Learning low-degree functions on the discrete hypercube

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Functional Analysis Seminar
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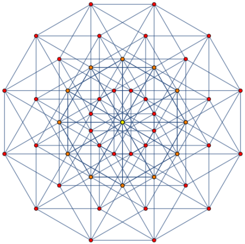

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Every function $f : \{-1,1\}^n \to \mathbb{R}$ admits a unique expansion

$$\forall\, x \in \{-1,1\}^n, \qquad f(x) = \sum_{S \subseteq \{1,\ldots,n\}} \hat{f}(S) w_S(x)$$

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where x is uniformly distributed on $\{-1,1\}^n$.

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$$\forall\, S \subseteq \{1,\dots,n\}, \qquad \hat{f}(S) = \mathbb{E}\big[f(x) w_S(x)\big],$$

where x is uniformly distributed on $\{-1,1\}^n$. We say that f has *degree* at most d if $\hat{f}(S) = 0$ when $|S| > d$.

Learning

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Let $\mathscr{F}$ be a class of functions on $\{-1,1\}^n$ and fix an unknown function $f \in \mathscr{F}$. Given access to data of the form

$$(X_1, f(X_1)), \ldots, (X_Q, f(X_Q))$$

where $X_1, \ldots, X_Q \in \{-1,1\}^n$, we want to algorithmically construct a hypothesis function $h : \{-1,1\}^n \to \mathbb{R}$ which well-approximates f.

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Query model. The algorithm can sequentially request any selection of samples $X_1, X_2, \ldots$.

Random example model. The samples $X_1, X_2, \ldots$ are i.i.d. random variables, uniformly distributed on the hypercube. In this model, the output function h is random and we want it to be a good approximation of f with high probability.

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Some structure is needed! If $\mathscr{F} = \{f : \{-1, 1\}^n \to \{0, 1\}\}$, one needs at least $(1 - \varepsilon)2^n$ values of an unknown $f \in \mathscr{F}$ in order to make an accurate hypothesis for f up to error ε.

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Structure = Low Complexity

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One of the first concept classes $\mathscr{F}$ that was rigorously studied was

$$\mathscr{F}_{n,d} = \left\{ f : \{-1,1\}^n \to [-1,1] : \ \mathrm{deg}(f) \leq d \right\}.$$

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To see that this many samples are also needed, observe that with fewer data points, the system would be undertermined. □

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Low-Degree Algorithm (Linial, Mansour, Nisan, 1989) We have

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Proof. Let $X_1, \ldots, X_Q$ i.i.d. random samples. For a subset S, let

$$\alpha_S = \frac{1}{Q} \sum_{j=1}^{Q} f(X_j) w_S(X_j),$$

which is a sum of bounded indep. variables with $\mathbb{E}[\alpha_S] = \hat{f}(S)$.

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Therefore, by the Chernoff bound, for $b > 0$ we have

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for

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How large can we take b?

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$$\forall\, x \in \{-1,1\}^n \qquad h_b(x) = \sum_{|S|\le d} \alpha_S w_S(x).$$

Then, if the high probability event holds

$$\|f - h_b\|_2^2 = \sum_{|S|\le d} \left(\alpha_S - \hat{f}(S)\right)^2 \le \sum_{j=0}^{d} \binom{n}{j} b^2 \le \varepsilon$$

for $b^2 \le \varepsilon / \sum_{j=0}^{d} \binom{n}{j}$ which completes the proof. □

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$$\sum_{|S| \leq d} \hat{f}(S)^2 \leq 1$$

so unless $b^2 \lesssim n^{-d}$ there is not much to gain by incorporating *all* the empirical coefficients α_S in the hypothesis function h_b. We should just make sure to include the few influential ones, say those larger than a. By Markov's inequality there are

$$\#\{S : \ |\hat{f}(S)| > a\} \leq \frac{1}{a^2} \sum_{S\colon \ |\hat{f}(S)| > a} \hat{f}(S)^2 \leq \frac{1}{a^2}.$$

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Then, we are left to estimate a term of the form

$$\sum_{S\colon \ |\hat{f}(S)| \leq a} \hat{f}(S)^2 \overset{??}{\ll} \varepsilon(a).$$

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Trivially, for $a_1, a_2, \ldots \in \mathbb{R}$,

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Littlewood's $\frac{4}{3}$-inequality. For $a_{ij} \in \mathbb{R}$, where $i, j \geq 1$

$$\Big(\sum_{i,j\geq 1} |a_{ij}|^{\frac{4}{3}} \Big)^{\frac{3}{4}} \leq \sqrt{2} \sup \Big\{ \Big| \sum_{i,j\geq 1} a_{ij} x_i y_j \Big| : \ \|x\|_\infty, \|y\|_\infty \leq 1 \Big\}.$$

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Bohnenblust–Hille inequality. For a degree-d polynomial $p(x) = \sum_{|\alpha|\leq d} c_\alpha x^\alpha$ on infinitely many variables,

$$\Big(\sum_{|\alpha|\leq d} |c_\alpha|^{\frac{2d}{d+1}}\Big)^{\frac{d+1}{2d}} \leq C_d \sup\big\{|p(x)| : \ \|x\|_\infty \leq 1\big\}.$$

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If p is a multilinear polynomial representing $f : \{-1,1\}^n \to \mathbb{R}$, the maximum on the RHS is attained at a vertex of $\{-1,1\}^n$. Thus, we can get an estimate on the hypercube

$$\Big(\sum_{|S| \leq d} |\hat{f}(S)|^{\frac{2d}{d+1}} \Big)^{\frac{d+1}{2d}} \leq B_d \|f\|_\infty$$

for functions of degree at most d.

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The idea of introducing a cutoff for the spectrum first appeared in an algorithm of Kushilevitz and Mansour (1993). Fix $b > 0$ and set

$$Q = \left\lceil \frac{2}{b^2} \log \left(\frac{2}{\delta} \sum_{j=0}^{d} \binom{n}{j} \right) \right\rceil$$

so that

$$\mathbb{P}\left\{ |\alpha_S - \hat{f}(S)| \leq b, \ \forall \ S \right\} \geq 1 - 2 \sum_{j=0}^{d} \binom{n}{j} \exp(-Qb^2/2) \geq 1 - \delta.$$

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Consider the random collection of sets

$$\Sigma_b = \left\{ S : \ |\alpha_S| > 2b \right\}.$$

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Then, on the high probability event, we have

$$\forall\ S \in \Sigma_b, \qquad |\hat{f}(S)| > b$$

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$$\|f - h_b\|_2^2 = \sum_{S \in \Sigma_b} \left(\alpha_S - \hat{f}(S)\right)^2 + \sum_{S \notin \Sigma_b} \hat{f}(S)^2 = (1) + (2).$$

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To bound (1), observe that

$$|\Sigma_b| \leq b^{-\frac{2d}{d+1}} \sum_{S \in \Sigma_b} \hat{f}(S)^{\frac{2d}{d+1}} \leq B_d^{\frac{2d}{d+1}} b^{-\frac{2d}{d+1}}$$

so that $(1) \leq B_d^{\frac{2d}{d+1}} b^{\frac{2}{d+1}}$.

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To bound (2), write

$$(2) = \sum_{S \notin \Sigma_b} \hat{f}(S)^2 \leq (3b)^{\frac{2}{d+1}} \sum_{S \notin \Sigma_b} |\hat{f}(S)|^{\frac{2d}{d+1}} \leq 3B_d^{\frac{2d}{d+1}} b^{\frac{2}{d+1}}.$$

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Putting everything together

$$\|f - h_b\|_2^2 \leq 4B_d^{\frac{2d}{d+1}} b^{\frac{2}{d+1}} \leq \varepsilon$$

for $b^2 \leq (\varepsilon/4)^{d+1} B_d^{-\frac{2d}{d+1}}$. □

Remarks

E.–Ivanisvili (2021). $Q_r(\mathscr{F}_{n,d}, \varepsilon, \delta) = O_{d,\varepsilon,\delta}(\log n)$.

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In fact, for n large enough,

$$c(1-\sqrt{\varepsilon})2^d \log\left(\frac{n}{\delta}\right) \le Q_r(\mathscr{F}_{n,d}, \varepsilon, \delta) \le \frac{B_d^{2d}}{\varepsilon^{d+1}} \log\left(\frac{n}{\delta}\right).$$

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• The best known bound for B_d is $B_d \le \exp(C\sqrt{d \log d})$. A (conjectured) polynomial bound on B_d would give almost optimal dependence on d also.

• The dependence on ε can be improved to ε^{-1} if the unknown function is a priori known to be Boolean.

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What about the class of bounded *approximate* polynomials,

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E.–Ivanisvili–Streck (2022). There exists $\eta = \eta(t,d) > 0$ s.t.

$$Q_r(\mathscr{F}_{n,d}(t), \eta + \varepsilon, \delta) \lesssim_{t,d,\varepsilon} \log\left(\frac{n}{\delta}\right).$$

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Warning! This is useful only when $\eta(t,d)$ is small.

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for $\varepsilon > 0$ arbitrarily small constant.

Beyond polynomials?

More concretely, consider $\mathscr{B}_{n,d}(t)$ the subclass of $\mathscr{F}_{n,d}(t)$ consisting of Boolean functions.

E.–Ivanisvili–Streck (2022). We have

$$t = o\Big(\frac{1}{\sqrt{d}}\Big) \quad \Longrightarrow \quad Q_r(\mathscr{B}_{n,d}(t), \varepsilon, \delta) \lesssim_{t,d,\varepsilon} \log\Big(\frac{n}{\delta}\Big)$$

for $\varepsilon > 0$ arbitrarily small constant.

Conversely, we can also prove that

$$t = \Omega\Big(\frac{1}{\sqrt{d}}\Big) \quad \Longrightarrow \quad Q_r\big(\mathscr{B}_{n,d}(t), \tfrac{1}{3}, \tfrac{1}{3}\big) \gtrsim_{t,d} n.$$

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As this estimate is in general optimal, the existing algorithm does not allow us to efficiently learn LTFs.

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$$(x_1 \wedge x_2) \vee (\neg x_2 \wedge \neg x_3) \vee (\neg x_1 \wedge x_3).$$

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and plugging this choice of d, one obtains new learning results for the class of DNF formulas.

Thank you!