On the approximation power of two-layer networks of random ReLUs

Daniel Hsu

Joint work with Clayton Sanford, Rocco Servedio, Manolis Vlatakis

Columbia University

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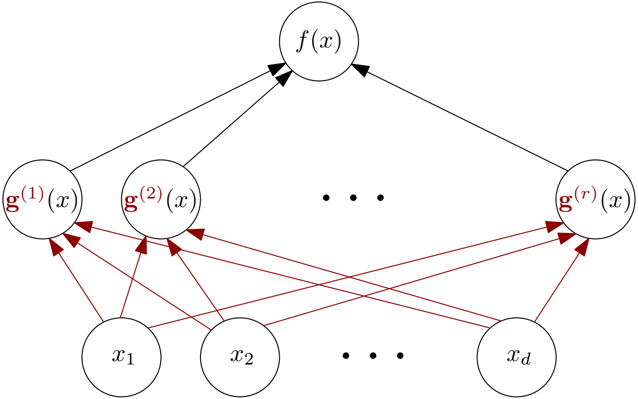
Two-layer networks of random ReLUs ("random ReLU networks")



$$f \in \operatorname{span}\Big\{\underbrace{x \mapsto \max\{0, \mathbf{w}^{(i)} \cdot x - \mathbf{b}^{(i)}\}}_{\mathbf{g}^{(i)}} : i \in [r]\Big\}, \qquad \big((\mathbf{w}^{(i)}, \mathbf{b}^{(i)})\big)_{i=1}^{r} \sim \mathcal{D}$$

Approximating Lipschitz functions by two-layer networks of random ReLUs

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Question:

What is the minimum width r s.t. $\mathcal{F}_r$ can ε-approximate any L-Lipschitz functions in $\mathcal{L}^2([-1,1]^d)$ (with high probability)?

$$\Pr\Big[\inf_{\hat{f} \in \mathcal{F}_r} \|\hat{f} - f^\star\|_{\mathcal{L}^2([-1,1]^d)} \; \leq \; \varepsilon \Big] \geq 0.9 \quad \text{for all } L\text{-Lipschitz } f^* \colon [-1,1]^d \to \mathbb{R}$$

$$\|f\|_{\mathcal{L}^2([-1,1]^d)} = \sqrt{\mathop{\mathbb{E}}_{\mathbf{x} \sim \mathrm{Unif}([-1,1]^d)} [f(\mathbf{x})^2]}$$

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Our work: upper- and lower-bounds on this minimum width, for all d, ε, and L

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1. Approximation capability of neural networks at (or near) random initialization

   [Andoni, Panigrahy, Valiant, & Zhang, '14; Bach, '17; Ji, Telgarsky, & Xian, '19; Yehudai & Shamir, '19; . . .]

   and kernel methods

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2. Interplay between dimension d and relative error ε/L

Our results (informally)

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$$\begin{aligned} &\leq \operatorname{poly}(d) && \text{if } L/\varepsilon = O(1) \\ &\leq \operatorname{poly}(L/\varepsilon) && \text{if } d = O(1) \\ &\geq \exp(\Omega(d)) && \text{if } L/\varepsilon = \Omega(\sqrt{d}) \end{aligned}$$

Some prior work

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	Width	Comments
Maiorov, '99	$\geq \exp(\Omega(d))$	$L/\varepsilon \to \infty$
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Maiorov's bound (for $H^1([-1,1]^d)$) applies to networks with arbitrary bottom-level weights, but only holds asymptotically as $L/\varepsilon \to \infty$

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Hard function of YS and KMS has $\mathrm{poly}(d)$ Lipschitz constant

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$\mathcal{L}^\infty$ approximation is stronger than $\mathcal{L}^2$ approximation

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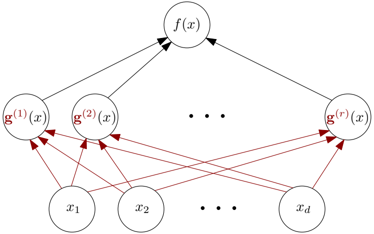
Upshot: Prior work doesn't reveal the correct minimum width for arbitrary d and L/ε

Outline for rest of talk

1. Upper- and lower-bounds on the minimum width
2. Proof sketches
3. Some consequences

Part 1. Upper- and lower-bounds on the minimum width



Our main results

$$\mathrm{MinWidth}_{\varepsilon,d,\mathcal{D}}(f^\star) \;:=\; \min\left\{r \in \mathbb{N} \;:\; \Pr\left[\inf_{\hat{f}\in\mathcal{F}_r} \|\hat{f} - f^\star\|_{\mathcal{L}^2([-1,1]^d)} \;\le\; \varepsilon\right] \ge 0.9\right\}$$

smallest width r s.t. $\mathcal{F}_r$ (with bottom-level weights $\sim \mathcal{D}$) ε-approximates $f^\star$ with probability $\geq 90\%$

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Lower-bound, in fact, applies to any target-independent $\mathcal{F}_r$ (not just span of random ReLUs)

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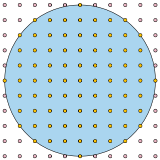

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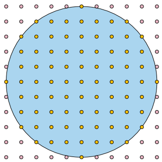

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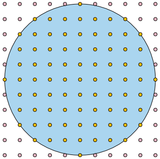

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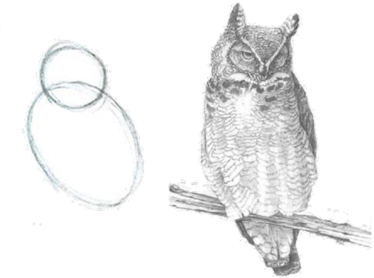
Theorems 1 & 2 $\implies \sup_{L\text{-Lipschitz } f^\star} \mathrm{MinWidth}_{\varepsilon,d,\mathcal{D}}(f^\star) = \begin{cases} \mathrm{poly}(d) & \text{if } L/\varepsilon = \Theta(1) \\ \mathrm{poly}(L/\varepsilon) & \text{if } d = \Theta(1) \\ \exp(\Theta(d)) & \text{if } L/\varepsilon = \Theta(\sqrt{d}) \end{cases}$

Part 2. Proof sketches



Proof of upper-bound (sketch)

Theorem 1 (upper bound). For any L, ε, d, there exists a parameter distribution $\mathcal{D}$ such that

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$$\sqrt{2}\sin(\pi\alpha \cdot x/2) \quad \text{and} \quad \sqrt{2}\cos(\pi\alpha \cdot x/2)$$

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   Basis of "sinusoidal ridge functions" are especially convenient for this step

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Theorem 2 (lower bound). For any L, ε, d, and parameter distribution $\mathcal{D}$,

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If $\mathcal{D}_{\mathrm{weights}}$ is invariant to coordinate permutations, then the hard-to-approximate function is *explicit*:

$$x \;\mapsto\; \varepsilon \sin(\;\pi(x_1 + x_2 + \cdots\;)\;)$$

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Lemma. Let H be a Hilbert space, and fix orthonormal $\varphi_1, \ldots, \varphi_N \in H$. Let $\mathbf{W}$ be (possibly random) finite-dimensional subspace of H with $r := \mathbb{E}[\dim(\mathbf{W})] < \infty$. Then there is some $i \in [N]$ such that

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Part 3. Some consequences

Depth separation

- Recent line-of-inquiry on separations between poly-size "shallow" nets and poly-size "deep" nets
  [Telgarsky, '16; Eldan & Shamir, '16; Daniely, '17; Safran & Shamir, '17; Safran, Eldan, & Shamir, '19; . . .]

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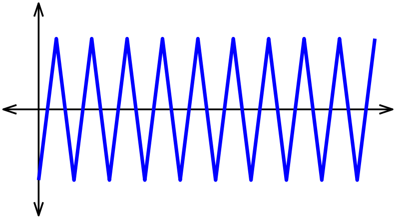
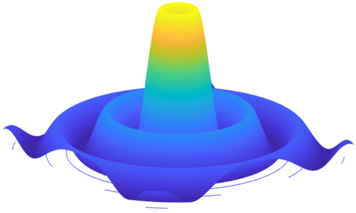


Telgarsky's iterated tent map



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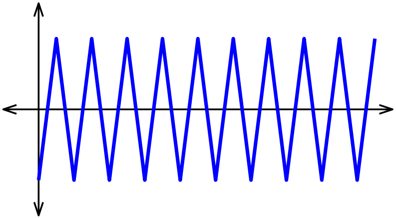

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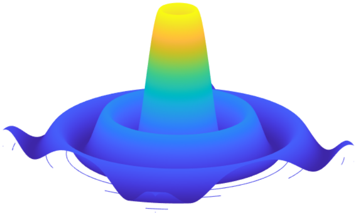

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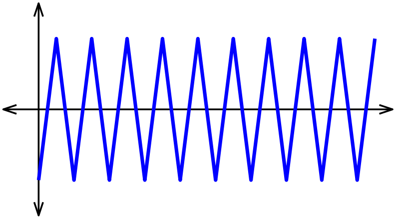

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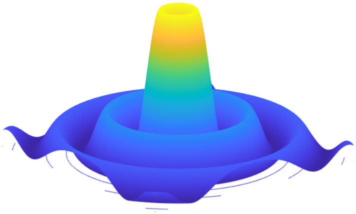

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  Our results $\Rightarrow$ No, for constant $\mathcal{L}^2$ approximation error

Lower-bounds for kernel methods

- Lower-bound applies to all methods that pick $\hat{f}$ from a target-independent subspace of dimension r — including **kernel methods** based on $r = n$ examples $(x^{(1)}, y^{(1)}), \ldots, (x^{(n)}, y^{(n)})$:

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Example: Lower-bound for learning parity functions under uniform distribution on $\{-1, 1\}^d$ with non-adaptive membership queries (MQs) [Bubeck (after Allen-Zhu & Li), '20]

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- Easy consequence of the key lemma!

Recap and closing

1. Width needed to approximate L-Lipschitz functions up to $\mathcal{L}^2([-1,1]^d)$ error ε:

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Thank you!

We gratefully acknowledge support from the NSF (CCF-{1563155, 1703925, 1740833, 1763970, 1814873} and IIS-{1563785, 1838154}), a Google Faculty Research Award, an Onassis Foundation Scholarship, a Sloan Research Fellowship, and the Simons Collaboration on Algorithms and Geometry.