

# CSC 665: Online convex optimization

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## 1 Background

### 1.1 Norms

**Definition 1.** A function  $\|\cdot\| : \mathbb{R}^d \rightarrow \mathbb{R}_+$  (that maps  $x$  to  $\|x\|$ ) is called a norm, if the following holds:

1. (Homogeneity)  $\forall a \in \mathbb{R}, \|ax\| = |a|\|x\|$ .
2. (Triangle inequality)  $\forall x, y \in \mathbb{R}^d, \|x + y\| \leq \|x\| + \|y\|$ .
3. (Point separation) If  $\|v\| = 0$ , then  $v = \vec{0}$ . In other words, all nonzero vectors have nonzero norms.

**Definition 2.** For a norm  $\|\cdot\|$ , define its dual norm as follows:

$$\|z\|_{\star} = \sup_{x: \|x\| \leq 1} \langle x, z \rangle.$$

(It can be checked that  $\|\cdot\|_{\star}$  also satisfies the requirements of a norm.)

**Example 1.** 1.  $\|\cdot\|_2$  has dual norm  $\|\cdot\|_2$ .

2. In general, for  $p, q \in [1, \infty]$  being conjugate exponents, that is  $\frac{1}{p} + \frac{1}{q} = 1$ ,  $\|\cdot\|_p$  has dual norm  $\|\cdot\|_q$ .

3. Given a positive definite matrix  $A$ , define  $\|x\|_A = \sqrt{x^{\top} A x}$ . It has dual norm  $\|\cdot\|_{A^{-1}}$ .

**Fact 1** (“Cauchy-Schwarz” for general norms). For any norm  $\|\cdot\|$  and its dual norm  $\|\cdot\|_{\star}$ , and any two points  $x, z \in \mathbb{R}^d$ ,

$$\langle x, z \rangle \leq \|x\| \|z\|_{\star}.$$

The fact simply follows from the definition of dual norm.

One might wonder,  $\|\cdot\|$  has dual norm  $\|\cdot\|_{\star}$ , but what is the dual norm of  $\|\cdot\|_{\star}$ ? It turns out that under mild assumptions, the dual of  $\|\cdot\|_{\star}$  is  $\|\cdot\|$ .

### 1.2 Convexity

**Definition 3.** Define convex sets and convex functions as follows:

1. For any  $u, v$  and any  $\alpha \in [0, 1]$ , the convex combination between  $u$  and  $v$  with coefficient  $\alpha$  is defined as  $\alpha u + (1 - \alpha)v$ .
2. A set  $\mathcal{C} \subset \mathbb{R}^d$  is convex, if for  $u$  and  $v$  in  $\mathcal{C}$ , and any coefficient  $\alpha \in [0, 1]$ , their convex combination with coefficient  $\alpha$  is in  $\mathcal{C}$ .
3. A function  $f : \mathcal{C} \rightarrow \mathbb{R}$  is convex, if (1) its domain  $\mathcal{C}$  is convex, (2) for any  $u, v$  in  $\mathcal{C}$ , and any  $\alpha \in [0, 1]$ ,  $f(\alpha u + (1 - \alpha)v) \leq \alpha f(u) + (1 - \alpha)f(v)$ .

If we have a convex function  $f$  on a convex domain  $\mathcal{C}$ , we define its extension to  $\mathbb{R}^d$  as

$$\bar{f}(x) = \begin{cases} f(x) & x \in \mathcal{C} \\ +\infty & x \notin \mathcal{C} \end{cases}. \quad (1)$$

Sometimes we will use  $f : \mathcal{C} \rightarrow \mathbb{R}$  and  $\bar{f} : \mathbb{R}^d \rightarrow \mathbb{R} \cup \{+\infty\}$  interchangeably.

**Fact 2** (Local minimum vs. global minimum). *Suppose  $f$  is a convex function. If  $x$  is a local minimum of  $f$ , in that there exists a radius  $r > 0$  such that for all  $y$  such that  $\|y - x\| \leq r$ ,  $f(x) \leq f(y)$ , then  $x$  is also a global minimum of  $f$ .*

**Definition 4** (Subgradient). *Given a convex function  $f : \mathcal{C} \rightarrow \mathbb{R}$  and a point  $v \in \mathcal{C}$ , define  $\partial f(v)$  as the set of  $g \in \mathbb{R}^d$ 's such that:*

$$\forall u \in \mathcal{C}, \quad f(u) \geq f(v) + \langle g, u - v \rangle.$$

Therefore, for convex  $f$ , if  $0 \in \partial f(x^*)$ , then  $x^*$  is the global minimum of  $f$ . However for  $f : \mathcal{C} \rightarrow \mathbb{R}$ , a global minimum of  $f$  in  $\mathcal{C}$  may not necessarily have zero subgradient: for example, suppose  $\mathcal{C} = [-1, +1]$  and  $f(x) = x$ , then the global minimum  $x^* = -1$ , but  $f$  has subgradient 1 on  $x^*$ . Nevertheless, we have the following first order optimality condition.

**Fact 3** (First order optimality condition). *For a convex set  $\mathcal{C}$  and  $f : \mathcal{C} \rightarrow \mathbb{R}$ . Suppose  $x^* \in \mathcal{C}$  is the global minimum of  $f$ , then we have that there exists  $g \in \partial f(x^*)$ :*

$$\forall x \in \mathcal{C}, \quad \langle g, x - x^* \rangle \geq 0. \quad (2)$$

The proof of this fact is not trivial and can be found at [1, Proposition 4.7.2]. We make the following two remarks:

1. The “exists  $g \in \partial f(x^*)$ ” cannot be replaced with “for any  $g \in \partial f(x^*)$ ”: for example, if  $f(x) = |x|$  over  $\mathcal{C} = [-1, +1]$ ,  $x^* = 0$ , but we can only take  $g = 0 \in \partial f(0)$  such that Equation (2) is true.
2. If  $f$  is differentiable, then the above fact is not hard to show: indeed, we only need to check that  $\forall x \in \mathcal{C}, \quad \langle \nabla f(x^*), x - x^* \rangle \geq 0$ . If this were not true, i.e.  $\langle \nabla f(x^*), x - x^* \rangle < 0$ , then it can be seen that

$$f(x^* + \alpha(x - x^*)) = f(x^*) + \alpha \cdot \langle \nabla f(x^*), x - x^* \rangle + o(\alpha),$$

and is smaller than  $f(x^*)$  when  $\alpha$  is small enough; contradiction.

**Fact 4.** *For any convex  $f : \mathcal{C} \rightarrow \mathbb{R}$  and a point  $v \in \mathcal{C}$ ,  $\partial f(v) \neq \emptyset$ , i.e. subgradient always exists. If  $f$  is differentiable at  $v$ , then  $\partial f(v) = \{\nabla f(v)\}$ .*

**Example 2.** *For function  $f(x) = |x|$ ,*

$$\partial f(x) = \begin{cases} +1 & x > 0, \\ [-1, +1] & x = 0, \\ -1 & x < 0. \end{cases}$$

**Definition 5** (Bregman divergence). *For a differentiable convex function  $f$ , define its induced Bregman divergence on points  $u$  and  $v$  as:*

$$D_f(u, v) = f(u) - f(v) - \langle \nabla f(v), u - v \rangle.$$

In words,  $D_f(u, v)$  is the gap between  $f$  and its first order approximation (using  $v$ ) at location  $u$ . By convexity of  $f$ ,  $D_f(u, v)$  is always nonnegative. Interestingly,  $D_f(u, v)$  may not agree with  $D_f(v, u)$ , as can be seen in the second example below.

**Example 3.** 1. If  $f(x) = \frac{\lambda}{2}\|x\|^2$ , then  $D_f(u, v) = \frac{\lambda}{2}\|u - v\|_2^2$ .

2. If  $f(x) = \sum_{i=1}^d x_i \ln x_i$ , then  $D_f(u, v) = \sum_{i=1}^d (u_i \ln \frac{u_i}{v_i} - u_i + v_i)$ . This is the unnormalized relative entropy between  $u$  and  $v$ ; if both  $u$  and  $v$  are in  $\Delta^{d-1}$ , then  $D_f(u, v)$  is the relative entropy between these two probability vectors.

**Fact 5** (Building convex functions from simple ones). Suppose  $f_1, \dots, f_n$  is a collection of convex functions.

1. If  $w_1, \dots, w_n \geq 0$ , then  $\sum_{i=1}^n w_i f_i(x)$  is convex.
2. Let  $f(x) = \max(f_1(x), \dots, f_n(x))$ . Then  $f$  is convex. Moreover, given an  $x$ ,  $\partial f(x)$  contains elements of  $\partial f_i(x)$ , where  $i \in \arg \max_{i=1}^n f_i(x)$ .

**Definition 6.**  $f$  is  $L$ -Lipschitz with respect to norm  $\|\cdot\|$  if for any  $u, v$ ,  $f(u) - f(v) \leq L\|u - v\|$ .

**Fact 6.** For any convex  $f : \mathcal{C} \rightarrow \mathbb{R}$ ,

$$f \text{ is } L\text{-Lipschitz} \Leftrightarrow \forall v, \forall g \in \partial f(v), \|g\|_* \leq L.$$

Therefore, for differentiable functions, to check Lipschitzness, it suffices to check that the gradients at all locations have uniformly-bounded norms.

### 1.3 Strong convexity

**Definition 7** (Strong convexity). A function  $f : \mathcal{C} \rightarrow \mathbb{R}$  is  $\lambda$ -strongly convex with respect to norm  $\|\cdot\|$ , if for any two points  $u, v \in \mathcal{C}$ , and  $\alpha \in [0, 1]$ ,

$$f(\alpha u + (1 - \alpha)v) \leq \alpha f(u) + (1 - \alpha)f(v) - \frac{\lambda}{2}\alpha(1 - \alpha)\|u - v\|^2.$$

Strong convexity requires that the gap between interpolated function values and the function value of the interpolated input to have a quadratic lower bound. Clearly, if  $f$  is  $\lambda$ -strongly convex, then  $f$  is  $\lambda'$ -strongly convex for  $\lambda' < \lambda$ . Moreover, a function  $f$  is 0-strongly convex iff  $f$  is convex.

We have the following simple additivity property on strong convexity simply by definition:

**Lemma 1.** If  $f_1$  and  $f_2$  are  $\lambda_1$ - and  $\lambda_2$ -strongly convex with respect to  $\|\cdot\|$  respectively, then  $f_1 + f_2$  is  $\lambda_1 + \lambda_2$ -strongly convex. Specifically, a  $\lambda$ -strongly convex function plus a convex function is still  $\lambda$ -strongly convex.

**Fact 7.** The following are equivalent:

1.  $f$  is  $\lambda$ -strongly convex.
2. For any  $v$  in  $\mathcal{C}$ , and  $g \in \partial f(v)$ ,

$$f(u) \geq f(v) + \langle g, u - v \rangle + \frac{\lambda}{2}\|u - v\|^2, \forall u \in \mathcal{C}.$$

3. For any  $v$  in  $\mathcal{C}$ , there exists a vector  $g$  such that:

$$f(u) \geq f(v) + \langle g, u - v \rangle + \frac{\lambda}{2}\|u - v\|^2, \forall u \in \mathcal{C}.$$

Properties 2 or 3 are sometimes easier to check than the original strong convexity definition. Specifically, if  $f$  is differentiable, using the equivalence between items 1 and 2, strong convexity is equivalent to a quadratic lower bound on Bregman divergence:  $D_f(u, v) \geq \frac{\lambda}{2}\|u - v\|^2$ .

**Example 4.** 1. If  $f(x) = \frac{\lambda}{2}\|x\|^2$ , then  $D_f(u, v) = \frac{\lambda}{2}\|u - v\|_2^2$ . Therefore  $f$  is  $\lambda$ -strongly convex with respect to  $\|\cdot\|_2$ .

2. If  $f(x) = \sum_{i=1}^d x_i \ln x_i$ ,  $x \in \left\{x \in \mathbb{R}^d : x_i > 0, \forall i, \text{ and } \sum_{i=1}^d x_i \leq B_1\right\}$ , then it can be checked by second-order Taylor's Theorem that  $D_f(u, v) \geq \frac{1}{2B_1}\|u - v\|_1^2$ , in other words,  $f$  is  $\frac{1}{B_1}$ -strongly convex with respect to  $\|\cdot\|_1$ .

Strongly convex functions have unique global minima, as given by the following fact:

**Fact 8.** If  $f : \mathcal{C} \rightarrow \mathbb{R}$  is  $\lambda$ -strongly convex, and  $x^*$  is a global minimum of  $f$  in  $\mathcal{C}$ , then  $f(x) - f(x^*) \geq \frac{\lambda}{2}\|x - x^*\|^2$ . Consequently, if  $x \in \mathcal{C}$  is such that  $f(x) \leq f(x^*)$ , then  $x = x^*$ .

*Proof.* Note that for all  $g \in \partial f(x^*)$ , we have that for all  $x \in \mathcal{C}$ ,

$$f(x) - f(x^*) \geq \langle g, x - x^* \rangle + \frac{\lambda}{2}\|x - x^*\|^2.$$

Now, by first order optimality condition (Fact 3), we also have that there exists  $g_0 \in \partial f(x^*)$ , such that for all  $x \in \mathcal{C}$ ,

$$\langle g_0, x - x^* \rangle \geq 0.$$

Combining the above two inequalities, we immediately conclude that

$$f(x) - f(x^*) \geq \frac{\lambda}{2}\|x - x^*\|^2.$$

The second statement directly follows from the point separation property of norms.  $\square$

For twice-differentiable  $f$ , strong convexity with respect to  $\|\cdot\|_2$  reduces to the following simple criterion.

**Fact 9.** Suppose  $f$  is twice differentiable.  $f$  is  $\lambda$ -strongly convex with respect to  $\|\cdot\|_2$  iff for any  $x$ ,  $\nabla^2 f(x) \succeq \lambda I$ .

## 1.4 Smoothness

**Definition 8** (Smoothness). A differentiable function  $f$  is called  $\beta$ -smooth with respect to norm  $\|\cdot\|$ , if for any  $u, v$ ,  $\|\nabla f(u) - \nabla f(v)\|_* \leq \beta\|u - v\|$ . In other words,  $\nabla f$  is  $\beta$ -Lipschitz with respect to  $\|\cdot\|$ .

**Fact 10.** The following are equivalent:

1.  $f$  is  $\beta$ -smooth with respect to norm  $\|\cdot\|$ .
2. For any  $u, v$ ,  $f(u) \leq f(v) + \langle \nabla f(v), u - v \rangle + \frac{\beta}{2}\|u - v\|^2$ .
3. For any  $u, v$ ,  $f(u) \geq f(v) + \langle \nabla f(v), u - v \rangle + \frac{1}{2\beta}\|\nabla f(u) - \nabla f(v)\|^2$ .

It can be seen that, smoothness is opposite to strong convexity: it asks for a function  $f$ ,  $D_f(u, v) \leq \frac{\beta}{2}\|u - v\|^2$  for any  $u, v$ . Therefore, if  $f$  is both  $\lambda$ -strongly convex and  $\beta$ -smooth, then  $\lambda \leq \beta$ .

Again for twice-differentiable function  $f$  and  $\ell_2$  norm, we have a simpler way to check smoothness:

**Fact 11.** Suppose  $f$  is twice differentiable.  $f$  is  $\beta$ -smooth with respect to  $\|\cdot\|_2$  iff for any  $x$ ,  $\nabla^2 f(x) \preceq \beta I$ .

## 1.5 Legendre-Fenchel duality

Main idea: given convex function  $f : \mathcal{C} \rightarrow \mathbb{R}$ , use all its tangents to characterize it.

Fix a slope  $s$ , we would like find a tangent of  $f$  with slope  $s$ . One characterization of the tangent is that, go over all  $x$ 's, look at the gaps between  $f(x)$  and  $\langle s, x \rangle$ , and find the location with the smallest gap. This smallest gap is the offset  $b$ , such that  $\langle s, x \rangle + b$  is the tangent of  $f$  with slope  $s$ .

As discussed above, the offset can be written as:

$$b(s) = \min_{x \in \mathcal{C}} (f(x) - \langle s, x \rangle).$$

We define the Legendre-Fenchel conjugate of  $f$  as  $-b(s)$ , denoted as  $f^*(s)$ .

**Definition 9.** Given convex function  $f : \mathcal{C} \rightarrow \mathbb{R}$ , its Legendre-Fenchel conjugate (dual),  $f^*$ , is defined as

$$f^*(s) = \max_{x \in \mathcal{C}} (\langle s, x \rangle - f(x)).$$

**Remark.** Alternatively, if we extend  $f$  to domain  $\mathbb{R}^d$  using the definition of  $\bar{f}$  in Equation 1, and taking the Legendre-Fenchel dual, we get the same  $f^*$ . Namely,

$$\max_{x \in \mathcal{C}} (\langle s, x \rangle - f(x)) = \max_{x \in \mathbb{R}^d} (\langle s, x \rangle - \bar{f}(x)).$$

This can be easily seen by noting that if  $x \notin \mathcal{C}$ , then it must not achieve the maximum on the function of  $x$  on the right hand side, as  $\langle s, x \rangle - \bar{f}(x) = -\infty$ .

As  $f^*$  is the pointwise maximum of a collection of convex functions,  $f^*$  is convex. Can we give a characterization of the subgradient of  $f^*$ ? Using a generalization of Fact 5, and the facts that  $h_x(s) = \langle s, x \rangle - f(x)$  has subgradient  $x$ , and  $f^*(s) = \max_x h_x(s)$ , we can see that

$$\operatorname{argmax}_{x \in \mathcal{C}} (\langle s, x \rangle - f(x)) \in \partial f^*(s).$$

Let us look at the dual of  $f^*$ , that is  $f^{**}(x) = \max_s (\langle x, s \rangle - f^*(s))$ . This equation has a nice geometric interpretation. Recall that for each  $s$ ,  $\langle x, s \rangle - f^*(s)$  is the tangent of  $f$  of slope  $s$ ; therefore, by varying  $s$  in  $\mathbb{R}$ , we get a collection of lines below  $f$ .  $f^{**}$  is an upper envelope of these lines. Curiously, under mild assumptions,  $f^{**}$  is exactly the original function  $f$ .

**Fact 12.** Suppose  $f$  is closed (in that  $\{(x, t) \in \mathbb{R}^{d+1} : f(x) \leq t\}$  is a closed set) and convex, then  $f^{**} = f$ . In words, the dual of the dual is the original function.

The following simple fact is by the definition of Legendre-Fenchel conjugate function:

**Fact 13** (Fenchel-Young's Inequality). For any pairs of  $x$  and  $s$  in  $\mathbb{R}^d$ ,

$$f(x) + f^*(s) \geq \langle x, s \rangle.$$

**Example 5.** 1. Suppose  $f(x) = \begin{cases} 0 & \|x\| \leq 1 \\ +\infty & \|x\| > 1 \end{cases}$ . Its conjugate function  $f^*(s) = \max_{x: \|x\| \leq 1} \langle x, s \rangle = \|s\|_*$ .

2. For conjugate exponents  $p, q \in (1, \infty)$  such that  $\frac{1}{p} + \frac{1}{q} = 1$ , if  $f(x) = \frac{x^p}{p}$ , then  $f^*(s) = \frac{s^q}{q}$ . This is the classical Young's inequality.

3. For any norm  $\|\cdot\|$ , if  $f(x) = \frac{\lambda}{2} \|x\|^2$ , then  $f^*(s) = \frac{1}{2\lambda} \|s\|_*^2$ .

4. If  $f(x) = \begin{cases} \sum_{i=1}^d x_i \ln x_i, & x \in \Delta^{d-1} \\ +\infty, & x \notin \Delta^{d-1} \end{cases}$ , then  $f^*(s) = \ln \sum_{s=1}^d e^{s_i}$ .

5. If  $f(x) = \begin{cases} \sum_{i=1}^d x_i \ln x_i, & x \succ 0 \\ +\infty, & x \not\succ 0 \end{cases}$ , then  $f^*(s) = \sum_{i=1}^d e^{s_i-1}$ .

If  $f \geq g$ , then by the definition of conjugate function,  $f^* \leq g^*$ .

It can be shown that for a strongly convex  $f$ ,  $f^*$  is differentiable. Specifically,

$$\nabla f^*(s) = \operatorname{argmax}_{x \in \mathcal{C}} (\langle s, x \rangle - f(x)),$$

as  $f$  is strongly convex, the right hand side has unique element and the equality is thus well-defined.

**Fact 14.**  $f$  is  $\lambda$ -strongly convex with respect to  $\|\cdot\|$  iff  $f^*$  is  $\frac{1}{\lambda}$ -smooth with respect to  $\|\cdot\|_*$ .

*Proof.* We only show the “only if” here. The proof of the “if” statement can be found at [9, Theorem 3]. Our goal is to show that for  $u, v$ ,

$$\|x_u - x_v\|_* \leq \frac{1}{\lambda} \|u - v\|,$$

where

$$\begin{aligned} x_u &= \nabla f^*(u) = \operatorname{argmin}_{x \in \mathcal{C}} h_u(x), \text{ where } h_u(x) = (f(x) - \langle u, x \rangle), \\ x_v &= \nabla f^*(v) = \operatorname{argmin}_{x \in \mathcal{C}} h_v(x), \text{ where } h_v(x) = (f(x) - \langle v, x \rangle). \end{aligned}$$

Note that  $h_u$  and  $h_v$  are close to each other when  $u$  and  $v$  are close: but close functions may not necessarily imply that their optimal points are close to each other; for example,  $f(x) = 0.01x$  has minimum at  $-\infty$ , and  $f(x) = -0.01x$  has minimum at  $+\infty$ ; luckily, for strongly convex functions that differ by a small linear function, we show that their minimum points are close.

By the strong convexity of  $h_u(x)$  (resp.  $h_v(x)$ ) and the optimality of  $x_u$  (resp.  $x_v$ ), and Fact 8, we have:

$$\begin{aligned} h_u(x_v) &\geq h_u(x_u) + \frac{\lambda}{2} \|x_u - x_v\|^2, \\ h_v(x_u) &\geq h_v(x_v) + \frac{\lambda}{2} \|x_u - x_v\|^2. \end{aligned}$$

Summing the two inequalities up,

$$\langle u - v, x_u - x_v \rangle \geq \lambda \|x_u - x_v\|^2.$$

By the generalized Cauchy-Schwarz, we have

$$\lambda \|x_u - x_v\|^2 \leq \|u - v\| \|x_u - x_v\|,$$

implying

$$\|x_u - x_v\|_* \leq \frac{1}{\lambda} \|u - v\|.$$

□

The above fact shows that, if  $f$  is more “curved”, then  $f^*$  is more “flat”, and vice versa.

## 2 Online convex optimization

Setup [5, 18]: see Framework 1.

Equivalent goal: minimize regret against *the best fixed point in hindsight*:

$$\operatorname{Reg}(T, \mathcal{C}) = \max_{w^* \in \mathcal{C}} \operatorname{Reg}(T, w^*) = \sum_{t=1}^T f_t(w_t) - \min_{w^* \in \mathcal{C}} \sum_{t=1}^T f_t(w^*),$$

where

$$\operatorname{Reg}(T, w^*) = \sum_{t=1}^T f_t(w_t) - \sum_{t=1}^T f_t(w^*).$$

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**Algorithm 1** Online convex optimization (OCO)

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**Require:** Convex decision set  $\mathcal{C}$ .

**for** timesteps  $t = 1, 2, \dots, T$ : **do**

    Learner chooses  $w_t \in \mathcal{C}$ ,

    Learner receives a convex loss  $f_t$ .

**end for**

Goal: minimize cumulative loss  $\sum_{t=1}^T f_t(w_t)$ .

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**Definition 10.** Suppose for every  $f_t$ ,  $f_t(w) = \langle g_t, w \rangle$  for some vector  $g_t$ , then the OCO problem is called an online linear optimization (OLO) problem.

## 2.1 Follow the regularized leader (FTRL) for OLO

Given a  $\lambda$ -strongly convex regularization function  $\Phi$ , set

$$\begin{aligned} w_t &= \underset{w}{\operatorname{argmin}} \sum_{s=1}^{t-1} \langle g_s, w \rangle + \Phi(w) \\ &= \underset{w}{\operatorname{argmax}} \langle -G_{t-1}, w \rangle - \Phi(w) \\ &= \nabla \Phi^*(-G_{t-1}), \end{aligned}$$

where  $G_t = \sum_{s=1}^t g_s$  is the cumulative gradients. the mapping  $\nabla \Phi^*$  is called the *mirror map* or *link function*, that “transports” the cumulative negative gradient to a point in the decision space.

**Example 6.** We give a few instantiations of FTRL:

1. Hedge as FTRL: let  $g_t = \ell_t$  for every  $t$ , and let  $\Phi(w) = \begin{cases} \frac{1}{\eta} \sum_{i=1}^d w_i \ln w_i, & w \in \Delta^{d-1} \\ +\infty, & w \notin \Delta^{d-1} \end{cases}$ , then it can be checked that

$$w_{t,i} = \exp \left( -\eta \sum_{s=1}^{t-1} \ell_{s,i} \right).$$

2. Online gradient descent: let  $\Phi(w) = \frac{1}{2\eta} \|w\|_2^2$ , then  $R^*(G) = \frac{\eta}{2} \|G\|_2^2$ , and  $\nabla R^*(G) = \eta G$ . Therefore,  $w_t = -\eta G_{t-1} = -\sum_{s=1}^{t-1} \eta g_s$ . This is the cumulative sum of negative gradients, times a stepsize of  $\eta$ .

3. Online gradient descent with lazy projections: let  $\Phi(w) = \begin{cases} \frac{1}{2\eta} \|w\|^2, & w \in \mathcal{C} \\ +\infty, & w \notin \mathcal{C} \end{cases}$ , then it can be shown that,

$$w_t = \underset{w \in \mathcal{C}}{\operatorname{argmin}} \|w - (-\eta G_{t-1})\|_2,$$

which is the  $\ell_2$ -projection of the point returned by online gradient descent to the convex set  $\mathcal{C}$ .

In this theorem below, we will show that FTRL has a small regret given an appropriately-tuned step size  $\eta$ .

**Theorem 1.** If  $R$  is  $\lambda$ -strongly convex with respect to  $\|\cdot\|$ , then FTRL has the following regret against benchmark  $w^*$ :

$$\operatorname{Reg}(T, w^*) = \sum_{t=1}^T \langle g_t, w_t - w^* \rangle \leq \Phi(w^*) - \min_{w'} \Phi(w') + \frac{1}{\lambda} \sum_{t=1}^T \|g_t\|_{w^*}^2.$$

*Proof.* Recall that  $f_t(w) = \langle g_t, w \rangle$ . We break the proof into two steps:

1. Consider a 'look-ahead' prediction strategy named the "be-the-regularized leader" (BTRL), that is, at time  $t$ ,  $w_{t+1}$ 's are selected as the decision point. We will show that BTRL has a small regret.
2. Note that BTRL cannot be implemented as a real algorithm:  $w_{t+1}$  relies on information on  $g_t$ , which is unavailable at the beginning of round  $t$ . Nevertheless, we will show that  $w_t$ , the decision point selected by FTRL, is close to  $w_{t+1}$ , therefore the regret of FTRL can be bounded in terms of that of BTRL.

**Step 1: Analysis of BTRL.** Denote by  $f_0(w) = \Phi(w)$ . Consider a modification of the original OCO game: there is an extra round of online convex optimization at the beginning, namely round 0. Therefore, algorithmically, BTRL is equivalent to Be-the-leader (BTL) on  $\{f_0, f_1, \dots, f_T\}$ . We will show that BTL has nonpositive regret on this modified OCO game, and relate this regret guarantee to that of the original OCO game.

**Lemma 2** (Be the leader). *For any  $w^*$ ,*

$$\sum_{t=0}^T f_t(w_{t+1}) \leq \sum_{t=0}^T f_t(w^*).$$

*Proof.* This is best illustrated by iteratively relaxing the right hand side; as  $w_{T+1} = \operatorname{argmin}_w \sum_{t=0}^T f_t(w)$ , we have that

$$\sum_{t=0}^T f_t(w_{T+1}) \leq \sum_{t=0}^T f_t(w^*).$$

Now let us focus on all but the last term in the left hand side, that is,  $\sum_{t=0}^{T-1} f_t(w_{t+1})$ . As  $w_T = \operatorname{argmin}_w \sum_{t=0}^{T-1} f_t(w)$ , we have that

$$\left( \sum_{t=0}^{T-1} f_t(w_T) \right) + f_T(w_{T+1}) \leq \sum_{t=0}^T f_t(w_{T+1}) \leq \sum_{t=0}^T f_t(w^*).$$

By iteratively using the fact that  $w_\tau = \operatorname{argmin}_w \sum_{t=0}^{\tau-1} f_t(w)$ , we have that

$$\left( \sum_{t=0}^{\tau-1} f_t(w_\tau) \right) + f_\tau(w_{\tau+1}) + \dots + f_T(w_{T+1}) \leq \sum_{t=0}^T f_t(w^*).$$

The lemma is a direct consequence of the above inequality in the case of  $\tau = 1$ . □

Lemma 2 immediately implies that:

$$\sum_{t=1}^T \langle g_t, w_{t+1} - w^* \rangle \leq \Phi(w^*) - \Phi(w_1). \quad (3)$$

**Step 2: relating BTRL to FTRL.** Our next task will be to upper bound  $\sum_{t=1}^T \langle g_t, w_t - w_{t+1} \rangle$ , the difference of the cumulative losses of FTRL and BTRL.

**Lemma 3** (Stability).

$$\sum_{t=1}^T \langle g_t, w_t - w_{t+1} \rangle \leq \frac{1}{\lambda} \sum_{t=1}^T \|g_t\|_*^2. \quad (4)$$



*Proof.* We will show that for every  $t$ ,  $\langle g_t, w_t - w_{t+1} \rangle \leq \frac{1}{\lambda} \|g_t\|_*^2$ . To show this, by generalized Cauchy-Schwarz, it suffices to show that

$$\|w_t - w_{t+1}\| \leq \frac{1}{\lambda} \|g_t\|_*.$$

By definition of  $w_t = \nabla \Phi^*(-G_{t-1})$  and  $w_{t+1} = \nabla \Phi^*(-G_t)$ , we see that

$$\|w_t - w_{t+1}\| = \|\nabla \Phi^*(-G_{t-1}) - \nabla \Phi^*(-G_t)\|.$$

Recall that  $\Phi$  is  $\lambda$ -strongly convex, by Fact 14,  $\Phi^*$  is  $\frac{1}{\lambda}$ -smooth. Therefore the right hand side is indeed at most  $\frac{1}{\lambda} \| -G_{t-1} - (-G_t) \| = \frac{1}{\lambda} \|g_t\|_*$ .  $\square$

The theorem is proved by summing Equations (3) and (4) together.  $\square$

## 2.2 FTRL for general OCO

It turns out that a low-regret algorithm for OLO immediately yields an algorithm for OCO. To see this, suppose that at every iteration  $t$ ,  $f_t$  is a general convex function. Now, suppose that  $g_t \in \partial f_t(w_t)$  is a subgradient of  $f_t$  at location  $w_t$ . We have that for any  $w^*$ ,

$$f_t(w_t) - f_t(w^*) \leq \langle g_t, w_t - w^* \rangle.$$

Therefore, if we let  $\tilde{f}_t(w) = \langle g_t, w \rangle$ , and run FTRL on  $\tilde{f}_t$ 's, we get that

$$\sum_{t=1}^T \langle g_t, w_t - w^* \rangle \leq R(T)$$

for some regret function  $R(T)$ . This implies that

$$\text{Reg}(T, w^*) = \sum_{t=1}^T f_t(w_t) - f_t(w^*) \leq \sum_{t=1}^T \langle g_t, w_t - w^* \rangle \leq R(T).$$

## 2.3 Instantiations of FTRL: theoretical guarantees

1. Online gradient descent (OGD) [18]:  $\Phi(w) = \frac{1}{2\eta} \|w\|_2^2$ , which is  $\frac{1}{\eta}$ -strongly convex wrt  $\|\cdot\|_2$ . FTRL with  $\Phi$  has regret

$$\text{Reg}(T, w^*) \leq \frac{\|w^*\|_2^2}{2\eta} + \eta \sum_{t=1}^T \|g_t\|_2^2,$$

for all benchmark  $w^* \in \mathbb{R}^d$ .

Suppose we would like to guarantee  $\text{Reg}(T, \mathcal{C})$  with  $\mathcal{C} \subset \{w : \|w\| \leq B_2\}$ . If in addition, it is known apriori that  $\|g_t\| \leq R_2$ , then

$$\text{Reg}(T, \mathcal{C}) \leq \frac{B_2^2}{2\eta} + \eta T R_2^2.$$

We can setting  $\eta = \frac{B_2}{R_2 \sqrt{2T}}$  that minimize the regret bound, which gives  $B_2 R_2 \sqrt{2T}$ .

2. OGD with lazy projections:

$$\Phi(w) = \begin{cases} \frac{1}{2\eta} \|w\|_2^2 & w \in \mathcal{C} \\ +\infty & w \notin \mathcal{C} \end{cases},$$

which is also  $\frac{1}{\eta}$ -strongly convex wrt  $\|\cdot\|_2$ . Note that FTRL in this case ensures  $w_t \in \mathcal{C}$  at every round. This is useful in error or safety critical settings (for example, taking actions in  $\mathcal{C}$  prevents self-driving cars from falling off cliffs). FTRL with  $\Phi$  has regret:

$$\text{Reg}(T, w^*) \leq \frac{\|w^*\|_2^2}{2\eta} + \eta \sum_{t=1}^T \|g_t\|_2^2,$$

for all benchmark  $w^* \in \mathcal{C}$ . Again, setting  $\eta = \frac{B_2}{R_2\sqrt{2T}}$  guarantees  $\text{Reg}(T, \mathcal{C}) \leq B_2 R_2 \sqrt{2T}$ .

3.  $p$ -norm algorithms ( $p \in (1, 2]$ ) [6, 4]: It is known that  $\Phi(w) = \frac{1}{2\eta} \|w\|_p^2$  is  $\frac{p-1}{\eta}$ -strongly convex wrt  $\|\cdot\|_p$  (see [16, Lemma 17] or [cesa2006prediction, Corollary 2.1]). FTRL with  $R$  has regret:

$$\text{Reg}(T, w) \leq \frac{\|w\|_p^2}{2\eta} + \frac{\eta}{p-1} \sum_{t=1}^T \|g_t\|_q^2.$$

If  $\mathcal{C} \subset \{w : \|w\|_p \leq B_p\}$ , and for all  $t$ ,  $\|g_t\|_q \leq R_q$ , setting  $\eta = \frac{B_p}{R_q \sqrt{2(p-1)T}}$  implies that

$$\text{Reg}(T, \mathcal{C}) \leq B_p R_q \sqrt{\frac{2T}{p-1}}.$$

4. Exponentiated gradient (Hedge) [3, 10]: consider the negative entropy regularizer

$$\Phi(w) = \begin{cases} \frac{1}{\eta} \sum_{i=1}^d w_i \ln x_i, & w \in \Delta^{d-1}, \\ +\infty, & \text{otherwise.} \end{cases}$$

Recall that by the calibration exercise,  $\Phi(w)$  is 1-strongly convex with respect to  $\|\cdot\|_1$ . Therefore, FTRL with  $R$  has regret:

$$\text{Reg}(T, w^*) \leq \frac{\sum_{i=1}^d w_i^* \ln w_i^* - \min_{w' \in \Delta^{d-1}} \sum_{i=1}^d w_i' \ln w_i'}{\eta} + \eta \sum_{t=1}^T \|g_t\|_\infty^2.$$

It can be seen that  $\sum_{i=1}^d w_i^* \ln w_i^* \leq 0$ , on the other hand,  $\min_{w' \in \Delta^{d-1}} \sum_{i=1}^d w_i' \ln w_i' = -\max_{w' \in \Delta^{d-1}} H(w)$ , where  $H(w)$  is the entropy of probability vector  $w$ . Therefore, it is  $-\ln d$ . This implies that the first term is at most  $\frac{\ln d}{\eta}$ . Now suppose we know that all  $t$  is such that  $\|g_t\|_\infty \leq R_\infty$ , we have

$$\text{Reg}(T, w) \leq \frac{\ln d}{\eta} + \eta T R_\infty^2.$$

Setting  $\eta = \frac{\sqrt{\ln d}}{R_\infty \sqrt{T}}$  gives that

$$\text{Reg}(T, \Delta^{d-1}) \leq 2R_\infty \sqrt{T \ln d}.$$

(The above regularizer can also be used to deal with a scaled version of probability simplex:

$$\left\{ w : \forall i, w_i > 0, \sum_{i=1}^d w_i = B_1 \right\},$$

for general  $B_1 > 0$ ; we skip the discussion for brevity.)

---

**Algorithm 2** Online linear classification (with FTRL)

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**Require:** Regularizer  $R$ , stepsize  $\eta$ .

**for** timesteps  $t = 1, 2, \dots, T$ : **do**

Learner chooses  $w_t = \operatorname{argmin}_w \left( \frac{1}{\eta} \Phi(w) + \sum_{s=1}^{t-1} \langle g_s, w \rangle \right) = \nabla \left( \frac{1}{\eta} \Phi \right)^* \left( - \sum_{s=1}^{t-1} g_s \right) \in \mathbb{R}^d$ ,

Learner receives an example  $(x_t, y_t)$ .

Learner suffers from zero-one loss  $M_t = \mathbf{1}(\langle w_t, y_t x_t \rangle \leq 0)$ .

Induced loss  $f_t(w) = \mathbf{1}(\langle w_t, y_t x_t \rangle \leq 0)(1 - \langle w, y_t x_t \rangle)$ .

Let  $g_t = \nabla f_t(w)|_{w=w_t} = \begin{cases} 0 & M_t = 0 \\ -y_t x_t & M_t = 1 \end{cases} \in \partial f_t(w_t)$ .

**end for**

Goal: minimize cumulative zero-one loss  $\sum_{t=1}^T M_t$ .

---

## 2.4 Applications of FTRL to online linear classification

**Theorem 2.** Suppose  $R$  is 1-strongly convex defined on  $\mathcal{C}$  with respect to  $\|\cdot\|$ , and for all  $x_t$ ,  $\|x_t\|_* \leq R$ . Moreover, suppose for all  $w$ ,  $\Phi(w) \geq \Phi_{\min}$ . Then, for any  $w^* \in \mathcal{C}$ ,

$$\sum_{t=1}^T M_t \leq \frac{1}{1 - \eta R^2} \left( L_T(w^*) + \frac{\Phi(w^*) - \Phi_{\min}}{\eta} \right),$$

where  $L_T(w) = \sum_{t=1}^T (1 - \langle w, y_t x_t \rangle)_+$  is the cumulative hinge loss of  $w$ . Specifically, if there exists  $w^* \in \mathcal{C}$  such that the data is separable by a margin of 1:  $\forall t, \langle w^*, y_t x_t \rangle \geq 1$ , then setting  $\eta = \frac{1}{2R^2}$  implies that

$$\sum_{t=1}^T M_t \leq 2R^2 \cdot (\Phi(w^*) - \Phi_{\min}),$$

in other words, the algorithm has a finite mistake bound.

*Proof.* As  $R$  is 1-strongly convex wrt  $\|\cdot\|$ ,  $\frac{\Phi}{\eta}$  is  $\frac{1}{\eta}$ -strongly convex wrt  $\|\cdot\|$ . By the guarantees of OCO with respect to  $\{f_t(\cdot)\}$ 's, we have that for all  $w^*$ ,

$$\sum_{t=1}^T f_t(w_t) - \sum_{t=1}^T f_t(w^*) \leq \frac{\Phi(w^*) - \min_{w'} \Phi(w')}{\eta} + \sum_{t=1}^T \eta \|g_t\|^2 \leq \frac{\Phi(w^*) - \Phi_{\min}}{\eta} + \sum_{t=1}^T \eta \|g_t\|^2,$$

where the second inequality uses the uniform lower bound of  $\Phi$ .

We have the following observations:

1.  $g_t = 0$  if  $M_t = 0$ ; therefore, the second term on the right hand side is at most  $\eta R^2 (\sum_{t=1}^T M_t)$ .
2. Moreover,  $f_t(w_t) = \mathbf{1}(\langle w_t, y_t x_t \rangle \leq 0)(1 - \langle w_t, y_t x_t \rangle)$ . Observe that  $f_t(w_t) \geq 0$ . Moreover, if  $M_t = 1$ , then  $f_t(w_t) \geq 1$ . Therefore,  $\sum_{t=1}^T M_t \leq \sum_{t=1}^T f_t(w_t)$ .
3.  $f_t(w) \leq \mathbf{1}(\langle w_t, y_t x_t \rangle \leq 0)(1 - \langle w, y_t x_t \rangle)_+ \leq (1 - \langle w, y_t x_t \rangle)_+$ , which is the instantaneous hinge loss of  $w$ .

Combining the above insights, we get

$$\sum_{t=1}^T M_t \cdot (1 - \eta R^2) \leq L_T(w^*) + \frac{\Phi(w^*) - \Phi_{\min}}{\eta},$$

that is,

$$\sum_{t=1}^T M_t \leq \frac{1}{1 - \eta R^2} (L_t(w^*) + \frac{\Phi(w^*) - \Phi_{\min}}{\eta}).$$

The second claim of the theorem follows simply from algebra and the fact that  $L_t(w^*) = 0$ .  $\square$

**Instantiations.** We consider two settings of  $\Phi$ :

1. Let  $\Phi(w) = \frac{1}{2}\|w\|^2$ . This gives the well-known Perceptron algorithm [15]:

$$w_t = \underset{w}{\operatorname{argmin}} \left( \frac{1}{2\eta} \|w\|_2^2 + \sum_{s=1}^{t-1} \langle g_s, w \rangle \right) = -\eta \cdot \sum_{s=1}^{t-1} g_s.$$

Suppose all examples lies in  $\{x : \|x\|_2 \leq R_2\}$ . By Theorem 2, Perceptron has a mistake bound of

$$\sum_{t=1}^T M_t \leq \frac{1}{1 - \eta R_2^2} (L_T(w^*) + \eta \|w^*\|^2),$$

for any  $w^* \in \mathbb{R}^d$ .

Now, if the data is linearly separable by margin 1 by classifier  $w$  such that  $\|w\|_2 \leq B_2$ , then setting  $\eta = \frac{1}{2R_2^2}$  gives that

$$\sum_{t=1}^T M_t \leq 2R_2^2 B_2^2.$$

This is a variant of the well-known Percetron convergence theorem by Novikoff [15].

2. Let  $\Phi(w) = \begin{cases} \sum_{i=1}^d w_i \ln w_i, & w \in \Delta^{d-1}, \\ +\infty, & \text{otherwise.} \end{cases}$ . This gives the Winnow [11] algorithm:

$$w_{t,i} = \exp \left\{ -\eta \sum_{s=1}^{t-1} g_{s,i} \right\}, \forall i \in \{1, \dots, d\}.$$

Suppose all examples lies in  $\{x : \|x\|_\infty \leq R_\infty\}$ . Also, as discussed before, we can set  $\Phi_{\min} = -\ln d$  and  $\Phi(w) - \Phi_{\min} \leq \ln d$  for all  $w^* \in \Delta^{d-1}$ . Therefore, FTRL with  $\Phi$  has a mistake bound of

$$\sum_{t=1}^T M_t \leq \frac{1}{1 - \eta R_\infty^2} (L_T(w^*) + \eta \ln d).$$

for all  $w^* \in \Delta^{d-1}$ .

If the data is linearly separable by margin 1 by classifier  $w^*$  in  $\Delta^{d-1}$ , then setting  $\eta = \frac{1}{2R_\infty^2}$  gives that

$$\sum_{t=1}^T M_t \leq 2R_\infty^2 \ln d.$$

This mistake bound is in general incomparable with the Perceptron mistake bound (see our discussions on  $\ell_2$ - $\ell_2$  vs.  $\ell_1$ - $\ell_\infty$  margin bounds before.)

## 2.5 FTRL with adaptive regularization

As we have seen before, the choice of regularizer is crucial to obtain good online prediction performance. However, if we are faced with a stream of data, it is difficult to know which regularizer to choose ahead of the time. In this section, we will look at FTRL with adaptive regularization, which is a systematic way to achieve online performance guarantees that adapts to the geometry of the data on the fly.

Our starting point is to consider the following algorithm:

$$w_t = \operatorname{argmin}_w \left( \Phi_{t-1}(w) + \sum_{s=1}^{t-1} \langle g_s, w \rangle \right) = \nabla \Phi_{t-1}^*(-G_{t-1}),$$

where  $\{\Phi_t\}_{t=0}^T$  is a sequence of regularizers, and recall that  $G_{t-1} = \sum_{s=1}^{t-1} g_s$  is the sum of the gradients up to time  $t-1$ . We called the above algorithm FTRL with adaptive regularization, abbreviated as FTRL-AR. Specifically, we will be looking at sequences of  $\{\Phi_t\}$ 's such that they are generated on the fly, and can thus carry information on the past  $g_t$ 's.

**Theorem 3** (Modified from Lemma 1 of [14]). *Suppose FTRL-AR uses  $\Phi_t$ 's that are 1-strongly convex with respect to time-varying norm  $\|\cdot\|_t$ . Then it has the following upper bound on its cumulative loss guarantee:*

$$\sum_{t=1}^T \langle g_t, w_t \rangle \leq R_0^*(0) - R_T^*(-G_T) + \sum_{t=1}^T \|g_t\|_{*,t-1}^2.$$

Consequently,

$$\operatorname{Reg}(T, w^*) = \sum_{t=1}^T \langle g_t, x_t - w^* \rangle \leq R_T(w^*) + R_0^*(0) + \sum_{t=1}^T \|g_t\|_{*,t-1}^2.$$

Note that the above theorem supercedes Theorem 1, as it is a direct consequence of the above theorem by taking  $R_t \equiv R_0$  for all  $t$ , and observing that  $R_0^*(0) = -\min_{w'} R_0(w')$ .

*Proof.* It suffices to show that

$$\langle g_t, w_t \rangle \leq R_{t-1}^*(-G_{t-1}) - R_t^*(-G_t) + \|g_t\|_{*,t-1}^2,$$

as the theorem concludes by summing this inequality up over all  $t$ 's.

To show the above inequality, it suffices for us to show that

$$R_t^*(-G_t) - R_{t-1}^*(-G_{t-1}) + \langle g_t, w_t \rangle \leq \|g_t\|_{*,t-1}^2.$$

The above inequality is true by the following observations: first, as  $R_t \geq R_{t-1}$ ,  $R_t^* \leq R_{t-1}^*$ ; second,  $w_t = \nabla R_{t-1}^*(-G_{t-1})$ , therefore, the left hand side of the inequality is at most

$$R_{t-1}^*(-G_t) - R_{t-1}^*(-G_{t-1}) - \langle \nabla R_{t-1}^*(-G_{t-1}), -g_t \rangle = D_{R_{t-1}^*}(-G_t, -G_{t-1});$$

recall that  $D_f(\cdot, \cdot)$  is the Bregman divergence induced by  $f$ . third, as  $R_{t-1}$  is 1-strongly convex wrt  $\|\cdot\|_{t-1}$ ,  $R_{t-1}^*$  is 1-smooth wrt  $\|\cdot\|_{*,t-1}$ , implying that the right hand side is at most  $\frac{1}{2} \|\nabla R_{t-1}^*(-G_{t-1}) - \nabla R_{t-1}^*(-G_t)\|_{*,t-1}^2 = \frac{1}{2} \|g_t\|_{*,t-1}^2$ .  $\square$

Using the above meta-theorem, we can instantiate with different adaptive regularizers and get online learning algorithms with different degrees of adaptivity. Below, we focus on a specific family of regularizer; that is, the squared Mahalanobis norm regularizer:

$$\Phi_t(w) = \frac{1}{2} \|w\|_{A_t}^2,$$

where  $A_t \succeq A_{t-1}$  for all  $t \geq 1$ . Observe that  $\Phi_t(w)$  is 1-strongly convex with norm  $\|w\|_t = \|w\|_{A_t}$ . Meanwhile,  $\|g\|_{t,\star} = \|g\|_{A_t^{-1}}$ . FTRL-AR selects the following point at round  $t$ :

$$w_t = \nabla \Phi_{t-1}^*(-G_{t-1}) = -A_{t-1}^{-1} G_{t-1}.$$

Therefore, we have the following simple corollary:

**Corollary 1.** *Suppose FTRL-AR is executed with  $\Phi_t(w) = \frac{1}{2}\|w\|_{A_t}^2$  for a sequence of monotonically increasing positive definite matrices  $\{A_t\}$ . Then,*

$$\text{Reg}(T, w^\star) \leq \frac{1}{2}\|w\|_{A_T}^2 + \sum_{t=1}^T \|g_t\|_{A_{t-1}^{-1}}^2.$$

We discuss several nice consequences of the corollary below.

**Online gradient descent with adaptive step-sizes [18].** One instantiation of Corollary 1 is to let  $A_t = \frac{\sqrt{t+1}}{\eta_0} I_d$ , which implies that,

$$\text{Reg}(T, w^\star) \leq \frac{\sqrt{T+1}}{2\eta_0} \|x^\star\|_2^2 + \sum_{t=1}^T \eta_0 \cdot \frac{\|g_t\|^2}{\sqrt{t}}.$$

Suppose the benchmark set  $\mathcal{C}$  is defined as  $\{w : \|w^\star\| \leq B_2\}$ . If one knows that  $\|g_t\|_2 \leq R_2$ , then setting  $\eta_0 = \frac{R_2}{B_2}$  gives

$$\text{Reg}(T, w^\star) \leq O\left(R_2 B_2 \sqrt{T}\right), \quad \forall w \in \mathcal{C}.$$

Even we don't have any prior knowledge on the norm of the  $g_t$ 's, setting  $\eta_0 = 1$  gives

$$\text{Reg}(T, w^\star) \leq O\left((R_2^2 + B_2^2)\sqrt{T}\right), \quad \forall w \in \mathcal{C}.$$

**Regularization that depends on historical gradient lengths.** We let  $\sigma > 0$ , and  $A_t = \frac{\sqrt{\sigma + \sum_{s=1}^t \|g_s\|^2}}{\eta_0} I_d$ . Corollary 1 implies that, with this setting of  $\Phi_t$ ,

$$\text{Reg}(T, w^\star) \leq \frac{\sqrt{\sigma + \sum_{s=1}^t \|g_s\|^2}}{2\eta_0} \|w^\star\|^2 + \sum_{s=1}^t \frac{\eta_0 \|g_s\|^2}{\sqrt{\sigma + \sum_{s=1}^{t-1} \|g_s\|^2}}$$

If  $\sigma \geq \max_{t=1}^T \|g_t\|_2^2$ <sup>1</sup>, it can be shown that second term on the right hand side is at most

$$2 \sum_{s=1}^t \frac{\eta_0 \|g_s\|^2}{\sqrt{\sigma + \sum_{s=1}^t \|g_s\|^2}} \leq 4 \sqrt{\sigma + \sum_{s=1}^t \|g_s\|^2}.$$

where the inequality is from Lemma 7.

Therefore, the regret is at most:

$$\text{Reg}(T, w^\star) = O\left(\sqrt{\sigma + \sum_{s=1}^t \|g_s\|^2} \left(\frac{\|w^\star\|^2}{\eta_0} + \eta_0\right)\right).$$

If  $\eta_0 = \|w^\star\|$ , and  $\sigma$  is a constant factor away from  $\max_{t=1}^T \|g_t\|_2^2$ , then the regret guarantee is  $O(\|w^\star\| \sqrt{\sum_{s=1}^t \|g_s\|^2})$ , which can be much better than  $R_2^2 B_2^2$ .

---

<sup>1</sup>It turns out that a sibling of FTRL, namely Online Mirror Descent, can get rid of this extra  $\sigma$  while achieving the same guarantee. We refer the reader to [13, Lecture 5].

**Adaptive subgradient methods (Adagrad)** [12, 2]. More generally, we allow adaptive regularization matrix  $A_t$  being a general diagonal matrix, or even a matrix with nonzero diagonal entries.

Specifically, one can let

$$A_t = \frac{1}{\eta} \left( \sigma I + \text{diag} \left( \sum_{s=1}^t g_s g_s^\top \right) \right)^{\frac{1}{2}}$$

be a diagonal adaptive regularizer. Here the  $\text{diag}(M)$  takes a full  $d \times d$  matrix and set all its off-diagonal entries to be zero. The induced FTRL algorithm is called *AdaGrad with diagonal matrices*. This is one of the most widely used gradient-based optimization algorithm in modern machine learning.

Specifically, we can look at the point it selects at iteration  $t$ ,  $w_t$ :

$$w_{t,i} = -\eta \cdot \frac{\sum_{s=1}^{t-1} g_{s,i}}{\sqrt{\sigma + \sum_{s=1}^{t-1} g_{s,i}^2}}, \quad \forall i \in \{1, \dots, d\}.$$

Intuitively, the algorithm is performing online gradient descent on every coordinate separately: for coordinate  $i$ , if we have seen a big cumulative gradient along the direction of  $e_i$ , then we decrease the learning rate on that direction, as we have already learned a lot there.

Corollary 1 gives that,

$$\text{Reg}(T, w^*) \leq O \left( \frac{\|w^*\|_{A_T}^2}{2} + \eta \sum_{t=1}^T \sum_{i=1}^d \frac{g_{t,i}^2}{\sqrt{\sigma + \sum_{s=1}^{t-1} g_{s,i}^2}} \right).$$

If  $\sigma \geq \max_{t=1}^T \max_{i=1}^d g_{t,i}^2$ , then using Lemma 7 and a similar reasoning as the last subsection (such that we can replace the  $t-1$  by  $t$  in the denominator with only a constant factor overhead), we can show that the second term is at most  $\sum_{i=1}^d \sqrt{\sum_{t=1}^T g_{t,i}^2}$ .

Thus, note that  $\|w\|_M^2 \leq \|w\|_\infty^2 \sum_{i=1}^d M_{ii}$  for diagonal  $M$ , we get that the above is at most

$$\text{Reg}(T, w^*) \leq O \left( \left( \frac{\|w^*\|_\infty^2}{\eta} + \eta \right) \cdot \left( \sum_{i=1}^d \sqrt{\sum_{t=1}^T g_{t,i}^2} \right) \right).$$

If  $\eta = \|w^*\|_\infty$ , then AdaGrad gives a regret bound of  $O \left( \|w^*\|_\infty \cdot \left( \sum_{i=1}^d \sqrt{\sum_{t=1}^T g_{t,i}^2} \right) \right)$ , which is a new regret guarantee incomparable with the ones obtained by (variants of) online gradient descent discussed above.

**Example 7.** Let us compare the regret bound of AdaGrad with that obtained by online gradient descent with optimal tuning of step size, that is:

$$\text{Reg}(T, w^*) = O \left( \|w^*\|_2 \sqrt{\sum_{t=1}^T \|g_t\|_2^2} \right) = O \left( \|w^*\|_2 \sqrt{\sum_{t=1}^T \sum_{i=1}^d g_{t,i}^2} \right).$$

Suppose the  $g_{t,i}$ 's are such that only  $g_{t,1}$ 's are nonzero. Then the second fact on the regret bounds agree with each other. Therefore, in terms of the final regret bound, AdaGrad is better, as  $\|w^*\|_\infty \leq \|w^*\|_2$ .

Alternatively, one can let

$$A_t = \frac{1}{\eta} \left( \sigma I + \sum_{s=1}^t g_s g_s^\top \right)^{\frac{1}{2}}$$

be a nondiagonal adaptive regularizer. The induced FTRL algorithm is called *AdaGrad with full matrices*. We can still apply Corollary 1 to obtain a regret guarantee, but the interpretation is slightly more involved, and we refer the reader to [7, Section 5.6] for details.

### 3 OCO for strongly convex functions

Motivating example: we would like a fast optimizer for regularized loss minimization, e.g. soft-margin SVM or logistic regression:

$$\min_w F(w), \quad \text{where } F(w) = \mathbb{E}_{(x,y) \sim D} \left( \frac{\lambda}{2} \|w\|_2^2 + (1 - \langle w, yx \rangle)_+ \right),$$

or  $F(w) = \mathbb{E}_{(x,y) \sim D} \left( \frac{\lambda}{2} \|w\|_2^2 + \ln(1 + \exp(-\langle w, yx \rangle)) \right)$ . Throughout the rest of the section, let us consider soft-margin SVM for concreteness.

Here, letting  $f(w, (x, y)) = \frac{\lambda}{2} \|w\|_2^2 + (1 - \langle w, yx \rangle)_+$ , we can write  $F(w) = \mathbb{E}_{(x,y) \sim D} f(w, (x, y))$ .

If one can develop a fast OCO algorithm with  $\left\{ f_t(w) \triangleq f(w, (x_t, y_t)) \right\}_{t=1}^T$ , with a small regret guarantee  $R(T)$ , as we have seen before, one can use online-to-batch conversion, and run the OCO algorithm on  $f_t$ 's induced by iid  $(x_t, y_t) \sim D$  to get a  $\bar{w}_T$  that has excess expected regularized loss  $\frac{R(T)}{T}$ , in other words,

$$\mathbb{E} F(\bar{w}_T) - \min_w F(w) \leq \frac{R(T)}{T}.$$

One baseline is the FTRL algorithm with squared norm regularizer  $\Phi(w) = \frac{1}{2\eta} \|w\|^2$ , with surrogate convex function  $\tilde{f}_t(w) = \langle g_t, w \rangle$ , where  $g_t \in \partial f(w_t)$ . This achieves a regret of  $O(\sqrt{T})$ ; moreover, each step, the algorithm simply calculates  $w_t = -\eta \sum_{s=1}^t g_{t-1}$ , which can be maintained efficiently on the fly. It can be checked that to guarantee an expected excess loss of  $\epsilon$ , the computational complexity is  $O(\frac{d}{\epsilon^2})$ .

In fact, we can do better! In this section, we show that by utilizing the structure that all  $f_t$ 's are  $\lambda$ -strongly convex, one can design a better OCO algorithm with regret bound much better than  $O(\sqrt{T})$ , that is,  $O(\frac{\ln T}{\lambda})$ .

How to achieve this? We will use the adaptive regularization method developed in the last section.

**Theorem 4.** *Suppose all  $f_t$ 's are  $\lambda$ -strongly convex and  $L$ -Lipschitz wrt  $\|\cdot\|_2$ . Then FTRL-AR with adaptive regularizer  $R_t(w) = \frac{\lambda}{2} \|w\|^2 + \sum_{s=1}^t \frac{\lambda}{2} \|w_s - w\|^2$  has regret*

$$\text{Reg}(T, w^*) = O\left(\frac{L^2 \ln T}{\lambda}\right).$$

*Proof.* Recall that FTRL-AR has the following regret guarantee:

$$\sum_{t=1}^T \langle g_t, w_t - w^* \rangle \leq R_0^*(0) + R_T(w^*) + \sum_{t=1}^T \|w_t\|_{\star, t-1}^2.$$

How can the above regret relate to  $\text{Reg}(T, w^*) = \sum_{t=1}^T f_t(w_t) - f_t(w^*)$ ? Now because  $f_t$  is  $\lambda$ -strongly convex, we have a tighter bound on it. Specifically, for all  $g_t \in \partial f_t(w_t)$ , we have

$$f_t(w_t) - f_t(w^*) \leq \langle g_t, w_t - w^* \rangle - \frac{\lambda}{2} \|w_t - w^*\|^2.$$

This implies that,

$$\text{Reg}(T, w^*) \leq \sum_{t=1}^T \langle g_t, w_t - w^* \rangle - \sum_{t=1}^T \frac{\lambda}{2} \|w_t - w^*\|^2.$$



This motivates the definition of  $R_T$ , so that  $R_T(w^*)$  cancels out the negative terms induced by linear approximation. Observe that  $R_t$  is 1-strongly convex with respect to  $\|\cdot\|_t = \|\cdot\|_{\lambda(t+1)I}$ . We therefore get:

$$\text{Reg}(T, w^*) \leq \frac{\lambda}{2} \|w^*\|^2 + \sum_{t=1}^T \frac{\|g_t\|^2}{\lambda t} \leq \frac{\lambda}{2} \|w^*\|^2 + \frac{L^2}{\lambda} (1 + \ln T) = O\left(\frac{L^2 \ln T}{\lambda}\right).$$

where the penultimate inequality uses the  $L$ -Lipschitzness of  $f$  and Fact 6, and the last inequality uses the simple fact that  $\sum_{t=1}^T \frac{1}{t} \leq 1 + \ln T$ .  $\square$

What is the induced FTRL-AR algorithm? It can be shown that

$$\begin{aligned} w_t &= \underset{w}{\operatorname{argmin}} \left( \sum_{s=1}^{t-1} \langle g_s, w \rangle + \frac{\lambda}{2} \|w\|^2 + \sum_{s=1}^{t-1} \frac{\lambda}{2} \|w_s - w\|^2 \right) \\ &= \frac{1}{t} \left( \sum_{s=1}^{t-1} w_s - \frac{1}{\lambda} \sum_{s=1}^{t-1} g_s \right), \end{aligned}$$

which can be obtained on the fly with  $O(d)$  time per round by maintaining  $\sum_{s=1}^{t-1} w_s$  and  $\sum_{s=1}^{t-1} g_s$  online. Therefore, to obtain an excess loss guarantee of  $\epsilon$ , one can let run FTRL-AR with the specified regularizer with  $T = O\left(\frac{1}{\lambda\epsilon} \ln \frac{1}{\lambda\epsilon}\right)$ , which has a total running time of  $\tilde{O}\left(\frac{d}{\lambda\epsilon}\right)$  (where  $\tilde{O}$  ignores logarithmic factors).

**Below are materials not covered in the class and can be safely skipped!**

**A brief introduction to online gradient descent.\*** Here we introduce an alternative method for online strongly convex optimization called *online gradient descent (OGD)*. OGD and FTRL are closely related; it can be shown that FTRL with certain regularizer is algorithmically equivalent to OGD with a fixed stepsize, under natural assumptions. In a nutshell, OGD performs the following steps of update at every round:

$$w_{t+1} \triangleq w_t - \eta_t g_t, \text{ where } g_t \in \partial f_t(w_t),$$

here,  $\eta_t > 0$  is the time-varying step size parameter. Intuitively, if all  $f_t \equiv f$ 's are the same, then OGD selects  $w_t$ 's that walks in the negative gradient direction of  $f$ , making the function value smaller.

The following theorem is now well-known; see [8, Theorem 1] or [17, Section 14.4.4 and 14.5.3].

**Theorem 5.** *If all  $f_t$ 's are  $\lambda$ -strongly convex and  $L$ -Lipschitz wrt  $\|\cdot\|_2$ , then OGD with  $\eta_t = \frac{1}{\lambda t}$  has the following regret guarantee:*

$$\text{Reg}(T, w^*) = O\left(\frac{L^2 \ln T}{\lambda}\right).$$

*Proof.* We have the following key claim:

$$\langle g_t, w_t - w^* \rangle = \frac{\|w_t - w^*\|^2 - \|w_{t+1} - w^*\|^2}{2\eta_t} + \eta_t \|g_t\|^2 \quad (5)$$

$$\leq \frac{\lambda t \|w_t - w^*\|^2}{2} - \frac{\lambda t \|w_{t+1} - w^*\|^2}{2} + \frac{1}{\lambda t} L^2. \quad (6)$$

This inequality has a nice intuitive explanation: if we have a larger instantaneous regret  $\langle g_t, w_t - w^* \rangle$  at round  $t$ , then  $w_{t+1}$  will be brought closer to  $w^*$ , as the right hand side is larger. Hence, we can think of  $\|w_t - w^*\|^2$  as some kind of “potential function” as in the analysis of Consistency and Halving in online classification.

Equation (5) is true, because of the following simple calculation:

$$\|w_{t+1} - w^*\|^2 = \|w_t - w^* - \eta_t g_t\|^2 = \|w_t - w^*\|^2 - 2\langle \eta_t g_t, w_t - w^* \rangle + \|\eta_t g_t\|^2.$$

Now continuing Equation 6, we would like to relate it to the instantaneous regret  $f_t(w_t) - f_t(w^*)$ . Recall that by strong convexity, we have

$$f_t(w_t) - f_t(w^*) \leq \langle g_t, w_t - w^* \rangle - \frac{\lambda}{2} \|w_t - w^*\|^2,$$

This implies that

$$f_t(w_t) - f_t(w^*) \leq \frac{\lambda(t-1)\|w_t - w^*\|^2}{2} - \frac{\lambda t \|w_{t+1} - w^*\|^2}{2} + \frac{1}{\lambda t} L^2.$$

Observe that the first two terms on the right hand side is *telescoping*: summing over all  $t = 1, 2, \dots, T$ , we get

$$\text{Reg}(T, w^*) = \sum_{t=1}^T f_t(w_t) - f_t(w^*) \leq \frac{\lambda \cdot 0 \|w_1 - w^*\|^2}{2} - \frac{\lambda \cdot T \|w_{T+1} - w^*\|^2}{2} + \left( \sum_{t=1}^T \frac{1}{\lambda t} \right) L^2 \leq \frac{L^2(1 + \ln T)}{\lambda}.$$

□

## 4 OCO for exp-concave functions<sup>\*</sup>

**Motivating example 1: sequential investing.** There are  $d$  types of assets (e.g. stocks, bonds, commodities), with different growth rates at every timestep.

Suppose we start with unit wealth,  $W_1 \leftarrow 1$ .

For  $t = 1, 2, \dots, T$ :

1. Given the current wealth  $W_t$ , allocate  $w_t \in \Delta^{d-1}$  (spend  $w_{t,i}$  fraction of current wealth, i.e.  $W_t \cdot w_{t,i}$ , to asset  $i$ )
2. Receive where  $c_t \in \mathbb{R}_+^d$ , and  $c_{t,i}$  is the growth of the asset  $i$  at timestep  $t$  (defined as the ratio between the prices of stock  $i$  at timestep  $t+1$  and  $t$ ).
3. Cash out all assets, get new wealth  $W_{t+1}$ . Observe that

$$W_{t+1} = W_t \left( \sum_{i=1}^d w_{t,i} c_{t,i} \right),$$

i.e.  $\ln(W_{t+1}) = \ln(W_t) - f_t(w_t)$ , where loss

$$f_t(w_t) = -\ln(\langle c_t, w_t \rangle).$$

Consequently,  $\ln(W_{T+1}) = -\sum_{t=1}^T f_t(w_t)$ , and therefore, maximizing  $W_{T+1}$  amounts to minimizing the cumulative loss.

Goal: compete with the best constant rebalanced portfolio in hindsight (abbrev. CRP; that is, at the beginning of every day, allocate a constant fraction  $w^* \in \Delta^{d-1}$  to all assets. This has the advantage that the portion of each asset is well-controlled, and therefore can effective control risk.) Concretely,

$$\text{Reg}(T, w^*) = \sum_{t=1}^T f_t(w_t) - \sum_{t=1}^T f_t(w^*).$$

**Motivating example 2: online least squares regression.** For  $t = 1, 2, \dots, T$ :

1. Output a linear predictor  $w_t \in \mathbb{R}^d$ .
2. Receive example  $(x_t, y_t) \in \mathbb{R}^d \times \mathbb{R}$ .
3. Suffer loss  $f_t(w_t)$ , where  $f_t(w) = \frac{1}{2}(\langle w, x_t \rangle - y_t)^2$ .

$$\text{Reg}(T, w^*) = \sum_{t=1}^T f_t(w_t) - \sum_{t=1}^T f_t(w^*).$$

The common characteristic of the above two OCO problems are that the  $f_t$ 's are structured: they are compositions of a univariate “strongly convex” function and a linear function. It turns out that they both belong to the family called *exp-concave* functions.

**Definition 11.**  $f$  is called  $\alpha$ -exp-concave, if  $\exp(-\alpha f(x))$  is a concave function.

Clearly,  $f(x) = -\ln(\langle c, x \rangle)$  is 1-exp-concave.

**Lemma 4.**  $f$  is  $\alpha$ -exp-concave, iff for every  $x$ ,

$$\nabla^2 f(x) \succeq \alpha \nabla f(x) \cdot \nabla f(x)^\top.$$

*Proof.*  $h(x) = \exp(-\alpha f(x))$  is concave iff for every  $x$ , the hessian of  $h$  is negative semidefinite. Observe that

$$\nabla^2 h(x) = \alpha^2 \nabla f(x) \nabla f(x)^\top \exp(-\alpha f(x)) - \alpha \nabla^2 f(x) \exp(-\alpha f(x)) \preceq 0.$$

The lemma is proved in light of the fact that  $\exp(-\alpha f(x)) > 0$ .  $\square$

It can be readily seen that for  $\alpha < \gamma$ , if  $f$  is  $\gamma$ -exp-concave, then  $f$  is  $\alpha$ -exp-concave.

The following lemma shows that a univariate strongly convex function, composed with a linear function, is exp-concave.

**Lemma 5.** *Suppose  $h$  is  $\lambda$ -strongly convex and has gradient at most  $G$ . Then for any vector  $w$ ,  $h(\langle w, x \rangle)$  is  $\frac{\lambda}{G^2}$ -exp-concave.*

*Proof.* Because  $\nabla h(\langle w, x \rangle) = h'(\langle w, x \rangle)w$ , we have the following two simple observations:

$$\nabla^2 h(\langle w, x \rangle) = h''(\langle w, x \rangle)ww^\top \succeq \lambda ww^\top.$$

$$\nabla h(\langle w, x \rangle) \cdot \nabla h(\langle w, x \rangle)^\top \preceq h'(\langle w, x \rangle)^2 ww^\top \leq G^2 ww^\top.$$

The lemma is shown in light of Lemma 4.  $\square$

For online least-square regression with domain  $\{w : \|w\|_2 \leq B\}$  and all  $x \in \{x : \|x\|_2 \leq R\}$  and  $y \in [-Y, Y]$ , one can take  $h(z) = \frac{1}{2}(z - y)^2$ , which is 1-strongly convex, and has gradient norm at most  $RB + Y$ . Therefore,  $f(w) = \frac{1}{2}(\langle w, x \rangle - y)^2$  is  $\frac{1}{(RB+Y)^2}$ -exp-concave.

For exp-concave functions, one can have a more refined lower bound than linear approximation.

**Lemma 6.** *If  $f$  is  $\alpha$ -exp-concave and  $L$ -Lipschitz, then for any two points  $u, v \in \{w : \|w\|_2 \leq B\}$ , we have*

$$f(u) \geq f(v) + \langle \nabla f(v), u - v \rangle + \frac{\tilde{\alpha}}{2}(u - v)^\top \nabla f(v) \nabla f(v)^\top (u - v),$$

where  $\tilde{\alpha} = \min(\frac{1}{16BL}, \frac{\alpha}{2})$ .

*Proof.* Let  $\gamma \leq \alpha$  be a number to be decided. By the concavity of  $\exp(-\gamma f(w))$ , we have that for any two points  $u, v$  with norm at most  $B$ ,

$$\exp(-\gamma f(u)) \leq \exp(-\gamma f(v)) - \gamma \exp(-\gamma f(v)) \langle \nabla f(v), u - v \rangle.$$

In other words,

$$\exp(-\gamma(f(u) - f(v))) \leq 1 - \gamma \langle \nabla f(v), u - v \rangle.$$

Therefore,

$$-\gamma(f(u) - f(v)) \leq \ln\left(1 - \gamma \langle \nabla f(v), u - v \rangle\right).$$

Let us take  $\gamma = \min(\alpha, \frac{1}{8BL})$ . This ensures that  $\gamma \leq \alpha$ , and  $\left|\gamma \langle \nabla f(v), u - v \rangle\right| \leq \frac{1}{8BL} \cdot 2BL \leq \frac{1}{4}$ . Using the simple fact that  $\ln(1 - z) \leq -z - \frac{1}{4}z^2$  for all  $z \in [-\frac{1}{4}, \frac{1}{4}]$ , we have that

$$-\gamma(f(u) - f(v)) \leq -\gamma \langle \nabla f(v), u - v \rangle - \frac{1}{4}\gamma^2(\langle \nabla f(v), u - v \rangle)^2.$$

The lemma is proved by dividing both sides by  $-\gamma$  and recognizing that  $\tilde{\alpha} = \frac{\gamma}{2}$ .  $\square$

**Algorithm with logarithmic regret: adaptive regularization.** We will be using Lemma 6 and the insights similar to OCO for strongly-convex optimization to develop an algorithm with a  $O(\log T)$  regret.

Recall that AR-FTRL has the following regret guarantee:

$$\sum_{t=1}^T \langle g_t, w_t - w^* \rangle \leq R_0^*(0) + R_T(w^*) + \sum_{t=1}^T \|g_t\|_{\star, t-1}^2.$$

In addition, by Lemma 6, we have that

$$\sum_{t=1}^T f_t(w_t) - f_t(w^*) \leq \sum_{t=1}^T \langle g_t, w_t - w^* \rangle - \sum_{t=1}^T \frac{\tilde{\alpha}}{2} (w^* - w_t)^\top \nabla f(w_t) \nabla f(w_t)^\top (w^* - w_t). \quad (7)$$

Using the same idea behind logarithmic regret for strongly convex functions (Theorem 4), we choose a specialized regularizer that takes advantage of the negative terms relating OCO with  $\{f_t\}$  and OLO with  $\{w \mapsto \langle g_t, w \rangle\}$ , that induces a logarithmic regret algorithm.

**Theorem 6.** Suppose  $f_t$ 's are all  $\alpha$ -exp-concave, and are  $L$ -Lipschitz wrt  $\|\cdot\|_2$ . Denote by  $\mathcal{C} = \{w : \|w\|_2 \leq B\}$  be the feasible set. Then, FTRL-AR with adaptive regularizer  $\{\Phi_t\}$ , where  $\Phi_t(w) = \frac{\alpha L^2}{2} \|w\|_2^2 + \sum_{s=1}^t \frac{\tilde{\alpha}}{2} (w - w_s)^\top \nabla f_s(w_s) \nabla f_s(w_s)^\top (w - w_s)$  has regret

$$\text{Reg}(T, w^*) \leq O\left(d \cdot \left(\frac{1}{\alpha} + LB\right) \ln T\right),$$

against all  $w^* \in \mathcal{C}$ . Recall that  $\tilde{\alpha} = \min(\frac{1}{16BL}, \frac{\alpha}{2})$  is defined in Lemma 6.

*Proof.* Observe that for every  $t$ ,  $\Phi_t(x)$  is 1-strongly convex with respect to  $\|\cdot\|_t = \|\cdot\|_{A_t}$ , where  $A_t = \tilde{\alpha} \left( L^2 I + \sum_{s=1}^t \nabla f_s(w_s) \nabla f_s(w_s)^\top \right)$ .

With this choice of  $\{\Phi_t\}$ , theorem 3 implies that

$$\sum_{t=1}^T \langle g_t, x_t - w^* \rangle \leq \frac{\tilde{\alpha} L^2}{2} \|w^*\|^2 + \sum_{t=1}^T \frac{\tilde{\alpha}}{2} (w^* - w_t)^\top \nabla f_t(w_t) \nabla f_t(w_t)^\top (w - w_t) + \sum_{t=1}^T \|g_t\|_{\star, t-1}^2.$$

In combination with Equation (7), note that the quadratic terms on  $w$  cancel out completely. We have:

$$\text{Reg}(T, w^*) \leq \frac{\tilde{\alpha} L^2}{2} \|w^*\|_2^2 + \sum_{t=1}^T \|g_t\|_{A_t^{-1}}^2. \quad (8)$$

As  $A_{t-1} \succeq \tilde{\alpha} L^2 I$ ,  $A_t = A_{t-1} + \tilde{\alpha} g_t g_t^\top \preceq 2A_{t-1}$ . This implies that we can simplify the right hand side of Equation (8) as follows:

$$\begin{aligned} (8) &\leq \frac{\tilde{\alpha} L^2 B^2}{2} + 2 \sum_{t=1}^T \|g_t\|_{A_t^{-1}}^2 \\ &= O\left(\frac{1}{\tilde{\alpha}} \sum_{t=1}^T \text{tr}((g_t g_t^\top) \cdot A_t^{-1})\right) \\ &= O\left(\frac{1}{\tilde{\alpha}} (\ln \det(A_T) - \ln \det(A_0))\right) \\ &= O\left(\frac{1}{\tilde{\alpha}} \left(\sum_{i=1}^d \ln \frac{\lambda_i}{\tilde{\alpha} L^2}\right)\right) = O\left(\frac{d}{\tilde{\alpha}} \ln T\right), \end{aligned}$$

where the first equality is based on the observation that  $\tilde{\alpha} \leq \frac{1}{LB}$ ; the second equality is from Lemma 10; in the penultimate equality, we denote by  $\{\lambda_i\}_{i=1}^d$  the  $d$  eigenvalues of  $A_T$ , and the last inequality uses the AM-GM inequality and the fact that  $\sum_{i=1}^d \lambda_i = \text{tr}(A_T) \leq \tilde{\alpha}(T+1)L^2$ . The theorem follows from expanding the definition of  $\tilde{\alpha}$ .  $\square$

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## A Auxiliary lemmas

**Lemma 7.** Suppose  $a_1, \dots, a_T \geq 0$  is a sequence of positive numbers, with  $a_1 > 0$ . Let  $A_t = \sum_{s=1}^t a_s$ . Then

$$\sum_{t=1}^T \frac{a_t}{\sqrt{A_t}} \leq 2\sqrt{A_T}.$$

*Proof.* We note that each term on the left hand side is

$$\frac{a_t}{\sqrt{A_t}} = \frac{A_t - A_{t-1}}{\sqrt{A_t}} \leq 2 \cdot \frac{A_t - A_{t-1}}{\sqrt{A_t} + \sqrt{A_{t-1}}} \leq 2(\sqrt{A_t} - \sqrt{A_{t-1}}).$$

The lemma is concluded by summing over all  $t$ 's from 1 to  $T$ .  $\square$

We have the following matrix generalization of the above lemma.

**Lemma 8.** Suppose  $M_1, \dots, M_T \succeq 0$  is a sequence of positive semidefinite matrices, with  $M_1 \succ 0$ . Let  $N_t = \sum_{s=1}^t M_s$ . Then

$$\sum_{t=1}^T \text{tr} \left( N_t^{-\frac{1}{2}} M_t \right) \leq 2 \text{tr} \left( N_T^{\frac{1}{2}} \right).$$

*Proof.* We claim that

$$\text{tr} \left( N_t^{-\frac{1}{2}} M_t \right) = \text{tr} \left( N_t^{-\frac{1}{2}} (N_t - N_{t-1}) \right) \leq 2 \text{tr} \left( N_t^{\frac{1}{2}} \right) - 2 \text{tr} \left( N_{t-1}^{\frac{1}{2}} \right).$$

Indeed, by the concavity of function  $f(N) = 2 \text{tr} \left( N^{\frac{1}{2}} \right)$ , and the fact that  $\nabla f(N) = N^{-\frac{1}{2}}$ , we have that  $f(N) - f(N') \leq \langle \nabla f(N'), N - N' \rangle$ , which implies the last equality above by taking  $N = N_t$  and  $N' = N_{t-1}$ .  $\square$

Similarly as above, we also have the following lemma regarding the sum of a sequence of numbers divided by their cumulative sums.

**Lemma 9.** Suppose  $a_1, \dots, a_T \geq 0$  is a sequence of positive numbers, with  $a_1 > 0$ . Let  $A_t = \sum_{s=1}^t a_s$ . Then

$$\sum_{t=1}^T \frac{a_t}{A_t} \leq \ln \frac{A_T}{A_1}.$$

*Proof.* Each term on the left hand side can be upper bounded as:

$$\frac{a_t}{A_t} \leq -\ln \left( 1 - \frac{a_t}{A_t} \right) = \ln \frac{A_t}{A_{t-1}}.$$

The lemma is concluded by summing over all  $t$ 's from 1 to  $T$ .  $\square$

We also have its matrix generalization:

**Lemma 10.** Suppose  $M_1, \dots, M_T \succeq 0$  is a sequence of positive semidefinite matrices. Given  $N_0 \succ 0$ , let  $N_t = N_0 + \sum_{s=1}^t M_s$ . Then

$$\sum_{t=1}^T \text{tr} \left( N_t^{-1} M_t \right) \leq \ln \det(N_T) - \ln \det(N_0).$$

*Proof.* We claim that

$$\mathrm{tr} \left( N_t^{-1} M_t \right) \leq \ln \det(N_t) - \ln \det(N_{t-1}).$$

Ineed, by the concavity of function  $f(N) = \ln \det(N)$ , and the fact that  $\nabla f(N) = N^{-1}$ , we have that  $f(N) - f(N') \leq \langle \nabla f(N'), N - N' \rangle$ , which implies the last equality above by taking  $N = N_{t-1}$  and  $N' = N_t$ .  $\square$