Infinite Width, NTK, and Feature Learning

Student Meeting 1

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TU Delft

Agenda

Goal of this talk

- Introduce the infinite-width lens, NTK, and the lazy training regime via a simple one-layer example.
- Situate these ideas within related work: baseline results at infinite width and viewpoints that go beyond linearization.

What I would like from you

- Conceptual clarifications and critiques of how I'm connecting the papers.
- Suggestions for key references I might be missing.
- Pointers to alternative frameworks worth comparing (mean-field, functional-analytic, optimization bias).

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- Larger models keep improving, but we don't fully know *why*.
- **A solvable starting point:** infinite width gives a clean baseline; modern models are large-but-finite, deep, and do feature learning.
- **What can theory help in:** explanations of convergence/generalization, signals for when features move, and guidance on design choices (init, learning rate, normalization).

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  - Does the *kernel* change during training?
  - Do the model's internal features move?
  - Do training curves deviate from the NTK baseline prediction?
  - Possible causes: higher-order effects, useful parameter re-organization that push the model out of the lazy regime.

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Linearization at Initialization

First-order Taylor around $\boldsymbol{\theta}_0$:

$$f(\boldsymbol{x};\boldsymbol{\theta}) \approx f(\boldsymbol{x};\boldsymbol{\theta}_0) + \underbrace{\nabla_{\boldsymbol{\theta}} f(\boldsymbol{x};\boldsymbol{\theta}_0)^\top}_{:=\ \phi(\boldsymbol{x})^\top}(\boldsymbol{\theta} - \boldsymbol{\theta}_0).$$

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This induces the **Neural Tangent Kernel (NTK)** at $\boldsymbol{\theta}_0$:

$$K(\boldsymbol{x},\boldsymbol{x}') = \phi(\boldsymbol{x})^\top \phi(\boldsymbol{x}') = \nabla_{\boldsymbol{\theta}} f(\boldsymbol{x};\boldsymbol{\theta}_0)^\top \nabla_{\boldsymbol{\theta}} f(\boldsymbol{x}';\boldsymbol{\theta}_0).$$

Ref: (Jacot et al., 2018)

Illustrative Model (One Hidden Layer, No Biases)

Consider a m-width neural network

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Finite-width NTK:

$$\boxed{K_m(\boldsymbol{x}, \boldsymbol{x}') = \frac{1}{m} \sum_{r=1}^{m} \sigma(\mathbf{w}_r^\top \boldsymbol{x})\, \sigma(\mathbf{w}_r^\top \boldsymbol{x}') + \frac{1}{m} \sum_{r=1}^{m} a_r^2\, \sigma'(\mathbf{w}_r^\top \boldsymbol{x})\, \sigma'(\mathbf{w}_r^\top \boldsymbol{x}')\, \boldsymbol{x}^\top \boldsymbol{x}'.}$$

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Thus, in the infinite-width limit, the empirical NTK converges almost surely to a deterministic kernel

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Key point: in the wide limit, $K_t \approx K_0$ remains *essentially constant* during training (lazy regime).

Refs: (Neal, 1996; Lee et al., 2019)

Training dynamics: mini-derivation

Gradient flow & chain rule: Let $f_t(x_i) := f(x_i;\theta_t)$. Then

$$\frac{d}{dt} f_t(x_i) = \nabla_\theta f(x_i;\theta_t)^\top \dot{\theta}_t = -\nabla_\theta f(x_i;\theta_t)^\top \nabla_\theta L(\theta_t).$$

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Substitute and define the (time–dependent) NTK.

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Constant-kernel (NTK) regime. If $K_t \approx K_0 \equiv K$ (infinite width / lazy),

$$\dot{f}_t = -K(f_t - y) \quad \Rightarrow \quad \boxed{f_t = y + e^{-Kt}\,(f_0 - y).}$$

Refs: (Jacot et al., 2018; Lee et al., 2019)

Lazy Training

Lazy regime: parameter drift is small, $\|\boldsymbol{\theta}_t - \boldsymbol{\theta}_0\| \ll \|\boldsymbol{\theta}_0\|$.

- Features $\phi(\boldsymbol{x})$ and kernel K stay (approximately) constant.
- Training reduces to kernel regression with fixed K.

Limitation: suppresses *feature learning* (representation change).

Aim: quantify *when* lazy holds/breaks and *how* to model beyond it.

Diagnosing the transition to feature learning

Some signals to consider

- **Kernel drift:** Does the NTK matrix K_t change during training? Compare K_t to K_0 on the (same) data. Bigger change $\Rightarrow$ more feature learning.

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How to (often) push out of lazy

- larger learning rate
- smaller width
- more depth / biases / normalization

Beyond linearization I: quadratic / higher-order

$$f(\boldsymbol{x};\boldsymbol{\theta}) \approx f(\boldsymbol{x};\boldsymbol{\theta}_0) + \phi(\boldsymbol{x})^\top \Delta\boldsymbol{\theta} + \tfrac{1}{2}\,\Delta\boldsymbol{\theta}^\top H_f(\boldsymbol{x})\,\Delta\boldsymbol{\theta}, \qquad \Delta\boldsymbol{\theta} = \boldsymbol{\theta} - \boldsymbol{\theta}_0.$$

- **Mechanism (Bai and Lee (2020)):** construct regimes where the linear term is suppressed so the *quadratic* term governs the dynamics; extendable to $k > 2$ ("higher-order NTKs").
- **Findings:** with the linear term suppressed, progress comes from *feature changes*; this adaptive regime is easy to optimize and can beat NTK in sample use on simple tasks.

See: "Beyond Linearization: On Quadratic and Higher-Order Approximation of Wide Neural Networks."

Beyond linearization II: adaptive / time-varying kernels

- Zhang et al. (2024) replace the fixed NTK with a *time-varying* kernel K_t that evolves during training ("kernel drift").
- Features adapt during training and increasingly align with label-relevant directions (growing alignment).
- They provide a prototype of an over-parameterized Gaussian sequence model to analyze feature learning beyond the NTK picture.

See: "Towards a Statistical Understanding of Neural Networks: Beyond the NTK Theories."

Beyond NTK III: finite depth/width corrections

- Hanin and Nica (2019) study networks where depth d and width n grow together.
- Key finding: the NTK is **not deterministic** at init — its variance scales roughly $\exp(c\,d/n)$.
- Even the first SGD step can change K_t significantly $\Rightarrow$ kernels evolve, enabling *weak feature learning*.
- Proposed **weak feature learning regime:** $0 < d/n \ll 1$ where training is stable but K_t still moves.

See: Hanin & Nica, "Finite Depth and Width Corrections to the NTK."

Summary & discussion

- Infinite width as a clean baseline; NTK via linearization at initialization.
- Constant–kernel training dynamics: $\dot{f}_t = -K(f_t - y)$ with solution $f_t = y + e^{-Kt}(f_0 - y)$.
- Lazy training $\Rightarrow$ features (and K) stay essentially fixed.
- How to spot leaving lazy: *kernel drift* ($K_t \neq K_0$) and *feature drift* on a probe set.
- Beyond NTK in the literature:
  - *Quadratic / higher-order* near init (Bai and Lee, 2020).
  - *Adaptive / time-varying kernels* and alignment (Zhang et al., 2024).
  - *Finite depth/width corrections:* NTK variance grows with d/n; even early updates can move K_t (weak feature learning) (Hanin and Nica, 2019).

References

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