

Impact Statement

This paper presents work whose goal is to advance the field of Machine Learning. There are many potential societal consequences of our work, none which we feel must be specifically highlighted here.

Acknowledgements

We are grateful to Yasaman Bahri, Stefano Mannelli, Francesca Mignacco, Jascha Sohl-Dickstein, and Nikhil Vyas for useful conversations. We thank Clarissa Lauditi and Jacob Zavatore-Veth for comments on the manuscript.

B.B. is supported by a Google PhD Fellowship. A.A. is supported by a Fannie and John Hertz Fellowship. C.P. is supported by NSF grant DMS-2134157, NSF CAREER Award IIS-2239780, and a Sloan Research Fellowship. This work has been made possible in part by a gift from the Chan Zuckerberg Initiative Foundation to establish the Kempner Institute for the Study of Natural and Artificial Intelligence.

References

- Adlam, B. and Pennington, J. The neural tangent kernel in high dimensions: Triple descent and a multi-scale theory of generalization. In *International Conference on Machine Learning*, pp. 74–84. PMLR, 2020a.
- Adlam, B. and Pennington, J. Understanding double descent requires a fine-grained bias-variance decomposition. *Advances in neural information processing systems*, 33: 11022–11032, 2020b.
- Advani, M. S., Saxe, A. M., and Sompolinsky, H. High-dimensional dynamics of generalization error in neural networks. *Neural Networks*, 132:428–446, 2020.
- Alabdulmohsin, I., Zhai, X., Kolesnikov, A., and Beyer, L. Getting vit in shape: Scaling laws for compute-optimal model design. *arXiv preprint arXiv:2305.13035*, 2023.
- Arora, S. and Goyal, A. A theory for emergence of complex skills in language models. *arXiv preprint arXiv:2307.15936*, 2023.
- Atanasov, A., Bordelon, B., and Pehlevan, C. Neural networks as kernel learners: The silent alignment effect. In *International Conference on Learning Representations*, 2022. URL <https://openreview.net/forum?id=1NvflqAdoom>.
- Atanasov, A., Bordelon, B., Sainathan, S., and Pehlevan, C. The onset of variance-limited behavior for networks in the lazy and rich regimes. In *The Eleventh International Conference on Learning Representations*, 2023. URL <https://openreview.net/forum?id=JLINxPOVTh7>.
- Bachmann, G., Anagnostidis, S., and Hofmann, T. Scaling mpls: A tale of inductive bias. *Advances in Neural Information Processing Systems*, 36, 2024.
- Bahri, Y., Dyer, E., Kaplan, J., Lee, J., and Sharma, U. Explaining neural scaling laws. *arXiv preprint arXiv:2102.06701*, 2021.
- Bodin, A. and Macris, N. Model, sample, and epoch-wise descents: exact solution of gradient flow in the random feature model. *Advances in Neural Information Processing Systems*, 34:21605–21617, 2021.
- Bordelon, B. and Pehlevan, C. Learning curves for SGD on structured features. In *International Conference on Learning Representations*, 2022a. URL <https://openreview.net/forum?id=WPI2vbkAl3Q>.
- Bordelon, B. and Pehlevan, C. Self-consistent dynamical field theory of kernel evolution in wide neural networks. *arXiv preprint arXiv:2205.09653*, 2022b.
- Bordelon, B. and Pehlevan, C. Dynamics of finite width kernel and prediction fluctuations in mean field neural networks. *arXiv preprint arXiv:2304.03408*, 2023.
- Bordelon, B., Canatar, A., and Pehlevan, C. Spectrum dependent learning curves in kernel regression and wide neural networks. In *International Conference on Machine Learning*, pp. 1024–1034. PMLR, 2020.
- Bordelon, B., Noci, L., Li, M. B., Hanin, B., and Pehlevan, C. Depthwise hyperparameter transfer in residual networks: Dynamics and scaling limit, 2023.
- Caballero, E., Gupta, K., Rish, I., and Krueger, D. Broken neural scaling laws. *arXiv preprint arXiv:2210.14891*, 2022.
- Canatar, A., Bordelon, B., and Pehlevan, C. Spectral bias and task-model alignment explain generalization in kernel regression and infinitely wide neural networks. *Nature communications*, 12(1):2914, 2021.
- Caponnetto, A. and Vito, E. D. Fast rates for regularized least-squares algorithm. 2005.
- Cheng, C. and Montanari, A. Dimension free ridge regression. *arXiv preprint arXiv:2210.08571*, 2022.
- Chizat, L., Oyallon, E., and Bach, F. On lazy training in differentiable programming. *Advances in neural information processing systems*, 32, 2019.
- Cortes, C., Mohri, M., and Rostamizadeh, A. Algorithms for learning kernels based on centered alignment. *The Journal of Machine Learning Research*, 13(1):795–828, 2012.

- Crisanti, A. and Sompolinsky, H. Path integral approach to random neural networks. *Physical Review E*, 98(6): 062120, 2018.
- Cui, H., Loureiro, B., Krzakala, F., and Zdeborová, L. Generalization error rates in kernel regression: The crossover from the noiseless to noisy regime. *Advances in Neural Information Processing Systems*, 34:10131–10143, 2021.
- Dyer, E. and Gur-Ari, G. Asymptotics of wide networks from feynman diagrams. In *International Conference on Learning Representations*, 2020.
- d’Ascoli, S., Refinetti, M., Biroli, G., and Krzakala, F. Double trouble in double descent: Bias and variance (s) in the lazy regime. In *International Conference on Machine Learning*, pp. 2280–2290. PMLR, 2020.
- Fort, S., Dziugaite, G. K., Paul, M., Kharaghani, S., Roy, D. M., and Ganguli, S. Deep learning versus kernel learning: an empirical study of loss landscape geometry and the time evolution of the neural tangent kernel. In Larochelle, H., Ranzato, M., Hadsell, R., Balcan, M., and Lin, H. (eds.), *Advances in Neural Information Processing Systems 33: Annual Conference on Neural Information Processing Systems 2020, NeurIPS 2020, December 6-12, 2020, virtual*, 2020.
- Geiger, M., Jacot, A., Spigler, S., Gabriel, F., Sagun, L., d’Ascoli, S., Biroli, G., Hongler, C., and Wyart, M. Scaling description of generalization with number of parameters in deep learning. *Journal of Statistical Mechanics: Theory and Experiment*, 2020(2):023401, 2020.
- Gerbelot, C., Troiani, E., Mignacco, F., Krzakala, F., and Zdeborova, L. Rigorous dynamical mean field theory for stochastic gradient descent methods. *arXiv preprint arXiv:2210.06591*, 2022.
- Ghosh, N., Mei, S., and Yu, B. The three stages of learning dynamics in high-dimensional kernel methods. In *International Conference on Learning Representations*, 2022. URL <https://openreview.net/forum?id=EQmAP4F859>.
- Hastie, T., Montanari, A., Rosset, S., and Tibshirani, R. J. Surprises in high-dimensional ridgeless least squares interpolation. *Annals of statistics*, 50(2):949, 2022.
- Helias, M. and Dahmen, D. *Statistical field theory for neural networks*, volume 970. Springer, 2020.
- Hestness, J., Narang, S., Ardalani, N., Diamos, G., Jun, H., Kianinejad, H., Patwary, M. M. A., Yang, Y., and Zhou, Y. Deep learning scaling is predictable, empirically. *arXiv preprint arXiv:1712.00409*, 2017.
- Hoffmann, J., Borgeaud, S., Mensch, A., Buchatskaya, E., Cai, T., Rutherford, E., Casas, D. d. L., Hendricks, L. A., Welbl, J., Clark, A., et al. Training compute-optimal large language models. *arXiv preprint arXiv:2203.15556*, 2022.
- Jacot, A., Gabriel, F., and Hongler, C. Neural tangent kernel: Convergence and generalization in neural networks. *Advances in neural information processing systems*, 31, 2018.
- Kaplan, J., McCandlish, S., Henighan, T., Brown, T. B., Chess, B., Child, R., Gray, S., Radford, A., Wu, J., and Amodei, D. Scaling laws for neural language models. *arXiv preprint arXiv:2001.08361*, 2020.
- Long, P. M. Properties of the after kernel. *arXiv preprint arXiv:2105.10585*, 2021.
- Loureiro, B., Gerbelot, C., Cui, H., Goldt, S., Krzakala, F., Mezard, M., and Zdeborová, L. Learning curves of generic features maps for realistic datasets with a teacher-student model. *Advances in Neural Information Processing Systems*, 34:18137–18151, 2021.
- Loureiro, B., Gerbelot, C., Refinetti, M., Sicuro, G., and Krzakala, F. Fluctuations, bias, variance & ensemble of learners: Exact asymptotics for convex losses in high-dimension. In *International Conference on Machine Learning*, pp. 14283–14314. PMLR, 2022.
- Maloney, A., Roberts, D. A., and Sully, J. A solvable model of neural scaling laws. *arXiv preprint arXiv:2210.16859*, 2022.
- Mannelli, S. S., Krzakala, F., Urbani, P., and Zdeborova, L. Passed & spurious: Descent algorithms and local minima in spiked matrix-tensor models. In *international conference on machine learning*, pp. 4333–4342. PMLR, 2019.
- Martin, P. C., Siggia, E., and Rose, H. Statistical dynamics of classical systems. *Physical Review A*, 8(1):423, 1973.
- Mei, S. and Montanari, A. The generalization error of random features regression: Precise asymptotics and the double descent curve. *Communications on Pure and Applied Mathematics*, 75(4):667–766, 2022.
- Michaud, E. J., Liu, Z., Girit, U., and Tegmark, M. The quantization model of neural scaling. *arXiv preprint arXiv:2303.13506*, 2023.
- Mignacco, F. and Urbani, P. The effective noise of stochastic gradient descent. *Journal of Statistical Mechanics: Theory and Experiment*, 2022(8):083405, 2022.

- Mignacco, F., Krzakala, F., Urbani, P., and Zdeborová, L. Dynamical mean-field theory for stochastic gradient descent in gaussian mixture classification. *Advances in Neural Information Processing Systems*, 33:9540–9550, 2020.
- Muennighoff, N., Rush, A. M., Barak, B., Scao, T. L., Piktus, A., Tazi, N., Pyysalo, S., Wolf, T., and Raffel, C. Scaling data-constrained language models. *arXiv preprint arXiv:2305.16264*, 2023.
- Nakkiran, P., Neyshabur, B., and Sedghi, H. The deep bootstrap framework: Good online learners are good offline generalizers. In *International Conference on Learning Representations*, 2021a.
- Nakkiran, P., Neyshabur, B., and Sedghi, H. The deep bootstrap framework: Good online learners are good offline generalizers. In *International Conference on Learning Representations*, 2021b. URL <https://openreview.net/forum?id=guetrIHLFGI>.
- Paquette, C., Lee, K., Pedregosa, F., and Paquette, E. Sgd in the large: Average-case analysis, asymptotics, and stepsize criticality. In *Conference on Learning Theory*, pp. 3548–3626. PMLR, 2021.
- Roberts, D. A., Yaida, S., and Hanin, B. *The principles of deep learning theory*. Cambridge University Press Cambridge, MA, USA, 2022.
- Ruben, B. S. and Pehlevan, C. Learning curves for noisy heterogeneous feature-subsampled ridge ensembles. *ArXiv*, 2023.
- Simon, J. B., Dickens, M., Karkada, D., and DeWeese, M. R. The eigenlearning framework: A conservation law perspective on kernel regression and wide neural networks. *arXiv preprint arXiv:2110.03922*, 2021.
- Simon, J. B., Karkada, D., Ghosh, N., and Belkin, M. More is better in modern machine learning: when infinite overparameterization is optimal and overfitting is obligatory. *arXiv preprint arXiv:2311.14646*, 2023.
- Sompolinsky, H. and Zippelius, A. Dynamic theory of the spin-glass phase. *Physical Review Letters*, 47(5):359, 1981.
- Sorscher, B., Geirhos, R., Shekhar, S., Ganguli, S., and Morcos, A. Beyond neural scaling laws: beating power law scaling via data pruning. *Advances in Neural Information Processing Systems*, 35:19523–19536, 2022.
- Spigler, S., Geiger, M., and Wyart, M. Asymptotic learning curves of kernel methods: empirical data versus teacher–student paradigm. *Journal of Statistical Mechanics: Theory and Experiment*, 2020(12):124001, 2020.
- Varre, A. V., Pillaud-Vivien, L., and Flammarion, N. Last iterate convergence of sgd for least-squares in the interpolation regime. *Advances in Neural Information Processing Systems*, 34:21581–21591, 2021.
- Vyas, N., Bansal, Y., and Nakkiran, P. Limitations of the ntk for understanding generalization in deep learning. *arXiv preprint arXiv:2206.10012*, 2022.
- Vyas, N., Atanasov, A., Bordelon, B., Morwani, D., Sainathan, S., and Pehlevan, C. Feature-learning networks are consistent across widths at realistic scales. *arXiv preprint arXiv:2305.18411*, 2023.
- Yang, G., Hu, E. J., Babuschkin, I., Sidor, S., Liu, X., Farhi, D., Ryder, N., Pachocki, J., Chen, W., and Gao, J. Tuning large neural networks via zero-shot hyperparameter transfer. In Beygelzimer, A., Dauphin, Y., Liang, P., and Vaughan, J. W. (eds.), *Advances in Neural Information Processing Systems*, 2021. URL <https://openreview.net/forum?id=Bx6qKuBM2AD>.
- Zagoruyko, S. and Komodakis, N. Wide residual networks. *arXiv preprint arXiv:1605.07146*, 2016.
- Zavatone-Veth, J. A. and Pehlevan, C. Learning curves for deep structured gaussian feature models, 2023.
- Zavatone-Veth, J. A., Tong, W. L., and Pehlevan, C. Contrasting random and learned features in deep bayesian linear regression. *Physical Review E*, 105(6):064118, 2022.