t$, $\theta_t^j \leftarrow E^j(t)$ (the prediction of the jth base learner at time t). Play $\theta_t^{\text{alg}} = \sum_{j=1}^t v_t^{(j)} \theta_t^{(j)}$.
3. After receiving loss f_t, set $\hat{v}_{t+1}^{(t+1)} = 0$ and perform update for $1 \leq i \leq t$:
$$\hat{v}_{t+1}^{(i)} = \frac{v_t^{(i)} e^{-\zeta f_t(\theta_t^{(i)})}}{\sum_{j=1}^t v_t^{(j)} e^{-\zeta f_t(\theta_t^{(j)})}}$$
4. Addition step - Set $v_{t+1}^{(t+1)}$ to $1/(t+1)$ and for $i \neq t+1$:
$$v_{t+1}^{(i)} = (1 - (t+1)^{-1}) \hat{v}_{t+1}^{(i)}$$

Figure 1: FLH algorithm

Next, we describe the Online Newton Step (ONS) algorithm (see Hazan et al., 2007).

ONS: inputs - Exp-concavity factor α and $G, D > 0$. Decision set $\mathcal{D}$.

1. At round 1, predict 0.
2. Let $\beta = \frac{1}{2}\min\{\frac{1}{4GD}, \alpha\}$. At iteration $t > 1$ predict:
$$w_t \in \operatorname*{argmin}_{\theta \in \mathcal{D}} \|w_{t-1} - \frac{1}{\beta} A_{t-1}^{-1} \nabla_{t-1} - \theta\|_{A_{t-1}},$$
where $\nabla_i = \nabla f_i(w_i)$, $A_t = \frac{I_d}{\beta^2 D^2} + \sum_{i=1}^t \nabla_i \nabla_i^\top$.

Figure 2: ONS algorithm

B Detailed Proof

B.1 Proof of Lemma 2.2

Proof. To begin with, we know that

$$h_t(\theta) = -\mathbb{1}_t \cdot \frac{f(\omega)}{1 - F(\omega)} + (1 - \mathbb{1}_t) \cdot \frac{f(\omega)}{F(\omega)},$$

where $\omega = v_t - x_t^\top \theta$. Since $\exists \theta_t \in \mathcal{D}_t$ such that $v_t = J(x_t^\top \theta_t)$, given that $J'(u) \in (0, 1)$ (see Xu & Wang, 2021, Eq.(19)), we know that $\omega \in [J(-B) - B, J(B) + B]$ is bounded in a closed interval. Since we assume that $f(\omega) > 0, \forall \omega \in \mathbb{R}$, we know that $f_{\min} = \inf_{\omega \in [J(-B)-B, J(B)+B]} f(\omega) > 0$ and $F(\omega) \in [F(J(-B) - B), F(J(B) + B)] \subset (0, 1)$. Remember that we denote $B_f := \sup_{\omega \in \mathbb{R}} f(\omega) < +\infty$. As a result, we have

$$0 < f_{\min} \leq \frac{f(\omega)}{1 - F(\omega)} \leq \frac{B_f}{1 - F(J(B) + B)} < +\infty$$
$$0 < f_{\min} \leq \frac{f(\omega)}{F(\omega)} \leq \frac{B_f}{F(J(-B) - B)} < +\infty.$$

Since $h_t(\theta) = \frac{f(\omega)}{1-F(\omega)}$ for $\mathbb{1}_t = 1$ or $h(t) = \frac{f(\omega)}{F(\omega)}$ for $\mathbb{1}_t = 0$, we know that $|h_t(\theta)| \in [f_{\min}, \frac{B_f}{\min\{1-F(J(B)+B), F(J(-B)-B)\}}]$. Let $h_{\max} = \frac{B_f}{\min\{1-F(J(B)+B), F(J(-B)-B)\}}$ and $h_{\min} = f_{\min}$, and the lemma is therefore proved. ■

B.2 Proof of Lemma 3.3

Proof. We have that for any $\theta \in \mathcal{D}_\infty^B$,

$$\begin{aligned}|\hat{\ell}_t(\theta) - \hat{\ell}_t(\hat{\theta}_t)| &= \left|1/\sqrt{\beta} + \sqrt{\beta} \cdot \nabla \ell_t(\hat{\theta}_t)^\top (\theta - \hat{\theta}_t)\right| \cdot \left|\sqrt{\beta} \nabla \ell_t(\hat{\theta}_t)^\top (\theta - \hat{\theta}_t)\right| \\ &\leq \left(1 + 2GB\beta\sqrt{d}\right) |\nabla \ell_t(\hat{\theta}_t)^\top (\theta - \hat{\theta}_t)|,\end{aligned}$$

where in the last line we apply triangle inequality and the facts that $|\nabla \ell_t(\hat{\theta}_t)^\top (\theta - \hat{\theta}_t)| \leq G\|\theta - \hat{\theta}_t\|_2$ with $\|\theta - \hat{\theta}_t\|_2 \leq 2B\sqrt{d}$.

Putting $G' = 1 + 2GB\beta\sqrt{d}$ completes the lemma.

■

B.3 Proof of Lemma 3.4

Proof. For the simplicity of notation, we denote $\nabla_t := \nabla \ell_t(\hat{\theta}_t)$, and we have: $S_t(\theta) = \min_{x \in \mathcal{D}_t} |\nabla_t^\top (x - \theta)|$. Since $S_t(\theta)$ is convex in $\mathbb{R}^d$, we have:

$$S_t(\theta_2) \geq S_t(\theta_1) + \langle \nabla S_t(\theta_1), \theta_2 - \theta_1 \rangle, \forall \theta_1, \theta_2 \in \mathcal{D}_\infty^B.$$

Now we conduct an orthogonal decomposition: $\nabla S_t(\theta_1) = \mu_1 \nabla_t + \nabla_t^\perp$, where $\nabla_t^\top \nabla_t^\perp = 0$. Let $\theta_3 = \theta_2 + \mu_2 \nabla_t^\perp$, and we have $|\nabla_t^\top (x - \theta_2)| = |\nabla_t^\top (x - \theta_3)|, \forall x \in \mathbb{R}^d$. In other words, we have $S_t(\theta_2) = S_t(\theta_3)$ and therefore we have:

$$\begin{aligned}S_t(\theta_2) = S_t(\theta_3) &\geq S_t(\theta_1) + \langle \nabla S_t(\theta_1), \theta_3 - \theta_1 \rangle \\ &= S_t(\theta_1) + \langle \mu_1 \nabla_t + \nabla_t^\perp, \theta_2 + \mu_2 \nabla_t^\perp - \theta_1 \rangle \\ &= S_t(\theta_1) + \langle \nabla S_t(\theta_1), \theta_2 - \theta_1 \rangle + \mu_2 \langle \nabla_t^\perp, \nabla_t^\perp \rangle, \forall \theta_2 \in \mathbb{R}^d, \mu_2 \in \mathbb{R}\end{aligned}$$

In other words, $\mu_2 \|\nabla_t^\perp\|_2^2 \leq S_t(\theta_2) - S_t(\theta_1) - \langle \nabla S_t(\theta_1), \theta_2 - \theta_1 \rangle$. Denote $\eta_1 = \operatorname{argmin}_{x \in \mathcal{D}_t} |\nabla_t^\top (x - \theta_1)|$, and $\eta_2 = \operatorname{argmin}_{x \in \mathcal{D}_t} |\nabla_t^\top (x - \theta_2)|$. Notice that

$$\begin{aligned}S_t(\theta_2) - S_t(\theta_1) =& |\nabla_t^\top (\eta_2 - \theta_2)| - |\nabla_t^\top (\eta_1 - \theta_1)| \\ \leq& |\nabla_t^\top (\eta_1 - \theta_2)| - |\nabla_t^\top (\eta_1 - \theta_1)| \\ \leq& |\nabla_t^\top (\theta_1 - \theta_2)| \\ \leq& \|\nabla_t\|_2 \cdot \|\theta_1 - \theta_2\|_2 \\ \leq& G \cdot \|\theta_1 - \theta_2\|_2.\end{aligned} \tag{8}$$

Here the first inequality comes from the definition of η_2, the second inequality is an application of the triangular inequality, the third inequality is derived from Cauchy-Schwarz Inequality, and the last inequality is from Assumption A5 on the Lipschitzness of $\ell_t(\theta)$ over $\mathcal{D}_t$. Therefore, $S_t(\theta)$ is G-Lipschitz as well over $\mathcal{D}_\infty^B$, and we have:

$$\begin{aligned}\mu_2 \|\nabla_t^\perp\|_2^2 &\leq S_t(\theta_2) - S_t(\theta_1) - \langle \nabla S_t(\theta_1), \theta_2 - \theta_1 \rangle \\ &\leq 2G\|\theta_2 - \theta_1\|_2.\end{aligned}$$

This holds for any $\theta_1, \theta_2 \in \mathcal{D}_\infty^B$. However, we may fix θ_1 and θ_2 while also let $\mu_2 \to +\infty$ since it holds for any $\mu_2 \in \mathbb{R}$. If $\|\nabla_t^\perp\|_2 \neq 0$ then it will fall into a contradiction. Therefore, we know that $\nabla_t^\perp = \mathbf{0}$ and $\nabla S_t(\theta)$ is always in the same direction of ∇_t.

Without losing generality, denote $\nabla S_t(\theta_1) := \lambda \cdot \nabla_t$. In the following, we will prove that $\lambda = \pm 1$ or 0. From Eq. (8) line 3, we know that $S_t(\theta_2) - S_t(\theta_1) \leq |\nabla_t^\top(\theta_1 - \theta_2)|$. Combined with the convexity of $S_t(\theta)$, we have:

$$\begin{aligned} |\nabla_t^\top(\theta_1 - \theta_2)| \geq & S_t(\theta_2) - S_t(\theta_1) \\ \geq & \nabla S_t(\theta_1)^\top(\theta_2 - \theta_1) \\ = & \lambda \cdot \nabla_t^\top(\theta_2 - \theta_1). \end{aligned} \tag{9}$$

Notice that we can choose arbitrary θ_2 without changing λ, we may let $\theta_2 = 0$ and $\theta_2 = 2\theta_1$ in Eq. (9):

$$\pm\lambda \cdot \nabla_t^\top \theta_1 \leq |\nabla_t^\top \theta_1|$$

If $\nabla_t^\top \theta_1 \neq 0$, then we have $\lambda \in [-1, 1]$. Otherwise, we know from Eq. (9) that $|\nabla_t^\top \theta_2| \geq \lambda \cdot \nabla_t^\top \theta_2, \forall \theta_2$, and similarly we have $\lambda \in [-1, 1]$. Now we denote $\theta_4 := \frac{\theta_1 + \eta_1}{2}$, and we have:

$$\langle \nabla S_t(\theta_1), \theta_4 - \theta_1 \rangle + S_t(\theta_1) \leq S_t(\theta_4) \tag{10}$$

from the convexity of S_t. And we also have:

$$\begin{aligned} S_t(\theta_4) &= \min_{x \in \mathcal{D}_t} |\nabla_t^\top(x - \theta_4)| \\ &\leq |\nabla_t^\top(\eta_1 - \theta_4)| \\ &= |\nabla_t^\top \frac{\theta_1 - \eta_1}{2}| \\ &= \frac{1}{2} S_t(\theta_1) \\ &= |\nabla_t^\top(\theta_1 - \theta_4)| \\ &= S_t(\theta_1) - |\nabla^\top(\theta_1 - \theta_4)|. \end{aligned} \tag{11}$$

Combine Eq. (10) and (11), we have:

$$\langle \nabla S_t(\theta_1), \theta_4 - \theta_1 \rangle \leq S_t(\theta_4) - S_t(\theta_1) = -|\nabla_t^\top(\theta_1 - \theta_4)| \tag{12}$$

Plug in $\nabla S_t(\theta_1) = \lambda \nabla_t$ to Eq. (12), and we have:

$$\lambda \cdot \nabla_t^\top(\theta_4 - \theta_1) \leq -|\nabla_t^\top(\theta_1 - \theta_4)|. \tag{13}$$

According to Eq. (13), if $\nabla_t^\top(\theta_4 - \theta_1) > 0$, then we have $\lambda \leq -1$; if $\nabla_t^\top(\theta_4 - \theta_1) < 0$, then we have $\lambda \geq 1$. Since we already know that $\lambda \in [-1, 1]$, then for the two case we should have $\lambda = -1$ or $\lambda = 1$.

Finally, what if $\nabla_t^\top(\theta_4 - \theta_1) = 0$? In this case, it means that $\nabla_t^\top(\eta_1 - \theta_1)/2 = 0$. Since $\eta_1 = \text{argmin}_{x \in \mathcal{D}_t} |\nabla_t^\top(x - \theta_1)|$, we know that $S_t(\theta_1) = 0$ at this time. Since $S_t(\theta) \geq 0, \forall \theta \in \mathbb{R}^d$, we know that $S_t(\theta) \geq S_t(\theta_1) + \mathbf{0}^\top(\theta - \theta_1)$ and as a result $0 \in \partial S_t(\theta_1)$. This in fact holds the lemma.

■

B.4 Proof of Lemma 3.5

Proof. We begin by noticing that $\hat{\ell}_t(\theta)$ is exp-concave over $\mathcal{D}_\infty^B$. To see this, note that by the triangular inequality and Cauchy-Schwarz Inequality,

$$|\nabla \ell_t(\hat{\theta}_t)^\top(\theta - \hat{\theta}_t)\sqrt{\beta} + 1/(2\sqrt{\beta})| \leq |\nabla \ell_t(\hat{\theta}_t)^\top(\theta - \hat{\theta}_t)|\sqrt{\beta} + 1/(2\sqrt{\beta}) \leq 2GB\sqrt{d\beta} + 1/(2\sqrt{\beta}),$$

where we use the fact that $\|\nabla \ell_t(\hat{\theta}_t)\|_2 \leq G$ by Assumption A5 and $\|\theta - \hat{\theta}_t\|_2 \leq 2B\sqrt{d}$ as $\theta \in \mathcal{D}_\infty^B$ and $\hat{\theta}_t \in \mathcal{D}_t \subset \mathcal{D}_\infty^B$.

With γ as defined in the statement of the lemma, we have that the losses $\hat{\ell}_t(\theta)$ are 2γ exp-concave over $\mathcal{D}_\infty^B$. (see Cesa-Bianchi & Lugosi, 2006, Section 3.3).

Now we proceed to show that the losses $f_t(\theta)$ are in-fact exp-concave with appropriate exp-concavity factor.

For the sake of brevity, let us denote

$$\begin{aligned}\nabla \hat{\ell}_t(u) &= 2\sqrt{\beta}\left(\nabla \ell_t(\hat{\theta}_t)^\top (u-\hat{\theta}_t)\sqrt{\beta} + \frac{1}{2\sqrt{\beta}}\right)\nabla \ell_t(\hat{\theta}_t) \\ &:= p(u)\nabla \ell_t(\hat{\theta}_t).\end{aligned}$$

We have that for any $u, v \in \mathcal{D}_\infty^B$,

$$\begin{aligned}\hat{\ell}_t(v) \geq \hat{\ell}_t(u) &+ p(u)\nabla \ell_t(\hat{\theta}_t)^\top (v-u) \\ &+ \gamma\left(p(u)\nabla \ell_t(\hat{\theta}_t)^\top (v-u)\right)^2.\end{aligned} \tag{14}$$

Due to convexity, we have

$$S_t(v) \geq S_t(u) + \lambda \nabla \ell_t(\hat{\theta}_t)^\top (v-u), \tag{15}$$

for some $\lambda \in \{-1, 0, 1\}$ as per Lemma 3.4.

Adding Eq.(14) and (15), we obtain

$$\begin{aligned}f_t(v) &\geq f_t(u) + \nabla f_t(u)^\top (u-v) \\ &\quad + \gamma p(u)^2\left(\nabla \ell_t(\hat{\theta}_t)^\top (v-u)\right)^2 \\ &= f_t(u) + \nabla f_t(u)^\top (u-v) \\ &\quad + \gamma\left(\frac{p(u)}{\lambda + p(u)}\right)^2\left(\nabla f_t(u)^\top (v-u)\right)^2.\end{aligned} \tag{16}$$

Next, we proceed to obtain a lower bound on the exp-concavity factor. Note that

$$p(u) \geq 2\sqrt{\beta}\left(-2GB\sqrt{d\beta} + \frac{1}{2\sqrt{\beta}}\right) \geq 2\sqrt{\beta}\cdot\frac{1}{4\sqrt{\beta}} = \frac{1}{2}$$

where the first inequality is via Cauchy-Schwarz Inequality and the second inequality holds due to the fact that $\beta \leq 1/(8GB\sqrt{d})$ due to the setting in Theorem 3.1

Similarly we have that

$$|p(u) + \lambda| \leq 4GB\beta\sqrt{d} + 2 \leq 5/2,$$

where in the last line we used $\beta \leq 1/(8GB\sqrt{d})$.

Combining the last two displays, we have that

$$\gamma\left(\frac{p(u)}{\lambda + p(u)}\right)^2 \geq \gamma/25.$$

Applying this lower bound to Eq.(16) now yields the exp-concavity of $f_t(\theta)$ claimed in the lemma.

Next, we proceed to calculate the Lipschitz constant of f_t. Since $\|\nabla \ell_t(\hat{\theta}_t)\|_2 \leq G$, by Lemma 3.4 we conclude that $G'S_t(\theta)$ is $G'G$ Lipschitz in L2 norm across $\mathbb{R}^d$. Now using Lemma 3.3 we conclude that the losses f_t are $2G'G$ are Lipschitz in L2 norm across $\mathcal{D}_\infty^B$.

■

B.5 Proof of Lemma 3.8

Xu & Wang (2021, Lemma 7) has proved the $\frac{C_{down}}{C_{exp}}$-exp-concavity. Here we prove the other claim on Lipschitzness.

Proof. Notice that $\ell_t(\theta)$ is a continuous function. Therefore, for any $\theta_1, \theta_2 \in \mathcal{D}_t$, there exists a $\theta_3 = \epsilon\theta_1 + (1-\epsilon)\theta_2$ for some $\epsilon \in [0,1]$ such that

$$\begin{aligned}\ell_t(\theta_1) - \ell_t(\theta_2) &= \nabla \ell_t(\theta_3)^\top(\theta_1 - \theta_2) \\ &= h_t(\theta_3) x_t^\top(\theta_1 - \theta_2) \\ &\le h_{\max}\|x_t\|_2\|\theta_1 - \theta_2\|_2 \\ &= h_{\max}\|\theta_1 - \theta_2\|_2 \\ &= G\|\theta_1 - \theta_2\|_2\end{aligned} \tag{17}$$

where $h_{\max}$ is defined in Appendix B.1. In Eq.(17), the first equality is by Lagrange interpolation, the second equality is by definition of $h_t(\theta)$, the third inequality is by Cauchy-Schwarz Inequality, the fourth equality is by the assumption that $x_t \in \mathcal{D}_2^1$, and the last inequality is from the fact that $h_{\max} = G$. Since $\mathcal{D}_t$ is convex, we know that $\theta_3 \in \mathcal{D}_t$. Therefore, the lemma is proven.

■

B.6 Lower Bound Proof (Proof of Theorem 3.10)

Here we present and prove the following theorem, which is sufficient to show a $\Omega(T^{\frac{1}{3}}C_T^{\frac{2}{3}})$ lower bound for $C_T > \frac{1}{\sqrt{T}}$.

Theorem B.1. *Consider a feature-based dynamic pricing problem with $d = 1, x_t = 1, N_t \sim_{i.i.d.} \mathcal{N}(0,1), t = 1, 2, \ldots, T$ and $C_T > \frac{1}{\sqrt{T}}$ For any algorithm $\mathcal{A}$ there exists a specific setting such that $\mathcal{A}$ suffer $\Omega(T^{\frac{1}{3}}C_T^{\frac{2}{3}})$ expected regret even with y_t observable.*

The sufficiency comes from the fact that we cannot observe any realized y_t's in the pricing problem (but a binary indicator instead). In comparison, the lower bound in Theorem B.1 even works for observable y_t's, which is sufficient to derive the binary feedback (by comparing y_t with v_t).

Proof. To summarize the procedure of proof: Denote $[n] := \{1, 2, \ldots, n\}$ for any positive integer n. Define $\theta_0 = 1, \theta_1 = 1 + \delta(T, C_T)$ where $\delta = \frac{1}{40}(\frac{C_T}{T})^{\frac{1}{3}}$ is an additional amount. Then we construct a set $S \subset \{0,1\}^T$ consisting of randomly-sampled $\beta^{(i)} \in \{0,1\}^T, i = 1, 2, \ldots, N$ that we will use to construct $\theta_t^*(i)$ series (each i indicating a specific $\{\theta_t^*\}$ series) later. Afterward, we will show that the $\{\theta_t^*(i)\}$ and the $\{\theta_t^*(j)\}$ series are hard to distinguish by any algorithm, and we will further show that a large enough regret caused by this misspecification. In this way, we can prove an expected lower regret bound (where the expectation is also taken over different $\{\theta_t^*(i)\}$).

The process to sample each $\beta^{(i)}$ is as follows: We split $[T]$ uniformly into $m = \frac{C_T}{4\delta}$ intervals, with each length $\frac{4T\delta}{C_T}$. Since $\delta = \frac{1}{40}(\frac{C_T}{T})^{\frac{1}{3}}$ and $C_T \ge \frac{1}{\sqrt{T}}$, we know that $m \ge 10$. Denote these intervals as $I_1, I_2, \ldots, I_m$. For any $\beta^{(i)} \in S$, we construct it in a stochastic process: For each index interval $I_k, k = 1, 2, \ldots, m$, we generate a random variable $Z_k^{(i)} \sim Ber(\frac{1}{2})$ independently, and then let $\beta_l^{(i)} = Z_k^{(i)}, \forall l \in I_k$. Denote the vector $Z^{(i)} = [Z_1^{(i)}, Z_2^{(i)}, \ldots, Z_m^{(i)}]^\top \in \{0,1\}^m$, and we know that $\mathbb{E}[\|Z^{(i)} - Z^{(j)}\|_1] = \frac{m}{2}$. Accordingly, we have $\mathbb{E}[\|\beta^{(i)} - \beta^{(j)}\|_1] = \frac{m}{2} \cdot \frac{4T\delta}{C_T} = \frac{T}{2}$.

Therefore, according to Hoeffding's inequality, we have:

$$\begin{aligned}&\Pr[|\|Z^{(i)} - Z^{(j)}\|_1 - \frac{m}{2}| \le \frac{m}{6}] \ge 1 - 2 \cdot e^{-\frac{(\frac{m}{6})^2}{2m}} \\ \Leftrightarrow &\Pr[|\|\beta^{(i)} - \beta^{(j)}\|_1 - \frac{T}{2}| \le \frac{T}{6}] \ge 1 - 2 \cdot e^{-\frac{m}{72}}, \forall i, j \in [N].\end{aligned} \tag{18}$$

By applying a union bound over all $\binom{N}{2}$ pairs of $i, j \in [N]$, we have:

$$\Pr[|\|\beta^{(i)} - \beta^{(j)}\|_1 - \frac{T}{2}| \leq \frac{T}{6}, \forall i, j \in [N]] \geq 1 - N^2 \cdot e^{-\frac{m}{72}}.$$

Also, we know that $\Pr[\beta^{(i)} \neq \beta^{(j)}] = \Pr[Z^{(i)} \neq Z^{(j)}] = 1 - \frac{1}{2^m}$ for $i \neq j$. By applying a union bound over all $\binom{N}{2)}$ pairs of i, j, we have $\Pr[\beta^{(i)} \neq \beta^{(j)}] \geq 1 - \frac{N^2}{2^{m+1}}$. Combining these two probability bounds, we know that in this way we can find a satisfactory set S with probability at least $\Pr \geq 1 - N^2 \cdot (e^{-\frac{m}{72}} + 2^{-(m+1)})$. Let $N = e^{\frac{m}{200}}$ (and therefore $\log N = \frac{m}{200} = \frac{C_T}{800\delta}$), and then $\Pr \geq 1 - N^2 \cdot (e^{-\frac{m}{72}} + 2^{-(m+1)}) \geq 1 - (e^{-\frac{m}{300}} + e^{-\frac{3}{5}m})$. Since the total number of possible S (i.e., any set consisting N (repeatable) vectors $\beta \in \{0,1\}^T$) is $(2^m)^N$ and we are uniformly sampling from this whole family, the expected total number of satisfactory S is at least $(2^m)^N \cdot (1 - (e^{-\frac{m}{300}} + e^{-\frac{3}{5}m}))$. Since $m \geq 10$ as we showed above, we have $(2^m)^N \cdot (1 - (e^{-\frac{m}{300}} + e^{-\frac{3}{5}m})) \geq 2^{10\times 1} \cdot (1 - e^{-\frac{1}{30}} - e^{-6}) = 31.0325 > 1$. As a result, there must exist at least one satisfactory S in the whole possible set family, such that: (1) $\frac{T}{3} \leq \|\beta^{(i)} - \beta^{(j)}\|_1 \leq \frac{2T}{3}$, and (2) $\beta^{(i)} \neq \beta^{(j)}, \forall i \neq j \in [N]$. We here pick this satisfactory S and in the following we use it for further proof.

Now, for each $\beta^{(i)} \in S$, we generate a sequence of parameter $\{\theta_t^*(i)\}$ according to $\beta^{(i)}$: For $t = 1, 2, \ldots, T$, we let $\theta_t^*(i) = 1 + \delta \cdot \beta_t^{(i)}$, i.e., if $\beta^{(i)} = 0$, then $\theta_t^*(i) = \theta_0 = 1$; if $\beta^{(i)} = 1$, then $\theta_t^*(i) = 1 + \delta$. Therefore, we have the following result:

$$\mathrm{TV}(\{\theta_t^*(i)\}) \leq m \cdot \delta = \frac{C_T}{4} < C_T.$$

This is because $\|\theta_t^*(i) - \theta_{t+1}^*(i)\| > 0$ only if $\exists k \in [m]$ s.t. $t \in I_k, t+1 \in I_{k+1}$. As a result, the total variation of this $\{\theta_t^*(i)\}$ satisfies the upper bound C_T.

Now, let us consider the realized valuation sequence $\{y_t\}$. For any $i \in [N]$, denote

$$\mathbf{y}(i) := [x_1(1 + \beta_1^{(i)}\delta) + N_1, x_2(1 + \beta_2^{(i)}\delta) + N_2, \ldots, x_T(1 + \beta_T^{(i)}) + N_T]^\top$$

Let us denote the distribution of $\mathbf{y}(i)$ as $\mathbb{P}_i, i = 1, 2, \ldots, N$. Recall that $x_t = 1$ and $N_t \sim \mathcal{N}(0, 1), \forall t$, and we have $\mathbb{P}_i = [\mathcal{N}(1 + \beta_1^{(i)}\delta, 1), \mathcal{N}(1 + \beta_2^{(i)}\delta, 1), \ldots, \mathcal{N}(1 + \beta_T^{(i)}\delta)]^\top$. Consider the difference between $\mathbb{P}_i$ and $\mathbb{P}_j$ while fixing $\beta^{(i)}$ and $\beta^{(i)}$, and for any $i, j \in [N], i \neq j$ we have:

$$\begin{aligned} KL[\mathbb{P}_i || \mathbb{P}_j] =& \sum_{t=1}^{T} KL[\mathcal{N}(1 + \beta_t^{(i)}\delta, 1) || \mathcal{N}(1 + \beta^{(j)}\delta, 1)] \\ =& \sum_{t=1}^{T} \frac{(\beta_t^{(i)} - \beta_t^{(j)})^2 \delta^2}{2} \\ =& \frac{\delta^2}{2} \cdot \|\beta^{(i)} - \beta^{(j)}\|_2^2 \\ =& \frac{\delta^2}{2} \cdot \|\beta^{(i)} - \beta^{(j)}\|_1. \end{aligned} \tag{19}$$

Again, the KL-divergence is conditioning on $\beta^{(i)}$ and $\beta^{(j)}$. Here the first line is from the fact that y_t's are independent for every t, the second line is by $x_t = 1$, the third line is from the fact that $KL[\mathcal{N}(\mu_1, \sigma_1) || \mathcal{N}(\mu_2, \sigma_2)] = \log \frac{\sigma_2}{\sigma_1} + \frac{\sigma_1^2 + (\mu_1 - \mu_2)^2}{2\sigma_2^2} - \frac{1}{2}$, the fourth line is by calculation and the fifth line is from that $|\beta_t^{(i)} - \beta_t^{(j)}| \in \{0, 1\}$.

Here we introduce a Fano's Inequality as the following proposition:

Proposition B.2 (Fano's Inequality)**.** *Let $X_1, X_2, \ldots, X_n \sim_{i.i.d.} \mathbb{P}$ where $\mathbb{P} \in \{\mathbb{P}_1, \mathbb{P}_2, \ldots, \mathbb{P}_N\}$ is a distribution family. Let Ψ be any function of $X_1, X_2, \ldots, X_n$ taking values in $\{1, 2, \ldots, N\}$. Let $\alpha = \max_{j \neq k} KL(\mathbb{P}_j || \mathbb{P}_k)$.*[2] *Then*

$$\frac{1}{N} \sum_{j=1}^{N} \mathbb{P}_j(\Psi \neq j) \geq 1 - \frac{n\alpha + \log 2}{\log N}.$$

[2]Usually it is denoted as β, but here we denote it as α for clarity, since we have already defined $\beta^{(i)}$ as vectors in S.

According to Fano's Inequality, we have:

$$\inf_{\Psi:\mathbb{R}^T\to\{1,2,\dots,N\}} \sup_{i\in\{1,2,\dots,N\}} \mathbb{P}_i(\Psi \neq i) \geq \inf_{\Psi} \frac{1}{N}\sum_{i=1}^{N} \mathbb{P}_i(\Psi \neq i) \geq 1 - \frac{n\alpha + \log 2}{\log N} \geq \frac{1}{2} - \frac{n\alpha}{\log N}. \tag{20}$$

Here $n = 1$ since only one specific $\mathbf{y}(i)$ covers the whole time series and is only sampled once, and $\alpha = \max_{i,j\in[N],i\neq j} KL[\mathbf{y}(i)||\mathbf{y}(j)] = \max_{i,j\in[N],i\neq j} \frac{\delta^2}{2} \cdot \|\beta^{(i)} - \beta^{(j)}\|_1 \leq \frac{\delta^2 T}{3}$ is the upper bound of KL-divergences on different distributions. Now we specify the function $\Psi_{\mathcal{A}}$ for any pricing algorithm $\mathcal{A}$: At each round $t = 1, 2, \dots, T$, suppose the algorithm $\mathcal{A}$ proposes a price $v_t^{\mathcal{A}}$. Define a vector $\mathbf{w} = [w_1, w_2, \dots, w_T]^\top$ where $w_t = \mathbb{1}[v_t^{\mathcal{A}} \geq \frac{J(\theta_0)+J(\theta_1)}{2}]$ is a Boolean value. Then we let $\Psi_{\mathcal{A}} = \text{argmin}_i \in [N]\|\mathbf{w} - \beta^{(i)}\|_1$. Therefore, we have:

$$\begin{aligned}
2 \cdot \|\mathbf{w} - \beta^{(j)}\|_1 \geq & \|\beta^{(\Psi_{\mathcal{A}})} - \mathbf{w}\|_1 + \|\mathbf{w} - \beta^{(j)}\|_1 \\
\geq & \|\beta^{(\Psi_{\mathcal{A}})} - \beta^{(j)}\|_1, \forall j \in [N], j \neq \Psi_{\mathcal{A}} \\
\geq & \frac{T}{6}
\end{aligned}$$

Here the first inequality is from the optimality of $\Psi_{\mathcal{A}}$, the second inequality is from the triangular inequality, and the third inequality is from the Hoeffding bound in Eq. (18). Therefore we know that if $\Psi_{\mathcal{A}} \neq i$ then we have $\|\mathbf{w} - \beta^{(i)}\|_1 \geq \frac{T}{12}$, which further leads to

$$\begin{aligned}
& \sum_{t=1}^{T} (v_t^{\mathcal{A}} - J(x_t\theta_t^*(i)))^2 \\
\geq & \sum_{t=1}^{T} (\mathbb{1}[w_t = 1]\mathbb{1}[\beta_t^{(i)} = 0] + \mathbb{1}[w_t = 0]\mathbb{1}[\beta_t^{(i)} = 1])(v_t^{\mathcal{A}} - J(x_t\theta_t^*(i)))^2 \\
= & \sum_{t=1}^{T} \mathbb{1}[v_t^{\mathcal{A}} \geq \frac{J(\theta_0) + J(\theta_1)}{2}]\mathbb{1}[\beta_t^{(i)} = 0](v_t^{\mathcal{A}} - J(\theta_0))^2 + \mathbb{1}[v_t^{\mathcal{A}} < \frac{J(\theta_0) + J(\theta_1)}{2}]\mathbb{1}[\beta_t^{(i)} = 1](J(\theta_1 - v_t^{\mathcal{A}}))^2 \\
\geq & \sum_{t=1}^{T} \mathbb{1}[|w_t - \beta_t^{(i)}| = 1](\frac{J(\theta_1) - J(\theta_0)}{2})^2 \\
= & \|\mathbf{w} - \beta^{(i)}\|_1 (\frac{J(\theta_1) - J(\theta_0)}{2})^2 \\
\geq & \frac{T}{12} \cdot (\frac{J(\theta_0) - J(\theta_1)}{2})^2.
\end{aligned}$$

Here the first line is because we omit the case where $\mathbb{1}[w_t = \beta_t^{(i)}]$, the second line is from the definition of w_t, the third line is from the facts of $\theta_0 < \theta_1$ and $J'(u) > 0, \forall u \in \mathbb{R}$, the fourth line is by the definition of L_1-norm and the last line is from the fact we mentioned prior to this equation. Now we propose a lemma of properties:

Lemma B.3 (Properties of $g(v, u)$ and $J(u)$)**.** *For $g(v, u)$ and $J(u)$ with $N_t \sim \mathcal{N}(0, 1)$, we have:*

1. *$J(u) > u$ when $u \in (0, \sqrt{\frac{\pi}{2}})$ and $J(u) < u$ when $u \in (\sqrt{\frac{\Pi}{2}}, +\infty)$.*
2. *$\exists c_J > 0$ s.t. $J'(u) \geq c_J, \forall u \in [-B, B]$.*
3. *$\exists c_g > 0$ s.t. $g(J(u), u) - g(v, u) \geq c_g(J(u) - v)^2, \forall v \in [0, B + J(B)]$.*

We will show the proof of Lemma B.3 by the end of this section. With Lemma B.3, when $\Psi_A \neq i$, we have:

$$\begin{aligned}
\mathbf{Reg}_{\mathcal{A}} =& \sum_{t=1}^{T} g(J(x_t\theta_t^*(i)), x_t\theta_t^*(i)) - g(v_t^{\mathcal{A}}, x_t\theta_t^*(i)) \\
\geq& \sum_{t=1}^{T} c_g(v_t^{\mathcal{A}} - J(x_t\theta_t^*(i)))^2 \\
\geq& c_g \cdot \frac{T}{12} \cdot (\frac{J(\theta_0) - J(\theta_1)}{2})^2 \\
\geq& c_g \cdot \frac{T}{12} \cdot \frac{c_J^2}{4} \cdot (\theta_1 - \theta_0)^2 \\
\geq& \frac{c_g c_J^2 \cdot T\delta^2}{48}.
\end{aligned} \tag{21}$$

Finally, let $\delta = \frac{1}{40}(\frac{C_T}{T})^{\frac{1}{3}}$, and according to Eq. (19),(20) and (21), we have:

$$\begin{aligned}
\mathbb{E}[\mathbf{Reg}_{\mathcal{A}}] \geq& \sup_{i\in[N]} \mathbb{P}_i(\Psi_{\mathcal{A}} \neq i) \cdot (\sum_{t=1}^{T} g(J(x_t\theta_t^*(i)), x_t\theta_t^*(i)) - g(v_t^{\mathcal{A}}, x_t\theta_t^*(i))) \\
\geq& \sup_{i\in[N]} \mathbb{P}_i(\Psi_{\mathcal{A}} \neq i) \cdot \frac{c_g c_J^2 \cdot T\delta^2}{48} \\
\geq& (\frac{1}{2} - \frac{n\alpha}{\log N}) \cdot \frac{c_g c_J^2 \cdot T\delta^2}{48} \\
=& (\frac{1}{2} - \frac{\frac{\delta^2 T}{3}}{\frac{C_T}{800\delta}}) \cdot c_g c_J^2 \frac{\cdot T\delta^2}{48} \\
=& c_g c_J^2 (\frac{1}{2} - \frac{800}{3} \cdot \frac{\delta^3 T}{C_T}) \cdot \frac{\cdot T\delta^2}{48} \\
=& \frac{c_g c_J^2}{48} (\frac{1}{2} - \frac{1}{240}) \frac{T \cdot (\frac{C_T}{T})^{\frac{2}{3}}}{144} \\
\geq& \frac{c_g c_J^2}{307200} \cdot C_T^{\frac{2}{3}} T^{\frac{1}{3}}.
\end{aligned}$$

This holds the theorem. ■

Also, since our upper regret bound w.r.t. T and C_T is $\tilde{O}(1)$ when $C_T \leq \frac{1}{\sqrt{T}}$, which is trivial up to $\log T$ and d factors, we may conclude that our upper regret bound of $\tilde{O}(T^{\frac{1}{3}} C_T^{\frac{2}{3}} \vee 1)$ is optimal with respect to T and C_T.

Proof of Lemma B.3. We here prove each of them.

1. According to Xu & Wang (2021, Lemma 14), we know that $u - J(u)$ is monotonically increasing since $J'(u) \in (0, 1)$. Also, since $\frac{\partial g(v,u)}{\partial v}|_{v=J(u)} = 1 - F(J(u) - u) - J(u) \cdot f(J(u) - u) = 0$, we have $J(\sqrt{\frac{\pi}{2}}) = \sqrt{\frac{\pi}{2}}$. Therefore, $u - J(u) > 0$ when $u > \sqrt{\frac{\pi}{2}}$ and $u - J(u) < 0$ when $0 < u < \sqrt{\frac{\pi}{2}}$.

2. From Xu & Wang (2021, Appendix B.2.1.), we know that $J'(u) = 1 + \frac{1}{\phi'(\phi^{-1}(u))} \in (0, 1), \forall u \in \mathbb{R}$ where $\phi(\omega) = \frac{1-F(\omega)}{f(\omega)} - \omega$ is invertible and smooth for standard Gaussian distribution. Therefore, we know that $J'(u)$ is continuous. Therefore, $\exists c_J > 0$ such that $\inf_{u\in[-B,B]} J'(u) = c_J$.

3. From the optimality of $J(u)$ we know that $\frac{\partial g(v,u)}{\partial v}|_{v=J(u)} = 1 - F(J(u)-u) - J(u)\cdot f(J(u)-u) = 0$. Define $q(u) := 1 - F(J(u)-u) - J(u)\cdot f(J(u)-u)$. Since $q(u) = 0, \forall u \in \mathbb{R}$, we have:

$$\begin{aligned}
&\frac{\partial q(u)}{\partial u} = 0 \\
\Leftrightarrow &\left(J'(u)(J(u)^2 - u\cdot J(u) - 2) - (J(u)^2 - u\cdot J(u) - 1)\right) f(J(u)-u) = 0 \\
\Leftrightarrow &J'(u) = 1 + \frac{1}{J(u)^2 - u\cdot J(u) - 2}.
\end{aligned}$$

The second line is by standard Gaussian noises and some calculations, and the third line is from the fact that $f(x) > 0$ for standard Gaussian distribution. Since we already know that $J'(u) \in (0,1)$, we may then realized that $J(u)^2 - u\cdot J(u) - 2 < -1$. Notice that $\frac{\partial^2 g(v,u)}{\partial v^2} = (v^2 - vu - 2)f(v-u)$ for standard gaussian noise. Therefore, we have $\frac{\partial^2 g(v,u)}{\partial v^2} = (J(u)^2 - u\cdot J(u) - 2)f(J(u)-u) \leq (-1)\cdot f_{\min} < 0$ where $f_{\min}$ has been defined in Appendix B.1 as the universal lower bound of f. This means that $g(v,u)$ is $f_{\min}$-strongly concave at $v = J(u)$, which further leads to the fact that there exists a neighborhood $v \in [J(u) - B_u, J(u) + B_u]$ with constant[3] B_u such that $\frac{\partial^2 g(v,u)}{\partial v^2} \leq -\frac{f_{\min}}{2}$. As a result, for $v \in [J(u) - B_u, J(u) + B_u]$ we have

$$\begin{aligned}
g(J(u),u) - g(v,u) &= -\frac{\partial g(v,u)}{\partial v}|_{v=J(u)}(J(u)-u) - \frac{1}{2}\cdot\frac{\partial^2 g(v,u)}{\partial v^2}|_{v=v'\in[J(u),v] \text{ or } [v,J(u)]}(J(u)-v)^2 \\
&\geq -\frac{1}{2}(-\frac{f_{\min}}{2})(J(u)-v)^2 \\
&= \frac{f_{\min}}{4}(J(u)-v)^2.
\end{aligned}$$

Now, let us consider the case when $v \in [0, B + J(B)]$ but $v \notin [J(u) - B_u, J(u) + B_u]$. On the one hand, $(J(u)-v)^2 \leq (B + J(B) - (-B))^2 = (2B + J(B))^2$. On the other hand, $g(J(u),u) - g(v,u) \geq g(J(u),u) - \max\{g(J(u) - B_u, u), g(J(u) + B(u), u)\} > 0$. Denote $c_u := \inf_{u\in[-B,B]}\{g(J(u),u) - \max\{g(J(u) - B_u, u), g(J(u) + B(u), u)\}\}$, and we have $c_u > 0$. Therefore, we have:

$$g(J(u),u) - g(v,u) \geq c_u \geq \frac{c_u}{(2B + J(B))^2}(2B + J(B))^2 \geq \frac{c_u}{(2B + J(B))^2}(J(u)-v)^2.$$

Finally, let $c_g = \min\{\frac{f_{\min}}{4}, \frac{c_u}{(2B+J(B))^2}\}$, and we have proved the lemma.

■

[3] B_u can be defined as the inferior of all B_u over all $u \in [-B, B]$ and is still a positive constant.