Supplementary Material to "On Multilabel Classification and Ranking with Partial Feedback"

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5 Appendix

This appendix contains the proofs of all lemmas and theorems presented in the main text.

Proof: [Lemma 1] First observe that, for any given size s, the sequence $Y^*_{s,t}$ must contain the s top-ranked classes in the sorted order of $p_{i,t}$. This is because, for any candidate sequence $Y_s = \{j_1, j_2, \ldots, j_s\}$, we have $\mathbb{E}_t[\ell_{a,c}(Y^*_t, Y_s)] = (1-a)\sum_{i \in Y_s}\left(c(j_i,s) - \left(\frac{a}{1-a} + c(j_i,s)\right) p_{i,t}\right)$. If there exists $i \in Y_s$ which is not among the s-top ranked ones, then we could replace class i in position j_i within Y_s with class $k \notin Y_s$ such that $p_{k,t} > p_{i,t}$ obtaining a smaller loss.

Next, we show that the optimal ordering within $Y^*_{s,t}$ is precisely ruled by the nonicreasing order of $p_{i,t}$. By the sake of contradiction, assume there are i and k in $Y^*_{s,t}$ such that i preceeds k in $Y^*_{s,t}$ but $p_{k,t} > p_{i,t}$. Specifically, let i be in position j_1 and k be in position j_2 with $j_1 < j_2$ and such that $c(j_1,s) > c(j_2,s)$. Then, disregarding the common $(1-a)$-factor, switching the two classes within $Y^*_{s,t}$ yields an expected loss difference of

$$\begin{aligned}
&c(j_1,s) - \left(\tfrac{a}{1-a} + c(j_1,s)\right) p_{i,t} + c(j_2,s) - \left(\tfrac{a}{1-a} + c(j_2,s)\right) p_{k,t} \\
&- \left(c(j_1,s) - \left(\tfrac{a}{1-a} + c(j_1,s)\right) p_{k,t}\right) - \left(c(j_2,s) - \left(\tfrac{a}{1-a} + c(j_2,s)\right) p_{i,t}\right) \\
&= (p_{k,t} - p_{i,t})\,(c(j_1,s) - c(j_2,s)) > 0\,,
\end{aligned}$$

since $p_{k,t} > p_{i,t}$ and $c(j_1,s) > c(j_2,s)$. Hence switching would get a smaller loss which leads as a consequence to $Y^*_{s,t} = (j_1, j_2, \ldots, j_s)$. □

The algorithm in Figure 1 works by updating through the gradients $\nabla_{i,t}$ of a modular margin-based loss function $\sum_{i=1}^K L(\boldsymbol{w}_i^\top \boldsymbol{x})$ associated with the label generation model (2) so as to make the parameters $(\boldsymbol{u}_1, \ldots, \boldsymbol{u}_K) \in \mathcal{R}^{dK}$ therein achieve the Bayes optimality condition

$$(\boldsymbol{u}_1, \ldots, \boldsymbol{u}_K) = \arg \min_{\boldsymbol{w}_1,\ldots,\boldsymbol{w}_K \,:\, \boldsymbol{w}_i^\top \boldsymbol{x}_t \in D} \mathbb{E}_t\left[\sum_{i=1}^K L(s_{i,t}\, \boldsymbol{w}_i^\top \boldsymbol{x}_t)\right]\,, \tag{4}$$

where $\mathbb{E}_t[\cdot]$ above is over the generation of Y_t in producing the sign value $s_{i,t} \in \{-1, 0, +1\}$, conditioned on the past (in particular, conditioned on $\hat{Y}_t$). The requirement in (4) is akin to the classical construction of *proper scoring rules* in the statistical literature (e.g., [9]).

The following lemma faces the problem of hand-crafting a convenient loss function $L(\cdot)$ such that (4) holds.

Lemma 5. *Let $\boldsymbol{w}_1, \ldots, \boldsymbol{w}_K \in \mathcal{R}^{dK}$ be arbitrary weight vectors such that $\boldsymbol{w}_i^\top \boldsymbol{x}_t \in D$, $i \in [K]$, $(\boldsymbol{u}_1, \ldots, \boldsymbol{u}_K) \in \mathcal{R}^{dK}$ be defined in (2), $s_{i,t}$ be the updating signs computed by the algorithm at the end (Step 5) of time t, $L : D = [-R, R] \subseteq \mathcal{R} \to \mathcal{R}^+$ be a convex and differentiable function of its argument, with $g(\Delta) = -L'(\Delta)$. Then for any t we have*

$$\mathbb{E}_t\left[\sum_{i=1}^K L(s_{i,t}\, \boldsymbol{w}_i^\top \boldsymbol{x}_t)\right] \geq \mathbb{E}_t\left[\sum_{i=1}^K L(s_{i,t}\, \boldsymbol{u}_i^\top \boldsymbol{x}_t)\right],$$

i.e., (4) holds.

Proof: Let us introduce the shorthands $\Delta_i = \boldsymbol{u}_i^\top \boldsymbol{x}_t$, $\widehat{\Delta}_i = \boldsymbol{w}_{i,t}^\top \boldsymbol{x}_t$, $s_i = s_{i,t}$, and $p_i = \mathbb{P}(y_{i,t} = 1 \,|\, \boldsymbol{x}_t) = \frac{L'(-\Delta_i)}{L'(\Delta_i)+L'(-\Delta_i)}$. Moreover, let $\mathbb{P}_t(\cdot)$ be an abbreviation for the conditional probability $\mathbb{P}(\cdot \,|\, (y_1, \boldsymbol{x}_1), \ldots, (y_{t-1}, \boldsymbol{x}_{t-1}), \boldsymbol{x}_t)$. Recalling the way $s_{i,t}$ is constructed (Figure 1), we can write

$$\begin{aligned}\mathbb{E}_t\left[\sum_{i=1}^{K} L(s_{i,t}\,\widehat{\Delta}_i)\right] &= \sum_{i\in\hat{Y}_t}\Big(\mathbb{P}_t(s_{i,t}=1)\,L(\widehat{\Delta}_i) + \mathbb{P}_t(s_{i,t}=-1)\,L(-\widehat{\Delta}_i)\Big) + (K-|\hat{Y}_t|)\,L(0)\\ &= \sum_{i\in\hat{Y}_t}\Big(p_i\,L(\widehat{\Delta}_i) + (1-p_i)\,L(-\widehat{\Delta}_i)\Big) + (K-|\hat{Y}_t|)\,L(0)\;,\end{aligned}$$

For similar reasons,

$$\mathbb{E}_t\left[\sum_{i=1}^{K} L(s_{i,t}\,\Delta_i)\right] = \sum_{i\in\hat{Y}_t}\left(p_i\,L(\Delta_i) + (1-p_i)\,L(-\Delta_i)\right) + (K-|\hat{Y}_t|)\,L(0)\;.$$

Since $L(\cdot)$ is convex, so is $\mathbb{E}_t\left[\sum_{i=1}^{K} L(s_{i,t}\,\widehat{\Delta}_i)\right]$ when viewed as a function of the $\widehat{\Delta}_i$. We have that $\frac{\partial\,\mathbb{E}_t\left[\sum_{i=1}^{K} L(s_{i,t}\,\widehat{\Delta}_i)\right]}{\partial\widehat{\Delta}_i} = 0$ if and only if for all $i \in \hat{Y}_t$ we have that $\widehat{\Delta}_i$ satisfies

$$p_i = \frac{L'(-\widehat{\Delta}_i)}{L'(\widehat{\Delta}_i) + L'(-\widehat{\Delta}_i)}\;.$$

Since $p_i = \frac{L'(-\Delta_i)}{L'(\Delta_i)+L'(-\Delta_i)}$, we have that $\mathbb{E}_t\left[\sum_{i=1}^{K} L(s_{i,t}\,\widehat{\Delta}_i)\right]$ is minimized when $\widehat{\Delta}_i = \Delta_i$ for all $i \in [K]$. The claimed result immediately follows. □

Let now $Var_t(\cdot)$ be a shorthand for $Var(\cdot \,|\, (y_1, \boldsymbol{x}_1), \ldots, (y_{t-1}, \boldsymbol{x}_{t-1}), \boldsymbol{x}_t)$. The following lemma shows that under additional assumptions on the loss $L(\cdot)$, we are afforded to bound the variance of a difference of losses $L(\cdot)$ by the expectation of this difference. This will be key to proving the fast rates of convergence contained in the subsequent Lemma 9.

Lemma 6. *Let $(\boldsymbol{w}'_{1,t}, \ldots, \boldsymbol{w}'_{K,t}) \in \mathcal{R}^{dK}$ be the weight vectors computed by the algorithm in Figure 1 at the beginning (Step 2) of time t, $s_{i,t}$ be the updating signs computed at the end (Step 5) of time t, and $(\boldsymbol{u}_1, \ldots, \boldsymbol{u}_K) \in \mathcal{R}^{dK}$ be the comparison vectors defined through (2). Let $L : D = [-R, R] \subseteq \mathcal{R} \to \mathcal{R}^+$ be a $C^2(D)$ convex function of its argument, with $g(\Delta) = -L'(\Delta)$ and such that there are positive constants c'_L and c''_L with $(L'(\Delta))^2 \leq c'_L$ and $L''(\Delta) \geq c''_L$ for all $\Delta \in D$. Then for any $i \in \hat{Y}_t$*

$$0 \leq Var_t\left(L(s_{i,t}\,\boldsymbol{x}_t^\top \boldsymbol{w}'_{i,t}) - L(s_{i,t}\,\boldsymbol{u}_i^\top \boldsymbol{x}_t)\right) \leq \frac{2c'_L}{c''_L}\,\mathbb{E}_t\left[L(s_{i,t}\,\boldsymbol{x}_t^\top \boldsymbol{w}'_{i,t}) - L(s_{i,t}\,\boldsymbol{u}_i^\top \boldsymbol{x}_t)\right]\;.$$

Proof: Let us introduce the shorthands $\Delta_i = \boldsymbol{x}_t^\top \boldsymbol{u}_i$, $\widehat{\Delta}_i = \boldsymbol{x}_t^\top \boldsymbol{w}'_{i,t}$, $s_i = s_{i,t}$, and $p_i = \mathbb{P}(y_{i,t} = 1 \,|\, \boldsymbol{x}_t) = \frac{L'(-\Delta_i)}{L'(\Delta_i)+L'(-\Delta_i)}$. Then, for any $i \in [K]$,

$$Var_t\left(L(s_{i,t}\,\boldsymbol{x}_t^\top \boldsymbol{w}'_{i,t}) - L(s_{i,t}\,\boldsymbol{u}_i^\top \boldsymbol{x}_t)\right) \leq \mathbb{E}_t\left(\Big(L(s_i\,\widehat{\Delta}_i) - L(s_i\,\Delta_i)\Big)^2\right) \leq c'_L\,(\widehat{\Delta}_i - \Delta_i)^2\;. \tag{5}$$

Moreover, for any $i \in \hat{Y}_t$ we can write

$$\begin{aligned}
\mathbb{E}_t\left[L(s_i\,\widehat{\Delta}_i) - L(s_i\,\Delta_i)\right] &= p_i\,(L(\widehat{\Delta}_i) - L(\Delta_i)) + (1-p_i)\,(L(-\widehat{\Delta}_i) - L(-\Delta_i)) \\
&\geq p_i\,\left(L'(\Delta_i)(\widehat{\Delta}_i - \Delta_i) + \frac{c''_L}{2}(\widehat{\Delta}_i - \Delta_i)^2\right) \\
&\quad + (1-p_i)\,\left(L'(-\Delta_i)(\Delta_i - \widehat{\Delta}) + \frac{c''_L}{2}(\widehat{\Delta}_i - \Delta_i)^2\right) \\
&= p_i\,\frac{c''_L}{2}(\widehat{\Delta}_i - \Delta_i)^2 + (1-p_i)\,\frac{c''_L}{2}(\widehat{\Delta}_i - \Delta_i)^2 \\
&= \frac{c''_L}{2}(\widehat{\Delta}_i - \Delta_i)^2, \qquad (6)
\end{aligned}$$

where the second equality uses the definition of p_i. Combining (5) with (6) gives the desired bound. □

We continue by showing a one-step regret bound *for our original* loss $\ell_{a,c}$. The precise connection to loss $L(\cdot)$ will be established with the help of a later lemma (Lemma 9).

Lemma 7. *Let $L : D = [-R, R] \subseteq \mathcal{R} \to \mathcal{R}^+$ be a convex, twice differentiable, and nonincreasing function of its argument. Let $(\boldsymbol{u}_1, \ldots, \boldsymbol{u}_K) \in \mathcal{R}^{dK}$ be defined in (2) with $g(\Delta) = -L'(\Delta)$ for all $\Delta \in D$. Let also c_L be a positive constant such that*

$$\frac{L'(\Delta)\,L''(-\Delta) + L''(\Delta)\,L'(-\Delta)}{(L'(\Delta) + L'(-\Delta))^2} \geq -c_L$$

holds for all $\Delta \in D$. Finally, let $\Delta_{i,t}$ denote $\boldsymbol{u}_i^\top \boldsymbol{x}_t$, and $\widehat{\Delta}'_{i,t}$ denote $\boldsymbol{x}_t^\top \boldsymbol{w}'_{i,t}$, where $\boldsymbol{w}'_{i,t}$ is the i-th weight vector computed by the algorithm at the beginning (Step 2) of time t. If time t is such that $|\Delta_{i,t} - \widehat{\Delta}'_{i,t}| \leq \epsilon_{i,t}$ for all $i \in [K]$, then

$$\mathbb{E}_t[\ell_{a,c}(Y_t, \hat{Y}_t)] - \mathbb{E}_t[\ell_{a,c}(Y_t, Y_t^*)] \leq 2\,(1-a)\,c_L \sum_{i \in \hat{Y}_t} \epsilon_{i,t}\,.$$

Proof: Introduce the shorthand notation $p(\Delta) = \frac{g(-\Delta)}{g(\Delta)+g(-\Delta)}$. We can write

$$\begin{aligned}
&\mathbb{E}_t[\ell_{a,c}(Y_t, \hat{Y}_t)] - \mathbb{E}_t[\ell_{a,c}(Y_t, Y_t^*)] \\
&\qquad = (1-a) \sum_{i \in \hat{Y}_t} \left(c(\hat{j}_i, |\hat{Y}_t|) - \left(\tfrac{a}{1-a} + c(\hat{j}_i, |\hat{Y}_t|)\right)\,p(\Delta_{i,t})\right) \\
&\qquad\quad - (1-a) \sum_{i \in Y_t^*} \left(c(j_i^*, |Y_t^*|) - \left(\tfrac{a}{1-a} + c(j_i^*, |Y_t^*|)\right)\,p(\Delta_{i,t})\right),
\end{aligned}$$

where $\hat{j}_i$ denotes the position of class i in $\hat{Y}_t$ and j_i^* is the position of class i in Y_t^*. Now,

$$p'(\Delta) = \frac{-g'(-\Delta)\,g(\Delta) - g'(\Delta)\,g(-\Delta)}{(g(\Delta) + g(-\Delta))^2} = \frac{-L'(\Delta)\,L''(-\Delta) - L'(-\Delta)\,L''(\Delta)}{(L'(\Delta) + L'(-\Delta))^2} \geq 0$$

since $g(\Delta) = -L'(\Delta)$, and $L(\cdot)$ is convex and nonincreasing. Hence $p(\Delta)$ is itself a nondecreasing function of Δ. Moreover, the extra condition on L involving L' and L'' is a Lipschitz condition on $p(\Delta)$ via a uniform bound on $p'(\Delta)$. Hence, from $|\Delta_{i,t} - \widehat{\Delta}'_{i,t}| \leq \epsilon_{i,t}$ and the definition of $\hat{Y}_t$ we

can write

$$\begin{aligned}
&\mathbb{E}_t[\ell_{a,c}(Y_t,\hat{Y}_t)] - \mathbb{E}_t[\ell_{a,c}(Y_t,Y_t^*)] \\
&\qquad \le (1-a)\sum_{i\in\hat{Y}_t}\Big(c(\hat{j}_i,|\hat{Y}_t|) - \Big(\tfrac{a}{1-a}+c(\hat{j}_i,|\hat{Y}_t|)\Big)\,p([\widehat{\Delta}'_{i,t}-\epsilon_{i,t}]_D)\Big) \\
&\qquad\quad -(1-a)\sum_{i\in Y_t^*}\Big(c(j_i^*,|Y_t^*|) - \Big(\tfrac{a}{1-a}+c(j_i^*,|Y_t^*|)\Big)\,p([\widehat{\Delta}'_{i,t}+\epsilon_{i,t}]_D)\Big) \\
&\qquad \le (1-a)\sum_{i\in\hat{Y}_t}\Big(c(\hat{j}_i,|\hat{Y}_t|) - \Big(\tfrac{a}{1-a}+c(\hat{j}_i,|\hat{Y}_t|)\Big)\,p([\widehat{\Delta}'_{i,t}-\epsilon_{i,t}]_D)\Big) \\
&\qquad\quad -(1-a)\sum_{i\in\hat{Y}_t}\Big(c(\hat{j}_i,|\hat{Y}_t|) - \Big(\tfrac{a}{1-a}+c(\hat{j}_i,|\hat{Y}_t|)\Big)\,p([\widehat{\Delta}'_{i,t}+\epsilon_{i,t}]_D)\Big) \\
&\qquad = (1-a)\sum_{i\in\hat{Y}_t}\Big(c(\hat{j}_i,|\hat{Y}_t|)\,\Big(p([\widehat{\Delta}'_{i,t}+\epsilon_{i,t}]_D) - p([\widehat{\Delta}'_{i,t}-\epsilon_{i,t}]_D)\Big)\Big) \\
&\qquad \le 2\,(1-a)\,c_L\sum_{i\in\hat{Y}_t}\epsilon_{i,t}\ ,
\end{aligned}$$

the last inequality deriving from $c(i,s)\le 1$ for all $i\le s\le K$, and

$$p([\widehat{\Delta}'_{i,t}+\epsilon_{i,t}]_D) - p([\widehat{\Delta}'_{i,t}-\epsilon_{i,t}]_D) \le c_L\big([\widehat{\Delta}'_{i,t}+\epsilon_{i,t}]_D - [\widehat{\Delta}'_{i,t}-\epsilon_{i,t}]_D\big) \le 2\,c_L\,\epsilon_{i,t}. \quad \square$$

Likewise, we provide a similar bound for the ranking loss.

Lemma 8. *Under the same assumptions and notation as in Lemma 7, combined with the independence assumption $\mathbb{P}_t(y_{1,t},...,y_{K,t}) = \prod_{i\in[K]} p_{i,t}$, let the Algorithm in Figure 1 be working with $a\to 1$ and strictly decreasing cost values $c(i,s)$. Let $\boldsymbol{w}'_{i,t}$ be the i-th weight vector computed by this algorithm at the beginning (Step 2) of time t. If this algorithm ranks classes as $\widehat{p}_{j_1,t}\ge\ldots\ge\widehat{p}_{j_{S_t},t}\ge 0$, and time t is such that $|\Delta_{i,t}-\widehat{\Delta}'_{i,t}|\le\epsilon_{i,t}$ for all $i\in[K]$, then*

$$\begin{aligned}
&\mathbb{E}_t[\ell_{rank,t}(Y_t,(\widehat{p}_{j_1,t},\ldots,\widehat{p}_{j_{S_t},t},0,\ldots,0))] - \mathbb{E}_t[\ell_{rank,t}(Y_t,(p_{i_{1,t}},\ldots,p_{i_{S_t},t},0,\ldots,0))] \\
&\qquad\qquad \le 4\,S_t\,c_L\sum_{i\in\hat{Y}_t}\epsilon_{i,t}\ ,
\end{aligned}$$

where the $p_{i,t}=\mathbb{P}_t(y_{i,t}=1\,|\,\boldsymbol{x}_t)$ are sorted as $p_{i_1,t}\ge\ldots\ge p_{i_{S_t},t}\ge 0$, and $\hat{Y}_t=(j_1,j_2,\ldots,j_{S_t})$.

Proof: Recall the notation $\mathbb{P}_t(\cdot)=\mathbb{P}(\cdot\,|\,\boldsymbol{x}_t)$, and $p_{i,t}=p(\Delta_{i,t})=\frac{g(-\Delta_{i,t})}{g(\Delta_{i,t})+g(-\Delta_{i,t})}$. For notational convenience, in this proof we drop subscript t from $p_{i,t}$, S_t, $y_{i,t}$, and $\hat{Y}_t$. Consider $\mathbb{E}_t[\ell_{rank,t}(Y_t,\hat{Y})]$, and introduce the shorthand

$$p_{i,j} = p_i\,p_j = p_i - \mathbb{P}_t(y_i>y_j).$$

Disregarding the term $S\sum_{i\in[K]}p_i$, which is independent of $\hat{Y}$, we can write

$$\begin{aligned}
\mathbb{E}_t[\ell_{rank,t}(Y_t,\hat{Y})] &= \sum_{i,j\in\hat{Y},\,i<j}\mathbb{P}_t(y_i>y_j)\ \big(\{p_i<p_j\}+\tfrac{1}{2}\,\{p_i=p_j\}\big) \\
&\quad+\sum_{i,j\in\hat{Y},\,i<j}\mathbb{P}_t(y_j>y_i)\ \big(\{p_j<p_i\}+\tfrac{1}{2}\,\{p_j=p_i\}\big) - S\sum_{i\in\hat{Y}}p_i \\
&= \sum_{i,j\in\hat{Y},\,i<j}(p_i-p_{i,j})\{p_i<p_j\}+(p_i-p_{i,j})\tfrac{1}{2}\,\{p_i=p_j\} \\
&\quad+\sum_{i,j\in\hat{Y},\,i<j}(p_j-p_{i,j})\{p_j<p_i\}+(p_j-p_{i,j})\tfrac{1}{2}\,\{p_j=p_i\} - S\sum_{i\in\hat{Y}}p_i \\
&= \sum_{i,j\in\hat{Y},\,i<j}(p_i-p_j)\{p_i<p_j\}+\tfrac{1}{2}\,(p_i-p_j)\,\{p_i=p_j\}+p_j-p_{i,j} - S\sum_{i\in\hat{Y}}p_i \\
&= \sum_{i,j\in\hat{Y},\,i<j}(\min\{p_i,p_j\}-p_ip_j) - S\sum_{i\in\hat{Y}}p_i
\end{aligned}$$

which can be finally seen to be equal to

$$-\sum_{i\in\hat{Y}}(S+1-\hat{j}_i)\,p_i-\sum_{i,j\in\hat{Y},\,i<j}p_i\,p_j\,, \tag{7}$$

where $\hat{j}_i$ is the position of class i within $\hat{Y}_t$ in decreasing order of p_i.

Denote by Y_t^* the sequences determined by $f^*(\boldsymbol{x}_t;S)$, the optimal ranking operating on the p_i's, and let $\hat{j}_i$ and j_i^* be the position of class i in decreasing order of p_i within $\hat{Y}$ and Y_t^*, respectively.

Proceeding as in Lemma 7 and recalling (7) we can write

$$\begin{aligned}
&\mathbb{E}_t[\ell_{rank,t}(Y_t,\widehat{f}(\boldsymbol{x}_t;S))]-\mathbb{E}_t[\ell_{rank,t}(Y_t,f^*(\boldsymbol{x}_t;S)]\\
&\quad=\sum_{i\in Y_t^*}(S+1-j_i^*)\,p_i+\sum_{i,j\in Y_t^*,\,i<j}p_i\,p_j-\sum_{i\in\hat{Y}}(S+1-\hat{j}_i)\,p_i-\sum_{i,j\in\hat{Y},\,i<j}p_i\,p_j\\
&\quad\le\sum_{i\in Y_t^*}(S+1-j_i^*)\,p([\widehat{\Delta}'_{i,t}+\epsilon_{i,t}]_D)+\sum_{i,j\in Y_t^*,\,i<j}p([\widehat{\Delta}'_{i,t}+\epsilon_{i,t}]_D)\,p([\widehat{\Delta}'_{j,t}+\epsilon_{j,t}]_D)\\
&\qquad-\sum_{i\in\hat{Y}}(S+1-\hat{j}_i)\,p([\widehat{\Delta}'_{i,t}-\epsilon_{i,t}]_D)-\sum_{i,j\in\hat{Y},\,i<j}p([\widehat{\Delta}'_{i,t}-\epsilon_{i,t}]_D)\,p([\widehat{\Delta}'_{j,t}-\epsilon_{j,t}]_D)\\
&\quad\le\sum_{i\in\hat{Y}}(S+1-\hat{j}_i)\,\Big(p([\widehat{\Delta}'_{i,t}+\epsilon_{i,t}]_D)-p([\widehat{\Delta}'_{i,t}-\epsilon_{i,t}]_D)\Big)\\
&\qquad+\sum_{i,j\in\hat{Y},\,i<j}\Big(p([\widehat{\Delta}'_{i,t}+\epsilon_{i,t}]_D)\,p([\widehat{\Delta}'_{j,t}+\epsilon_{j,t}]_D)-p([\widehat{\Delta}'_{i,t}-\epsilon_{i,t}]_D)\,p([\widehat{\Delta}'_{j,t}-\epsilon_{j,t}]_D)\Big)\\
&\quad\le 2Sc_L\sum_{i\in\hat{Y}}\epsilon_{i,t}+\sum_{i,j\in\hat{Y},\,i<j}2c_L\,(\epsilon_{i,t}+\epsilon_{j,t})\\
&\quad=2\,S\,c_L\sum_{i\in\hat{Y}}\epsilon_{i,t}+2\,(S-1)\,c_L\sum_{i\in\hat{Y}}\epsilon_{i,t}\\
&\quad<4\,S\,c_L\sum_{i\in\hat{Y}}\epsilon_{i,t}\,,
\end{aligned}$$

as claimed. □

Lemma 9. *Let $L:D=[-R,R]\subseteq\mathcal{R}\to\mathcal{R}^+$ be a $C^2(D)$ convex and nonincreasing function of its argument, $(\boldsymbol{u}_1,\ldots,\boldsymbol{u}_K)\in\mathcal{R}^{dK}$ be defined in (2) with $g(\Delta)=-L'(\Delta)$ for all $\Delta\in D$, and such that $\|\boldsymbol{u}_i\|\le U$ for all $i\in[K]$. Assume there are positive constants c'_L and c''_L with $(L'(\Delta))^2\le c'_L$ and $L''(\Delta)\ge c''_L$ for all $\Delta\in D$. With the notation introduced in Figure 1, we have that*

$$(\boldsymbol{x}^\top\boldsymbol{w}'_{i,t}-\boldsymbol{u}_i^\top\boldsymbol{x})^2\le\boldsymbol{x}^\top A_{i,t-1}^{-1}\boldsymbol{x}\,\left(U^2+\frac{d\,c'_L}{(c''_L)^2}\,\ln\left(1+\frac{t-1}{d}\right)+\frac{12}{c''_L}\,\left(\frac{c'_L}{c''_L}+3L(-R)\right)\,\ln\frac{K(t+4)}{\delta}\right)$$

holds with probability at least $1-\delta$ for any $\delta<1/e$, uniformly *over $i\in[K]$, $t=1,2,\ldots$, and $\boldsymbol{x}\in\mathcal{R}^d$.*

Proof: For any given class i, the time-t update rule $\boldsymbol{w}'_{i,t}\to\boldsymbol{w}_{i,t+1}\to\boldsymbol{w}'_{i,t+1}$ in Figure 1 allows us to start off from [7] (proof of Theorem 2 therein), from which one can extract the following inequality

$$\begin{aligned}
&d_{i,t-1}(\boldsymbol{u}_i,\boldsymbol{w}'_{i,t})\\
&\quad\le U^2+\frac{1}{(c''_L)^2}\sum_{k=1}^{t-1}r_{i,k}-\frac{2}{c''_L}\sum_{k=1}^{t-1}\left(\nabla_{i,k}^\top(\boldsymbol{w}'_{i,k}-\boldsymbol{u}_i)-\frac{c''_L}{2}\,\left(s_{i,k}\,\boldsymbol{x}_k^\top(\boldsymbol{w}'_{i,k}-\boldsymbol{u}_i)\right)^2\right),
\end{aligned}\tag{8}$$

where we set $r_{i,k}=\nabla_{i,k}^\top A_{i,k}^{-1}\nabla_{i,k}$. Using the lower bound on the second derivative of L we have

$$\begin{aligned}
&L(s_{i,k}\,\boldsymbol{x}_k^\top\boldsymbol{w}'_{i,k})-L(s_{i,k}\,\boldsymbol{u}_i^\top\boldsymbol{x}_k)\\
&\qquad\le L'(s_{i,k}\,\boldsymbol{x}_k^\top\boldsymbol{w}'_{i,k})(s_{i,k}\boldsymbol{x}_k^\top\boldsymbol{w}'_{i,k}-s_{i,k}\,\boldsymbol{u}_i^\top\boldsymbol{x}_k)-\frac{c''_L}{2}(s_{i,k}\,\boldsymbol{x}_k^\top\boldsymbol{w}'_{i,k}-s_{i,k}\,\boldsymbol{u}_i^\top\boldsymbol{x}_k)^2\\
&\qquad=\nabla_{i,k}^\top(\boldsymbol{w}'_{i,k}-\boldsymbol{u}_i)-\frac{c''_L}{2}\,\left(s_{i,k}\,\boldsymbol{x}_k^\top(\boldsymbol{w}'_{i,k}-\boldsymbol{u}_i)\right)^2\,.
\end{aligned}$$

Plugging back into (8) yields

$$d_{i,t-1}(\boldsymbol{u}_i, \boldsymbol{w}'_{i,t}) \leq U^2 + \frac{1}{(c''_L)^2} \sum_{k=1}^{t-1} r_{i,k} - \frac{2}{c''_L} \sum_{k=1}^{t-1} \left(L(s_{i,k}\, \boldsymbol{x}_k^\top \boldsymbol{w}'_{i,k}) - L(s_{i,k}\, \boldsymbol{u}_i^\top \boldsymbol{x}_k) \right) \quad (9)$$

We now borrow a proof technique from [4] (see also [1, 5] and references therein). Define $L_{i,k} = L(s_{i,k}\, \boldsymbol{x}_k^\top \boldsymbol{w}'_{i,k}) - L(s_{i,k}\, \boldsymbol{u}_i^\top \boldsymbol{x}_k)$ and $L'_{i,k} = \mathbb{E}_k[L_{i,k}] - L_{i,k}$. Notice that the sequence of random variables $L'_{i,1}, L'_{i,2}, \ldots$, forms a martingale difference sequence such that, for any $i \in \hat{Y}_k$:

i. $\mathbb{E}_k[L_{i,k}] \geq 0$, by Lemma 6;

ii. $|L'_{i,k}| \leq 2L(-R)$, since $L(\cdot)$ is nonincreasing over D, and $s_{i,k}\, \boldsymbol{x}_k^\top \boldsymbol{w}'_{i,k},\ s_{i,k}\, \boldsymbol{u}_i^\top \boldsymbol{x}_k \in D$;

iii. $Var_k(L'_{i,k}) = Var_k(L_{i,k}) \leq \frac{2c'_L}{c''_L}\, \mathbb{E}_k[L_{i,k}]$ (again, because of Lemma 6).

On the other hand, when $i \notin \hat{Y}_k$ then $s_{i,k} = 0$, and the above three properties are trivally satisfied. Under the above conditions, we are in a position to apply any fast concentration result for bounded martingale difference sequences. For instance, setting for brevity $B = B(t, \delta) = 3 \ln \frac{K(t+4)}{\delta}$, [8] allows us derive the inequality

$$\sum_{k=1}^{t-1} \mathbb{E}_k[L_{i,k}] - \sum_{k=1}^{t-1} L_{i,k} \geq \max \left\{ \sqrt{\frac{8c'_L}{c''_L}\, B \sum_{k=1}^{t-1} \mathbb{E}_k[L_{i,k}]}, 6L(-R)\, B \right\},$$

that holds with probability at most $\frac{\delta}{Kt(t+1)}$ for any $t \geq 1$. We use the inequality $\sqrt{cb} \leq \frac{1}{2}(c+b)$ with $c = \frac{4c'_L}{c''_L}\, B$, and $b = 2 \sum_{k=1}^{t-1} \mathbb{E}_k[L_{i,k}]$, and simplify. This gives

$$-\sum_{k=1}^{t-1} L_{i,k} \leq \left(\frac{2c'_L}{c''_L} + 6L(-R) \right) B$$

with probability at least $1 - \frac{\delta}{Kt(t+1)}$. Using the Cauchy-Schwarz inequality

$$(\boldsymbol{x}^\top \boldsymbol{w}'_{i,t} - \boldsymbol{u}_i^\top \boldsymbol{x})^2 \leq \boldsymbol{x}^\top A_{i,t-1}^{-1}\, \boldsymbol{x}\, d_{i,t-1}(\boldsymbol{u}_i, \boldsymbol{w}'_{i,t})$$

holding for any $\boldsymbol{x} \in \mathcal{R}^d$, and replacing back into (9) allows us to conclude that

$$(\boldsymbol{x}^\top \boldsymbol{w}'_{i,t} - \boldsymbol{u}_i^\top \boldsymbol{x})^2 \leq \boldsymbol{x}^\top A_{i,t-1}^{-1} \boldsymbol{x} \left(U^2 + \frac{1}{(c''_L)^2} \sum_{k=1}^{t-1} r_{i,k} + \frac{12}{c''_L} \left(\frac{c'_L}{c''_L} + 3L(-R) \right) \ln \frac{K(t+4)}{\delta} \right) \quad (10)$$

holds with probability at least $1 - \frac{\delta}{Kt(t+1)}$, *uniformly* over $\boldsymbol{x} \in \mathcal{R}^d$.

The bounds on $\sum_{k=1}^{t-1} r_{i,k}$ can be obtained in a standard way. Applying known inequalities (e.g., [2, 3, 5, 7]), and using the fact that $\nabla_{i,k} = L'(s_{i,k}\, \boldsymbol{x}_k^\top \boldsymbol{w}'_{i,k})\, s_{i,k} \boldsymbol{x}_k$ we have

$$\begin{aligned}
\sum_{k=1}^{t-1} r_{i,k} &= \sum_{k=1}^{t-1} |s_{i,j}|\, (L'(s_{i,k}\, \boldsymbol{x}_k^\top \boldsymbol{w}'_{i,k}))^2\, \boldsymbol{x}_k^\top A_{i,k}^{-1} \boldsymbol{x}_k \\
&\leq c'_L \sum_{k=1}^{t-1} |s_{i,k}| \boldsymbol{x}_k^\top A_{i,k}^{-1} \boldsymbol{x}_k \\
&\leq c'_L \sum_{k=1}^{t-1} \ln \frac{|A_{i,k}|}{|A_{i,k-1}|} \\
&= c'_L \ln \frac{|A_{i,t-1}|}{|A_{i,0}|} \\
&\leq d\, c'_L \ln \left(1 + \frac{t-1}{d} \right).
\end{aligned}$$

Piecing together as in (10) and stratifying over $t = 1, 2, \ldots$, and $i \in [K]$ concludes the proof. □

We are now ready to put all pieces together.

Proof: [Theorem 2] From Lemma 7 and Lemma 9, we see that with probability at least $1-\delta$,

$$R_T \leq 2\,(1-a)\,c_L \sum_{t=1}^{T} \sum_{i \in \hat{Y}_t} \epsilon_{i,t}, \tag{11}$$

when $\epsilon_{i,t}^2$ is the one given in Figure 1. We continue by proving a pointwise upper bound on the sum in the RHS. More in detail, we will find an upper bound on $\sum_{t=1}^{T} \sum_{i \in \hat{Y}_t} \epsilon_{i,t}^2$, and then derive a resulting upper bound on the RHS of (11).

From Lemma 9 and the update rule (Step 5) of the algorithm we can write

$$\begin{aligned}
\epsilon_{i,t}^2 &\leq C\, \boldsymbol{x}_t^\top A_{i,t-1}^{-1} \boldsymbol{x}_t \\
&= C\, \frac{\boldsymbol{x}_t^\top (A_{i,t-1} + |s_{i,t}|\, \boldsymbol{x}_t \boldsymbol{x}_t^\top)^{-1} \boldsymbol{x}_t}{1 - |s_{i,t}| \boldsymbol{x}_t^\top (A_{i,t-1} + |s_{i,t}|\, \boldsymbol{x}_t \boldsymbol{x}_t^\top)^{-1} \boldsymbol{x}_t} \\
&= C\, \frac{\boldsymbol{x}_t^\top A_{i,t}^{-1} \boldsymbol{x}_t}{1 - |s_{i,t}| \boldsymbol{x}_t^\top (A_{i,t-1} + |s_{i,t}|\, \boldsymbol{x}_t \boldsymbol{x}_t^\top)^{-1} \boldsymbol{x}_t} \\
&\leq C\, \frac{\boldsymbol{x}_t^\top A_{i,t}^{-1} \boldsymbol{x}_t}{1 - |s_{i,t}| \boldsymbol{x}_t^\top (A_0 + |s_{i,t}|\, \boldsymbol{x}_t \boldsymbol{x}_t^\top)^{-1} \boldsymbol{x}_t} \\
&= C\, \frac{\boldsymbol{x}_t^\top A_{i,t}^{-1} \boldsymbol{x}_t}{1 - \frac{1}{2}} \\
&= 2\, C\, \boldsymbol{x}_t^\top A_{i,t}^{-1} \boldsymbol{x}_t\,.
\end{aligned}$$

Hence, if we set $r_{i,t} = \boldsymbol{x}_t^\top A_{i,t}^{-1} \boldsymbol{x}_t$ and proceed as in the proof of Lemma 9, we end up with the upper bound $\sum_{t=1}^{T} \epsilon_{i,t}^2 \leq 2\, C\, d\, \ln\left(1 + \frac{T}{d}\right)$, holding for all $i \in [K]$. Denoting by M the quantity $2\, C\, d\, \ln\left(1 + \frac{T}{d}\right)$, we conclude from (11) that

$$R_T \leq 2\,(1-a)\,c_L\, \max\left\{ \sum_{i \in [K]} \sum_{t=1}^{T} \epsilon_{i,t} \,\Big|\, \sum_{t=1}^{T} \epsilon_{i,t}^2 \leq M,\;\; i \in [K] \right\} = 2\,(1-a)\,c_L\, K \sqrt{T\,M}\,,$$

as claimed. □

Proof: [Theorem 3] As we said, we change the definition of $\epsilon_{i,t}^2$ in the Algorithm in Figure 1 to

$$\epsilon_{i,t}^2 = \max\left\{ \boldsymbol{x}^\top A_{i,t-1}^{-1} \boldsymbol{x} \left(\frac{2\, d\, c'_L}{(c''_L)^2} \ln\left(1 + \frac{t-1}{d}\right) + \frac{12}{c''_L} \left(\frac{c'_L}{c''_L} + 3L(-R) \right) \ln \frac{K(t+4)}{\delta} \right), 4\,R^2 \right\}.$$

First, notice that the $4R^2$ cap seamlessly applies, since $(\boldsymbol{x}^\top \boldsymbol{w}'_{i,t} - \boldsymbol{u}_i^\top \boldsymbol{x})^2$ in Lemma 9 is bounded by $4\,R^2$ anyway. With this modification, we have that Theorem 2 only holds for t such that $\frac{d\, c'_L}{(c''_L)^2} \ln\left(1 + \frac{t-1}{d}\right) \geq U^2$, i.e., for $t \geq d \left(\exp\left(\frac{(c''_L)^2\, U^2}{c'_L\, d} \right) - 1 \right) + 1$, while for $t < d \left(\exp\left(\frac{(c''_L)^2\, U^2}{c'_L\, d} \right) - 1 \right) + 1$ we have in the worst-case scenario the maximum amount of regret at each step. From Lemma 7 we see that this maximum amount (the cap on $\epsilon_{i,t}^2$ is needed here) can be bounded by $4\,(1-a)\,c_L\,|\hat{Y}_t|\,R \leq 4\,(1-a)\,c_L\,K\,R$. □

Proof: [Theorem 4] We start from the one step-regret delivered by Lemma 8, and proceed as in the proof of Theorem 2. This yields

$$\begin{aligned} R_T &\leq 4\, c_L \sum_{t=1}^{T} S_t \sum_{i \in \hat{Y}_t} \epsilon_{i,t} \\ &\leq 4\, S\, c_L \sum_{t=1}^{T} \sum_{i \in \hat{Y}_t} \epsilon_{i,t} \\ &\leq 4\, S\, c_L \sum_{t=1}^{T} \sum_{i \in [K]} \epsilon_{i,t} \\ &= 4\, S\, c_L \sum_{i \in [K]} \sum_{t=1}^{T} \epsilon_{i,t}, \end{aligned}$$

with probability at least $1-\delta$, where $\epsilon_{i,t}^2$ is the one given in Figure 1. Let M be as in the proof of Theorem 2. If $N_{i,T}$ denotes the total number of times class i occurs in $\hat{Y}_t$, we have that $\sum_{t=1}^{T} \epsilon_{i,t}^2 \leq M$, implying $\sum_{t=1}^{T} \epsilon_{i,t} \leq \sqrt{N_{i,T}\, M}$ for all $i \in [K]$. Moreover, $\sum_{i \in [K]} N_{i,T} \leq ST$. Hence

$$R_T \leq 4\, S\, c_L \sum_{i \in K]} \sqrt{N_{i,T}\, M} \leq 4\, c_L \sqrt{M\, S\, K\, T}\,,$$

as claimed. □

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