Scaling description of generalization with number of parameters in deep learning

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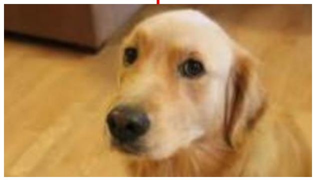
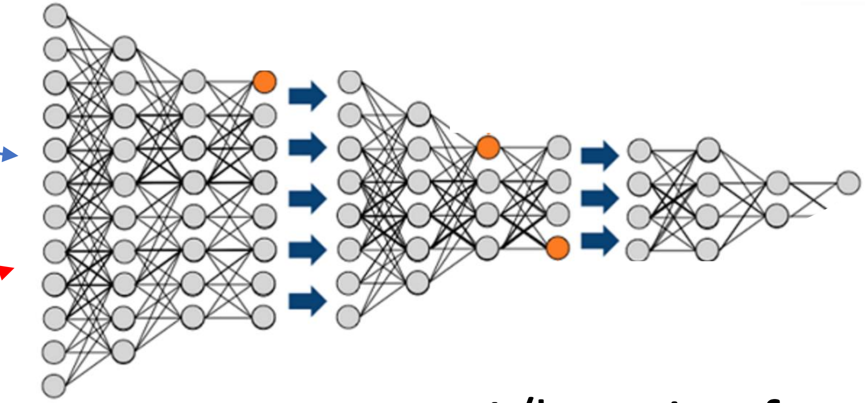
arxiv 1901.01608

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Deep learning





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$$f_{\mathbf{w}}(\mathbf{x}_i)$$

<0

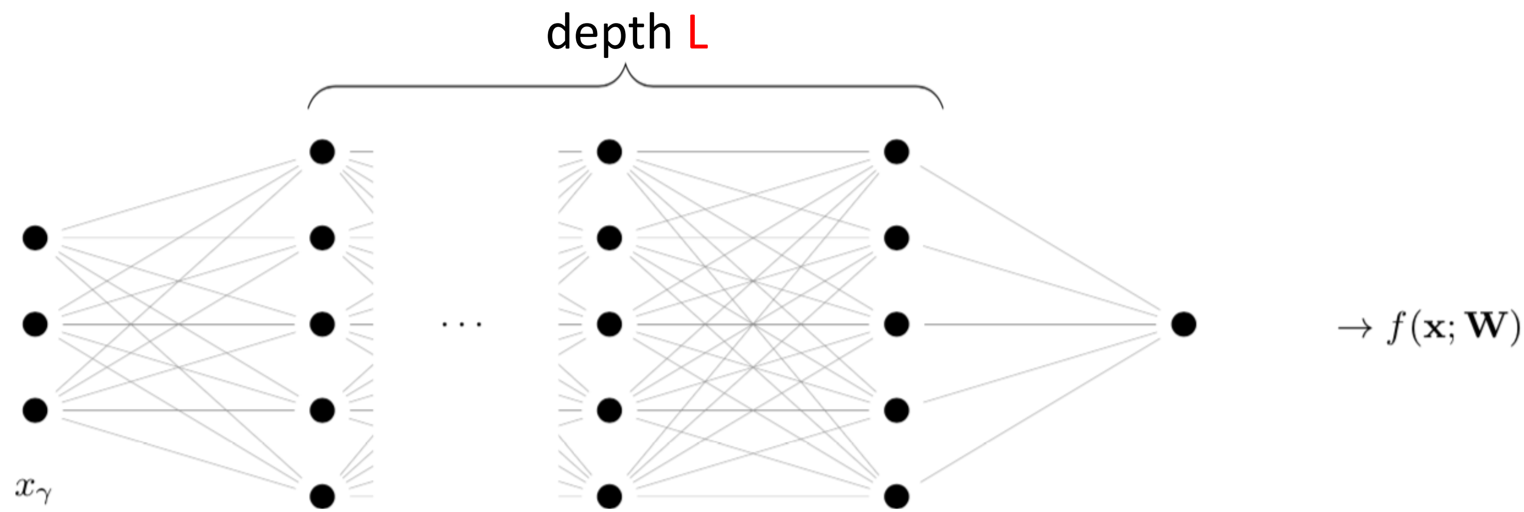
1/learning from example

2/ can predict!

- Revolution in Artificial Intelligence
- Principles to understand why It works lacking

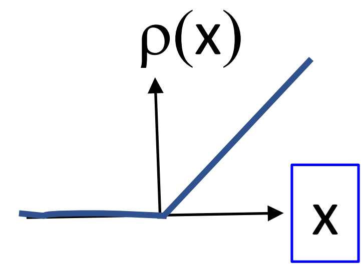
Set-up

- binary classification task, P training data $\{\mathbf{x}_i, y_i = \pm 1\}$
- Deep net $f_{\mathbf{W}}(\mathbf{x}_i)$ with N parameters, width h (N~h^2)



$$\boxed{a_\beta = \rho\Big(\sum_{\alpha \in \text{ previous layer}} W_{\alpha,\beta}\, a_\beta - B_\beta\Big)}$$

ρ: non-linear function



Learning

- Learning: gradient descent in loss function $\mathcal{L} = \frac{1}{P}\sum_{i}^{P} l_i(f_{\mathbf{w}}(x_i))$

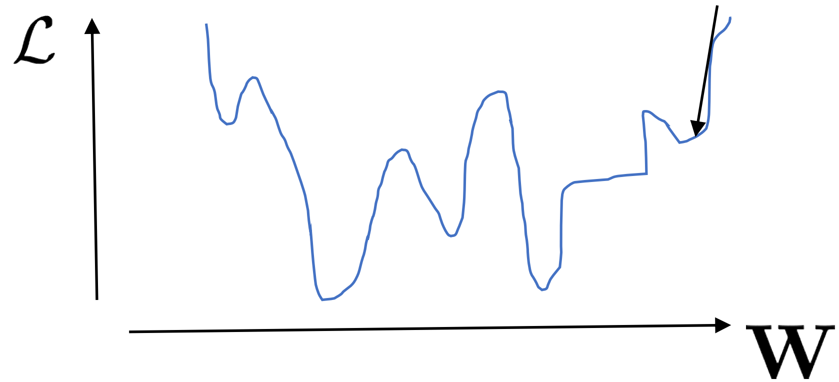
- Quadratic Hinge Loss:

$$l_i(f_{\mathbf{w}}(x_i)) = 0 \quad \text{if} \quad f_{\mathbf{w}}(x_i)y_i > 1$$

$$l_i(f_{\mathbf{w}}(x_i)) = (f_{\mathbf{w}}(x_i)y_i - 1)^2 \quad \text{if} \quad f_{\mathbf{w}}(x_i)y_i < 1$$

- $\mathcal{L} = 0 \Leftrightarrow f_{\mathbf{w}}(x_i)y_i > 1 \forall i$ satisfability problem

Learning= descent in Loss Landscape



- High dimensional, not convex

landscape.

<u>Question:</u> why not stuck in bad local

minima? Landscape geometry?

Choromanska et al. 15, *Soudry, Hoffer 17' Cooper 18' Baity-Jesy et al. 18*

- sharp jamming transition in the landscape separating glassy landscape from an over-parametrized-phase with $\mathcal{L} = 0$.

Achievable if N~P

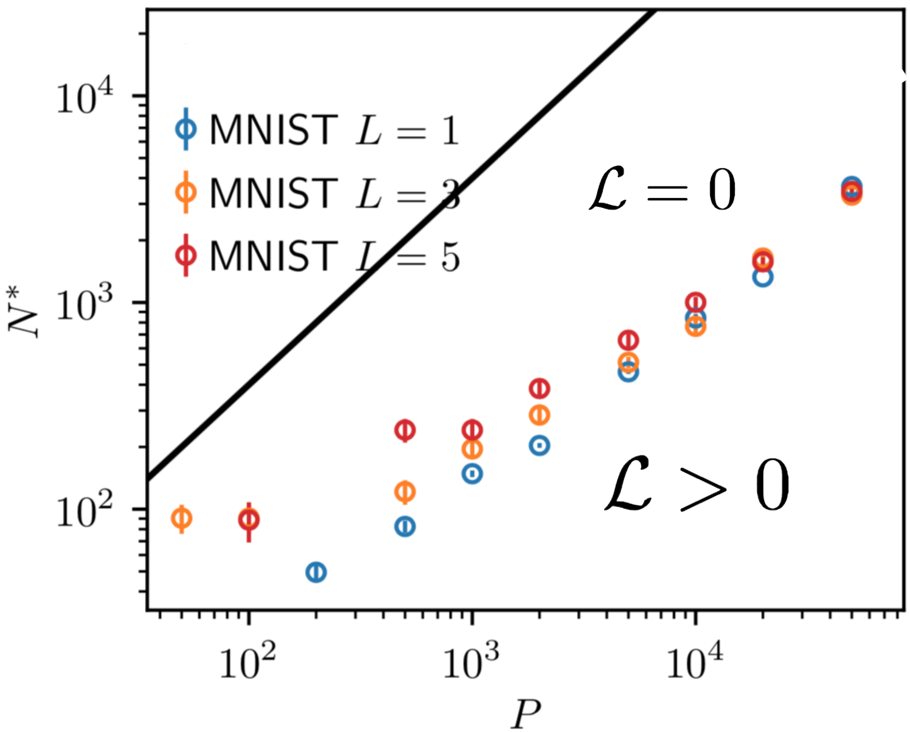
Geiger et al. 18, Spigler et al. 18 (see Silvio's talk)

- Why deep nets have predictive power while N > P, or even N>>P??

Empirical tests: MNIST (parity)

- $6*10^4$ images of digits

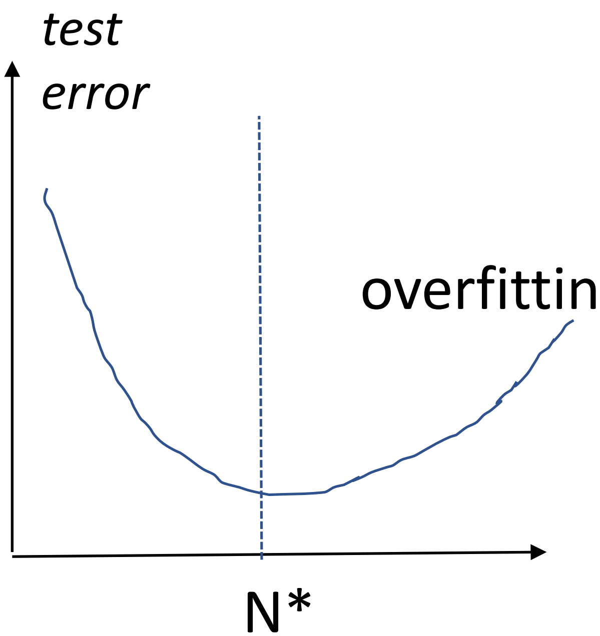
Geiger et al., arxiv 180909349



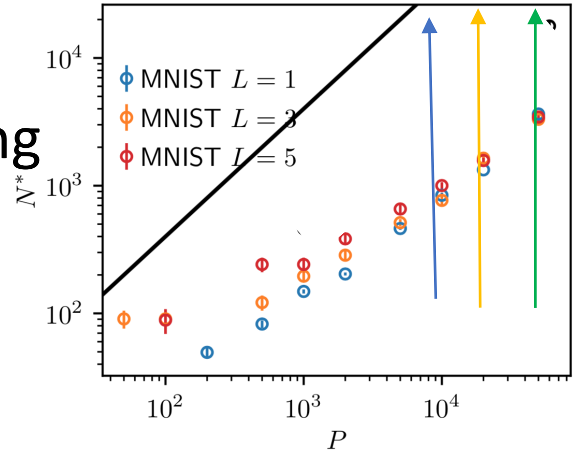
- position of transition depends on dynamics (GD, adams, fire...)

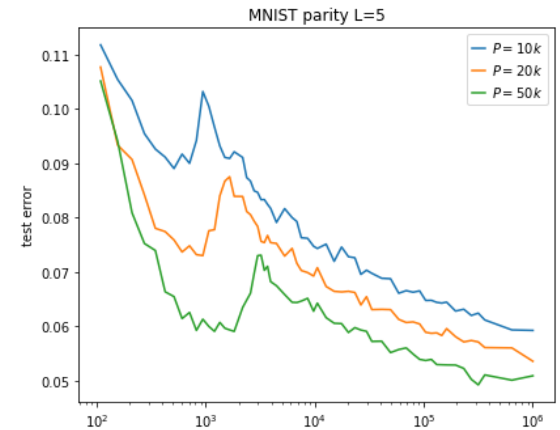
Generalization

Spigler et al. arxiv 1810.09665



test error





N

see also Advani and Saxe 17,
Neal et al. 18, Neyshabur et al., 15, 17.

2 interesting asymptotic regimes:

- peak at the jamming transition

- performance improves with N in the SAT phase???

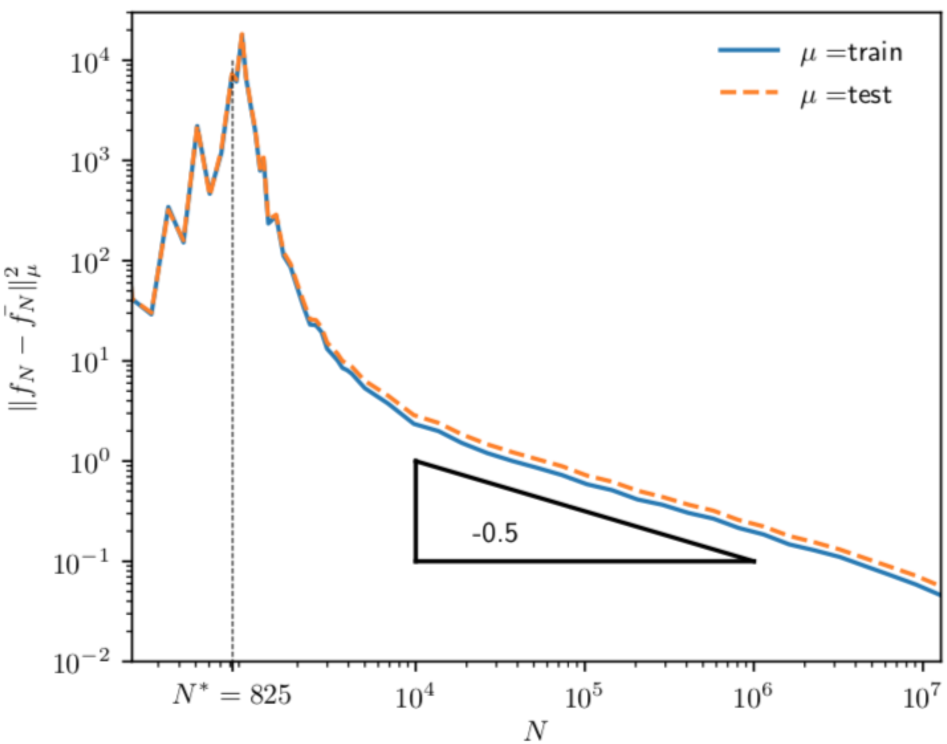
works by Rakhlin, Srebro: increased regularization with N

Quantitative description? importance of N=

Quantifying fluctuations induced by initialization

- fixed data set, output function f stochastic due to initialization
- This stochasticity is reduced as N grows *Neal et al. arxiv 1810591*

$\bar{f}_N$: ensemble average of f_N on (20) initial conditions



$$||f||^2_\mu = \int d\mu(x) f(x)^2$$

$$\boxed{||f_N - \bar{f}_N||_\mu \sim N^{-1/4}}$$

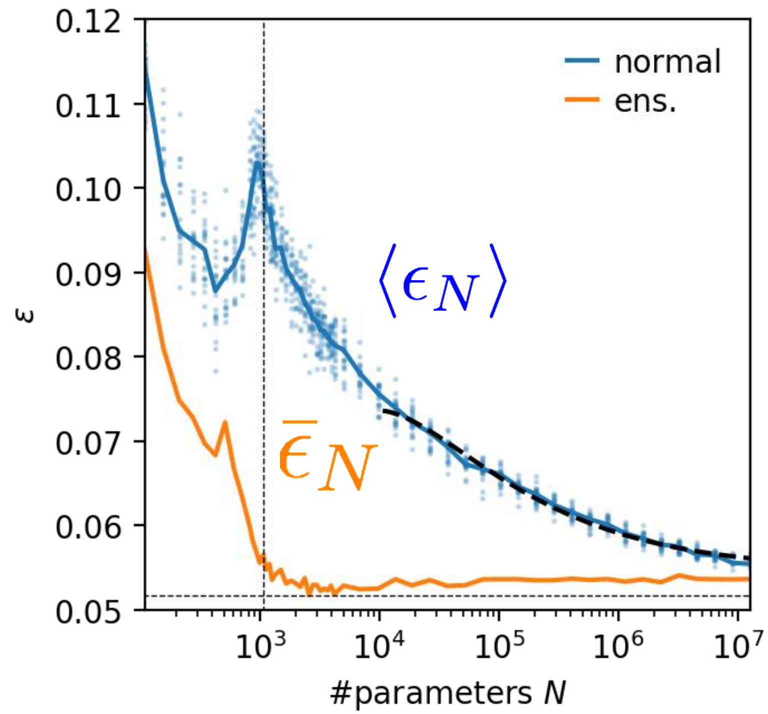
(to be explained later)

Test and practical consequences

Geiger et al., arxiv 1901.01608

- Reduce fluctuations by averaging

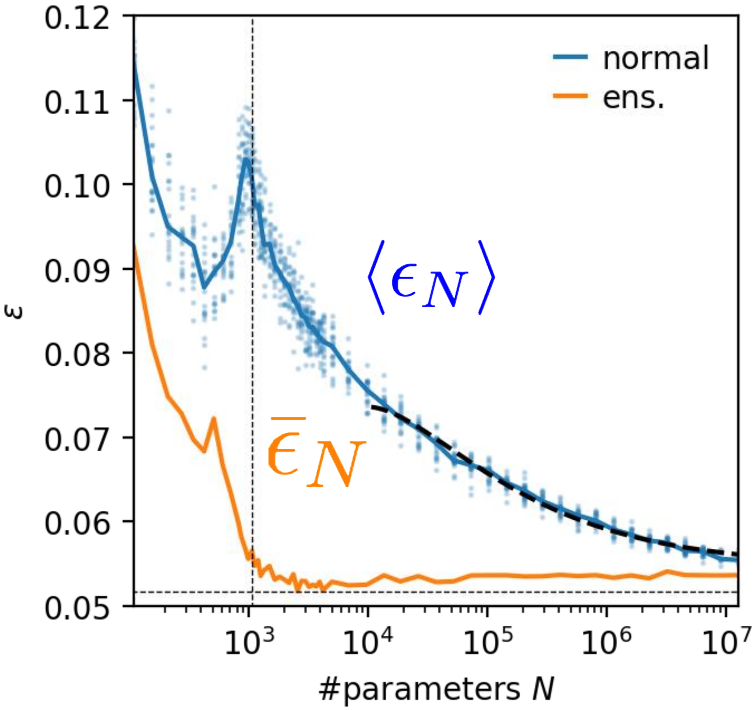
$\bar{\epsilon}_N$: test error of $\bar{f}_N$



- test error becomes nearly flat for N>N*, optimal near N*

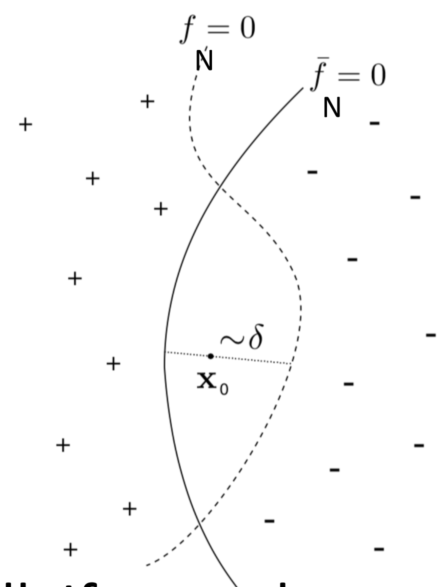
- *Best procedure: ensemble average near jamming transition!!!*

Scaling argument for generalization error



- seek to compute $\langle \epsilon_N \rangle - \bar{\epsilon}_N$

using $\delta f_N = f_N - \bar{f}_N$ very small



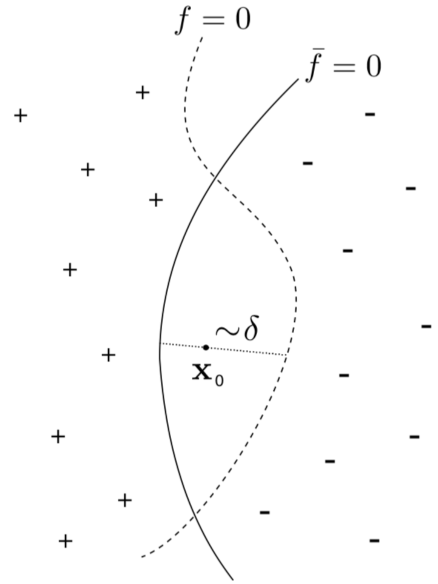
decision boundary

- signed distances $\delta(x)$ becomes small. If smooth:

$$\delta(x) = \frac{\delta f_N(x)}{||\nabla \bar{f}_N(x)||} + \mathcal{O}(\delta f_N^2)$$

$$\begin{cases} \delta(x) \sim ||\delta f_N||_\mu \\ \langle \delta(x) \rangle \sim ||\delta f_N||_\mu^2 \end{cases}$$

Scaling argument for generalization error

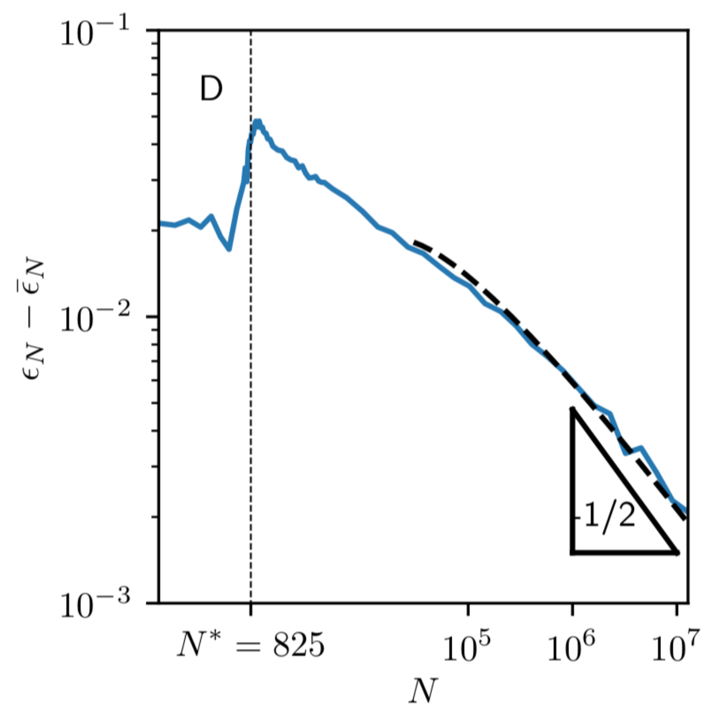


$$\Delta\epsilon = \int_B dx^{d-1}\left[\frac{\partial\epsilon}{\partial\delta(x)}\delta(x) + \frac{1}{2}\frac{\partial^2\epsilon}{\partial^2\delta(x)}\delta^2(x) + \mathcal{O}(\delta^3(x))\right].$$

$$\langle\Delta\epsilon\rangle = c_0||\delta f||^2 + \mathcal{O}(||\delta f||^3)$$

expect c_0>0 if $\bar{\epsilon}$ small

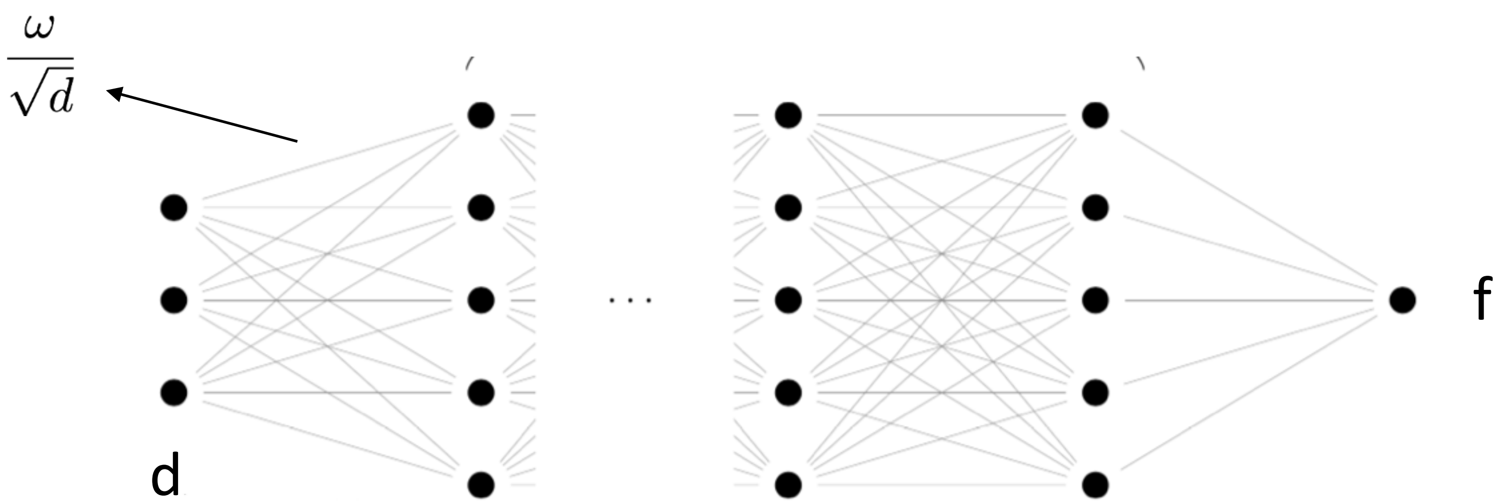
$$\boxed{\langle\epsilon_N\rangle - \bar{\epsilon}_N \sim ||\bar{f}_N - f_N||^2 \sim 1/\sqrt{N}}$$



Propagation in infinitely wide nets at t=0

Neal 96, williams 98, Lee et al 18, Ganguli et al.

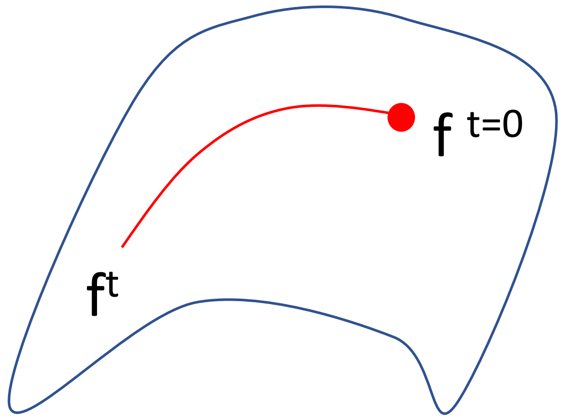
<u>set-up:</u> initialization iid weights = $\frac{\omega}{h^{1/2}}$ where $\omega \sim \mathcal{N}(0,1)$



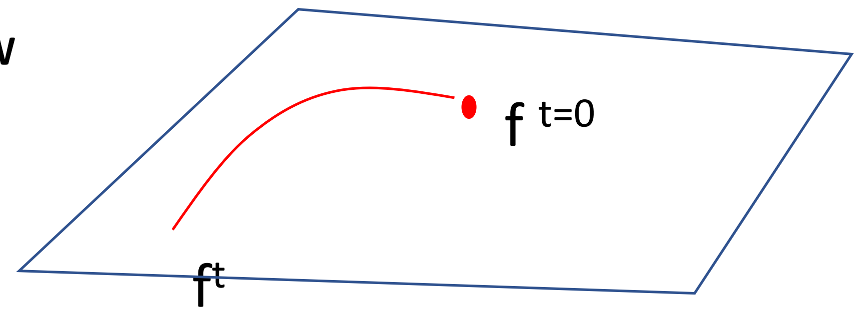
- Non-trivial limit for propagation, pre-activation $\alpha \sim 1$ and f ~ 1
- pre-activation and output are iid gaussian processes as $h \to \infty$

Learning: Neural Tangent Kernel

Jacot, Gabriel, Hongler NIPS 18



manifold f_w



small h: $\partial f / \partial w$ evolves

large h: $\partial f / \partial w$ fixed

“lazy learning”:

- weights change a little bit $\omega^t - \omega^0 \sim 1/h$
- sufficient to change f (positive interference)
- does not change $\partial f / \partial w$

Results

Jacot, Gabriel, Hongler NIPS 18

$$\mathcal{L} = \frac{1}{P}\sum_{i}^{P} l_i(f_{\mathbf{W}}(x_i))$$

gradient descent

$$\frac{df(x)}{dt} = -\frac{1}{P}\sum_{i=1}^{P} \Theta_N^t(x_i, x)\, l_i'(f(x_i))$$

$$\Theta_N^t(x_i, x) = \sum_{\omega} \frac{\partial f^t(x_i)}{\partial \omega}\frac{\partial f^t(x)}{\partial \omega}$$

useless in general...

<u>Theorem:</u> kernel does not depend on initialization at large N, nor on time

$$\boxed{\lim_{N\to\infty} \Theta_N^t(x_i, x) = \Theta_\infty(x_i, x)}$$

$$\boxed{\frac{df(x)}{dt} = -\frac{1}{P}\sum_{i=1}^{P} \Theta_\infty(x_i, x)\, l_i'(f(x_i))}$$

deep learning equivalent to kernel learning as $N \to \infty$

Finite N *Geiger et al. 19, Jacot et al 19*

- Fluctuations of $\Theta_N^{t=0}$ go as $1/\sqrt{h} \sim N^{-1/4}$
- evolution in time much smaller $\theta_N^t - \theta_N^{t=0} \sim 1/\sqrt{N}$

$$\frac{df(x)}{dt} = -\frac{1}{P}\sum_{i=1}^{P} \Theta_N^t(x_i, x) l_i'(f(x_i))$$

- leads to fluctuations of similar magnitude for output function (proof mean square loss)

$$\boxed{||f_N - \bar{f}_N||_\mu \sim N^{-1/4}}$$

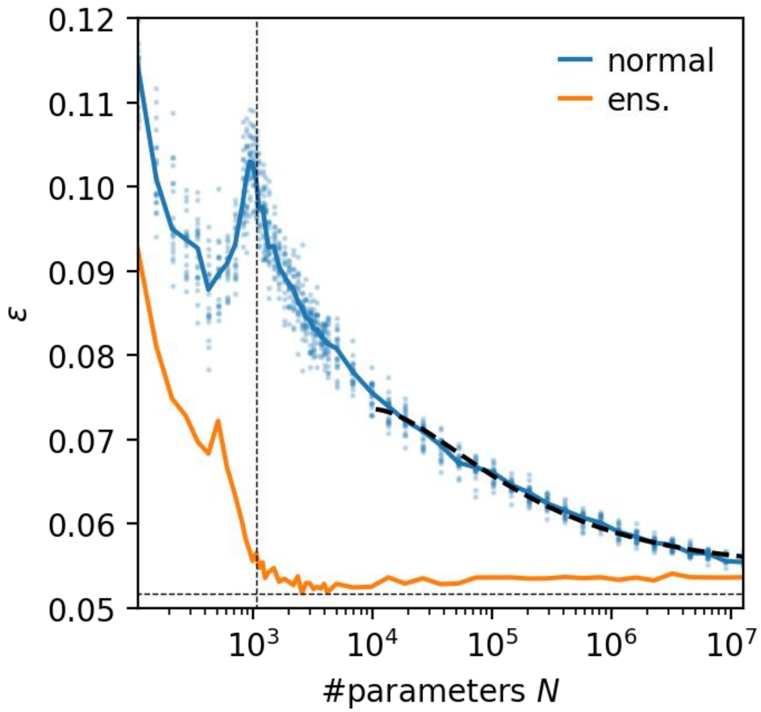
Is learning features useful?

- neurons pattern of activity barely changes as $N \to \infty$

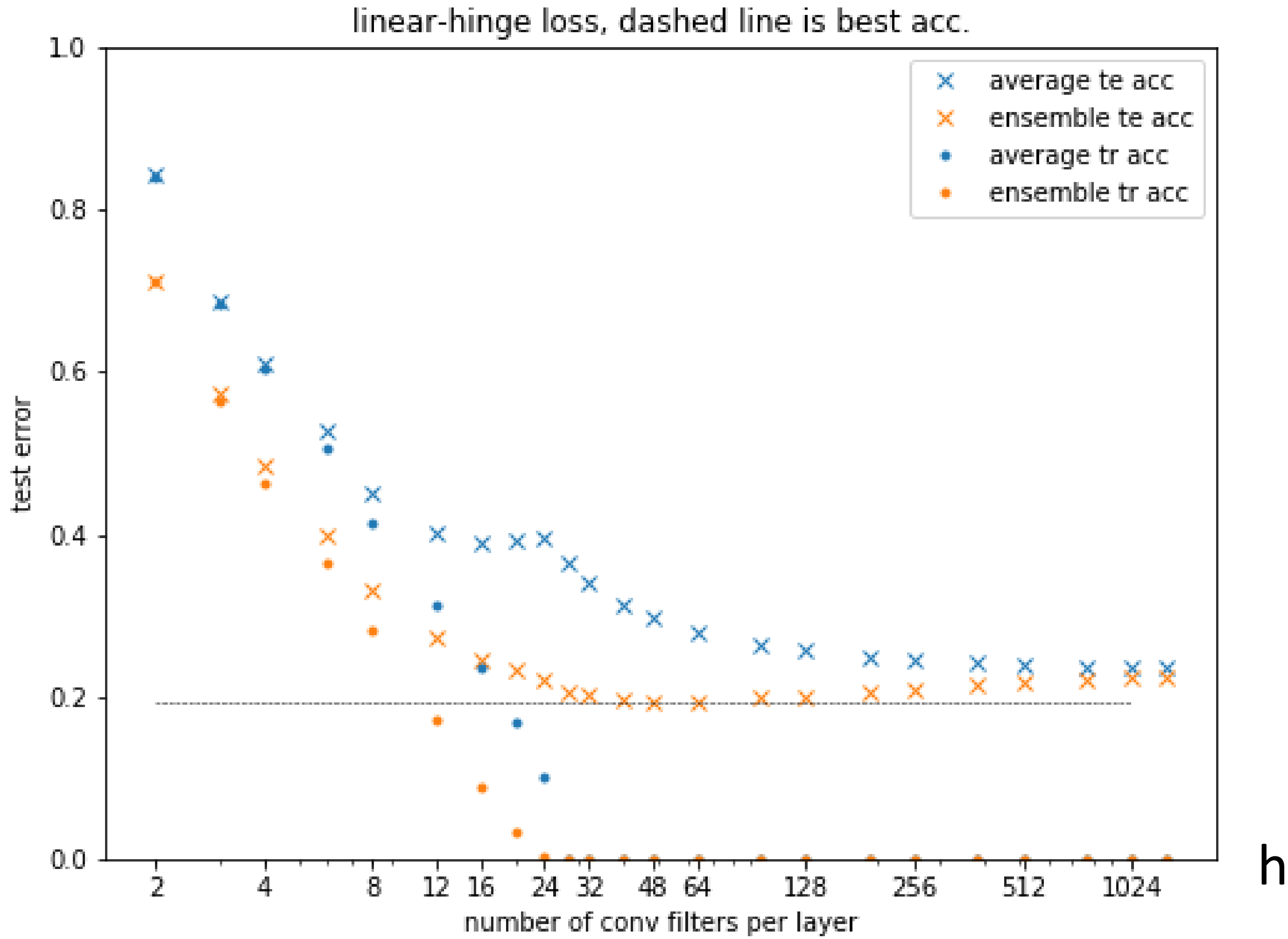
$$\alpha^t(x) - \alpha^{t=0}(x) \sim 1/\sqrt{h}$$

- success of deep learning believes to be associated with the emergence of good features....

- Small effect FCC on MNIST.



Is learning features useful? CNN data



Conclusion

- Deep nets fit all data if N>N*, jamming transition
- Performance keep increasing passed N* because fluctuations induced by initialization diminish
- fluctuations are induced by the fluctuations of the kernel, fixed at infinite N
- In practice: best procedure= ensemble averaging just above N*
- Question future: scaling performance swith P?

Results

- <u>Theorem 3:</u> Dynamics find global minimum of the loss if loss l_i convex and activation function non-polynomial

Gram matrix $\Theta_\infty(x_i, x_j)$ positive definite

$$\frac{df(x)}{dt} = -\frac{1}{P}\sum_{i=1}^{P}\Theta_\infty(x_i, x)l_i'(f(x_i))$$

- <u>Result 4:</u> smoothness of $f^t(x)$ can be deduced

$$f^t(x) = f^{t=0}(x) + \sum_{i=1}^{P} c_i(t)\Theta_\infty(x, x_i)$$

Why does deep learning work?

- when can one fit the data (not stuck bad minimum)?

crank up the number of parameters

- Why does it generalize well, even when the number of parameters is large?

Generalization keeps improving with number of parameters...

<u>MENU:</u>

1/ Quantification of evolution of generalization with number of parameters

2/ Neural Tangeant Kernel (NTK)

3/ NTK and generalization as number of parameters becomes asymptotically large