
Lifelong Learning with Non-i.i.d. Tasks

Supplementary material

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Theorem 1. *Let P be any distribution over H , fixed before observing the sample S . Then for any $\delta > 0$ the following holds uniformly for all distributions Q over H with probability at least $1 - \delta$:*

$$\text{er}(Q) \leq \widehat{\text{er}}(Q) + \frac{1}{\sqrt{m}} \text{KL}(Q||P) + \frac{1 + 8 \log(1/\delta)}{8\sqrt{m}}. \quad (1)$$

Proof. Let $f(Q) = \text{er}(Q) - \widehat{\text{er}}(Q) = \mathbf{E}_{h \sim Q} (\mathbf{E}_{(x,y) \sim D} \ell(h(x), y) - \frac{1}{m} \sum_{i=1}^m \ell(h(x_i), y_i))$. From Donsker-Varadhan's variational formula one obtains that for any $\lambda > 0$:

$$f(Q) \leq \frac{1}{\lambda} \left(\text{KL}(Q||P) + \log \mathbf{E}_{h \sim P} \exp \lambda \left(\mathbf{E}_{(x,y) \sim D} \ell(h(x), y) - \frac{1}{m} \sum_{i=1}^m \ell(h(x_i), y_i) \right) \right). \quad (2)$$

Since loss function is bounded by 1, from Hoeffding's lemma we know that:

$$\mathbf{E}_{(x_i, y_i) \sim D} \exp \left(\frac{\lambda}{m} (\mathbf{E}_{(x,y) \sim D} \ell(h(x), y) - \ell(h(x_i), y_i)) \right) \leq \exp \left(\frac{\lambda^2}{8m^2} \right). \quad (3)$$

Because the sample points are i.i.d., we can obtain that:

$$\mathbf{E}_{S \sim D^m} \exp \lambda \left(\mathbf{E}_{(x,y) \sim D} \ell(h(x), y) - \frac{1}{m} \sum_{i=1}^m \ell(h(x_i), y_i) \right) \leq \exp \left(\frac{\lambda^2}{8m} \right). \quad (4)$$

By combining the fact, that P doesn't depend on S , and Markov's inequality, we obtain that with probability at least $1 - \delta$:

$$\mathbf{E}_{h \sim P} \exp \lambda \left(\mathbf{E}_{(x,y) \sim D} \ell(h(x), y) - \frac{1}{m} \sum_{i=1}^m \ell(h(x_i), y_i) \right) \leq \frac{1}{\delta} \exp \left(\frac{\lambda^2}{8m} \right). \quad (5)$$

By plugging it into (2) and setting $\lambda = \sqrt{m}$ we obtain the statement of the theorem. \square

Lemma 2. *Let $X_1, \dots, X_n \in \Omega$ be a sequence of random variables and $g : \Omega \rightarrow [0, 1]$ be a function such that $\mathbf{E}[g(X_i)|X_1, \dots, X_{i-1}] = b_i$. Let Z_1, \dots, Z_n be independent Bernoulli random variables such that $\mathbf{E}[Z_i] = b_i$. Then for any convex function f :*

$$\mathbf{E}[f(g(X_1), \dots, g(X_n))] \leq \mathbf{E}[f(Z_1, \dots, Z_n)]. \quad (6)$$

Proof. Any point $x = (x_1, \dots, x_n) \in [0, 1]^n$ can be written as a linear combination of the extreme points $\nu = (\nu_1, \dots, \nu_n) \in \{0, 1\}^n$ in the following way:

$$x = \sum_{\nu \in \{0,1\}^n} \left(\prod_{i=1}^n ((1 - x_i)(1 - \nu_i) + x_i \nu_i) \right) \nu. \quad (7)$$

Therefore by convexity of f we have that:

$$f(x) \leq \sum_{\nu \in \{0,1\}^n} \left(\prod_{i=1}^n ((1-x_i)(1-\nu_i) + x_i\nu_i) \right) f(\nu). \quad (8)$$

By taking expectations on both sides we obtain that:

$$\begin{aligned} & \mathbf{E}_{X_1^n} f(g(X_1), \dots, g(X_n)) \leq \\ & \mathbf{E}_{X_1^n} \left[\sum_{\nu \in \{0,1\}^n} \left(\prod_{i=1}^n ((1-g(X_i))(1-\nu_i) + g(X_i)\nu_i) \right) f(\nu) \right] = \\ & \sum_{\nu \in \{0,1\}^n} \mathbf{E}_{X_1^n} \left[\prod_{i=1}^n ((1-g(X_i))(1-\nu_i) + g(X_i)\nu_i) \right] f(\nu) = \\ & \sum_{\nu \in \{0,1\}^n} \mathbf{E}_{X_1^{n-1}} \left[\mathbf{E}_{X_n} \left[\prod_{i=1}^n ((1-g(X_i))(1-\nu_i) + g(X_i)\nu_i) | X_1^{n-1} \right] \right] f(\nu) = \\ & \sum_{\nu \in \{0,1\}^n} \mathbf{E}_{X_1^{n-1}} \left[\left(\prod_{i=1}^{n-1} ((1-g(X_i))(1-\nu_i) + g(X_i)\nu_i) \right) \mathbf{E}_{X_n} [(1-g(X_n))(1-\nu_i) + g(X_n)\nu_i | X_1^{n-1}] \right] f(\nu) = \\ & \sum_{\nu \in \{0,1\}^n} \mathbf{E}_{X_1^{n-1}} \left[\left(\prod_{i=1}^{n-1} ((1-g(X_i))(1-\nu_i) + g(X_i)\nu_i) \right) ((1-b_n)(1-\nu_i) + b_n\nu_i) \right] f(\nu) = \dots \\ & \sum_{\nu \in \{0,1\}^n} \left(\prod_{i=1}^n ((1-b_i)(1-\nu_i) + b_i\nu_i) \right) f(\nu) = \mathbf{E}_{Z_1^n} [f(Z_1^n)]. \end{aligned}$$

□

Theorem 5. For any fixed hyper-prior distribution \mathcal{P} with probability at least $1 - \delta$ the following holds uniformly for all hyper-posterior distributions \mathcal{Q} :

$$\tilde{\text{er}}(\mathcal{Q}) \leq \hat{\text{er}}(\mathcal{Q}) + \frac{1}{(n-1)\sqrt{m}} \text{KL}(\mathcal{Q} \times Q_2 \times \dots \times Q_n || \mathcal{P} \times P_2 \times \dots \times P_n) + \frac{(n-1) + 8 \log(1/\delta)}{8(n-1)\sqrt{m}}, \quad (9)$$

where P_2, \dots, P_n are some reference prior distributions that should not depend on the training sets corresponding to subsequent tasks. In particular, it can be just one prior distribution P fixed before observing any data, or posterior distribution corresponding to the previous task, ie $P_i = Q_{i-1}$.

Proof. By applying KL-inequality we obtain:

$$\begin{aligned} \tilde{\text{er}}(\mathcal{Q}) - \hat{\text{er}}(\mathcal{Q}) & \leq \frac{1}{\lambda} \left(\text{KL}(\mathcal{Q} \times Q_2 \times \dots \times Q_n || \mathcal{P} \times P_2 \times \dots \times P_n) + \right. \\ & \left. \log \mathbf{E}_{A \sim \mathcal{P}} \mathbf{E}_{h_2 \sim P_2} \dots \mathbf{E}_{h_n \sim P_n} \exp \left(\frac{\lambda}{n-1} \sum_{i=2}^n \left(\mathbf{E}_{(x,y) \sim D_i} \ell(h_i(x), y) - \frac{1}{m} \sum_{j=1}^m \ell(h(x_j^i), y_j^i) \right) \right) \right). \end{aligned}$$

Due to independence of any prior P_i and consequent sample sets S_i, \dots, S_n , we obtain that:

$$\begin{aligned} & \mathbf{E}_{S_1, \dots, S_n} \mathbf{E}_{A \sim \mathcal{P}} \mathbf{E}_{h_2 \sim P_2} \dots \mathbf{E}_{h_n \sim P_n} f_2(h_2, S_1) \dots f_n(h_n, S_n) = \\ & \mathbf{E}_{A \sim \mathcal{P}} \mathbf{E}_{S_1} \mathbf{E}_{h_2 \sim P_2} \mathbf{E}_{S_2} f_2(h_2, S_2) \dots \mathbf{E}_{h_n \sim P_n} \mathbf{E}_{S_n} f_n(h_n, S_n), \end{aligned}$$

where

$$f_i(h_i, S_i) = \frac{\lambda}{n-1} \left(\mathbf{E}_{(x,y) \sim D_i} \ell(h_i(x), y) - \frac{1}{m} \sum_{j=1}^m \ell(h_i(x_j^i), y_j^i) \right). \quad (10)$$

Due to Hoeffding's lemma, boundness of the loss and the fact that training samples are i.i.d., the following holds:

$$\mathbf{E}_{S_n} f_n(h_n, S_n) \leq \exp \left(\frac{\lambda^2}{8(n-1)^2 m} \right). \quad (11)$$

Therefore:

$$\mathbf{E}_{S_1, \dots, S_n} \mathbf{E}_{A \sim \mathcal{P}} \mathbf{E}_{h_2 \sim P_2} \dots \mathbf{E}_{h_n \sim P_n} f_2(h_2, S_1) \dots f_n(h_n, S_n) \leq \exp\left(\frac{\lambda^2}{8(n-1)m}\right). \quad (12)$$

By using Markov's inequality and setting $\lambda = (n-1)\sqrt{m}$ we obtain the statement of the theorem. \square

The KL-term in the above theorem can be simplified:

$$\text{KL}(\mathcal{Q} \times Q_2 \times \dots \times Q_n || \mathcal{P} \times P_2 \times \dots \times P_n) = \text{KL}(\mathcal{Q} || \mathcal{P}) + \sum_{i=2}^n \mathbf{E}_{A \sim \mathcal{Q}} \text{KL}(Q_i || P_i).$$