# Non-Gaussian Tensor Programs

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## Abstract

The Tensor Programs framework has produced a series of powerful results by 1) expressing any deep learning computation of concern as a principled composition of elementwise nonlinearities and matrix multiplication, and 2) inductively reasoning about the program behavior as the sizes of the matrices in the program tend to infinity. For example, this framework showed that infinitely wide neural networks of *any architecture* exhibit Gaussian process behavior at initialization and evolve like a kernel model during training in the so-called NTK parametrization [21, 22, 26]. Moreover, this framework yielded a novel parameterization, coined $\mu$P [24], that for the first time enabled hyperparameter tuning for enormous networks too expensive to train more than once [25]. However, this framework has so far been limited to Gaussian initialized weights, while uniform or truncated Gaussian distributions are more prevalent in practice. This work extends Tensor Programs to general non-Gaussian initializations, thus recovering all of the above results in all practical settings.

## 1 Introduction

Just like autograd [17] empirically automates the calculation of chain rule of arbitrary computation graphs, Tensor Programs (TP) [20] has automated the theoretical calculation of infinite-width limits of the same (where width of a computation graph corresponds to the size of matrices). What previously were difficult limits to calculate, now becomes routine via TP. For example, [10] in 1994 showed that randomly initialized wide shallow neural networks are Gaussian Processes (which is called the Neural Network-Gaussian Process Correspondence, or NNGP Correspondence), but only recently this has been extended to deep perceptrons [8, 9] and more advanced architectures such as convolutional neural networks [2, 11], and each such extension requires painstaking calculations and careful applications of Law of Large Numbers and Central Limit Theorem. But with Tensor Programs, one can show that NNGP Correspondence holds for any architecture all at once [21]. Similarly, in a certain parametrization, a wide multi-layer perceptron (MLP) evolves like a linear model during training [6], but showing this for advanced architectures was very difficult. TP [22, 26] again was able to prove this behavior for any architecture. Finally, TP gave rise to the Dynamical Dichotomy Theorem [24], a classification of all natural infinite-width limits of neural networks, and led to the discovery of Maximal Update Parametrization, or $\mu$P. These results underlie the hyperparameter transfer technology that for the first time enabled the hyperparameter tuning of enormous neural networks too expensive to train more than once [25].

However, these results were only proven for neural networks randomly initialized with *Gaussian* weights. But in practice, non-Gaussian initializations such as uniform or truncated Gaussian, proliferate. Could such non-Gaussian initializations possess different behavior in wide neural networks?

In this work, we answer NO: under mild conditions, non-Gaussian iid initializations behave the same as Gaussian initializations with the same variance in wide neural networks. From the perspective of universality [14] from statistical mechanics, this is not unexpected; yet proving such results rigorously

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has always been tricky [18]. In our work, we apply the interpolation technique of [1] to interpolate between a non-Gaussian Tensor Program in question and the corresponding Gaussian Tensor Program, and show that this continuous interpolation in the infinite-width limit has identially zero derivative, and therefore the two programs have the same limits.

This result also makes the proof of the Semicircle and Marchenko-Pastur Laws in [23] automatically valid for non-Gaussian random matrix ensembles. Likewise, it shows that the asymptotic singular value distribution of the input-output Jacobian of a random neural network does not depend on the distribution of random initialization beyond its variance.

## 2 Setup

Given initial vectors $g^1, \ldots, g^{M_0} \in \mathbb{R}^n$ and initial scalars $c^1, \ldots, c^{M_0} \in \mathbb{R}$, consider the following iteration for $m = M_0 + 1, \ldots, M$ that generates new vectors $g^{M_0+1}, \ldots, g^M \in \mathbb{R}^n$ and scalars $c^{M_0+1}, \ldots, c^M \in \mathbb{R}$:

$$g^m_\alpha = \sum_{\beta=1}^n A^{m,T_m}_{\alpha\beta} x^m_\beta, \quad c^m = \frac{1}{n}\sum_{\beta=1}^n x^m_\beta, \quad \text{where } x^m_\alpha = \phi^m(g^1_\alpha, \ldots, g^{m-1}_\alpha, c^1, \ldots, c^{m-1}). \quad (1)$$

Here $\phi^m$ is a scalar function with $2m-2$ arguments, $A^m$ is an $n \times n$ matrix, and $T_m \in \{1, \top\}$ marks whether this matrix should be transposed or not. The matrices $A^m$ for different $m$ can possibly be the same. In this work, we shall call any computation of this form a *Tensor Program*, or TP.

This formulation of a Tensor Program is equivalent to NETSOR$\top^+$ in [23], as shown in Appendix D. As such, Eq. (1) can express any computation expressible in a DL framework such as PyTorch [13], including gradient descent iterations of neural networks of any architecture, e.g. [24, 26]. This expressivity allows one to treat a wide range of problems uniformly using just Theorem 1 below.

For example, consider the first forward pass of a simple MLP with scalar input $\xi$ and output $f(\xi)$:

$$f(\xi) = V^\top \sigma(W\sigma(\xi U)),$$

where $\xi \in \mathbb{R}; U, V \in \mathbb{R}^n; W \in \mathbb{R}^{n\times n}$. We can express this in a TP as follows: $g^1 = U, g^2 = nV$ are the initial vectors and $c^1 = \xi, c^2 = 1$ are initial scalars (where $c^2$ will just be ignored). Then the program computes

$$g^3 = A^3 x^3, \quad \text{where } A^3 = W, x^3 = \sigma(\xi U)$$
$$f(\xi) = c^4 = \frac{1}{n}\sum_{\beta=1}^n x^4_\beta, \quad \text{where } x^4 = (nV) \odot \sigma(g^3)$$

with $c^3$ and $g^4$ computed but just discarded. See [21, 22, 26, 24] for more examples.

**Gaussian Tensor Programs.** [20, 23, 26] most commonly work under the following setup:

**Setup 1.** *Consider a Tensor Program with $M$ vectors $g^1, \ldots, g^M \in \mathbb{R}^n$ and scalars $c^1, \ldots, c^M$. Suppose 1) all initial vectors $g^1, \ldots, g^{M_0}$ are sampled as $(g^1_\alpha, \ldots, g^{M_0}_\alpha) \sim \mathcal{N}(\mu^{in}, \Sigma^{in})$ iid over $\alpha = 1, \ldots, n$, for some $\mu^{in} \in \mathbb{R}^{M_0}, \Sigma^{in} \in \mathbb{R}^{M_0\times M_0}$; 2) all initial scalars $c^1, \ldots, c^{M_0}$ have almost sure limits as $n \to \infty$; 3) all matrices $A^m$ have iid entries from $\mathcal{N}(0, n^{-1})$; 4) any two matrices $A^m, A^l$ are either equal or independently sampled; 5) all the nonlinearities $\phi^m$ are pseudo-Lipschitz.*[1]

Under this setup, the following Master theorem holds:

**Theorem 1** ([23])**.** *Consider Setup 1. Then, as $n \to \infty$, for any pseudo-Lipschitz $\psi$,*

$$\frac{1}{n}\sum_{\alpha=1}^n \psi\left(g^1_\alpha, \ldots, g^M_\alpha, c^1, \ldots, c^M\right) \xrightarrow{a.s.} \mathring{\Psi}, \quad (2)$$

*where $\mathring{\Psi}$ is a deterministic scalar given by a certain recurrent formula. Moreover, if all nonlinearities $\phi^m$ are linearly bounded and $\psi$ is quadratically bounded, we get convergence also in mean.*

[1] A function $f : \mathbb{R}^k \to \mathbb{R}$ is called *pseudo-Lipschitz* if $|f(x) - f(y)| \le C\|x - y\|(1 + \sum_{i=1}^k |x_i|^d + |y_i|^d)$ for some $C, d > 0$.

**Non-Gaussian Tensor Programs.** We shall generalize Theorem 1 to non-Gaussian distributions.

**Definition 1.** *We say $f : \mathbb{R}^k \to \mathbb{R}$ is* polynomially smooth *if it is $C^\infty$ and its partial derivatives of any order are polynomially bounded, i.e. for any multidegree $\boldsymbol{\alpha} \geq 0$, $\left|\frac{\partial^{|\boldsymbol{\alpha}|}}{\partial \mathbf{x}^{\boldsymbol{\alpha}}} f(\mathbf{x})\right| \leq C(1 + |x_1|^p + \cdots + |x_k|^p)$ for some $C, p > 0$ that may depend on $\alpha$.*

**Setup 2.** *Consider Setup 1, but replace 3) and 5) with the following: 3*) all matrices $A^m$ have iid entries from a distribution (that could vary with $m$) with zero mean, variance $n^{-1}$, and all higher moment existing; 5*) all the nonlinearities $\phi^m$ are polynomially smooth. We further require 6) all moments of initial scalars $c^1, \ldots, c^{M_0}$ to exist and converge as $n \to \infty$.*

**Theorem 2** (Ours)**.** *Consider Setup 2. Then, as $n \to \infty$, for any polynomially smooth $\psi$,*

$$\frac{1}{n} \sum_{\alpha=1}^{n} \psi(g_\alpha^1, \ldots, g_\alpha^M, c^1, \ldots, c^M) \xrightarrow{prob.} \mathring{\Psi} \tag{3}$$

*with the same $\mathring{\Psi}$ as in Theorem 1 (but here convergence is in probability). Moreover, if all the nonlinearities $\phi^m$ are linearly bounded and $\psi$ is quadratically bounded, then the expectation of the LHS of Eq.* (3) *converges to the RHS.*

In short, Theorem 2 relaxes matrix sampling to be non-Gaussian in general, at the cost of a) requiring more smoothness in nonlinearities, and b) weakening almost sure convergence to in-probability. Note that Setup 2 still requires initial vectors to be Gaussian, but this is not essential, as we discuss in Appendix A.

**On Tensor Programs with variable dimensions.** While Setup 1 and 2 assume all hidden dimensions to be equal, Theorem 1 holds also for Tensor Programs with variable dimensions, see e.g. [23]. Since our proof technique is based on interpolation between Gaussian and non-Gaussian weights, it can be straightforwardly extended to variable dimensions, as long as Theorem 1 holds in this setting.

# 3 Applications

As mentioned in the introduction, the Tensor Programs series of papers so far has proven a wide range of results, which typically have the characteristic of *architectural universality*, i.e., covering any neural architectures. But all of such results have assumed Gaussian weight initialization. Now, armed with Theorem 2, we show the same results hold with *non-Gaussian* weight initialization as well, under mild assumptions, thus extending them to other prevalent initializations such as uniform and truncated Gaussian. This demonstrates these results to be *distributional universal*, i.e., independent of specifics of weight sampling. Theorem 2 here acts like a drop-in replacement for Theorem 1 in their proofs, except we need to a) add more smoothness assumptions on nonlinearities, and b) any almost sure convergence is weakened to convergence in probability.

Our Theorem 2 can be applied to a very general class of neural networks as given by the following:

**Setup 3.** *Consider a neural network whose forward pass can be expressed as Eq.* (1) *where $T_m = 1$ for all $m$. Suppose 1) all the activation functions are polynomially smooth; 2) a bias vector of the output layer is initialized with zeros; 3) bias vectors of all other layers are initialized with elementwise images of iid Gaussian vectors under polynomially smooth nonlinearities; 4) weights of the input layer are initialized with elementwise images of iid Gaussian matrices of appropriate sizes under polynomially smooth nonlinearities; 5) weights of the output layer are initialized with iid Gaussians with zero mean and variance inversely proportional to the number of input neurons of this layer; 6) weights of any other layer are initialized iid from a distribution with zero mean and variance inversely proportional to the number of input neurons of this layer, with all higher moments existing.*

**NNGP Correspondence.** The following result is an immediate consequence of our Theorem 2 and Proposition G.4 of [21]:

**Corollary 1.** *Consider Setup 3. At initialization, as width tends to infinity, the neural network function converges weakly to a Gaussian Process (GP). Moreover, the empirical kernel associated to this network converges pointwise in probability to the kernel of this GP.*

**NTK correspondence.** We can directly plug our Theorem 2 into the proof of [26] and obtain

**Corollary 2.** *Consider Setup 3 and assume NTK parameterization.*[2] *Then under SGD weight updates, NTK of the network at any optimization step converges pointwise in probability to a finite deterministic limit that does not depend on the timestep. Moreover, the output of the network at any timestep converges pointwise to the output of a kernel method with this limit as a kernel.*

In Appendix C, we present a variant of Theorem 2 which works for non-smooth but Lipschitz nonlinearities (like ReLU or MaxPool). It allows to generalize Corollary 1 to ReLU nets, but not Corollary 2 (that's because a Tensor Program expressing the backward pass of a ReLU net has ReLU derivatives, which are not even continuous, as nonlinearities).

**Random Matrix Theory.** Our Theorem 2 implies the semi-circle law for non-Gaussian Wigner matrices, the Marchenko-Pastur law for $AA^\top$, where $A$ is non-Gaussian, and Free Independence Principle for Tensor Programs with non-Gaussian initial weights, thus generalizing TP3; we discuss these results in Appendix B.

**Classification of Infinite-Width Limits.** Consider now an $L$-hidden-layer perceptron trained using stochastic gradient descent (SGD). TP4 [24] proposes the notion of *an abc-parameterization*, which is specified by a set of numbers $\{a_l, b_l\}_l \cup \{c\}$: (1) each weight is parameterized as $W^l = n^{-a_l} w^l$ for the actual trainable parameter $w^l$, (2) $w^l_{\alpha\beta} \sim \mathcal{N}(0, n^{-2b_l})$ at initialization, and (3) the SGD learning rate is taken as $\eta n^{-c}$ for some constant $\eta$.

When $c$ is too small (i.e. learning rate is too large), SGD can lead to blowup of logits; such a parameterization is called unstable. When $c$ is too large, the function computed by the network does not change with time; such a parameterization is called trivial. The result below follows from Theorem 1:

**Corollary 3** (Dynamical dichotomy; [24])**.** *Any nontrivial stable abc-parameterization yields a (discrete-time) infinite-width limit. This limit either (1) allows the last layer embedding to evolve nontrivially, or (2) is described by kernel gradient descent in function space, but not both.*

The first situation is called feature learning, as opposed to the second one, called kernel learning. Feature learning is argued to be a more sensible learning regime for a neural network.

In TP4, [24] proposed the so-called $\mu$-parameterization, which uniquely exhibits maximal feature learning in the infinite-width limit among all abc-parameterizations. In TP5, [25] generalized this $\mu$-parameterization to the Adam optimizer [7] and a wider class of architectures and used it to facilitate hyperparameter tuning of large models.

Since Dynamical dichotomy (Corollary 3) is a direct consequence of convergence of averages given by Theorem 1, we can readily apply our Theorem 2 for the same purpose:

**Corollary 4** (Dynamical dichotomy; ours)**.** *Consider an $L$-hidden-layer perceptron trained using stochastic gradient descent (SGD) under abc-parameterization, but with $w_l$ sampled independently from a distribution with zero mean, variance $n^{-2b_l}$, and all higher moments existing, for $l = 2, \ldots, L$. Then the statement of Corollary 3 holds.*

The $\mu$-parameterization in this case is the same, and can be recovered by the same argument as in TP4. We therefore theoretically justify the hyperparameter tuning technique used in TP5 for neural networks with non-Gaussian initializations commonly used in practice.

**On potential societal impacts.** Our work concerns generic behavior of neural nets in the limit of infinite width and therefore does not provide any foreseen societal impacts. The only direct practical application of our work we are aware of is theoretical justification for the hyperparameter tuning method of TP5 [25] for non-Gaussian weight initializations. However, what our work provides is merely justification for this method, while the method itself existed before our work (and was well-justified for Gaussian weight initializations).

[2] For more context on NTK theory, see the seminal work of [6].

# 4 Proof of Theorem 2

Denote the matrices, the vectors, and the scalars of our non-Gaussian Tensor Program as $\tilde{A}^{M_0+1}, \dots, \tilde{A}^M$, $\tilde{g}^1, \dots, \tilde{g}^M$, and $\tilde{c}^1, \dots, \tilde{c}^M$, resepctively. Consider the same Tensor Program with Gaussian weights with zero mean and the same variance $n^{-1}$ Denote its matrices as $A^{M_0+1}, \dots, A^M$, vectors as $g^1, \dots, g^M$, and scalars as $c^1, \dots, c^M$. Note that initial vectors and scalars of both programs coincide, i.e. $g^m = \tilde{g}^m$ and $c^m = \tilde{c}^m$ $\forall m \in [M_0]$.

For the sake of brevity, we will denote all the nonlinearities $\phi^m$ by the same letter $\phi$ in the sequel, ignoring the fact that they can be different functions with different number of arguments.

**Limitations of the proof technique of Theorem 1.** Let us first review the idea of Theorem 1 proof, as given in [23]. For simplicity, let us ignore the scalars in the program and assume that each vector is generated with a fresh new matrix each time (i.e. no weights are shared).

Theorem 1 is then proven by induction on $m$. For $m = M_0$, for any polynomially bounded $\phi$, $\frac{1}{n}\sum_\alpha \phi(g^1_\alpha, \dots, g^{M_0}_\alpha) \xrightarrow{\text{a.s.}} \mathbb{E}_{Z\sim\mathcal{N}(\mu^{in},\Sigma^{in})}\phi(Z)$ by Law of Large Numbers (LLN) since $[g^1_\alpha, \dots, g^{M_0}_\alpha] \sim \mathcal{N}(\mu^{in}, \Sigma^{in})$ independently for each coordinate $\alpha \in [n]$.

Suppose $\frac{1}{n}\sum_\beta \phi(g^1_\beta, \dots, g^{m-1}_\beta) \xrightarrow{\text{a.s.}} \mathring{\Psi}_\phi$ for some $\mathring{\Psi}_\phi$, and any polynomially bounded $\phi$. Conditioned on all initial vectors and all previous matrices $A^{M_0+1}, \dots, A^{m-1}$, $g^m_\alpha = \sum_\beta A^m_{\alpha\beta}\phi(g^1_\beta, \dots, g^{m-1}_\beta)$ is Gaussian as a linear combination of Gaussians. Variance of this Gaussian is $\frac{1}{n}\sum_\beta \phi^2(g^1_\beta, \dots, g^{m-1}_\beta)$, which converges almost surely to a deterministic limit $\mathring{\Psi}_{\phi^2}$ by induction hypothesis. Therefore $g^m_\alpha$ converges almost surely to a Gaussian independent on $g^1, \dots, g^{M_0}$ and $A^{M_0+1}, \dots, A^{m-1}$. Of course, $\frac{1}{n}\sum_\beta \phi(g^1_\beta, \dots, g^m_\beta) \xrightarrow{\text{a.s.}} \mathring{\Psi}_\phi$ for some (new) $\mathring{\Psi}_\phi$, and any polynomially bounded $\phi$ then.

If we relax our assumption that no weights are shared, $g^1, \dots, g^{m-1}$ may depend on $A^m$ in the induction step. This situation is treated using a Gaussian conditioning argument, which we do not discuss here. Note that in this case, $g^m_\alpha$ may depend on $g^1_\alpha, \dots, g^{m-1}_\alpha$.

Unfortunately, for non-Gaussian weights $\tilde{A}$, the same argument cannot be applied readily. Indeed, $\tilde{g}^m_\alpha = \sum_\beta \tilde{A}^m_{\alpha\beta}\phi(\tilde{g}^1_\beta, \dots, \tilde{g}^{m-1}_\beta)$ is a sum of dependent non-Gaussian random variables, it does not generally have a closed-form expression as a function of $\frac{1}{n}\sum_\beta \phi(\tilde{g}^1_\beta, \dots, \tilde{g}^{m-1}_\beta)$ for some $\phi$.

We therefore apply a different argument. The idea is to interpolate the weights from the Gaussian ones, for which convergence of $\frac{1}{n}\sum_\alpha \psi(g^1_\alpha, \dots, g^M_\alpha)$ is given by Theorem 1, to the non-Gaussian ones, and show that the above average does not change along this interpolation in the limit of large $n$.

**Our proof.** [1] proved a result similar to our Theorem 2 for approximate message passing; see Appendix E for comparison. Their argument was based on the following weight interpolation: $A^m(t) = \sqrt{1-t}A^m + \sqrt{t}\tilde{A}^m$ $\forall m \in [M_0+1 : M]$. We are going to use the same interpolation technique. Denote the vectors corresponding to $A^{M_0+1}(t), \dots, A^M(t)$ as $g^1(t), \dots, g^M(t)$ and denote the corresponding scalars as $c^1(t), \dots, c^M(t)$. Define

$$\Psi_n(t) = \frac{1}{n}\sum_{\alpha=1}^{n} \psi\left(g^1_\alpha(t), \dots, g^M_\alpha(t), c^1(t), \dots, c^M(t)\right). \tag{4}$$

We are going to prove the following proposition:

**Proposition 1.** $\forall \chi \in Lip(\mathbb{R}) \cap C^1(\mathbb{R})$

$$\sup_{s\in[0,1/\sqrt{2}]} \left|\partial_s \mathbb{E}\left[\chi(\Psi_n(s^2))\right]\right| = O(n^{-1/2}), \qquad \sup_{s\in[0,1/\sqrt{2}]} \left|\partial_s \mathbb{E}\left[\chi(\Psi_n(1-s^2))\right]\right| = O(n^{-1/2}). \tag{5}$$

Once it is proven, we get by dominated convergence,

$$\limsup_{n\to\infty} \left|\mathbb{E}\left[\chi(\Psi_n(1/2))\right] - \mathbb{E}\left[\chi(\Psi_n(0))\right]\right| =$$
$$= \limsup_{n\to\infty} \left|\int_0^{\frac{1}{\sqrt{2}}} \partial_s \mathbb{E}\left[\chi(\Psi_n(s^2))\right] ds\right| = \int_0^{\frac{1}{\sqrt{2}}} \lim_{n\to\infty} \left|\partial_s \mathbb{E}\left[\chi(\Psi_n(s^2))\right]\right| ds = 0. \tag{6}$$

Therefore the limit exists and equals to zero. By a similar argument, we get $\lim_{n\to\infty} |\mathbb{E}[\chi(\Psi_n(1))] - \mathbb{E}[\chi(\Psi_n(1/2))]| = 0$. Hence $\lim_{n\to\infty} |\mathbb{E}[\chi(\Psi_n(1))] - \mathbb{E}[\chi(\Psi_n(0))]| = 0$.

Note that Theorem 1 implies weak convergence of $\Psi(0)$:

$$\lim_{n\to\infty} \mathbb{E}[\chi(\Psi_n(0))] = \chi(\mathring{\Psi}) \qquad \forall \chi \in Lip_b(\mathbb{R}) \cap C^1(\mathbb{R}). \tag{7}$$

The above then means that $\Psi_n(1) = \tilde{\Psi}_n = \frac{1}{n}\sum_{\alpha=1}^{n} \psi\left(\tilde{g}_\alpha^1, \ldots, \tilde{g}_\alpha^M, \tilde{c}^1, \ldots, \tilde{c}^M\right)$ converges weakly to the same quantity, $\mathring{\Psi}$. Since the weak limit is deterministic, weak convergence further upgrades to convergence in probability.

Similarly, if all $\phi$ are linearly bounded and $\psi$ is quadratically bounded, Theorem 1 gives convergence of expectations: $\lim_{n\to\infty} \mathbb{E}[\Psi_n(0)] = \mathring{\Psi}$. From the previous, we have $\lim_{n\to\infty} |\mathbb{E}[\Psi_n(1)] - \mathbb{E}[\Psi_n(0)]| = 0$ by taking $\chi$ to be identity. Therefore $\lim_{n\to\infty} \mathbb{E}[\tilde{\Psi}_n] = \lim_{n\to\infty} \mathbb{E}[\Psi_n(1)] = \mathring{\Psi}$.

*Proof of Proposition 1.* We need the following lemma in order to validate swapping the $s$-derivative and expectation:

**Lemma 1.** $\forall \chi \in Lip(\mathbb{R}) \cap C^1(\mathbb{R})\ \forall n \geq 1$

$$\mathbb{E}\left(\sup_{s\in[0,1/\sqrt{2}]} \left|\partial_s[\chi(\Psi_n(s^2))]\right|\right) < \infty, \qquad \mathbb{E}\left(\sup_{s\in[0,1/\sqrt{2}]} \left|\partial_s[\chi(\Psi_n(1-s^2))]\right|\right) < \infty. \tag{8}$$

For $s \in [0, 1/\sqrt{2}]$, we apply Cauchy-Schwarz and get

$$\left|\partial_s \mathbb{E}[\chi(\Psi_n(s^2))]\right| = \left|\mathbb{E}[\chi'(\Psi_n(s^2))\partial_s\Psi_n(s^2)]\right| \leq \sqrt{\mathbb{E}\left([\chi'(\Psi_n(s^2))]^2\right)\mathbb{E}\left([\partial_s\Psi_n(s^2)]^2\right)}. \tag{9}$$

Similarly, $\left|\partial_s \mathbb{E}[\chi(\Psi_n(1-s^2))]\right| \leq \sqrt{\mathbb{E}\left([\chi'(\Psi_n(1-s^2))]^2\right)\mathbb{E}\left([\partial_s\Psi_n(1-s^2)]^2\right)}$.

Since $\chi$ is Lipschitz and continuously differentiable, $\mathbb{E}\left([\chi'(\Psi_n(s^2))]^2\right)$ and $\mathbb{E}\left([\chi'(\Psi_n(1-s^2))]^2\right)$ are uniformly bounded on $s \in [0, 1/\sqrt{2}]$. We are going to prove the following lemma below:

**Lemma 2.** $\sup_{s\in[0,1/\sqrt{2}]} \mathbb{E}\left([\partial_s\Psi(s^2)]^2\right) = O(n^{-1})$*, and* $\sup_{s\in[0,1/\sqrt{2}]} \mathbb{E}\left([\partial_s\Psi(1-s^2)]^2\right) = O(n^{-1})$.

Once it is proven, the statement of Proposition 1 follows. Indeed,

$$\sup_{s\in[0,1/\sqrt{2}]} \left|\partial_s \mathbb{E}[\chi(\Psi_n(s^2))]\right| \leq \sup_{s\in[0,1/\sqrt{2}]} \sqrt{\mathbb{E}\left([\chi'(\Psi_n(s^2))]^2\right)\mathbb{E}\left([\partial_s\Psi_n(s^2)]^2\right)} = O(n^{-1/2}). \tag{10}$$

The asymptotics of the second limit is given by a similar argument. □

### 4.1 Proof of Lemma 2 in a simple scenario

To make our arguments clear, we illustrate the proof of Lemma 2 on the simplest non-trivial case of $M_0 = 1$, $M = 2$, with no dependence on $c^1$ or $c^2$: $\Psi_n(t) = \frac{1}{n}\sum_\alpha \psi(g_\alpha^1, g_\alpha^2(t))$, $g^2(t) = A(t)\phi(g^1)$, $g^1 \sim \mathcal{N}(0, I)$. The full proofs of Lemmas 1 and 2 can be found in Appendix F.

Consider the exact expression of $\partial_s\Psi_n(s^2)$:

$$\partial_s\Psi_n(s^2) = \frac{1}{n}\sum_\alpha \partial_2\psi\left(g_\alpha^1, \sum_\beta A_{\alpha\beta}(s^2)\phi(g_\beta^1)\right)\sum_\beta \partial_s A_{\alpha\beta}(s^2)\phi(g_\beta^1); \tag{11}$$

the exact expression of $\partial_s\Psi_n(1-s^2)$ is similar. For any finite $n$, Lemma 1 follows from the facts that $\sup_{s\in[0,1]} |a(s^2)| \leq |a| + |\tilde{a}|$, $\sup_{s\in[0,1/\sqrt{2}]} |\partial_s a(s^2)| \leq |a| + |\tilde{a}|$, initial vectors are Gaussian, initial scalars have all moments, and $\phi$ and $\psi$ are polynomially smooth. We do not present the full proof of Lemma 1 in the main due to space constraints.

Lemma 2 follows from the exact expression of $\partial_s \Psi_n(s^2)$ and $\partial_s \Psi_n(1-s^2)$ too:

$$[\partial_s \Psi_n(s^2)]^2 = \frac{1}{n^2} \sum_{\alpha,\beta} \sum_{\tilde{\alpha},\tilde{\beta}} \partial_2 \psi\left(g^1_\alpha, g^2_\alpha(s^2)\right) \partial_2 \psi\left(g^1_{\tilde{\alpha}}, g^2_{\tilde{\alpha}}(s^2)\right) \phi(g^1_\beta)\phi(g^1_{\tilde{\beta}}) \partial_s A_{\alpha\beta}(s^2) \partial_s A_{\tilde{\alpha}\tilde{\beta}}(s^2). \tag{12}$$

Since $g^2(s^2) = A(s^2)\phi(g^1)$ is a function of weights, we can re-write the above expression as

$$[\partial_s \Psi_n(s^2)]^2 = \frac{1}{n^2} \sum_{\alpha,\beta} \sum_{\tilde{\alpha},\tilde{\beta}} f_{\alpha,\beta,\tilde{\alpha},\tilde{\beta}}(A(s^2)) \partial_s A_{\alpha\beta}(s^2) \partial_s A_{\tilde{\alpha}\tilde{\beta}}(s^2), \tag{13}$$

where $f_{\alpha,\beta,\tilde{\alpha},\tilde{\beta}}(A) = \partial_2 \psi\left(g^1_\alpha, (A\phi(g^1))_\alpha\right) \partial_2 \psi\left(g^1_{\tilde{\alpha}}, (A\phi(g^1))_{\tilde{\alpha}}\right) \phi(g^1_\beta)\phi(g^1_{\tilde{\beta}})$.

Since $\mathbb{E}\left[\partial_s A_{\alpha\beta}(s^2) \partial_s A_{\tilde{\alpha}\tilde{\beta}}(s^2)\right] = 0$ if $\alpha \neq \tilde{\alpha}$ or $\beta \neq \tilde{\beta}$ but it is not zero otherwise, it is necessary to study these two cases separately. Let $[\partial_s \Psi_n(s^2)]^2 = \left([\partial_s \Psi_n(s^2)]^2\right)_{1,1} + \left([\partial_s \Psi_n(s^2)]^2\right)_2$, where

$$\left([\partial_s \Psi_n(s^2)]^2\right)_2 = \frac{1}{n^2} \sum_{\alpha,\beta} f_{\alpha,\beta,\alpha,\beta}(A(s^2)) \left[\partial_s A_{\alpha\beta}(s^2)\right]^2, \tag{14}$$

and

$$\left([\partial_s \Psi_n(s^2)]^2\right)_{1,1} = \frac{1}{n^2} \sum_{\substack{\alpha,\beta,\tilde{\alpha},\tilde{\beta}: \\ \alpha \neq \tilde{\alpha} \text{ or } \beta \neq \tilde{\beta}}} f_{\alpha,\beta,\tilde{\alpha},\tilde{\beta}}(A(s^2)) \partial_s A_{\alpha\beta}(s^2) \partial_s A_{\tilde{\alpha}\tilde{\beta}}(s^2). \tag{15}$$

We can write the sums over indices as sums over sets $\Gamma^{(2)} = \{(\alpha,\beta,\tilde{\alpha},\tilde{\beta}) : \ \alpha = \tilde{\alpha},\ \beta = \tilde{\beta}\}$ and $\Gamma^{(1,1)} = \{(\alpha,\beta,\tilde{\alpha},\tilde{\beta}) : \ \alpha \neq \tilde{\alpha} \text{ or } \beta \neq \tilde{\beta}\}$. For every configuration $(\alpha,\beta,\tilde{\alpha},\tilde{\beta}) \in \Gamma^{(1,1)}$, enumerate the set of all (distinct) weights $\{A_{\alpha\beta}\}_{\alpha,\beta=1}^n$ in such a way that $a_1 = A_{\alpha\beta}$ and $a_2 = A_{\tilde{\alpha}\tilde{\beta}}$; the order of the rest can be arbitrary. Similarly, for every configuration $(\alpha,\beta,\tilde{\alpha},\tilde{\beta}) \in \Gamma^{(2)}$, enumerate the set of all weights $\{A_{\alpha\beta}\}_{\alpha,\beta=1}^n$ in such a way that $a_1 = A_{\alpha\beta} = A_{\tilde{\alpha}\tilde{\beta}}$. Recall $N$ is the number of all distinct weights; in our illustrative example, $N = n^2$. The above expressions take the following form:

$$\left([\partial_s \Psi_n(s^2)]^2\right)_2 = \frac{1}{n^2} \sum_{u \in \Gamma^{(2)}} f_u(a_1(s^2), \ldots, a_N(s^2)) \left[\partial_s a_1(s^2)\right]^2, \tag{16}$$

and

$$\left([\partial_s \Psi_n(s^2)]^2\right)_{1,1} = \frac{1}{n^2} \sum_{u \in \Gamma^{(1,1)}} f_u(a_1(s^2), \ldots, a_N(s^2)) \partial_s a_1(s^2) \partial_s a_2(s^2). \tag{17}$$

Since we are interested in $\mathbb{E}\left([\partial_s \Psi_n(s^2)]^2\right) \leq \mathbb{E}\left(\left([\partial_s \Psi_n(s^2)]^2\right)_2\right) + \mathbb{E}\left(\left([\partial_s \Psi_n(s^2)]^2\right)_{1,1}\right)$, we need upper-bounds for the following expectations:

$$\mathbb{E}\left(\left([\partial_s \Psi_n(s^2)]^2\right)_2\right) \leq n^{-2} \left|\Gamma^{(2)}\right| \sup_{u \in \Gamma^{(2)}} \left|\mathbb{E}\left(f_u(a_1(s^2), \ldots, a_N(s^2)) \left[\partial_s a_1(s^2)\right]^2\right)\right|; \tag{18}$$

$$\mathbb{E}\left(\left([\partial_s \Psi_n(s^2)]^2\right)_{1,1}\right) \leq n^{-2} \left|\Gamma^{(1,1)}\right| \sup_{u \in \Gamma^{(1,1)}} \left|\mathbb{E}\left(f_u(a_1(s^2), \ldots, a_N(s^2)) \partial_s a_1(s^2) \partial_s a_2(s^2)\right)\right|, \tag{19}$$

uniform on $s \in [0, 1/\sqrt{2}]$. In our simple example, cardinalities of Gamma-terms can be easily bounded using their definitions: $\left|\Gamma^{(2)}\right| \leq n^2$ and $\left|\Gamma^{(1,1)}\right| \leq n^4$.

Let us bound $\sup_{u \in \Gamma^{(1,1)}} \left|\mathbb{E}\left(f_u(a_1(s^2), \ldots, a_N(s^2)) \partial_s a_1(s^2) \partial_s a_2(s^2)\right)\right|$. We start with Taylor-expanding $f_u$ wrt the first two arguments up to some order $K$ to be specified later:

$$f_u(x_1, \ldots, x_N) = \sum_{k=0}^{K} \frac{1}{k!} \sum_{j_1, j_2 \geq 0,\ j_1 + j_2 = k} [x_1]^{j_1} [x_2]^{j_2} \times \partial_1^{j_1} \partial_2^{j_2} f_u(0, 0, x_3, \ldots, x_N) +$$
$$+ \frac{1}{K!} \sum_{j_1, j_2 \geq 0,\ j_1 + j_2 = K+1} [x_1]^{j_1} [x_2]^{j_2} \times \int_0^1 \partial_1^{j_1} \partial_2^{j_2} f_u(\xi x_1, \xi x_2, x_3, \ldots, x_N)\, d\xi. \tag{20}$$

The expectation we are interested in therefore takes the following form:

$$\mathbb{E}\left[f_u(a_1,\dots,a_N)[\partial_s a_1][\partial_s a_2]\right] =$$
$$= \sum_{k=0}^{K} \frac{1}{k!} \sum_{\substack{j_1,j_2\geq 0,\\ j_1+j_2=k}} \mathbb{E}\left[[\partial_s a_1][\partial_s a_2][a_1]^{j_1}[a_2]^{j_2}\right] \times \mathbb{E}\left[\partial_1^{j_1}\partial_2^{j_2} f_u(0,0,a_3,\dots,a_N)\right] +$$
$$+ \frac{1}{K!} \sum_{\substack{j_1,j_2\geq 0,\\ j_1+j_2=K+1}} \mathbb{E}\left[[\partial_s a_1][\partial_s a_2][a_1]^{j_1}[a_2]^{j_2} \times \int_0^1 \partial_1^{j_1}\partial_2^{j_2} f_u(\xi a_1,\xi a_2,a_3,\dots,a_N)\,d\xi\right], \quad (21)$$

where we have omitted $s^2$ in the arguments of $a$'s for brevity.

We split the expectation of the remainder term using Cauchy-Schwarz:

$$\left|\mathbb{E}\left[[\partial_s a_1][\partial_s a_2][a_1]^{j_1}[a_2]^{j_2} \times \int_0^1 \partial_1^{j_1}\partial_2^{j_2} f_u(\xi a_1,\xi a_2,a_3,\dots,a_N)\,d\xi\right]\right| \leq$$
$$\leq \sqrt{\mathbb{E}\left[([\partial_s a_1][\partial_s a_2][a_1]^{j_1}[a_2]^{j_2})^2\right] \times \mathbb{E}\left[\left(\int_0^1 \partial_1^{j_1}\partial_2^{j_2} f_u(\xi a_1,\xi a_2,a_3,\dots,a_N)\,d\xi\right)^2\right]}. \quad (22)$$

We claim that $\mathbb{E}\left[\partial_1^{j_1}\partial_2^{j_2} f_u(0,0,a_3,\dots,a_N)\right]$ and $\mathbb{E}\left[\left(\int_0^1 \partial_1^{j_1}\partial_2^{j_2} f_u(\xi a_1,\xi a_2,a_3,\dots,a_N)\,d\xi\right)^2\right]$ are bounded uniformly over $u \in \Gamma^{(1,1)}$, $\xi \in [0,1]$, and $s \in [0,1/\sqrt{2}]$. This claim follows from Lemma 9, the main technical lemma of the present work, proven in Appendix H.4.

We are left to bounding $\mathbb{E}\left[[\partial_s a_1][\partial_s a_2][a_1]^{j_1}[a_2]^{j_2}\right]$ and $\mathbb{E}\left[\left([\partial_s a_1][\partial_s a_2][a_1]^{j_1}[a_2]^{j_2}\right)^2\right]$ uniformly on $s \in [0,1/\sqrt{2}]$. We prove the following Lemma in Appendix G.1:

**Lemma 3.** *Let $a$ and $\tilde{a}$ be independent random variables with zero mean, variance $n^{-1}$, and all higher moments existing. Define $a(t) = \sqrt{1-t}a + \sqrt{t}\tilde{a}$. The following holds:*

1. $\mathbb{E}\left[\partial_s a(s^2)\right] = \mathbb{E}\left[\partial_s a(1-s^2)\right] = 0\ \forall s \in [0,1)$;
2. $\mathbb{E}\left[a(s^2)\partial_s a(s^2)\right] = \mathbb{E}\left[a(1-s^2)\partial_s a(1-s^2)\right] = 0\ \forall s \in [0,1)$;
3. $\sup_{s\in[0,1/\sqrt{2}]}\left(\mathbb{E}\left[\left|[a(s^2)]^j\partial_s a(s^2)\right|^k\right]\right) = O\left(n^{-(j+1)k/2}\right)$, *and*
   $\sup_{s\in[0,1/\sqrt{2}]}\left(\mathbb{E}\left[\left|[a(1-s^2)]^j\partial_s a(1-s^2)\right|^k\right]\right) = O\left(n^{-(j+1)k/2}\right)\ \forall j \geq 0\ \forall k \geq 0.$

This gives $\mathbb{E}\left[[\partial_s a_1][\partial_s a_2][a_1]^{j_1}[a_2]^{j_2}\right] = 1_{j_1\geq 2}1_{j_2\geq 2}O\left(n^{-(2+j_1+j_2)/2}\right)$ and $\mathbb{E}\left[\left([\partial_s a_1][\partial_s a_2][a_1]^{j_1}[a_2]^{j_2}\right)^2\right] = O\left(n^{-(2+j_1+j_2)}\right)$, both uniformly over $s \in [0,1/\sqrt{2}]$. This implies that the first four terms in our Taylor expansion zero-out:

$$\sum_{\substack{j_1,j_2\geq 0,\\ j_1+j_2=k}} \mathbb{E}\left[[\partial_s a_1][\partial_s a_2][a_1]^{j_1}[a_2]^{j_2}\right] \times \mathbb{E}\left[\partial_1^{j_1}\partial_2^{j_2} f_u(0,0,a_3,\dots,a_N)\right] = 1_{k\geq 4}O\left(n^{-(2+k)/2}\right) \quad (23)$$

uniformly over $s \in [0,1/\sqrt{2}]$. Taking $K=3$, we get:

$$\mathbb{E}\left[f_u(a_1,\dots,a_N)[\partial_s a_1][\partial_s a_2]\right] \leq$$
$$\leq \frac{1}{3!}\sum_{\substack{j_1,j_2\geq 0,\\ j_1+j_2=4}} \sqrt{\mathbb{E}\left[([\partial_s a_1][\partial_s a_2][a_1]^{j_1}[a_2]^{j_2})^2\right] \times \mathbb{E}\left[\left(\int_0^1 \partial_1^{j_1}\partial_2^{j_2} f_u(\xi a_1,\xi a_2,a_{3:N})\,d\xi\right)^2\right]} =$$
$$= O(n^{-(2+4)/2}) = O(n^{-3}) \quad (24)$$

uniformly over $u \in \Gamma^{(1,1)}$ and $s \in [0,1/\sqrt{2}]$. From Eq. (19), $\mathbb{E}\left(\left([\partial_s \Psi_n(s^2)]^2\right)_{1,1}\right) \leq n^{-2}\left|\Gamma^{(1,1)}\right| O(n^{-3}) = O(n^{-1})$ uniformly over $s \in [0,1/\sqrt{2}]$.

In order to upper-bound $\mathbb{E}\left[f_u(a_1,\ldots,a_N)[\partial_s a_1]^2\right]$ in our simple case, it suffices to directly apply Cauchy-Schwarz:

$$\mathbb{E}\left[f_u(a_1,\ldots,a_N)[\partial_s a_1]^2\right] \leq \sqrt{\mathbb{E}\left([\partial_s a_1]^4\right) \times \mathbb{E}\left([f_u(a_1,\ldots,a_N)]^2\right)} = O(n^{-1}) \tag{25}$$

uniformly over $u \in \Gamma^{(2)}$ and $s \in [0, 1/\sqrt{2}]$. From Eq. (18), $\mathbb{E}\left(\left([\partial_s \Psi_n(s^2)]^2\right)_2\right) \leq n^{-2}\left|\Gamma^{(2)}\right| O(n^{-1}) = O(n^{-1})$ uniformly over $s \in [0, 1/\sqrt{2}]$. This gives $\mathbb{E}\left([\partial_s \Psi_n(s^2)]^2\right) = O(n^{-1})$ uniformly over $s \in [0, 1/\sqrt{2}]$.

# 5 Related works

The Tensor Programs series discusses different applications of the (Gaussian) Master theorem proven by [20]. They include: Gaussian process behavior at initialization (TP1, [21]), convergence to a kernel method (TP2, [22]), Free Independence Principle (TP3, [23]), dynamical dichotomy and $\mu$-parameterization (TP4, [24]), and finally application of $\mu$P to hyperparameter tuning (TP5, [25]).

Neural networks converge to Gaussian processes as their width goes to infinity, as was proven by [8, 9] for fully-connected nets, and by [11, 2] for convolutional nets; see also [5]. Using the Master theorem, [21] showed that this behavior holds for a very wide class of architectures, including not only convolutional, but also graph convolutional and recurrent neural nets, ResNets, networks with batch normalization, and networks with attention.

The seminal work of [6] demonstrated that under certain parameterization, the learning dynamics a neural net converges to that of a kernel method. The corresponding kernel was called Neural Tangent Kernel, or NTK, and drawn a lot of attention in recent years. While the result of [6] was proven only for fully-connected nets with smooth activations, the Master theorem allows to generalize this result for a wider class of architectures (the same as mentioned above), see [22].

[16, 15, 19] and others studied trainability of very deep and wide neural networks using random matrix theory. Their analysis crucially relied on the assumption that hidden representations of a neural network at initialization were *freely independent* from the weights. TP3 [23] was among the first works to validate this assumption rigorously; see also [12].

Infinite-width behavior of a neural net depends on scaling of its hyperparameters (like initial weights variance and learning rate) with width. Dynamical dichotomy proposed in TP4 [24] is a classification of scalings that are meaningful in a certain sense. Another classification of scalings with a different notion of meaningfulness was proposed earlier by [3, 4], but only for two-layered networks.

A distribution universality property similar to our Theorem 2 was shown by [1] for approximate messaging passing. However, their model does not cover most of possible neural network computations; see Appendix E for discussion.

# 6 Limitations of our results

First, our Theorem 2 is applicable only to Tensor Programs with smooth nonlinearities, which draws out several popular activation functions like ReLU or MaxPool. Our Theorem 9 (see Appendix C) does not really solve the issue since a Tensor Program expressing the backward pass involves derivatives of the activation functions, which are not even continuous for ReLU. As a workaround, we could consider their smoothed versions (e.g. Softplus instead of ReLU) with a controllable smoothness parameter, and put this parameter very close to zero, thus getting "almost ReLU".

Second, we prove convergence in probability, which is weaker than almost sure convergence that holds in the Gaussian case. Because of this, we are only able to prove a weaker (but more traditional) version of the semi-circle law and Free Independence Principle, compared to TP3 [23]; see Appendix B.

# 7 Conclusions

We present a generalization of the Master theorem of [20] to non-Gaussian weight initializations. Our generalization allows for the same applications as the original Master theorem, thus broadening the scope of applicability of the Tensor Programs machinery.

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# Checklist

1. For all authors...
   (a) Do the main claims made in the abstract and introduction accurately reflect the paper's contributions and scope? [Yes] See Section 2 for scope and Section 2, 3, and 4 for contributions.
   (b) Did you describe the limitations of your work? [Yes] See Section 6.
   (c) Did you discuss any potential negative societal impacts of your work? [Yes] See the last paragraph of Section 3.
   (d) Have you read the ethics review guidelines and ensured that your paper conforms to them? [Yes]
2. If you are including theoretical results...
   (a) Did you state the full set of assumptions of all theoretical results? [Yes] See Section 2 and Setup 2 in particular.
   (b) Did you include complete proofs of all theoretical results? [Yes] See Section 4 and Appendices C and F to H.
3. If you ran experiments...
   (a) Did you include the code, data, and instructions needed to reproduce the main experimental results (either in the supplemental material or as a URL)? [N/A]
   (b) Did you specify all the training details (e.g., data splits, hyperparameters, how they were chosen)? [N/A]
   (c) Did you report error bars (e.g., with respect to the random seed after running experiments multiple times)? [N/A]
   (d) Did you include the total amount of compute and the type of resources used (e.g., type of GPUs, internal cluster, or cloud provider)? [N/A]
4. If you are using existing assets (e.g., code, data, models) or curating/releasing new assets...
   (a) If your work uses existing assets, did you cite the creators? [N/A]
   (b) Did you mention the license of the assets? [N/A]

(c) Did you include any new assets either in the supplemental material or as a URL? [N/A]

(d) Did you discuss whether and how consent was obtained from people whose data you're using/curating? [N/A]

(e) Did you discuss whether the data you are using/curating contains personally identifiable information or offensive content? [N/A]

5. If you used crowdsourcing or conducted research with human subjects...

(a) Did you include the full text of instructions given to participants and screenshots, if applicable? [N/A]

(b) Did you describe any potential participant risks, with links to Institutional Review Board (IRB) approvals, if applicable? [N/A]

(c) Did you include the estimated hourly wage paid to participants and the total amount spent on participant compensation? [N/A]

# A On Gaussian Initial Vectors

While Setup 2 assumes all initial vectors to be Gaussian, it does not constrain us to have Gaussian initial bias vectors, or Gaussian initial input layer weights. Indeed, as, say, initial bias vectors, we can use images of Gaussian input vectors of the program under polynomially smooth maps. These elementwise maps can be then absorbed into subsequent nonlinearities that use those input vectors.

# B Additional applications of Theorem 2

TP3 demonstrates the following applications of Theorem 1: the semi-circle law for Gaussian orthogonal ensembles (GOE), the Marchenko-Pastur law for Wishart ensembles, and the free independence principle for neural nets with Gaussian initialization. Here we prove results of a similar kind in general, not necessarily Gaussian, setup. For the Gaussian case, our results are, however, weaker as we are not able to prove almost sure convergence without relying on Gaussianity. Nevertheless, while being weaker, they have more traditional forms, compared to the ones of [23], as we demonstrate below.

**Semicircle law for non-Gaussian Wigner ensembles.** The semicircle law for GOE proven in [23] is the following result:

**Theorem 3.** *For each $n \geq 1$, define the random matrix $A = W + W^\top$ for iid Gaussian matrix $W \in \mathbb{R}^{n\times n}$, $W_{\alpha\beta} \sim \mathcal{N}(0, 1/2n)$. Let $\lambda_1, \ldots, \lambda_n \in \mathbb{R}$ be the eigenvalues of $A$ and $\mu_n = \frac{1}{n}\sum_{\alpha=1}^n \delta_{\lambda_\alpha}$ be their empirical distribution. Then $\mu_n \xrightarrow{a.s.} \mu_{sc}$, where $\mu_{sc}$ is the distribution with density $\propto \sqrt{4-x^2}$.*

Here by almost sure (weak) convergence of measures we mean that for every compactly supported, continuous $\phi : \mathbb{R} \to \mathbb{R}$, as $n \to \infty$, we have

$$\frac{1}{n}\sum_{\alpha=1}^n \phi(\lambda_\alpha) \xrightarrow{\text{a.s.}} \mathbb{E}_{\lambda\sim\mu_{sc}}\phi(\lambda). \tag{26}$$

In order to be able to apply Tensor Programs machinery to prove this result, [23] uses the moment method which states that it suffices to prove almost sure convergene of moments of $\mu_n$:

$$\mathbb{E}_{\lambda\sim\mu_n}\lambda^r = \frac{1}{n}\sum_{\alpha=1}^n \lambda_\alpha^r = n^{-1}\operatorname{tr}(A^r) \xrightarrow{\text{a.s.}} \mathbb{E}_{\lambda\sim\mu_{sc}}\lambda^r \quad \forall r \in \mathbb{N}. \tag{27}$$

The trace can be expressed as $\operatorname{tr}(A^r) = \mathbb{E}_z[z^\top A^r z]$ for $z_\alpha \sim \mathcal{N}(0,1)$ iid for each $\alpha \in [n]$. For Gaussian $z$, $A^r z$ can be expressed as a vector in the following Tensor Program:

$$g^1 = z, \quad g^{2k} = W(g^{2k-1} + g^{2k-2}), \quad g^{2k+1} = W^T(g^{2k-1} + g^{2k-2}) \quad \forall k \in [r]. \tag{28}$$

Here each nonlinearity simply adds two vectors. Note that these nonlinearities are linear polynomials. Then we get

$$n^{-1}\operatorname{tr}(A^r) = \frac{1}{n}\mathbb{E}_{z\sim\mathcal{N}(0,1)}[z^\top A^r z] =$$
$$= \frac{1}{n}\sum_{\alpha=1}^{n}\mathbb{E}_{g_\alpha^1\sim\mathcal{N}(0,1)}\left[g_\alpha^1\left(g_\alpha^{2r}+g_\alpha^{2r+1}\right)\right] = \frac{1}{n}\sum_{\alpha=1}^{n}\mathbb{E}_{g_\alpha^1\sim\mathcal{N}(0,1)}\psi(g_\alpha^1,\ldots,g_\alpha^{2r+1}), \quad (29)$$

where $\psi(x_1,\ldots,x_{2r+1}) = x_1(x_{2r}+x_{2r+1})$ — a quadratic polynomial.

The only thing that prevents us from directly applying Theorem 1 to the expression above is conditional expectation. [23] proves the following conditional theorem:

**Theorem 4** ([23])**.** *Consider Setup 1 and assume $\psi$ is quadratically bounded and all the nonlinearities are linearly bounded. Let $S$ be a subset of initial vector. Then, as $n\to\infty$,*

$$\frac{1}{n}\sum_{\alpha=1}^{n}\mathbb{E}_S\psi\left(g_\alpha^1,\ldots,g_\alpha^M,c^1,\ldots,c^M\right) \xrightarrow{a.s.} \mathring{\Psi}, \quad (30)$$

*where $\mathring{\Psi}$ is the same as in Theorem 1.*

Therefore $n^{-1}\operatorname{tr}(A^r) \xrightarrow{\text{a.s.}} \mathring{\Psi}$ for certain $\mathring{\Psi}$. Comparing with Eq. (27), what remains to establish Theorem 3 is to prove that $\mathring{\Psi}$ equals to the $r$-th moment of the semicircle law. It was proven in [23] and we do not reproduce it here.

Using the same technique as in the proof of our Theorem 2, we could prove a result similar to Theorem 4, but without Gaussian assumption. A corrolary would be

$$\mathbb{E}_{\tilde\lambda\sim\tilde\mu_n}\tilde\lambda^r = \frac{1}{n}\sum_{\alpha=1}^{n}\tilde\lambda_\alpha^r = n^{-1}\operatorname{tr}(\tilde A^r) \to \mathbb{E}_{\lambda\sim\mu_{sc}}\lambda^r \quad \text{in prob.} \quad \forall r\in\mathbb{N}, \quad (31)$$

where $\tilde A = \tilde W + \tilde W^\top$ and $\tilde W$ is an $n\times n$ matrix with iid entries with zero mean, variance $1/(2n)$, and with all higher moments existing. However, since the result above is in-probability, it does not correspond to any commonly-used notion of random measure convergence. Nevertheless, apart from convergence in probability, our Theorem 2 gives also convergence of expectations which implies

$$\mathbb{E}_{\tilde\mu_n}\mathbb{E}_{\tilde\lambda\sim\tilde\mu_n}\tilde\lambda^r = \mathbb{E}_{\tilde\mu_n}\left(\frac{1}{n}\sum_{\alpha=1}^{n}\tilde\lambda_\alpha^r\right) = n^{-1}\mathbb{E}_{\tilde A}\operatorname{tr}(\tilde A^r) \to \mathbb{E}_{\lambda\sim\mu_{sc}}\lambda^r \quad \forall r\in\mathbb{N}. \quad (32)$$

This is equivalent to weak convergence of expected measures, as stated in the following theorem:

**Theorem 5** (Ours)**.** *For each $n\geq 1$, define the random matrix $\tilde A = \tilde W + \tilde W^\top$ for $\tilde W$ being an $n\times n$ matrix with iid entries with zero mean, variance $1/(2n)$, and with all higher moments existing. Let $\tilde\lambda_1,\ldots,\tilde\lambda_n\in\mathbb{R}$ be the eigenvalues of $\tilde A$ and $\tilde\mu_n = \frac{1}{n}\sum_{\alpha=1}^{n}\delta_{\tilde\lambda_\alpha}$ be their empirical distribution. Then $\mathbb{E}\,\tilde\mu_n \Rightarrow \mu_{sc}$, where $\mu_{sc}$ is the distribution with density $\propto\sqrt{4-x^2}$.*

This result follows from the expression of an expected trace as an expectation of a certain $\psi$-function as a Tensor Program:

$$n^{-1}\mathbb{E}_{\tilde A}\operatorname{tr}(\tilde A^r) = \frac{1}{n}\mathbb{E}_{\tilde A}\mathbb{E}_{z\sim\mathcal{N}(0,1)}[z^\top\tilde A^r z] =$$
$$= \frac{1}{n}\sum_{\alpha=1}^{n}\mathbb{E}_{\tilde W}\mathbb{E}_{\tilde g_\alpha^1\sim\mathcal{N}(0,1)}\left[\tilde g_\alpha^1\left(\tilde g_\alpha^{2r}+\tilde g_\alpha^{2r+1}\right)\right] = \frac{1}{n}\sum_{\alpha=1}^{n}\mathbb{E}\,\psi(\tilde g_\alpha^1,\ldots,\tilde g_\alpha^{2r+1}), \quad (33)$$

where again $\psi(x_1,\ldots,x_{2r+1}) = x_1(x_{2r}+x_{2r+1})$. Its convergence is given by our Theorem 2.

Since the Tensor Program is the same as the one used in Theorem 3, the limit is the same too. This means we have just proven Eq. (32) and thus Theorem 5.

**Marchenko-Pastur law for non-Gaussian Wishart ensembles.** Using exactly the same machinery as for the semi-circle law, [23] proves the Marchenko-Pastur law for Wishart ensembles, i.e. for matrices of the form $AA^\top$, where $A$ is an $m \times n$ Gaussian matrix with zero mean and variance $n^{-1}$, and $m/n \to \rho \in (0, \infty)$ as $n \to \infty$. Our Theorem 2 (with a remark on programs with variable dimensions, see Section 2) gives a similar result with no assumptions on Gaussianity of $A$:

**Theorem 6** (Ours)**.** *For each $n \geq 1$, let $\tilde{A}$ be an $m \times n$ matrix with iid entries with zero mean, variance $1/n$, and with all higher moments existing. Let $\tilde{\lambda}_1, \ldots, \tilde{\lambda}_n \in \mathbb{R}$ be the eigenvalues of $\tilde{A}\tilde{A}^\top$ and $\tilde{\mu}_n = \frac{1}{n}\sum_{\alpha=1}^n \delta_{\tilde{\lambda}_\alpha}$ be their empirical distribution. Let $m$ go to infinity as $n \to \infty$ such that $m/n \to \rho \in (0, \infty)$. Then $\mathbb{E}\,\tilde{\mu}_n \Rightarrow \mu_{mp}$, where $\mu_{mp}$ has "density" $p_{mp}(x)$ given below:*

$$p_{mp}(x) = \max(0, 1 - \rho^{-1})\delta(x) + \frac{1}{\rho 2\pi x}\sqrt{(b-x)(x-a)}1_{x\in[a,b]}, \tag{34}$$

*where $\delta(x)$ is the Dirac Delta, $a = (1 - \sqrt{\rho})^2$, and $b = (1 + \sqrt{\rho})^2$.*

**Free Indepedence Principle for Tensor Programs with non-Gaussian weights.** Using the same machinery again, [23] proves Free Independence Principle for Tensor Programs:

**Theorem 7** ([23])**.** *Consider Setup 1. Let $\mathcal{D}$ denote the collection of diagonal matrices formed from bounded coordinatewise images of vectors in the program:*

$$\mathcal{D} = \left\{\operatorname{diag}\left(\psi\left(g^1, \ldots, g^M\right)\right) : \ \psi : \mathbb{R}^M \to \mathbb{R} \text{ is bounded}\right\}. \tag{35}$$

*Then $\mathcal{D}$, along with the random matrix collections $\{A, A^\top\}$ for all matrices in the program are almost surely asymptotically free as $n \to \infty$.*

Here by almost sure asymptotical freeness we mean the following:

**Definition 2.** *Fix $k$. Consider collections of random matrices $\mathcal{W}_n^1, \ldots, \mathcal{W}_n^k \subseteq \mathbb{R}^{n\times n}$ for each $n \geq 1$, of constant cardinalities (with $n$). We say $\mathcal{W}_n^1, \ldots, \mathcal{W}_n^k$ are almost surely asymptotically freely independent (or just almost surely asymptotically free), if*

$$n^{-1}\operatorname{tr}\left(\prod_{i=1}^k \left(P_i(\mathcal{W}_n^{j_i}) - \tau_i\right)\right) \xrightarrow{a.s.} 0, \tag{36}$$

*where $\tau_i = n^{-1}\operatorname{tr}(P_i(\mathcal{W}_n^{j_i}))$, $P_i$ is a non-commutative polynomial in $|\mathcal{W}_n^{j_i}|$ variables, $j_1, \ldots, j_k \in [k]$ are indices with no two adjacent $j_i$ equal, and $\{P_i\}_i$, $\{j_i\}_i$ independent on $n$.*

The proof strategy for Theorem 7 is very similar to the one of Theorem 3. The trace in each $\tau_i$ can be expressed as an expectation $\mathbb{E}_{z\sim\mathcal{N}(0,1)}[z^\top P_i(\mathcal{W}_n^{j_i})z]$ and $P_i(\mathcal{W}_n^{j_i})z$ can be expressed as a vector. Therefore each $\tau_i$ can be thought as a scalar in a new Tensor Program, and the "outer" trace in Eq. (36) can be expressed as conditional expectation using the same trick. We refer the reader to [23] for details.

For the same reasons as before, we are not able to prove almost sure asymptotical freeness for non-Gaussian Tensor Programs. Nevertheless, we are able to prove more traditional asymptotical freeness in expectation in our non-Gaussian case:

**Definition 3.** *Fix $k$. Consider collections of random matrices $\mathcal{W}_n^1, \ldots, \mathcal{W}_n^k \subseteq \mathbb{R}^{n\times n}$ for each $n \geq 1$, of constant cardinalities (with $n$). We say $\mathcal{W}_n^1, \ldots, \mathcal{W}_n^k$ are asymptotically freely independent in expectation (or just asymptotically free), if*

$$n^{-1}\mathbb{E}\left[\operatorname{tr}\left(\prod_{i=1}^k \left(P_i(\mathcal{W}_n^{j_i}) - \tau_i\right)\right)\right] \to 0, \tag{37}$$

*where $\tau_i = n^{-1}\mathbb{E}\operatorname{tr}(P_i(\mathcal{W}_n^{j_i}))$, $P_i$ is a non-commutative polynomial in $|\mathcal{W}_n^{j_i}|$ variables, $j_1, \ldots, j_k \in [k]$ are indices with no two adjacent $j_i$ equal, and $\{P_i\}_i$, $\{j_i\}_i$ independent on $n$.*

**Theorem 8** (ours)**.** *Consider Setup 2 and assume all nonlinearities to be linearly bounded. Let $\tilde{\mathcal{D}}$ denote the collection of diagonal matrices formed from bounded polynomially smooth coordinatewise images of vectors in the program:*

$$\tilde{\mathcal{D}} = \left\{\operatorname{diag}\left(\psi\left(\tilde{g}^1, \ldots, \tilde{g}^M\right)\right) : \ \psi : \mathbb{R}^M \to \mathbb{R} \text{ is bounded}\right\}. \tag{38}$$

*Then $\tilde{\mathcal{D}}$, along with the random matrix collections $\{\tilde{A}, \tilde{A}^\top\}$ for all matrices in the program are asymptotically free in expectation as $n \to \infty$.*

Using the same trick as for the semi-circle law, each $\tau_i$ can be expressed as an expectation of an empirical average of a certain (quadratically bounded) $\psi$-function for a Tensor Program with linearly bounded polynomially smooth nonlinearities. Therefore its convergence is given by our Theorem 2 and the limit is the same as in the Gaussian case. Thinking about each $\tau_i$ as a scalar in a new Tensor Program, we can express Eq. (37) again as an expectation of an empirical average of a certain (quadratically bounded) $\psi$-function for this new Tensor Program with linearly bounded polynomially smooth nonlinearities. Its convergence is given by the same theorem and the limit is the same as in the Gaussian case, i.e. zero.

# C Non-Gaussian Master theorem for Lipschitz nonlinearities

One of the limitations of our Theorem 2 is smoothness requirement. In the present section, we prove a similar result that assumes nonlinearities to be Lipschitz but not necessarily smooth:

**Setup 4.** *Consider a Tensor Program of width $n$ with $M$ vectors $\tilde{g}^1, \dots, \tilde{g}^M$ and $M$ scalars $\tilde{c}^1, \dots, \tilde{c}^M$. Suppose 1) all initial vectors $\tilde{g}^1, \dots, \tilde{g}^{M_0}$ are sampled as $(\tilde{g}^1_\alpha, \dots, \tilde{g}^{M_0}_\alpha) \sim \mathcal{N}(\mu^{in}, \Sigma^{in})$ iid over $\alpha = 1, \dots, n$, for some $\mu^{in} \in \mathbb{R}^{M_0}, \Sigma^{in} \in \mathbb{R}^{M_0 \times M_0}$; 2) all the initial scalars have a.s. limits as $n \to \infty$ and all their moments exist and converge; 3) all the matrices are sampled independently from a sub-Gaussian distribution with zero mean and variance $n^{-1}$; 4) any two matrices $\tilde{A}^m, \tilde{A}^l$ are either equal or independently sampled; 5) all the nonlinearities $\phi$ in the program are Lipschitz.*

**Theorem 9** (Ours)**.** *Consider Setup 4. Then, as $n \to \infty$, for any Lipschitz $\psi : \mathbb{R}^M \to \mathbb{R}$,*

$$\frac{1}{n} \sum_{\alpha=1}^{n} \psi(\tilde{g}^1_\alpha, \dots, \tilde{g}^M_\alpha, \tilde{c}^1, \dots, \tilde{c}^M) \xrightarrow{prob.} \mathring{\Psi} \tag{39}$$

*with the same $\mathring{\Psi}$ as in Theorem 1. Moreover, the expectation of the LHS of Eq.* (39) *converges to the RHS.*

The following result is an immediate consequence of the above theorem:

**Corollary 5** (Convergence to GP at initialization)**.** *Consider a neural network under Setup 3 with 1) and 6) replaced with the following: 1*) all activation functions are Lipschitz; 6*) weights of any layer except for the input and output ones are initialized iid from a* ***sub-Gaussian*** *distribution with zero mean and variance inversely proportional to the number of input neurons of this layer. Then the (pre-activation) output of any neuron in the network converges in distribution to a Gaussian process.*

*Proof.* We use the fact that when all matrices in Eq. (1) are not transposed, the limit in Theorem 1 (and hence in our Theorem 9) takes the form $\mathring{\Psi} = \mathbb{E}_{z \sim \mathcal{N}(\mu, \Sigma)} \psi(z)$, where $\mu$ and $\Sigma$ are computed using a certain recurrent formula; see [21].

Let $g^1, \dots, g^B$ be the pre-activation outputs of a given layer on a batch of inputs of size $B$. Let $\psi$ be Lipschitz and bounded, and depend only on these $B$ vectors. Then for any $\alpha \in [n]$, by symmetry of neurons, $\mathbb{E}\left[\psi(g^1_\alpha, \dots, g^B_\alpha)\right] \to \mathbb{E}_{z \sim \mathcal{N}(\mu, \Sigma)} \psi(z)$ from Theorem 9. This means that on any batch of inputs of size $B$, outputs of a given neuron $g^1_\alpha, \dots, g^B_\alpha$ converge weakly to a Gaussian vector. This means that the output of this neuron converges weakly to a Gaussian process as a function of network's input. □

The proof of Theorem 9 is based on interpolating Lipschitz nonlinearities with linearly smooth ones. The following lemma constructs the required interpolation:

**Lemma 4.** *Let $\phi : \mathbb{R}^k \to \mathbb{R}$ be Lipschitz with Lipschitz constant $L$. Then there exists a family of linearly smooth functions $(\phi_\delta : \mathbb{R}^k \to \mathbb{R})_{\delta > 0}$ with Lipschitz constants $\leq L$ such that $\sup_{x \in \mathbb{R}^k} |\phi(x) - \phi_\delta(x)| \leq \delta$.*

*Proof.* Let $\zeta \in C^\infty(\mathbb{R}^k)$ be a non-negative smooth function that sums to one, supported on the unit ball. Let $\zeta_\delta(x) = (L/\delta)^k \zeta(xL/\delta)$. Set

$$\phi_\delta(x) = [\phi * \zeta_\delta](x) = \int_{\mathbb{R}^k} \zeta_\delta(y) \phi(x - y)\, dy =$$
$$= (L/\delta)^k \int_{\mathbb{R}^k} \zeta(yL/\delta) \phi(x - y)\, dy = \int_{\mathbb{R}^k} \zeta(z) \phi(x - z\delta/L)\, dz. \tag{40}$$

We have for any $x \in \mathbb{R}^k$,

$$|\phi_\delta(x) - \phi(x)| = \left| \int_{\mathbb{R}^k} \zeta(z) \left(\phi(x - z\delta/L) - \phi(x)\right) dz \right| \leq \delta \int_{\|z\|_2 \leq 1} \zeta(z) z \, dz \leq \delta. \tag{41}$$

Moreover,

$$\left|\partial_{j_1,\ldots,j_p} \phi_\delta(x)\right| = (L/\delta)^{k+\sum_{i=1}^p j_i} \left| \int_{\mathbb{R}^k} \partial_{j_1,\ldots,j_p} \zeta((x-y)L/\delta)\phi(y)\, dy \right| =$$

$$= (L/\delta)^{k+\sum_{i=1}^p j_i} \left| \int_{\|y\|_2 \leq \delta/L} \partial_{j_1,\ldots,j_p} \zeta(yL/\delta)\phi(x-y)\, dy \right| < \infty. \tag{42}$$

□

*Proof of Theorem 9.* Let $L$ be the Lipschitz constant for $\phi$ and $\psi$. Let $(\phi^\delta)_\delta$ and $(\psi^\delta)_\delta$ be the corresponding families of linearly smooth functions from the lemma above. Define the "smoothed" version of the given Tensor Program:

$$g_\alpha^{m,\delta} = \sum_{\beta=1}^n A_{\alpha\beta}^{m,T_m} \phi^\delta(g_\beta^{1,\delta}, \ldots, g_\beta^{m-1,\delta}, c^{1,\delta}, \ldots, c^{m-1,\delta}), \tag{43}$$

$$c^{m,\delta} = \frac{1}{n} \sum_{\beta=1}^n \phi^\delta(g_\beta^{1,\delta}, \ldots, g_\beta^{m-1,\delta}, c^{1,\delta}, \ldots, c^{m-1,\delta}) \tag{44}$$

for $m \in [M_0 + 1 : M]$. As before, we put "tildas" in order to mark that computation is performed using non-Gaussian weights $\tilde{A}$.

**Lemma 5.** *Under premise of Theorem 9,* $\forall n \geq 1\ \forall \delta > 0$

$$\left\|\psi(\tilde{g}^1, \ldots, \tilde{g}^M, \tilde{c}^1, \ldots, \tilde{c}^M) - \psi^\delta(\tilde{g}^{1,\delta}, \ldots, \tilde{g}^{M,\delta}, \tilde{c}^{1,\delta}, \ldots, \tilde{c}^{M,\delta})\right\|_2 \leq$$

$$\leq \sqrt{n}\delta P\left(L\|\tilde{A}^1\|_2, \ldots, L\|\tilde{A}^M\|_2\right), \tag{45}$$

*where $P$ is a polynomial.*

*Proof.* We prove by induction that $\forall m \in [M_0 : M-1]$

$$\left\|\phi(\tilde{g}^1, \ldots, \tilde{g}^m, \tilde{c}^1, \ldots, \tilde{c}^m) - \phi^\delta(\tilde{g}^{1,\delta}, \ldots, \tilde{g}^{m,\delta}, \tilde{c}^{1,\delta}, \ldots, \tilde{c}^{m,\delta})\right\|_2 \leq$$

$$\leq \sqrt{n}\delta P\left(L\|\tilde{A}^1\|_2, \ldots, L\|\tilde{A}^m\|_2\right) \tag{46}$$

for some polynomial $P$.

Induction base: since $\tilde{g}^1 = \tilde{g}^{1,\delta}, \ldots, \tilde{g}^{M_0} = \tilde{g}^{M_0,\delta}$,

$$\left\|\phi(\tilde{g}^1, \ldots, \tilde{g}^{M_0}, \tilde{c}^1, \ldots, \tilde{c}^{M_0}) - \phi^\delta(\tilde{g}^{1,\delta}, \ldots, \tilde{g}^{M_0,\delta}, \tilde{c}^{1,\delta}, \ldots, \tilde{c}^{M_0,\delta})\right\|_2 \leq \sqrt{n}\delta. \tag{47}$$

Induction step:

$$\left\|\phi(\tilde{g}^1, \ldots, \tilde{g}^m, \tilde{c}^1, \ldots, \tilde{c}^m) - \phi^\delta(\tilde{g}^{1,\delta}, \ldots, \tilde{g}^{m,\delta}, \tilde{c}^{1,\delta}, \ldots, \tilde{c}^{m,\delta})\right\|_2 \leq$$

$$\leq \left\|\phi(\tilde{g}^1, \ldots, \tilde{g}^m, \tilde{c}^1, \ldots, \tilde{c}^m) - \phi^\delta(\tilde{g}^1, \ldots, \tilde{g}^m, \tilde{c}^1, \ldots, \tilde{c}^m)\right\|_2 +$$

$$+ \left\|\phi^\delta(\tilde{g}^1, \ldots, \tilde{g}^m, \tilde{c}^1, \ldots, \tilde{c}^m) - \phi^\delta(\tilde{g}^{1,\delta}, \ldots, \tilde{g}^{m,\delta}, \tilde{c}^{1,\delta}, \ldots, \tilde{c}^{m,\delta})\right\|_2 \leq$$

$$\leq \sqrt{n}\delta + L \sum_{m'=M_0+1}^m \left(\|\tilde{g}^{m'} - \tilde{g}^{m',\delta}\|_2 + |\tilde{c}^{m'} - \tilde{c}^{m',\delta}|\right) \leq$$

$$\leq \sqrt{n}\delta + L \sum_{m'=M_0+1}^m \left(\|\tilde{A}^{m'}\|_2 + n^{-1}\right) \left\|\phi(\tilde{g}^{1:m'-1}) - \phi^\delta(\tilde{g}^{1:m'-1,\delta})\right\|_2 \leq$$

$$\leq \sqrt{n}\delta \left(1 + \sum_{m'=M_0+1}^m L\left(1 + \|\tilde{A}^{m'}\|_2\right) P(L\|\tilde{A}^1\|_2, \ldots, L\|\tilde{A}^{m'-1}\|_2)\right). \tag{48}$$

Doing the same step one more time for $\psi$ gives the result. □

From the lemma above,

$$|\tilde{\Psi}_n - \tilde{\Psi}_n^\delta| = \frac{1}{n}\left\|\psi(\tilde{g}^1,\dots,\tilde{g}^M,\tilde{c}^1,\dots,\tilde{c}^M) - \psi^\delta(\tilde{g}^{1,\delta},\dots,\tilde{g}^{M,\delta},\tilde{c}^{1,\delta},\dots,\tilde{c}^{M,\delta})\right\|_1 \leq$$
$$\leq \frac{1}{\sqrt{n}}\left\|\psi(\tilde{g}^1,\dots,\tilde{g}^M,\tilde{c}^1,\dots,\tilde{c}^M) - \psi^\delta(\tilde{g}^{1,\delta},\dots,\tilde{g}^{M,\delta},\tilde{c}^{1,\delta},\dots,\tilde{c}^{M,\delta})\right\|_2 \leq$$
$$\leq \delta P(L\|\tilde{A}^1\|_2,\dots,L\|\tilde{A}^M\|_2). \quad (49)$$

Therefore, for any Lipschitz $\chi$ with Lipschitz constant $L_\chi$,

$$|\chi(\tilde{\Psi}_n) - \chi(\tilde{\Psi}_n^\delta)| \leq L_\chi|\tilde{\Psi}_n - \tilde{\Psi}_n^\delta| \leq \delta L_\chi P(L\|\tilde{A}^1\|_2,\dots,L\|\tilde{A}^M\|_2). \quad (50)$$

Since entries of $\tilde{A}$ are sub-gaussian, expectation of this difference is bounded as $n \to \infty$. Hence $\mathbb{E}\left(|\chi(\tilde{\Psi}_n) - \chi(\tilde{\Psi}_n^\delta)|\right)$ goes to zero as $\delta \to 0+$ uniformly wrt $n$. Therefore $n$ and $\delta$ limits are interchangeable:

$$\lim_{\delta\to 0+}\lim_{n\to\infty}\mathbb{E}\left(|\chi(\tilde{\Psi}_n) - \chi(\tilde{\Psi}_n^\delta)|\right) = \lim_{n\to\infty}\lim_{\delta\to 0+}\mathbb{E}\left(|\chi(\tilde{\Psi}_n) - \chi(\tilde{\Psi}_n^\delta)|\right) = 0, \quad (51)$$

where we exchanged $\delta$-limit and expectation using dominated convergence. Therefore

$$\lim_{n\to\infty}\mathbb{E}\left(\chi(\tilde{\Psi}_n)\right) = \lim_{n\to\infty}\mathbb{E}\left(\chi(\tilde{\Psi}_n^\delta)\right) + o_{\delta\to 0+}(1) \quad (52)$$

For any bounded Lipschitz $\chi$, by Theorem 2,

$$\lim_{n\to\infty}\mathbb{E}\left(\chi(\tilde{\Psi}_n)\right) = \lim_{\delta\to 0+}\lim_{n\to\infty}\mathbb{E}\left(\chi(\tilde{\Psi}_n^\delta)\right) = \lim_{\delta\to 0+}\chi(\mathring{\Psi}^\delta). \quad (53)$$

Exactly the same logic applies to $\Psi_n$:

$$\lim_{n\to\infty}\mathbb{E}\left(\chi(\Psi_n)\right) = \lim_{\delta\to 0+}\chi(\mathring{\Psi}^\delta). \quad (54)$$

Therefore $\Psi_n$ and $\tilde{\Psi}_n$ have the same weak limit. On the other hand, by Theorem 1, $\Psi_n$ converges weakly to $\mathring{\Psi}$:

$$\lim_{n\to\infty}\mathbb{E}\left(\chi(\tilde{\Psi}_n)\right) = \lim_{n\to\infty}\mathbb{E}\left(\chi(\Psi_n)\right) = \chi(\mathring{\Psi}) \quad \forall\chi \in Lip_b(\mathbb{R}). \quad (55)$$

It means that $\tilde{\Psi}_n$ converges to $\mathring{\Psi}$ in probability.

Since $\phi^\delta$ and $\psi^\delta$ are both polynomially (and even linearly) smooth and Lipschitz, Theorem 2 also gives convergence of expectations:

$$\lim_{n\to\infty}\mathbb{E}\left[\tilde{\Psi}_n\right] = \lim_{\delta\to 0+}\lim_{n\to\infty}\mathbb{E}\left[\tilde{\Psi}_n^\delta\right] = \lim_{\delta\to 0+}\mathring{\Psi}^\delta. \quad (56)$$

By applying the same argument to $\Psi_n$, we conclude that their expectations have the same limit. On the other hand, since $\phi$ and $\psi$ are Lipschitz, by Theorem 1, $\mathbb{E}\,\Psi_n$ also converges to $\mathring{\Psi}$:

$$\lim_{n\to\infty}\mathbb{E}\left[\tilde{\Psi}_n\right] = \lim_{n\to\infty}\mathbb{E}\left[\Psi_n\right] = \mathring{\Psi}. \quad (57)$$

□

# D Tensor Program formulation equivalence

The Tensor Program series [21, 22, 23, 26, 24, 25] defines a Tensor Program as a pair of initial state and a sequence of commands. The initial state consists of variables of three different types: A, G, and C, which correspond to matrices, vectors, and scalars in Eq. (1), resepctively. In its body, the program can also generate X-vars (that correspond to a vector $x$ in Eq. (1)), which are size-$n$ vectors but with a different meaning compared to G-vars. The G- and C-vars in the initial state are called input variables.

Each command takes some variables from the state, generates a new variable, and appends it to the state. In the most general version of a Tensor Program, NETSOR$\top^+$ , the following commands are available:

- Trsp. Input: $A$ : A. Output $A^\top$ : A.
- MatMul. Input: $A$ : A, $x$ : X. Output: $Ax$ : G.
- Nonlin$^+$. Input: $g^1$ : G, $\ldots$, $g^k$ : G, $c^1$ : C, $\ldots$, $c^l$ : C. Output: $x$ : X, where $x_\alpha = \phi(g^1_\alpha, \ldots, g^k_\alpha, c^1, \ldots, c^l)\ \forall \alpha \in [n]$.
- Moment. Input: $g^1$ : G, $\ldots$, $g^k$ : G, $c^1$ : C, $\ldots$, $c^l$ : C. Output: $c$ : C, where $c = \frac{1}{n}\sum_{\alpha=1}^n \phi(g^1_\alpha, \ldots, g^k_\alpha, c^1, \ldots, c^l)$.

It is easy to see that the iteration of Eq. (1) can be expressed as a NETSOR$\top^+$ program above. Note that in all Master theorems, we care only about vectors of type G and scalars. Let us now show that for any NETSOR$\top^+$ program, we can construct an iteration in the form of Eq. (1) that generates the same set of G- and C-vars.

Note that G-vars can only be generated by MatMul. Each such MatMul uses a single X-var which can be generated only by Nonlin$^+$. For the $m$-th G-var, we therefore get the following iteration:

$$g^m_\alpha = \sum_{\beta=1}^n A^{m,T_m}_{\alpha\beta} \phi^m(g^1_\beta, \ldots, g^{k_m}_\beta, c^1, \ldots, c^{l_m}),$$

where we put $T_m = 1$ if the corresponding A-var has undergone Trsp even number of times by the moment of generating the above G-var, or $T_m = \top$ otherwise. By generating "placeholder" G- or C-vars (say, zeros), we can assume w.l.o.g. that $k_m = l_m = m - 1$. Moreover, we can generate a G-var and a C-var at the same time using the same function $\phi^m$ as a subsequent nonlinearity may not depend on one of them if not necessary. This gives us an iteration of the form of Eq. (1).

# E Comparison with Chen and Lam [1]

The work of [1] considers the following iteration:

$$\tilde{x}^2_\alpha = \phi^2\left(\sum_\delta \tilde{A}_{\alpha\beta} x^1_\beta\right), \quad \tilde{x}^m_\alpha = \phi^m\left(\sum_\delta \tilde{A}_{\alpha\beta}\tilde{x}^{m-1}_\beta, \tilde{x}^{m-2}_\alpha, \ldots, \tilde{x}^2_\alpha, x^1_\alpha\right) \quad \forall m > 2\ \forall \alpha \in [n], \tag{58}$$

where $\tilde{A}$ is a sum of two **symmetric** $n \times n$ matrices: one has iid sub-Gaussian entries with zero mean and variance $n^{-1}$, while the other is a deterministic matrix divided by $n$. Denote the first matrix as $\tilde{Z}$, and the second as $X/n$, so $\tilde{A} = \tilde{Z} + X/n$. Let $A = Z + X/n$, where $Z$ is a symmetric iid Gaussian matrix with zero mean and variance $n^{-1}$. Consider the corresponding iteration:

$$x^2_\alpha = \phi^2\left(\sum_\delta A_{\alpha\beta} x^1_\beta\right), \quad x^m_\alpha = \phi^m\left(\sum_\delta A_{\alpha\beta}x^{m-1}_\beta, x^{m-2}_\alpha, \ldots, x^2_\alpha, x^1_\alpha\right) \quad \forall m > 2\ \forall \alpha \in [n], \tag{59}$$

The main result of [1] follows:

**Theorem 10** ([1]). *Take $M \geq 2$ and a function $\psi$ with $M$ arguments. Suppose $\psi$ and all $\phi^m$ for $m \in [2 : M]$ are Lipschitz. Then*

$$\lim_{n\to\infty}\left|\frac{1}{n}\sum_{\alpha=1}^n \left(\psi(x^1_\alpha, \ldots, x^M_\alpha) - \psi(\tilde{x}^1_\alpha, \ldots, \tilde{x}^M_\alpha)\right)\right| = 0 \tag{60}$$

*in probability.*

In this formulation, $\frac{1}{n}\sum_{\alpha=1}^n \psi(x^1_\alpha, \ldots, x^M_\alpha)$ does not converge to $\mathbb{E}_{z\sim\mathcal{N}(\mu,\Sigma)}\psi(z)$ for some $\mu$ and $\Sigma$ since $x^1_\alpha, \ldots, x^M_\alpha$ are images of nonlinear functions. Therefore the above formulation does not allow for a clear Gaussian process interpretation as in our Corollary 1 or Corollary 5.

One can show equivalence of our iteration (1) and the above iteration in a certain scenario. Namely for the above, let $X$ be and identity matrix and assume $x^1$ is an elementwise image of a Gaussian vector. For our iteration (1), let $M_0 = 1$, let us generate a "twin" variable for each vector, where the only difference is that one uses $A^m$, while the other uses $A^{m,\top}$, and let each nonlinearity use a

sum of $x^j_\alpha$, $\bar{x}^j_\alpha$, and $c^j$ for each $j \in [m-1]$, where $\bar{x}^j$ is a twin variable for $x^j$. Equivalence is then showed by reorganizing nonlinearities of the two variants.

Apart from equivalence in the above scenario, the use of iteration (58) for expressing deep learning computations is very limited. First, iteration (58) assumes weight matrices to be symmetric, while such weight initializations are rarely used in practice. Second, iteration (58) applies the same weight matrix each time. While some layers in neural nets can indeed share weights, assuming that all layers share weights strictly limits us to vanilla recurrent neural nets, drawing out even simplest feedforward nets. Third, the form $A = Z + X/n$ has no clear interpretation in typical neural network computations. And last, iteration (58) assumes only one input variable. In terms of neural network computations, this limits us to a single input, no bias vectors, and no output layer. It automatically draws out the ability to express a backward pass (and therefore learning process). Moreover, we cannot hope even to show Gaussian process behavior (as in Corollary 1) as it requires evaluating the network on a batch of inputs of any finite size.

While our proof is based on the same weight interpolation idea as the proof of Theorem 10, certain crucial details are different. While Theorem 10 requires everything to be Lipschitz, our Theorem 2 allows for certain smooth polynomially bounded nonlinearities and $\psi$-functions. While restricting oneself to Lipschitz nonlinearities still allows to express a forward pass of a, say, ReLU net, it does not allow for expressing its backward pass since the derivative of a ReLU is not Lipschitz (and not even continuous). Moreover, computing a kernel (NNGP or NTK, see Corollary 1 and Corollary 2) requires a quadratic $\psi$-function.

# F Proof of Lemmas 1 and 2

## F.1 Proof of Lemma 1

Observe that $\partial_s \Psi(s^2) = 2s\dot{\Psi}(s^2)$ and $\partial_s \Psi(1-s^2) = -2s\dot{\Psi}(1-s^2)$, where $\dot{\Psi}$ is a derivative of $\Psi$ wrt its argument. The following lemma gives exact expression for $\dot{\Psi}$:

**Lemma 6.** *$\dot{\Psi}(t)$ can be expressed as a sum of a finite, not depending on $n$, number of terms of the form*

$$\frac{1}{n}\sum_{\gamma}\sum_{\beta_1}\dots\sum_{\beta_w}\pi_{\beta_{1:w}}(a_1(t),\dots,a_N(t))f_{\gamma,\beta_{1:w}}(a_1(t),\dots,a_N(t))\partial_t A^{m,T_m}_{\beta_w\gamma}(t), \tag{61}$$

*where $w \in [1:M-M_0]$, $m \in [M_0+1:M]$, $a_{1:N}$ is a collection of all weights in the program,*

$$f_{\gamma,\beta_{1:w}}(a_1,\dots,a_N) = \partial_{m_1+1}\psi(g^1_{\beta_1},\dots,g^M_{\beta_1},c^1,\dots,c^M)\times \\ \times\left[\prod_{j=2}^{w}\partial_{m_j+1}\phi(g^1_{\beta_j},\dots,g^{m_{j-1}}_{\beta_j},c^1,\dots,c^{m_{j-1}})\right]\phi(g^1_\gamma,\dots,g^{m_w}_\gamma,c^1,\dots,c^{m_w}), \tag{62}$$

*where $M > m_1 > \ldots > m_w = m-1 \in [M_0 : M-1]$, and*

$$\pi_{\beta_{1:w}}(a_1,\dots,a_N) = \prod_{k=2}^{w} a'_k, \qquad a'_k \in \left\{A^{m_{k-1}+1,T_{m_{k-1}+1}}_{\beta_{k-1}\beta_k}, n^{-1}\right\}. \tag{63}$$

See Appendix G.2 for the proof. Therefore $\partial_s\Psi(s^2)$ can be expressed as a sum of a finite, not depending on $n$, number of terms of the form

$$\frac{1}{n}\sum_{\gamma}\sum_{\beta_1}\dots\sum_{\beta_w}\pi_{\beta_{1:w}}(a_1(s^2),\dots,a_N(s^2))f_{\gamma,\beta_{1:w}}(a_1(s^2),\dots,a_N(s^2))\partial_s A^{m,T_m}_{\beta_w\gamma}(s^2) \tag{64}$$

since $s\partial_t A^{m,T_m}_{\beta_w\gamma}(t)|_{t=s^2} = \partial_s A^{m,T_m}_{\beta_w\gamma}(s^2)$; for $\partial_s\Psi(1-s^2)$, the expression is similar.

We are going to use the following definitions in the sequel:

**Definition 4.** *Let $\sigma_k = \mathrm{MatMul}$ if $a'_k = A^{m_{k-1}+1,T_{m_{k-1}+1}}_{\beta_{k-1}\beta_k}$ and $\sigma_k = \mathrm{Moment}$ otherwise. Let $w_{\mathrm{MatMul}} = \sum_{k=2}^{w} 1_{\sigma_k=\mathrm{MatMul}}$ and let $w_{\mathrm{Moment}} = \sum_{k=2}^{w} 1_{\sigma_k=\mathrm{Moment}}$.*

Note that $w_{\text{MatMul}} + w_{\text{Moment}} = w - 1$.

Since derivatives of $\phi$ and $\psi$ are polynomially bounded, $f$ is polynomially bounded as a function of weights, initial vectors, and initial scalars; $\pi$ is just a polynomial as a function of weights. Therefore since $\chi$ is Lipschitz, for any fixed $n$, $\chi'(\Psi(s^2))\partial_s\Psi(s^2)$ is polynomially bounded as a function of weights, $s$-derivatives of weights, initial vectors, and initial scalars. We conclude using the following lemma:

**Lemma 7.** *Let $h$ be a polynomially bounded function of weights $a_1(s^2), \dots, a_N(s^2)$, $s$-derivatives of weights, initial vectors, and initial scalars. Then*

$$\mathbb{E} \sup_{s\in[0,1/\sqrt{2}]} \left|h\left(a_1(s^2), \dots, a_N(s^2), \partial_s a_1(s^2), \dots, \partial_s a_N(s^2), g^1, \dots, g^{M_0}, c^1, \dots, c^{M_0}\right)\right| < \infty. \tag{65}$$

*The same holds if we substitute $s^2$ with $1 - s^2$.*

*Proof.* Let $P$ be the corresponding polynomial. Given a polynomial $P(x) = \sum b_k x^k$, define a polynomial $\tilde{P}(x) = \sum |b_k| x^k$. For brevity, we denote the set of arguments of $h$ as $x_1(s^2), \dots, x_K(s^2)$. We have

$$\sup_{s\in[0,1/\sqrt{2}]} \left|h\left(x_1(s^2), \dots, x_K(s^2)\right)\right| \le \sup_{s\in[0,1/\sqrt{2}]} \left|P\left(x_1(s^2), \dots, x_K(s^2)\right)\right| \le$$
$$\le \sup_{s\in[0,1/\sqrt{2}]} \tilde{P}\left(|x_1(s^2)|, \dots, |x_K(s^2)|\right) \le \tilde{P}\left(\sup_{s\in[0,1/\sqrt{2}]} |x_1(s^2)|, \dots, \sup_{s\in[0,1/\sqrt{2}]} |x_K(s^2)|\right). \tag{66}$$

Observe that $|a(s^2)| = |s\tilde{a} + \sqrt{1-s^2}a| \le |a| + |\tilde{a}|$ for $s \in [0,1]$ and $|\partial_s a(s^2)| = \frac{1}{2}|\tilde{a} - as/\sqrt{1-s^2}| \le |a| + |\tilde{a}|$ for $s \in [0, 1/\sqrt{2}]$. Therefore there exists a polynomial $\bar{P}$ with positive finite coefficients such that

$$\sup_{s\in[0,1/\sqrt{2}]} \left|h\left(x_1(s^2), \dots, x_K(s^2)\right)\right| \le \bar{P}\left(a_1, \dots, a_N, \tilde{a}_1, \dots, \tilde{a}_N, g^1, \dots, g^{M_0}, c^1, \dots, c^{M_0}\right). \tag{67}$$

Since all moments of $a_1, \dots, a_N$, $\tilde{a}_1, \dots, \tilde{a}_N$, $g^1, \dots, g^{M_0}$, and $c^1, \dots, c^{M_0}$ exist, expectation of the last polynomial is finite. □

### F.2 Proof of Lemma 2

Here we demonstrate the argument for $\mathbb{E}\left[[\partial_s\Psi(s^2)]^2\right]$ as the one for $\mathbb{E}\left[[\partial_s\Psi(1-s^2)]^2\right]$ is similar.

Due to Lemma 6, $\mathbb{E}\left[[\partial_s\Psi(s^2)]^2\right]$ can be expressed a sum of a finite, not depending on $n$, number of terms of the form

$$\frac{1}{n^2}\sum_{\gamma,\tilde{\gamma}}\sum_{\beta_1}\cdots\sum_{\beta_w}\sum_{\tilde{\beta}_1}\cdots\sum_{\tilde{\beta}_{\tilde{w}}} \mathbb{E}\left(\left[\pi_{\beta_{1:w}} f_{\gamma,\beta_{1:w}} \partial_s A^{m,T_m}_{\beta_w\gamma}\right] \times \left[\pi_{\tilde{\beta}_{1:\tilde{w}}} f_{\tilde{\gamma},\tilde{\beta}_{1:\tilde{w}}} \partial_s A^{\tilde{m},\tilde{T}_{\tilde{m}}}_{\tilde{\beta}_{\tilde{w}}\tilde{\gamma}}\right]\right), \tag{68}$$

where $w, \tilde{w} \in [1 : M - M_0]$, and $f$ and $\pi$ are functions of $a_1(s^2), \dots, a_N(s^2)$; for brevity, we shall supress the $s^2$-argument.We can equivalently express Eq. (68) as a finite, not depending on $n$, number of terms of one of the two following forms:

$$n^{-2} n^{-w_{\text{Moment}}} n^{-\tilde{w}_{\text{Moment}}} \sum_{(\gamma,\beta_{1:w},\tilde{\gamma},\tilde{\beta}_{1:\tilde{w}})\in\Gamma^{(2)}_{r_{1:\nu}}} \mathbb{E}\left(f_{\gamma,\beta_{1:w}} f_{\tilde{\gamma},\tilde{\beta}_{1:\tilde{w}}} [\partial_s a_1]^2 [a_1]^{r_1} \dots [a_\nu]^{r_\nu}\right), \tag{69}$$

where $r_1 \ge 0$, $r_k \ge 1$ for $k \in [2 : \nu]$, $\nu \in [1 : w_{\text{MatMul}} + \tilde{w}_{\text{MatMul}} + 1]$, and

$$n^{-2} n^{-w_{\text{Moment}}} n^{-\tilde{w}_{\text{Moment}}} \sum_{(\gamma,\beta_{1:w},\tilde{\gamma},\tilde{\beta}_{1:\tilde{w}})\in\Gamma^{(1,1)}_{r_{1:\nu}}} \mathbb{E}\left(f_{\gamma,\beta_{1:w}} f_{\tilde{\gamma},\tilde{\beta}_{1:\tilde{w}}} [\partial_s a_1][\partial_s a_2][a_1]^{r_1} \dots [a_\nu]^{r_\nu}\right), \tag{70}$$

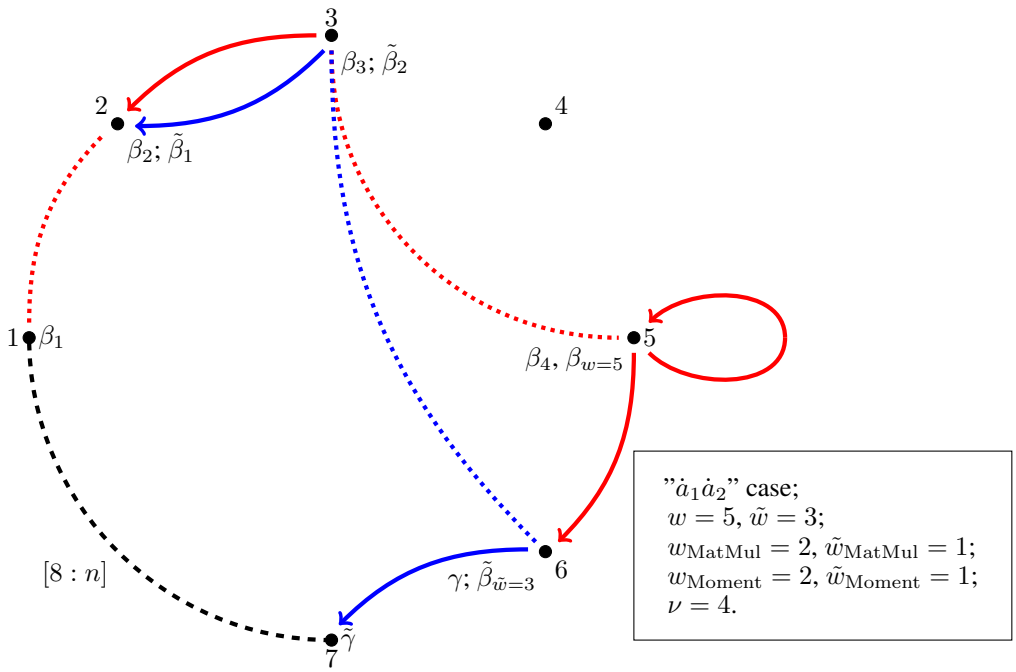


Figure 1: An example of a configuration graph — a subgraph of a union of two paths $(\beta_{1:w}, \gamma)$ and $(\tilde{\beta}_{1:\tilde{w}}, \tilde{\gamma})$ on an $n$-node graph, colored red and blue, consisting of $w$ and $\tilde{w}$ edges respectively. Some of the edges can be absent (dotted lines), resulting in $w_{\text{MatMul}} + 1$ edges in one path and $\tilde{w}_{\text{MatMul}} + 1$ in the other. The edge $(\beta_{k-1}, \beta_k)$ of the red path is present iff $\sigma_k = \text{MatMul}$, while the edge $(\tilde{\beta}_{k-1}, \tilde{\beta}_k)$ of the blue path is present iff $\tilde{\sigma}_k = \text{MatMul}$. The last edges of both paths, $(\beta_w, \gamma)$ and $(\tilde{\beta}_{\tilde{w}}, \tilde{\gamma})$, are always present; they coincide in the "$[\dot{a}_1]^2$" case while they do not in the "$\dot{a}_1\dot{a}_2$" one. Each present edge $(\beta_{k-1}, \beta_k)$ of the red path is directed "forward" if $T_k = 1$ and "backward" if $T_k = \top$; same for the blue path. The overall graph consists of $\nu$ multi-edges of different multiplicities. In our example, $\nu = 4$, one of the edges has multiplicity two and all others are of multiplicity one.

where $r_1 \geq 0$, $r_2 \geq 0$, $r_k \geq 1$ for $k \in [3:\nu]$, $\nu \in [2 : w_{\text{MatMul}} + \tilde{w}_{\text{MatMul}} + 2]$; $\sum_{k=1}^{\nu} r_k = w_{\text{MatMul}} + \tilde{w}_{\text{MatMul}}$ in both cases. We define $\Gamma^{(2)}_{r_{1:\nu}}$ as a set of $(\gamma, \beta_{1:w}, \tilde{\gamma}, \tilde{\beta}_{1:\tilde{w}})$ such that

$$\left[\pi_{\beta_{1:w}} \partial_s A^{m,T_m}_{\beta_w \gamma}\right] \left[\pi_{\tilde{\beta}_{1:\tilde{w}}} \partial_s A^{\tilde{m},\tilde{T}_{\tilde{m}}}_{\tilde{\beta}_{\tilde{w}} \tilde{\gamma}}\right] = n^{-w_{\text{Moment}}} n^{-\tilde{w}_{\text{Moment}}} [\partial_s a_1]^2 [a_1]^{r_1} \dots [a_\nu]^{r_\nu}. \tag{71}$$

Similarly, we define $\Gamma^{(1,1)}_{r_{1:\nu}}$ as a set of $(\gamma, \beta_{1:w}, \tilde{\gamma}, \tilde{\beta}_{1:\tilde{w}})$ such that

$$\left[\pi_{\beta_{1:w}} \partial_s A^{m,T_m}_{\beta_w \gamma}\right] \left[\pi_{\tilde{\beta}_{1:\tilde{w}}} \partial_s A^{\tilde{m},\tilde{T}_{\tilde{m}}}_{\tilde{\beta}_{\tilde{w}} \tilde{\gamma}}\right] = n^{-w_{\text{Moment}}} n^{-\tilde{w}_{\text{Moment}}} [\partial_s a_1][\partial_s a_2][a_1]^{r_1} \dots [a_\nu]^{r_\nu}. \tag{72}$$

We are going to bound only the second term Eq. (70) here as it is less technically involved. We put the bound for the first one in Appendix G.3. We have:

$$n^{-2-w_{\text{Moment}}-\tilde{w}_{\text{Moment}}} \left| \sum_{(\gamma,\beta_{1:w},\tilde{\gamma},\tilde{\beta}_{1:\tilde{w}}) \in \Gamma^{(1,1)}_{r_{1:\nu}}} \mathbb{E}\left(f_{\gamma,\beta_{1:w}} f_{\tilde{\gamma},\tilde{\beta}_{1:\tilde{w}}} [\partial_s a_1][\partial_s a_2][a_1]^{r_1} \dots [a_\nu]^{r_\nu}\right) \right| \leq$$
$$\leq n^{-2-w_{\text{Moment}}-\tilde{w}_{\text{Moment}}} \left|\Gamma^{(1,1)}_{r_{1:\nu}}\right| \sup_{\gamma,\beta_{1:w},\tilde{\gamma},\tilde{\beta}_{1:\tilde{w}}} \left|\mathbb{E}\left(f_{\gamma,\beta_{1:w}} f_{\tilde{\gamma},\tilde{\beta}_{1:\tilde{w}}} [\partial_s a_1][\partial_s a_2][a_1]^{r_1} \dots [a_\nu]^{r_\nu}\right)\right|. \tag{73}$$

Cardinality of $\Gamma^{(1,1)}_{r_{1:\nu}}$ is given by the following lemma:

**Lemma 8.** $\left|\Gamma^{(1,1)}_{r_{1:\nu}}\right| \leq C n^{\nu+2} n^{w_{\text{Moment}}} n^{\tilde{w}_{\text{Moment}}}$, *where $C$ depends neither on $n$, nor on $s$.*

*Proof.* Consider a set of $n$ vertices. For a given set of summation indices $(\beta_{1:w}, \gamma)$ associate a set of edges as follows. For each $k \in [2 : w]$, take an edge $(\beta_{k-1}, \beta_k)$ if $\sigma_k = \mathrm{MatMul}$, and also take an edge $(\beta_w, \gamma)$; overall, we get $w_{\mathrm{MatMul}} + 1$ edges. Direct each edge according to $T$; for example, direct the edge $(\beta_{k-1}, \beta_k)$ "forward" if $T_k = 1$ and "backward" if $T_k = \top$. Do the same for $(\tilde{\beta}_{1:\tilde{w}}, \tilde{\gamma})$; obtain a set of $\tilde{w}_{\mathrm{MatMul}} + 1$ directed edges. We shall refer the union of these two sets as a configuration graph; see Appendix F.2.

A configuration $(\gamma, \beta_{1:w}, \tilde{\gamma}, \tilde{\beta}_{1:\tilde{w}})$ lies in $\Gamma^{(1,1)}_{r_{1:\nu}}$ iff the corresponding configuration graph consists of $\nu$ directed multi-edges with multiplicities $r_1 + 1$, $r_2 + 1$, and $r_3, \ldots, r_\nu$. We need to compute the number of vertices such a graph traverses. If the graph traverses no more than $k$ vertices then the number of configurations satisfying the condition is no more than $Cn^k$, where $C$ is the number of non-isomorphic directed graphs with $w_{\mathrm{MatMul}} + \tilde{w}_{\mathrm{MatMul}} + 2$ edges and $\nu$ multi-edges; obviously, $C$ depends neither on $n$, nor on $s$.

Consider a non-directed graph with $\nu$ multi-edges. If it has $p$ connected components, it traverses $\nu + p$ vertices. Recall our configuration graph is a union of two paths, having $w$ and $\tilde{w}$ edges respectively, with some of the edges erased, resulting in $w_{\mathrm{MatMul}} + 1$ and $\tilde{w}_{\mathrm{MatMul}} + 1$ edges respectively. Overall, we had to erase $w_{\mathrm{Moment}} + \tilde{w}_{\mathrm{Moment}}$ edges. Given a union of paths, erasing $k$ edges results in introduction of no more than $k$ connected components. If there are only two paths from the beginning, we should have no more than $k + 2$ connected components after erasing $k$ edges.

In our case, $k = w_{\mathrm{Moment}} + \tilde{w}_{\mathrm{Moment}}$. Hence our configuration graph traverses no more than $\nu + 2 + w_{\mathrm{Moment}} + \tilde{w}_{\mathrm{Moment}}$ vertices. Therefore the number of configurations $(\gamma, \beta_{1:w}, \tilde{\gamma}, \tilde{\beta}_{1:\tilde{w}})$ in $\Gamma^{(1,1)}_{r_{1:\nu}}$ is not greater than $Cn^{\nu+2} n^{w_{\mathrm{Moment}}} n^{\tilde{w}_{\mathrm{Moment}}}$ for some constant $C$ independent on both $n$ and $s$. □

It remains to prove the following proposition:

**Proposition 2.**

$$\sup_{s \in [0, 1/\sqrt{2}]} \sup_{\substack{\gamma, \beta_{1:w}, \\ \tilde{\gamma}, \tilde{\beta}_{1:\tilde{w}}}} \left| \mathbb{E} \left( \left[ f_{\gamma, \beta_{1:w}} f_{\tilde{\gamma}, \tilde{\beta}_{1:\tilde{w}}} \right] (a_1, \ldots, a_N) [\partial_s a_1][\partial_s a_2][a_1]^{r_1} \ldots [a_\nu]^{r_\nu} \right) \right| = O(n^{-\nu-1}), \tag{74}$$

*where $a_1, \ldots, a_N$ are functions of $s^2$.*

*Proof.* Define $f = f_{\gamma, \beta_{1:w}} \times f_{\tilde{\gamma}, \tilde{\beta}_{1:\tilde{w}}}$. We start with Taylor-expanding $f$:

$$f(x_1, \ldots, x_N) = \sum_{k=0}^{K} \frac{1}{k!} \sum_{\substack{j_{1:\nu} \geq 0, \\ j_1 + \ldots + j_\nu = k}} [x_1]^{j_1} \ldots [x_\nu]^{j_\nu} \times \partial_1^{j_1} \ldots \partial_\nu^{j_\nu} f(0, \ldots, 0, x_{\nu+1}, \ldots, x_N) +$$
$$+ \frac{1}{K!} \sum_{\substack{j_{1:\nu} \geq 0, \\ j_1 + \ldots + j_\nu = K+1}} [x_1]^{j_1} \ldots [x_\nu]^{j_\nu} \times \int_0^1 \partial_1^{j_1} \ldots \partial_\nu^{j_\nu} f(\xi x_1, \ldots, \xi x_\nu, x_{\nu+1}, \ldots, x_N) \, d\xi, \tag{75}$$

where $K$ is a fixed number which we are going to choose later in the sequel.

The expectation we are interested in therefore takes the following form:

$$\mathbb{E} \left[ f(a_1, \ldots, a_N) [\partial_s a_1][\partial_s a_2][a_1]^{r_1} \ldots [a_\nu]^{r_\nu} \right] =$$
$$= \sum_{k=0}^{K} \frac{1}{k!} \sum_{\substack{j_{1:\nu} \geq 0, \\ j_1 + \ldots + j_\nu = k}} \mathbb{E} \left[ [\partial_s a_1][\partial_s a_2][a_1]^{j_1 + r_1} \ldots [a_\nu]^{j_\nu + r_\nu} \right] \mathbb{E} \left[ \partial_1^{j_1} \ldots \partial_\nu^{j_\nu} f(0_{1:\nu}, a_{\nu+1:N}) \right] +$$
$$+ \frac{1}{K!} \sum_{\substack{j_{1:\nu} \geq 0, \\ j_1 + \ldots + j_\nu = K+1}} \mathbb{E} \left[ [\partial_s a_1][\partial_s a_2][a_1]^{j_1 + r_1} \ldots [a_\nu]^{j_\nu + r_\nu} \int_0^1 \partial_1^{j_1} \ldots \partial_\nu^{j_\nu} f(\xi a_{1:\nu}, a_{\nu+1:N}) \, d\xi \right] \tag{76}$$

By Cauchy-Schwarz,

$$\left|\mathbb{E}\left[[\partial_s a_1][\partial_s a_2][a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu}\int_0^1 \partial_1^{j_1}\dots\partial_\nu^{j_\nu} f(\xi a_{1:\nu}, a_{\nu+1:N})\,d\xi\right]\right| \le$$
$$\le \sqrt{\mathbb{E}\left[([\partial_s a_1][\partial_s a_2][a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu})^2\right]\mathbb{E}\left[\left(\int_0^1 \partial_1^{j_1}\dots\partial_\nu^{j_\nu} f(\xi a_{1:\nu}, a_{\nu+1:N})\,d\xi\right)^2\right]}. \tag{77}$$

We need to bound $\mathbb{E}\left[\partial_1^{j_1}\dots\partial_\nu^{j_\nu} f(0_{1:\nu}, a_{\nu+1:N}(s^2))\right]$ and $\mathbb{E}\left[\partial_1^{j_1}\dots\partial_\nu^{j_\nu} f(\xi a_{1:\nu}(s^2), a_{\nu+1:N}(s^2))\right]$ uniformly over $\gamma$, $\beta_{1:w}$, $\tilde{\gamma}$, $\tilde{\beta}_{1:\tilde{w}} \in [n]$, $s \in [0, 1/\sqrt{2}]$, and $\xi \in [0,1]$. Such a bound is given by the following lemma, which we prove in Appendix H.4:

**Lemma 9.** *Consider a Tensor Program $\bar{\Pi}$ of width $n$ with matrices satisfying $\mathbb{E}\,\bar{A}_{\beta\gamma} = 0$ and $\mathbb{E}\,|\bar{A}_{\beta\gamma}|^k \le \nu_k n^{-k/2}$, $\nu_k \in \mathbb{R}_+\ \forall k \ge 1$, and with polynomially smooth nonlinearity $\bar{\phi}$. Denote the corresponding vectors as $\bar{g}^{1:M}$ and the corresponding scalars as $\bar{c}^{1:M}$.*

*Take $u \in \mathbb{N}$ and let $f_{1:u}$ be polynomially smooth. Let $P$ be a collection of weights in $\bar{\Pi}$. Then $\forall m_{1:u} \in [1:M]$*

$$\sup_{\alpha_1\in[n]}\dots\sup_{\alpha_u\in[n]}\mathbb{E}\left|\partial_P\prod_{i=1}^u f_i\left(\bar{g}^1_{\alpha_i},\dots,\bar{g}^{m_i}_{\alpha_i},\bar{c}^1,\dots,\bar{c}^{m_i}\right)\right| \le \bar{B}_{u,|P|}, \tag{78}$$

*where $\bar{B}_{u,|P|}$ is a continuous function of a finite number of (scaled) moments $\nu$.*

Indeed, the set $(0,\dots,0,a_{\nu+1}(s^2),\dots,a_N(s^2))$ satisfies the conditions on $\bar{A}$ for any $s \in [0,1]$. The corresponding moments $\nu$ are continous functions of $s$; since the constants in the lemma are also continuous functions of finite number of moments, we get

$$\sup_{s\in[0,1]}\mathbb{E}\left|\partial_1^{j_1}\dots\partial_\nu^{j_\nu} f(0,\dots,0,a_{\nu+1}(s^2),\dots,a_N(s^2))\right| \le$$
$$\le \max_{s\in[0,1]}\bar{B}_{u,k}(\nu_1(s^2),\dots,\nu_Q(s^2)) = O(1), \tag{79}$$

where $Q$ is the maximal index of the scaled moment which $\bar{B}_{u,k}$ depends on. Similarly,

$$\sup_{s\in[0,1]}\sup_{\xi\in[0,1]}\mathbb{E}\left[\left(\int_0^1 \partial_1^{j_1}\dots\partial_\nu^{j_\nu} f(\xi a_1(s^2),\dots,\xi a_\nu(s^2),a_{\nu+1}(s^2),\dots,a_N(s^2))\,d\xi\right)^2\right] \le$$
$$\le \max_{s\in[0,1]}\max_{\xi\in[0,1]}\bar{B}_{u,K+1}(\nu_1(\xi,s),\dots,\nu_Q(\xi,s)) = O(1), \tag{80}$$

where now we have a different $Q$ and moments depend both on $s \in [0,1]$ and on $\xi \in [0,1]$.

Hence it suffices to bound $\mathbb{E}\left[[\partial_s a_1][\partial_s a_2][a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu}\right]$ and $\mathbb{E}\left[([\partial_s a_1][\partial_s a_2][a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu})^2\right]$ uniformly over $s \in [0, 1/\sqrt{2}]$. There bounds follow from Lemma 3:

$$\sup_{s\in[0,1/\sqrt{2}]}\mathbb{E}\left[[\partial_s a_1][\partial_s a_2][a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu}\right] = O(n^{-1})\prod_{i=1}^\nu\left(1_{j_i+r_i\ge 2}O(n^{-(j_i+r_i)/2})\right); \tag{81}$$

$$\sup_{s\in[0,1/\sqrt{2}]}\mathbb{E}\left[([\partial_s a_1][\partial_s a_2][a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu})^2\right] = O(n^{-2})\prod_{i=1}^\nu O(n^{-(j_i+r_i)}). \tag{82}$$

This implies

$$\sum_{\substack{j_{1:\nu}\ge 0\\ j_1+\dots+j_\nu=k}}\mathbb{E}\left[[\partial_s a_1][\partial_s a_2][a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu}\right]\mathbb{E}\left[\partial_1^{j_1}\dots\partial_\nu^{j_\nu} f(0_{1:\nu},a_{\nu+1:N})\right] =$$
$$= O\left(n^{-\frac{2+k+\sum_{i=1}^\nu r_i}{2}}\right)1_{k+\sum_{i=1}^\nu r_i\ge 2s} = O\left(n^{-\frac{2+k+w_{\mathrm{MatMul}}+\tilde{w}_{\mathrm{MatMul}}}{2}}\right)1_{k+w_{\mathrm{MatMul}}+\tilde{w}_{\mathrm{MatMul}}\ge 2s} \tag{83}$$

uniformly over $s \in [0, 1/\sqrt{2}]$, and

$$\sum_{\substack{j_{1:\nu}\geq 0\\ j_1+\ldots+j_\nu=K+1}} \sqrt{\mathbb{E}\left[\left([\partial_s a_1][\partial_s a_2][a_1]^{j_1+r_1}\ldots[a_\nu]^{j_\nu+r_\nu}\right)^2\right]\mathbb{E}\left[\left(\int_0^1 \partial_1^{j_1}\ldots\partial_\nu^{j_\nu} f(\ldots)\,d\xi\right)^2\right]}$$
$$= O\left(n^{-\frac{2+(K+1)+\sum_{i=1}^{\nu} r_i}{2}}\right) = O\left(n^{-\frac{3+K+w_{\mathrm{MatMul}}+\tilde{w}_{\mathrm{MatMul}}}{2}}\right) \quad (84)$$

uniformly over $s \in [0, 1/\sqrt{2}]$.

Take $K = \max(0, 2\nu - w_{\mathrm{MatMul}} + \tilde{w}_{\mathrm{MatMul}})$; this gives

$$\sup_{s\in[0,1/\sqrt{2}]} \mathbb{E}\left[f(a_1(s^2),\ldots,a_N(s^2))[\partial_s a_1(s^2)][\partial_s a_2(s^2)][a_1(s^2)]^{r_1}\ldots[a_\nu(s^2)]^{r_\nu}\right] =$$
$$= \begin{cases} O\left(n^{-(w_{\mathrm{MatMul}}+\tilde{w}_{\mathrm{MatMul}})/2-1}\right), & w_{\mathrm{MatMul}}+\tilde{w}_{\mathrm{MatMul}} \geq 2\nu \\ O\left(n^{-\nu-1}\right), & w_{\mathrm{MatMul}}+\tilde{w}_{\mathrm{MatMul}} < 2\nu \end{cases} = O(n^{-\nu-1}), \quad (85)$$

which finishes the proof of the proposition. □

See Appendix G.3 for the bound for Eq. (69).

# G Auxiliary results

**Lemma 10.** *Let $\xi_1, \ldots, \xi_m$ be real-valued random variables with all of the moments existing. Then*

$$\mathbb{E}\,|\xi_1\ldots\xi_m| \leq \sqrt[m]{\mathbb{E}\left[|\xi_1|^m\right]\ldots\mathbb{E}\left[|\xi_m|^m\right]}. \quad (86)$$

*Proof.* By induction. Induction base is trivial. Induction step follows from Hölder inequality:

$$\mathbb{E}\,|\xi_1\ldots\xi_m| = \mathbb{E}\left[\left(|\xi_1\ldots\xi_{m-1}|^{\frac{m}{m-1}}\right)^{1-\frac{1}{m}}\left(|\xi_m|^m\right)^{\frac{1}{m}}\right] \leq$$
$$\leq \left(\mathbb{E}\left[|\xi_1\ldots\xi_{m-1}|^{\frac{m}{m-1}}\right]\right)^{1-\frac{1}{m}}\left(\mathbb{E}\left[|\xi_m|^m\right]\right)^{\frac{1}{m}} \leq \left(\mathbb{E}\left[|\xi_1|^m\right]\ldots\mathbb{E}\left[|\xi_{m-1}|^m\right]\right)^{\frac{1}{m}}\left(\mathbb{E}\left[|\xi_m|^m\right]\right)^{\frac{1}{m}}. \quad (87)$$

□

## G.1 Proof of Lemma 3

Recall $a(t) = \sqrt{1-t}a + \sqrt{t}\tilde{a}$; therefore

$$\partial_s a(s^2) = \tilde{a} - \frac{s}{\sqrt{1-s^2}}a, \qquad \partial_s a(1-s^2) = a - \frac{s}{\sqrt{1-s^2}}\tilde{a}. \quad (88)$$

Hence $\mathbb{E}\left[\partial_s a(s^2)\right] = \mathbb{E}\left[\partial_s a(1-s^2)\right] = 0\ \forall s \in [0,1)$ since $\mathbb{E}\,a = \mathbb{E}\,\tilde{a} = 0$.

Swapping $s^2$ with $1-s^2$ is equivalent to swapping $a$ and $\tilde{a}$. Since $a$ and $\tilde{a}$ have the same moment decay rates and we are only concerned with these rates, we consider only the case $s^2$ below.

The important property of the above interpolation is the following:

$$a(s^2)\partial_s a(s^2) = \left(s\tilde{a} + \sqrt{1-s^2}a\right)\left(\tilde{a} - \frac{s}{\sqrt{1-s^2}}a\right) = s\tilde{a}^2 - sa^2 + \frac{1-2s^2}{\sqrt{1-s^2}}\tilde{a}a, \quad (89)$$

which implies $\mathbb{E}\left[a(s^2)\partial_s a(s^2)\right] = 0\ \forall s \in [0,1)$.

Note that $\sup_{s\in[0,1/\sqrt{2}]}|a(s^2)| \leq |a| + |\tilde{a}|$ and $\sup_{s\in[0,1/\sqrt{2}]}|\partial_s a(s^2)| \leq |a| + |\tilde{a}|$. Therefore

$$\sup_{s\in[0,1/\sqrt{2}]} \mathbb{E}\left(\left|[a(s^2)]^j\partial_s a(s^2)\right|^k\right) = \sup_{s\in[0,1/\sqrt{2}]} \mathbb{E}\left(\left|a(s^2)\right|^{jk}\left|\partial_s a(s^2)\right|^k\right) \leq$$
$$\leq \mathbb{E}\left(\sup_{s\in[0,1/\sqrt{2}]}\left|a(s^2)\right|^{jk}\sup_{s\in[0,1/\sqrt{2}]}\left|\partial_s a(s^2)\right|^k\right) \leq \mathbb{E}\left[(|a|+|\tilde{a}|)^{(j+1)k}\right] = O(n^{-(j+1)k/2}). \quad (90)$$

### G.2 Proof of Lemma 6

For a nonlinearity $\phi$ depending elementwise on $m$ vectors and $m$ scalars, denote its derivative wrt $j$-th vector by $\partial_j^g \phi$ and the derivative wrt $j$-th scalar by $\partial_j^c \phi$.

Since some of the matrices in the program may coincide, define $\mathcal{M}$ as a set of equivalence classes between them, i.e. any $\mu \in \mathcal{M}$ is a subset of $[M_0+1:M]$ and $A^{m_1} = A^{m_2}$ iff $\{m_1, m_2\} \subset \mu$ for some $\mu \in \mathcal{M}$. We define $A^\mu$ to be $A^m$ for any $m \in \mu$.

The claim of the lemma follows from the fact that

$$\dot{\Psi}(t) = \frac{1}{n} \sum_{\mu} \sum_{\beta_1} \sum_{\alpha,\gamma} \left. \frac{\partial \psi(g^1_{\beta_1}, \ldots, g^M_{\beta_1}, c^1, \ldots, c^M)}{\partial A^\mu_{\alpha\gamma}} \right|_{\substack{a_1 = a_1(t) \\ \cdots \\ a_N = a_N(t)}} \partial_t A^\mu_{\alpha\gamma}(t) \tag{91}$$

and the following lemma:

**Lemma 11.** $\frac{\partial \psi(g^1_{\beta_1}, \ldots, g^M_{\beta_1}, c^1, \ldots, c^M)}{\partial A^\mu_{\alpha\gamma}}$ *can be expressed as a sum of a finite, not depending on $n$, number of terms of the form*

$$\sum_{\beta_2} \cdots \sum_{\beta_w} \pi_{\beta_{1:w}} \tilde{f}_{\alpha,\gamma,\beta_{1:w}}, \qquad \tilde{f}_{\alpha,\gamma,\beta_{1:w}} = \begin{cases} f_{\gamma,\beta_{1:w}}, & \text{if } T_m = 1 \text{ and } \beta_w = \alpha; \\ f_{\alpha,\beta_{1:w}}, & \text{if } T_m = \top \text{ and } \beta_w = \gamma; \\ 0, & \text{otherwise,} \end{cases} \tag{92}$$

*where $w \in [1 : M - M_0]$, $m \in [M_0 + 1 : M]$,*

$$\begin{aligned} f_{\gamma,\beta_{1:w}} &= \partial_{m_1+1} \psi(g^1_{\beta_1}, \ldots, g^M_{\beta_1}, c^1, \ldots, c^M) \times \\ &\times \left[ \prod_{j=2}^{w} \partial^{x_j}_{m_j+1} \phi(g^1_{\beta_j}, \ldots, g^{m_{j-1}}_{\beta_j}, c^1, \ldots, c^{m_{j-1}}) \right] \phi(g^1_\gamma, \ldots, g^{m_w}_\gamma, c^1, \ldots, c^{m_w}) \end{aligned} \tag{93}$$

*where $M > m_1 > \ldots > m_w = m - 1 \in [M_0 : M-1]$, $x_2, \ldots, x_j \in \{g, c\}$ and*

$$\pi_{\beta_{1:w}} = \prod_{k=2}^{w} a'_k, \qquad a'_k \in \left\{ A^{m_{k-1}+1, T_{m_{k-1}+1}}_{\beta_{k-1}\beta_k}, n^{-1} \right\}. \tag{94}$$

*Proof.* We claim that for any $m_0 \in [M_0 + 1 : M - 1]$, $\frac{\partial \phi(g^1_{\beta_1}, \ldots, g^{m_0}_{\beta_1}, c^1, \ldots, c^{m_0})}{\partial A^\mu_{\delta\gamma}}$ can be expressed as a sum of a finite, not depending on $n$, number of terms of the form

$$\sum_{\beta_2} \cdots \sum_{\beta_w} \pi^{\sigma_{2:w}}_{\beta_{1:w}} \tilde{f}^{m_{0:w}}_{\alpha,\gamma,\beta_{1:w}}, \qquad \tilde{f}^{m_{0:w}}_{\alpha,\gamma,\beta_{1:w}} = \begin{cases} f^{m_{0:w}}_{\gamma,\beta_{1:w}}, & \text{if } T_m = 1 \text{ and } \beta_w = \alpha; \\ f^{m_{0:w}}_{\alpha,\beta_{1:w}}, & \text{if } T_m = \top \text{ and } \beta_w = \gamma; \\ 0, & \text{otherwise,} \end{cases} \tag{95}$$

where $w \in [1 : m_0 - M_0]$, $m_0 > \ldots > m_w \in [M_0 : m_0 - 1]$,

$$f^{m_{0:w}}_{\gamma,\beta_{1:w}} = \left[ \prod_{j=1}^{w} \partial^{x_j}_{m_j+1} \phi(g^1_{\beta_j}, \ldots, g^{m_{j-1}}_{\beta_j}, c^1, \ldots, c^{m_{j-1}}) \right] \phi(g^1_\gamma, \ldots, g^{m_w}_\gamma, c^1, \ldots, c^{m_w}), \tag{96}$$

where $x_1, \ldots, x_j \in \{g, c\}$, and

$$\pi^{\sigma_{2:w}}_{\beta_{1:w}} = \prod_{k=2}^{w} a'_k, \qquad a'_k \in \left\{ A^{m_{k-1}+1, T_{m_{k-1}+1}}_{\beta_{k-1}\beta_k}, n^{-1} \right\}, \tag{97}$$

where $\sigma_2, \ldots, \sigma_w \in \{\text{Moment}, \text{MatMul}\}$. The claim of the lemma will follow by putting $m_0 = M$ since $\phi$ and $\psi$ have the same nature.

Proof by induction. Induction base ($m_0 = M_0 + 1$):

$$\frac{\partial \phi(g^1_{\beta_1}, \dots, g^{M_0+1}_{\beta_1}, c^1, \dots, c^{M_0+1})}{\partial A^{\mu}_{\delta\gamma}} =$$

$$= \partial^g_{M_0+1} \phi(g^1_{\beta_1}, \dots, g^{M_0+1}_{\beta_1}, c^1, \dots, c^{M_0+1}) \frac{\partial g^{M_0+1}_{\beta_1}}{\partial A^{\mu}_{\delta\gamma}} +$$

$$+ \partial^c_{M_0+1} \phi(g^1_{\beta_1}, \dots, g^{M_0+1}_{\beta_1}, c^1, \dots, c^{M_0+1}) \frac{\partial c^{M_0+1}}{\partial A^{\mu}_{\delta\gamma}} =$$

$$= \partial^g_{M_0+1} \phi(g^1_{\beta_1}, \dots, g^{M_0+1}_{\beta_1}, c^1, \dots, c^{M_0+1}) \times$$

$$\times \frac{\partial}{\partial A^{\mu}_{\alpha\gamma}} \left( \sum_{\alpha} A^{M_0+1, T_{M_0+1}}_{\beta_1 \alpha} \phi(g^1_{\alpha}, \dots, g^{M_0}_{\alpha}, c^1, \dots, c^{M_0}) \right) +$$

$$+ \partial^c_{M_0+1} \phi(g^1_{\beta_1}, \dots, g^{M_0+1}_{\beta_1}, c^1, \dots, c^{M_0+1}) \left[ \frac{1}{n} \sum_{\alpha} \frac{\partial \phi(g^1_{\alpha}, \dots, g^{M_0}_{\alpha}, c^1, \dots, c^{M_0})}{\partial A^{\mu}_{\alpha\gamma}} \right] =$$

$$= \partial^g_{M_0+1} \phi(g^1_{\beta_1}, \dots, g^{M_0+1}_{\beta_1}, c^1, \dots, c^{M_0+1}) \times$$

$$\times \begin{cases} \phi(g^1_{\gamma}, \dots, g^{M_0}_{\gamma}, c^1, \dots, c^{M_0}), & \text{if } T_{M_0+1} = 1, \alpha = \beta_1, M_0 + 1 \in \mu; \\ \phi(g^1_{\alpha}, \dots, g^{M_0}_{\alpha}, c^1, \dots, c^{M_0}), & \text{if } T_{M_0+1} = \top, \gamma = \beta_1, M_0 + 1 \in \mu. \end{cases} \tag{98}$$

It can expressed as a single term of the desired form with $w = 1$ and $m_1 = M_0$ if $M_0 + 1 \in \mu$, or as a sum of an empty set of terms otherwise.

Suppose the claim holds for $m_1 \in [M_0 + 1 : m_0 - 1]$; let us prove it for $m_0$:

$$\frac{\partial \phi(g^1_{\beta_1}, \dots, g^{m_0}_{\beta_1}, c^1, \dots, c^{m_0})}{\partial A^{\mu}_{\alpha\gamma}} =$$

$$= \sum_{m_1=M_0}^{m_0-1} \partial^g_{m_1+1} \phi(g^1_{\beta_1}, \dots, g^{m_0}_{\beta_1}, c^1, \dots, c^{m_0}) \frac{\partial g^{m_1+1}_{\beta_1}}{\partial A^{\mu}_{\alpha\gamma}} +$$

$$+ \sum_{m_1=M_0}^{m_0-1} \partial^c_{m_1+1} \phi(g^1_{\beta_1}, \dots, g^{m_0}_{\beta_1}, c^1, \dots, c^{m_0}) \frac{\partial c^{m_1+1}}{\partial A^{\mu}_{\alpha\gamma}} =$$

$$= \sum_{m_1=M_0}^{m_0-1} \partial^g_{m_1+1} \phi(g^1_{\beta_1}, \dots, g^{m_0}_{\beta_1}, c^1, \dots, c^{m_0}) \times$$

$$\times \frac{\partial}{\partial A^{\mu}_{\alpha\gamma}} \left( \sum_{\beta_2} A^{m_1+1, T_{m_1+1}}_{\beta_1 \beta_2} \phi(g^1_{\beta_2}, \dots, g^{m_1}_{\beta_2}, c^1, \dots, c^{m_1}) \right) +$$

$$+ \sum_{m_1=M_0}^{m_0-1} \partial^c_{m_1+1} \phi(g^1_{\beta_1}, \dots, g^{m_0}_{\beta_1}, c^1, \dots, c^{m_0}) \left[ \frac{1}{n} \sum_{\beta_2} \frac{\partial \phi(g^1_{\beta_2}, \dots, g^{m_1}_{\beta_2}, c^1, \dots, c^{m_1})}{\partial A^{\mu}_{\alpha\gamma}} \right] =$$

$$= \sum_{m_1=M_0}^{m_0-1} \partial_{m_1+1} \phi(g^1_{\beta_1}, \dots, g^{m_0}_{\beta_1}, c^1, \dots, c^{m_0}) \times$$

$$\times \begin{cases} \phi(g^1_{\gamma}, \dots, g^{m_1}_{\gamma}, c^1, \dots, c^{m_1}), & \text{if } T_{m_1+1} = 1, \alpha = \beta_1, m_1 + 1 \in \mu \\ \phi(g^1_{\alpha}, \dots, g^{m_1}_{\alpha}, c^1, \dots, c^{m_1}), & \text{if } T_{m_1+1} = \top, \gamma = \beta_1, m_1 + 1 \in \mu \end{cases} +$$

$$+ \sum_{m_1=M_0}^{m_0-1} \partial^g_{m_1+1} \phi(g^1_{\beta_1}, \dots, g^{m_0}_{\beta_1}, c^1, \dots, c^{m_0}) \sum_{\beta_2} A^{m_1+1, T_{m_1+1}}_{\beta_1 \beta_2} \frac{\partial \phi(g^1_{\beta_2}, \dots, g^{m_1}_{\beta_2}, c^1, \dots, c^{m_1})}{\partial A^{\mu}_{\alpha\gamma}} +$$

$$+ \sum_{m_1=M_0}^{m_0-1} \partial^c_{m_1+1} \phi(g^1_{\beta_1}, \dots, g^{m_0}_{\beta_1}, c^1, \dots, c^{m_0}) \left[ \frac{1}{n} \sum_{\beta_2} \frac{\partial \phi(g^1_{\beta_2}, \dots, g^{m_1}_{\beta_2}, c^1, \dots, c^{m_1})}{\partial A^{\mu}_{\alpha\gamma}} \right]. \tag{99}$$

The first sum is a sum of terms of the desired form with $w = 1$. By the induction hypothesis, the second sum is a sum of terms of the form

$$\partial_{m_1+1}\phi(g^1_{\beta_1}, \dots, g^{m_0}_{\beta_1}, c^1, \dots, c^{m_0}) \sum_{\beta_2} A^{m_1+1, T_{m_1+1}}_{\beta_1\beta_2} \sum_{\beta_3} \dots \sum_{\beta_w} \pi^{\sigma_{3:w}}_{\beta_{2:w}} \tilde{f}^{m_{1:w}}_{\alpha,\gamma,\beta_{2:w}} = \\ = \sum_{\beta_2} \dots \sum_{\beta_w} \pi^{\sigma_{2:w}}_{\beta_{1:w}} \tilde{f}^{m_{0:w}}_{\alpha,\gamma,\beta_{1:w}}, \quad (100)$$

where we define $\sigma_2 = \mathrm{MatMul}$. As for the third sum, the same holds, but we define $\sigma_2 = \mathrm{Moment}$. □

Due to the lemma above, $\partial_t \Psi$ is a sum of $O(1)$ terms of the form

$$\frac{1}{n} \sum_{\beta_1} \dots \sum_{\beta_w} \pi^t_{\beta_{1:w}} \sum_{\alpha,\gamma} \tilde{f}_{\alpha,\gamma,\beta_{1:w}} \partial_t A^{\mu}_{\alpha\gamma}, \quad (101)$$

where $w \in [1 : M - M_0]$ and $\tilde{f}$ and $\pi$ are functions of $a_1(t), \dots, a_N(t)$. Using the definition of $\tilde{f}$, we can rewrite the expression above equivalently as

$$\frac{1}{n} \sum_{\gamma} \sum_{\beta_1} \dots \sum_{\beta_w} \pi_{\beta_{1:w}} f_{\gamma,\beta_{1:w}} \partial_t A^{\mu, T_m}_{\beta_w\gamma}. \quad (102)$$

### G.3 Proof of Lemma 2: missing results for the "$[\dot{a}_1]^2$" case

We have to prove analogues of Lemma 8 and Proposition 2. Let us start with the lemma:

**Lemma 12.** $\left|\Gamma^{(2)}_{r_{1:\nu}}\right| \le C n^{\nu+1} n^{w_{\mathrm{Moment}}} n^{\tilde{w}_{\mathrm{Moment}}}$, *where $C$ depends neither on $n$, nor on $s$.*

*Proof.* Similarly to Lemma 8, we construct a configuration graph as a union of two path $(\beta_{1:w}, \gamma)$ and $(\tilde{\beta}_{1:\tilde{w}}, \tilde{\gamma})$ with some of the edges erased; we orient the ones that remain according to $T_k$ and $\tilde{T}_k$ respectively. Note that here, since we have $[\dot{a}_1]^2$ in the definition of $\Gamma^{(2)}$, the last edges of the two paths (which are always present) should coincide.

A configuration $(\gamma, \beta_{1:w}, \tilde{\gamma}, \tilde{\beta}_{1:\tilde{w}})$ lies in $\Gamma^{(2)}_{r_{1:\nu}}$ iff the corresponding configuration graph consists of $\nu$ directed multi-edges with multiplicities $r_1 + 2, r_2, \dots, r_\nu$. As before, we need to compute the number of vertices such a graph traverses. If the graph traverses no more than $k$ vertices then the number of configurations satisfying the condition is no more than $Cn^k$, where $C$ is the number of non-isomorphic directed graphs with $w_{\mathrm{MatMul}} + \tilde{w}_{\mathrm{MatMul}} + 2$ edges and $\nu$ multi-edges; obviously, $C$ depends neither on $n$, nor on $s$.

We proceed with the same logic as in Lemma 8. Consider a non-directed graph with $\nu$ multi-edges. If it has $p$ connected components, it traverses $\nu + p$ vertices. Recall our configuration graph is a union of two paths, having $w$ and $\tilde{w}$ edges respectively, with some of the edges erased, resulting in $w_{\mathrm{MatMul}} + 1$ and $\tilde{w}_{\mathrm{MatMul}} + 1$ edges respectively. Overall, we had to erase $w_{\mathrm{Moment}} + \tilde{w}_{\mathrm{Moment}}$ edges. Given a union of paths, erasing $k$ edges results in introduction of no more than $k$ connected components. Since there are only two paths from the beginning and the last edge of the two is the same, we should have no more than $k + 1$ connected components after erasing $k$ edges.

In our case, $k = w_{\mathrm{Moment}} + \tilde{w}_{\mathrm{Moment}}$. Hence our configuration graph traverses no more than $\nu + 1 + w_{\mathrm{Moment}} + \tilde{w}_{\mathrm{Moment}}$ vertices. Therefore the number of configurations $(\gamma, \beta_{1:w}, \tilde{\gamma}, \tilde{\beta}_{1:\tilde{w}})$ in $\Gamma^{(2)}_{r_{1:\nu}}$ is not greater than $Cn^{\nu+1} n^{w_{\mathrm{Moment}}} n^{\tilde{w}_{\mathrm{Moment}}}$ for some constant $C$ independent on both $n$ and $s$. □

Let us now turn to the analogue of Proposition 2:

**Proposition 3.**

$$\sup_{s \in [0, 1/\sqrt{2}]} \sup_{\gamma, \beta_{1:w}, \tilde{\gamma}, \tilde{\beta}_{1:\tilde{w}}} \left| \mathbb{E} \left( \left[ f_{\gamma,\beta_{1:w}} f_{\tilde{\gamma},\tilde{\beta}_{1:\tilde{w}}} \right] (a_1, \dots, a_N) [\partial_s a_1]^2 [a_1]^{r_1} \dots [a_\nu]^{r_\nu} \right) \right| = O(n^{-\nu}), \quad (103)$$

*where $a_1, \dots, a_N$ are functions of $s^2$.*

*Proof.* Similarly to the proof of Proposition 2, it suffices to bound $\mathbb{E}\left[[\partial_s a_1]^2[a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu}\right]$ and $\mathbb{E}\left[\left([\partial_s a_1]^2[a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu}\right)^2\right]$ uniformly over $s\in[0,1/\sqrt{2}]$. By Lemma 3,

$$\sup_{s\in[0,1/\sqrt{2}]}\mathbb{E}\left[[\partial_s a_1]^2[a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu}\right]=O(n^{-1})\left(\prod_{i=1}^{\nu}O(n^{-(j_i+r_i)/2})\right)\prod_{i=2}^{\nu}1_{j_i+r_i\geq 2}; \tag{104}$$

$$\sup_{s\in[0,1/\sqrt{2}]}\mathbb{E}\left[\left([\partial_s a_1]^2[a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu}\right)^2\right]=O(n^{-2})\prod_{i=1}^{\nu}O(n^{-(j_i+r_i)}). \tag{105}$$

This implies

$$\begin{aligned}\sum_{\substack{j_{1:\nu}\geq 0\\ j_1+\dots+j_\nu=k}}\mathbb{E}\left[[\partial_s a_1]^2[a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu}\right]\times\mathbb{E}\left[\partial_1^{j_1}\dots\partial_\nu^{j_\nu}f(0_{1:\nu},a_{\nu+1:N})\right]=\\ =O\left(n^{-\frac{2+k+\sum_{i=1}^{\nu}r_i}{2}}\right)1_{k+\sum_{i=2}^{\nu}r_i\geq 2\nu-2}\leq\\ \leq O\left(n^{-\frac{2+k+w_{\mathrm{MatMul}}+\tilde{w}_{\mathrm{MatMul}}}{2}}\right)1_{2+k+w_{\mathrm{MatMul}}+\tilde{w}_{\mathrm{MatMul}}\geq 2\nu}\end{aligned} \tag{106}$$

uniformly over $s\in[0,1/\sqrt{2}]$, and

$$\begin{aligned}\sum_{\substack{j_{1:\nu}\geq 0\\ j_1+\dots+j_\nu=K+1}}\sqrt{\mathbb{E}\left[\left([\partial_s a_1]^2[a_1]^{j_1+r_1}\dots[a_\nu]^{j_\nu+r_\nu}\right)^2\right]\mathbb{E}\left[\left(\int_0^1\partial_1^{j_1}\dots\partial_\nu^{j_\nu}f(\dots)\,d\xi\right)^2\right]}=\\ =O\left(n^{-\frac{2+(K+1)+\sum_{i=1}^{\nu}r_i}{2}}\right)=O\left(n^{-\frac{2+K+w_{\mathrm{MatMul}}+\tilde{w}_{\mathrm{MatMul}}}{2}}\right)\end{aligned} \tag{107}$$

uniformly over $s\in[0,1/\sqrt{2}]$.

Recall $f=f_{\gamma,\beta_{1:w}}\times f_{\tilde{\gamma},\tilde{\beta}_{1:\tilde{w}}}$. Take $K=\max(0,2\nu-2-w_{\mathrm{MatMul}}-\tilde{w}_{\mathrm{MatMul}})$; this gives

$$\begin{aligned}\sup_{s\in[0,1/\sqrt{2}]}\mathbb{E}\left[f(a_{1:N}(t))[[\partial_s a_1]^2[a_1]^{r_1}\dots[a_\nu]^{r_\nu}](t)\right]=\\ =\begin{cases}O\left(n^{-(w_{\mathrm{MatMul}}+\tilde{w}_{\mathrm{MatMul}})/2-1}\right), & w_{\mathrm{MatMul}}+\tilde{w}_{\mathrm{MatMul}}\geq 2\nu-2\\ O\left(n^{-\nu}\right), & w_{\mathrm{MatMul}}+\tilde{w}_{\mathrm{MatMul}}<2\nu-2\end{cases}=O(n^{-\nu}),\end{aligned} \tag{108}$$

which finishes the proof of the proposition. □

# H Uniform moment controls

**Definition 5.** *We say $f$ is linearly smooth if it is smooth and any its derivative of order $k\geq 1$ is bounded.*

**Lemma 13.** *Consider a Tensor Program $\bar{\Pi}$ of width $n$ with matrices satisfying $\mathbb{E}\,\bar{A}_{\beta\gamma}=0$ and $\mathbb{E}\,|\bar{A}_{\beta\gamma}|^k\leq\nu_k n^{-k/2}$, $\nu_k\in\mathbb{R}_+\ \forall k\geq 1$, and linearly smooth nonlinearity $\phi$. Denote the corresponding vectors as $\bar{g}^1,\dots,\bar{g}^M$ and the corresponding scalars as $\bar{c}^1,\dots,\bar{c}^M$.*

*Let $P$ be a collection of weights in $\bar{\Pi}$. Then $\forall m\in[M_0:M-1]\ \forall p\geq 1$*

$$\sup_{\alpha\in[n]}\mathbb{E}\left|\partial_P\phi(\bar{g}^1_\alpha,\dots,\bar{g}^m_\alpha,\bar{c}^1,\dots,\bar{c}^m)\right|^p\leq B_{p,|P|}n^{-p|P|/2}, \tag{109}$$

*where $B_{p,|P|}$ is a continuous function of a finite number of (scaled) moments $\nu$. Similarly, for a linearly smooth $\psi$, we have $\forall p\geq 1$*

$$\sup_{\alpha\in[n]}\mathbb{E}\left|\partial_P\psi(\bar{g}^1_\alpha,\dots,\bar{g}^M_\alpha,\bar{c}^1,\dots,\bar{c}^M)\right|^p\leq B_{p,|P|}n^{-p|P|/2}. \tag{110}$$

*Proof.* Consider the following two claims and induct on $m \in [M_0 : M-1]$: for any collection of weights $P$, $\forall p \geq 1$

1. $\sup_{\alpha\in[n]} \mathbb{E} \left|\sum_\beta \bar{A}^{m+1,T_{m+1}}_{\alpha\beta} \partial_P \phi(\bar{g}^1_\beta, \dots, \bar{g}^m_\beta, \bar{c}^1, \dots, \bar{c}^m)\right|^p \leq B_{p,|P|} n^{-p|P|/2}$;
2. $\sup_{\alpha\in[n]} \mathbb{E} \left|\partial_P \phi(\bar{g}^1_\alpha, \dots, \bar{g}^m_\alpha, \bar{c}^1, \dots, \bar{c}^m)\right|^p \leq B_{p,|P|} n^{-p|P|/2}$,

where $B_{p,|P|}$ is a continuous function of a finite number of scaled moments $\nu$. The additional claim of the lemma will follow from Claim $2(M)$ since $\phi$ and $\psi$ are of the same nature.

We will make use of the following lemma:

**Lemma 14.** $\forall k \geq 1\ \forall I \in [n]^k\ \exists \tilde{B}_k \in C(\mathbb{R}^k) : \forall m \in [M-1]$

$$\sup_{\alpha\in[n]} \mathbb{E} \left|\prod_{\beta\in I} \bar{A}^{m,T_m}_{\alpha\beta}\right| \leq \tilde{B}_k(\nu_1, \dots, \nu_k) n^{-k/2}. \tag{111}$$

*Proof.* Let $\mathbb{I}$ be the set of unique indices in $I$. Define $p_\beta = |\{j : \ I_j = \beta\}|$. Note that $\sum_{\beta\in\mathbb{I}} p_\beta = k$. Then, since elements of the matrix $A$ are independent,

$$\mathbb{E} \left|\prod_{\beta\in I} \bar{A}^{m,T_m}_{\alpha\beta}\right| = \prod_{\beta\in\mathbb{I}} \mathbb{E} \left|\bar{A}^{m,T_m}_{\alpha\beta}\right|^{p_\beta} \leq \prod_{\beta\in\mathbb{I}} \nu_{p_\beta} n^{-p_\beta/2} = n^{-k/2} \prod_{\beta\in\mathbb{I}} \nu_{p_\beta}, \tag{112}$$

and it does not depend on $\alpha$. Therefore the claim is valid for $\tilde{B}_k(\nu_1, \dots, \nu_k) = \prod_{\beta\in\mathbb{I}} \nu_{p_\beta}$. □

### H.1 Induction base

Both claims are trivial for $m = M_0$ and $|P| > 0$ since $\bar{g}^1, \dots, \bar{g}^{M_0}$ do not depend on any weights. For $|P| = 0$, we have for even $p$,

$$\mathbb{E} \left|\sum_\beta \bar{A}^{M_0+1,T_{M_0+1}}_{\alpha\beta} \phi(\bar{g}^1_\beta, \dots, \bar{g}^{M_0}_\beta, \bar{c}^1, \dots, \bar{c}^{M_0})\right|^p =$$

$$= \sum_{\beta_1} \dots \sum_{\beta_p} \mathbb{E} \left[\prod_{i=1}^p \bar{A}^{M_0+1,T_{M_0+1}}_{\alpha\beta_i} \phi(\bar{g}^1_{\beta_i}, \dots, \bar{g}^{M_0}_{\beta_i}, \bar{c}^1, \dots, \bar{c}^{M_0})\right]. \tag{113}$$

Since $\bar{g}^1, \dots, \bar{g}^{M_0}$ do not depend on $\bar{A}^{M_0+1}$ and $\mathbb{E}\, \bar{A}^{M_0+1,T_{M_0+1}}_{\alpha\beta_i} = 0$, only those expectations survive for which the indices $\beta_1, \dots, \beta_p$ are coupled into groups of even sizes. We get the maximal growth rate when these indices are paired; in this case, only half of the sums survive, which gives the growth rate $O(1)$. The leading constant is finite and depends only on $\nu_2$, in a continuous way, and does not depend on $\alpha$ by Lemma 14. The case of odd $p$ follows from Cauchy-Schwarz.

The second claim is trivial for $|P| = 0$ since $\bar{g}^1_\alpha, \dots, \bar{g}^{M_0}_\alpha \sim \mathcal{N}(\mu^{in}, \Sigma^{in})$ — they do not depend on $n$.

### H.2 Claim 2(m) implies Claim 1(m)

For this section, let us omit the superscript $m+1$ for $\bar{A}$ and the subscript $m+1$ for $T$, i.e. define $\bar{A}^T = \bar{A}^{m+1,T_{m+1}}$. As one shall further see, proving Claim 1 from Claim 2 never requires dealing with other weight matrices explicitly.

Observe

$$\mathbb{E} \left|\sum_\beta \bar{A}^T_{\alpha\beta} \partial_P \phi(\bar{g}^1_\beta, \dots, \bar{g}^m_\beta, \bar{c}^1, \dots, \bar{c}^m)\right|^p = \mathbb{E} \left[\sum_{\beta_1,\dots,\beta_p} \prod_{i=1}^p \bar{A}^T_{\alpha\beta_i} \partial_P \phi(\bar{g}^1_{\beta_i}, \dots, \bar{g}^M_{\beta_i}, \bar{c}^1, \dots, \bar{c}^m)\right]. \tag{114}$$

A naive bound that uses Cauchy-Schwarz and Claim 2(m) results in $O(n^p)O(n^{-p/2})O(n^{-p|P|/2}) = O(n^{-p(|P|-1)/2})$ — larger than required. Our idea will be to expand $\partial_P \phi(\bar{g}^1_{\beta_i}, \ldots, \bar{g}^M_{\beta_i}, \bar{c}^1, \ldots, \bar{c}^m)$ with respect to $\bar{A}^T_{\alpha\beta_i}$ for $i \in [p]$ at zero. The fastest growing term in this expansion will be the zero-order term. Since it will not depend on $\bar{A}^T_{\alpha\beta_i}$ for $i \in [p]$, the expectation above will become $O(n^{p/2})O(n^{-p/2})O(n^{-p|P|/2}) = O(n^{-p|P|/2})$ since weights have zero mean and therefore only a half of the sums will survive.

It is more convenient to expand $\partial_P \phi(\bar{g}^1_{\beta_i}, \ldots, \bar{g}^M_{\beta_i}, \bar{c}^1, \ldots, \bar{c}^m)$ not with respect to $\bar{A}^T_{\alpha\beta_i}$ for $i \in [p]$ directly, but with respect to a single parameter that interpolates $\bar{A}^T_{\alpha\beta_i}$ to zero. More specifically, let $\mathbb{I} = \{(\alpha, \beta_1), \ldots, (\alpha, \beta_p)\}$ if $T = 1$, let $\mathbb{I} = \{(\beta_1, \alpha), \ldots, (\beta_p, \alpha)$ otherwise, let $\mathring{A}^{\mathbb{I}}_{\beta'\gamma'} = \bar{A}_{\beta'\gamma'} 1_{(\beta',\gamma') \notin \mathbb{I}}$, and let $\bar{A}^{\mathbb{I}}(s) = (1-s)\mathring{A}^{\mathbb{I}} + s\bar{A}$. Denote the corresponding $\bar{g}^m$ as $\bar{g}^{m;\mathbb{I}}(s)$ and the corresponding $\bar{c}^m$ as $\bar{c}^{m;\mathbb{I}}(s)$. For brevity, we will also denote $\phi(\bar{g}^{1:m;\mathbb{I}}_\beta(s), \bar{c}^{1:m;\mathbb{I}}(s))$ as $\phi^{m;\mathbb{I}}_\beta(s)$. For even $p$, expanding $\partial_P \phi(\bar{g}^1_{\beta_i}, \ldots, \bar{g}^M_{\beta_i}, \bar{c}^1, \ldots, \bar{c}^m) = \partial_P \phi^{m;\mathbb{I}}_\beta(1)$ with respect to $s$ at $s = 0$,

$$\mathbb{E}\left|\sum_\beta \bar{A}^T_{\alpha\beta} \partial_P \phi(\bar{g}^1_\beta, \ldots, \bar{g}^m_\beta, \bar{c}^1, \ldots, \bar{c}^m)\right|^p =$$

$$= \mathbb{E}\left[\sum_{\beta_1,\ldots,\beta_p} \prod_{i=1}^p \bar{A}^T_{\alpha\beta_i} \partial_P \phi(\bar{g}^1_{\beta_i}, \ldots, \bar{g}^M_{\beta_i}, \bar{c}^1, \ldots, \bar{c}^m)\right] =$$

$$= \mathbb{E}\left[\sum_{\beta_1,\ldots,\beta_p} \prod_{i=1}^p \bar{A}^T_{\alpha\beta_i} \left(\underbrace{\sum_{k=0}^{p-1} \frac{1}{k!} \partial_s^k \partial_P \phi^{m;\mathbb{I}}_{\beta_i}(0)}_{M_i} + \underbrace{\frac{1}{(p-1)!} \int_0^1 (1-s)^{p-1} \partial_s^p \partial_P \phi^{m;\mathbb{I}}_{\beta_i}(s)\, ds}_{N_i}\right)\right] =$$

$$= \mathbb{E}\left[\sum_{\beta_1,\ldots,\beta_p} \left(\prod_{i=1}^p \bar{A}^T_{\alpha\beta_i}\right) \sum_{I \subseteq [p]} \left(\prod_{i \in I} M_i\right) \times \left(\prod_{i \in I^c} N_i\right)\right]. \quad (115)$$

We are going to bound this expression separately for each $I \subseteq [p]$. Note the following:

$$\partial_s^p \partial_P \phi^{m;\mathbb{I}}_{\beta_i}(s) = \sum_{j_1,\ldots,j_p=1}^p \partial_{P+\sum_{i'=1}^p [(\alpha,\beta_{j_{i'}})]^T} \phi^{m;\mathbb{I}}_{\beta_i}(s) \prod_{i'=1}^p \bar{A}^T_{\alpha\beta_{j_{i'}}}; \quad (116)$$

$$\partial_s^k \partial_P \phi^{m;\mathbb{I}}_{\beta_i}(0) = \sum_{j_1,\ldots,j_k=1}^p \partial_{P+\sum_{i'=1}^k [(\alpha,\beta_{j_{i'}})]^T} \phi^{m;\mathbb{I}}_{\beta_i}(0) \prod_{i'=1}^k \bar{A}^T_{\alpha\beta_{j_{i'}}}. \quad (117)$$

We see that by Claim 2(m) and Cauchy-Schwarz, the fastest growing term must be $\partial_P \phi^{m;\mathbb{I}}_{\beta_i}(0)$, i.e. the one with $k = 0$. This term is contained in $M_i$; therefore we suspect the fastest growing subset $I$ must be $[p]$. We start our analysis with that one.

Let $I = [p]$:

$$\mathbb{E}\left[\sum_{\beta_1,\ldots,\beta_p} \left(\prod_{i=1}^p \bar{A}^T_{\alpha\beta_i} M_i\right)\right] = \mathbb{E}\left[\sum_{\beta_1,\ldots,\beta_p} \left(\prod_{i=1}^p \bar{A}^T_{\alpha\beta_i} \sum_{k=0}^{p-1} \frac{1}{k!} \partial_s^k \partial_P \phi^{m;\mathbb{I}}_{\beta_i}(0)\right)\right] =$$

$$= \mathbb{E}\left[\sum_{\beta_1,\ldots,\beta_p} \sum_{k_1,\ldots,k_p=0}^{p-1} \prod_{i=1}^p \left(\bar{A}^T_{\alpha\beta_i} \frac{1}{k_i!} \partial_s^{k_i} \partial_P \phi^{m;\mathbb{I}}_{\beta_i}(0)\right)\right] =$$

$$= \mathbb{E}\left[\sum_{\beta_1,\ldots,\beta_p} \sum_{k_1,\ldots,k_p=0}^{p-1} \prod_{i=1}^p \left(\frac{1}{k_i!} \sum_{j_{1:k_i}=1}^p \partial_{P+\sum_{i'=1}^{k_i} [(\alpha,\beta_{j_{i'}})]} \phi^{m;\mathbb{I}}_{\beta_i}(0) \bar{A}^T_{\alpha\beta_i} \prod_{i'=1}^{k_i} \bar{A}^T_{\alpha\beta_{j_{i'}}}\right)\right]. \quad (118)$$

The fastest growing term is that with $k_1, \dots, k_p = 0$; using independency between $\partial_P \phi^{m;\mathbb{I}}_{\beta_i}(0)$ and $\bar{A}^T_{\alpha\beta_i}$ for any $i \in [p]$, we get

$$\mathbb{E}\left[\sum_{\beta_1,\dots,\beta_p}\left(\prod_{i=1}^p \bar{A}^T_{\alpha\beta_i} M_i\right)\right] \leq C\mathbb{E}\left[\sum_{\beta_1,\dots,\beta_p}\prod_{i=1}^p\left(\partial_P \phi^{m;\mathbb{I}}_{\beta_i}(0)\bar{A}^T_{\alpha\beta_i}\right)\right] =$$
$$= C\sum_{\beta_1,\dots,\beta_p}\mathbb{E}\left[\prod_{i=1}^p \bar{A}^T_{\alpha\beta_i}\right]\mathbb{E}\left[\prod_{i=1}^p \partial_P \phi^{m;\mathbb{I}}_{\beta_i}(0)\right] \leq C\tilde{B}_p(\nu_1,\dots,\nu_p)\prod_{i=1}^p \sqrt[p]{\mathbb{E}\left[\left(\partial_P \phi^{m;\mathbb{I}}_{\beta_i}(0)\right)^p\right]}, \tag{119}$$

where the last inequality holds due to Lemma 10 and since $\bar{A}^T$ has zero expectation. Using induction hypothesis and redefining the constants appropriately, we get this quantity to be bounded by $B_{p,|P|}n^{-p|P|/2}$.

We proceed our analysis with $I = [p]\backslash\{i^c\}$. While we will not be able to make use of zero expectation of $\bar{A}^T$ as before, we will observe slower growth rate of the corresponding term simply by applying Cauchy-Schwarz. Indeed, intuitively,

$$\mathbb{E}\left[\sum_{\beta_1,\dots,\beta_p}\left(\prod_{i=1}^p \bar{A}^T_{\alpha\beta_i}\right)\left(\prod_{i\in[p]\backslash\{i^c\}} M_i\right)\times(N_{i^c})\right] =$$
$$= O(n^p)O(n^{-p/2})O(n^{-(p-1)|P|/2})O(n^{-(p+|P|)/2})O(n^{-p/2}) = O(n^{-p(|P|+1)/2}), \tag{120}$$

which is even better than needed. Working more formally, we get

$$\mathbb{E}\left[\sum_{\beta_1,\dots,\beta_p}\left(\prod_{i=1}^p \bar{A}^T_{\alpha\beta_i}\right)\left(\prod_{i\in[p]\backslash\{i^c\}} M_i\right)\times(N_{i^c})\right] =$$
$$= \mathbb{E}\left[\sum_{\beta_1,\dots,\beta_p}\left(\prod_{i=1}^p \bar{A}^T_{\alpha\beta_i}\right)\left(\prod_{i\in[p]\backslash\{i^c\}} M_i\right)\times\right.$$
$$\left.\times\int_0^1(1-s)^{p-1}\left(\prod_{i'=1}^p \bar{A}^T_{\alpha\beta_{j_{i'}}}\right)\sum_{j_1,\dots,j_p=1}^p \partial_{P+\sum_{i'=1}^p[(\alpha,\beta_{j_{i'}})]^T}\phi^{m;\mathbb{I}}_{\beta_{i^c}}(s)\,ds\right] =$$
$$= \sum_{j_1,\dots,j_p=1}^p\int_0^1(1-s)^{p-1}\times$$
$$\times\,\mathbb{E}\left[\sum_{\beta_1,\dots,\beta_p}\left(\prod_{i=1}^p \bar{A}^T_{\alpha\beta_i}\right)\left(\prod_{i\in[p]\backslash\{i^c\}} M_i\right)\left(\prod_{i'=1}^p \bar{A}^T_{\alpha\beta_{j_{i'}}}\right)\partial_{P+\sum_{i'=1}^p[(\alpha,\beta_{j_{i'}})]^T}\phi^{m;\mathbb{I}}_{\beta_{i^c}}(s)\right]ds. \tag{121}$$

Applying Cauchy-Schwarz, we get

$$\mathbb{E}\left|\sum_{\beta_1,\dots,\beta_p}\left(\prod_{i=1}^p \bar{A}^T_{\alpha\beta_i}\right)\left(\prod_{i\in[p]\backslash\{i^c\}} M_i\right)\left(\prod_{i'=1}^p \bar{A}^T_{\alpha\beta_{j_{i'}}}\right)\partial_{P+\sum_{i'=1}^p[(\alpha,\beta_{j_{i'}})]^T}\phi^{m;\mathbb{I}}_{\beta_{i^c}}(s)\right| \leq$$
$$\leq \sum_{\beta_1,\dots,\beta_p}\sqrt{\mathbb{E}\left[\left(\prod_{i=1}^p \bar{A}^T_{\alpha\beta_i}\right)\left(\prod_{i'=1}^p \bar{A}^T_{\alpha\beta_{j_{i'}}}\right)\partial_{P+\sum_{i'=1}^p[(\alpha,\beta_{j_{i'}})]^T}\phi^{m;\mathbb{I}}_{\beta_{i^c}}(s)\right]^2\mathbb{E}\left[\prod_{i\in[p]\backslash\{i^c\}} M_i\right]^2}. \tag{122}$$

Let us work out the two multiplicants separately:

$$\mathbb{E}\left[\left(\prod_{i=1}^{p}\bar{A}^T_{\alpha\beta_i}\right)\left(\prod_{i'=1}^{p}\bar{A}^T_{\alpha\beta_{j_{i'}}}\right)\partial_{P+\sum_{i'=1}^{p}[(\alpha,\beta_{j_{i'}})]^T}\phi^{m;\mathbb{I}}_{\beta_{i^c}}(s)\right]^2 \leq$$
$$\leq \mathbb{E}\left[\left(\prod_{i=1}^{p}\bar{A}^T_{\alpha\beta_i}\right)^2\left(\prod_{i'=1}^{p}\bar{A}^T_{\alpha\beta_{j_{i'}}}\right)^2\right]\mathbb{E}\left[\partial_{P+\sum_{i'=1}^{p}[(\alpha,\beta_{j_{i'}})]^T}\phi^{m;\mathbb{I}}_{\beta_{i^c}}(s)\right]^2 \leq$$
$$\leq \tilde{B}_p(\nu_1,\dots,\nu_{4p})n^{-2p}B_{p,|P|}n^{-p-|P|}. \quad (123)$$

The bound is uniform over $\alpha$ due to Lemma 14 and uniform over $s\in[0,1]$ by induction hypothesis. As before, we redefine $B_{p,|P|}$, so the quantity is bounded by $B_{p,|P|}n^{-3p-|P|}$.

For the second multiplicant, we will need the following estimate.

$$\mathbb{E}\left|\partial_s^k\partial_P\phi^{m;\mathbb{I}}_{\beta_i}(0)\right|^p = \mathbb{E}\left|\sum_{j_1,\dots,j_k=1}^{p}\partial_{P+\sum_{i'=1}^{k}[(\alpha,\beta_{j_{i'}})]}\phi^{m;\mathbb{I}}_{\beta_i}(0)\prod_{i'=1}^{k}\bar{A}^T_{\alpha\beta_{j_{i'}}}\right|^p =$$
$$= \mathbb{E}\sum_{j_1^1,\dots,j_k^1=1}^{p}\cdots\sum_{j_1^p,\dots,j_k^p=1}^{p}\prod_{l=1}^{p}\left[\partial_{P+\sum_{i'=1}^{k}[(\alpha,\beta_{j^l_{i'}})]}\phi^{m;\mathbb{I}}_{\beta_i}(0)\prod_{i'=1}^{k}\bar{A}^T_{\alpha\beta_{j^l_{i'}}}\right] =$$
$$= \sum_{j_1^1,\dots,j_k^1=1}^{p}\cdots\sum_{j_1^p,\dots,j_k^p=1}^{p}\mathbb{E}\left[\prod_{l=1}^{p}\partial_{P+\sum_{i'=1}^{k}[(\alpha,\beta_{j^l_{i'}})]}\phi^{m;\mathbb{I}}_{\beta_i}(0)\right]\mathbb{E}\left[\prod_{l=1}^{p}\prod_{i'=1}^{k}\bar{A}^T_{\alpha\beta_{j^l_{i'}}}\right] \leq$$
$$\leq \sum_{j_1^1,\dots,j_k^1=1}^{p}\cdots\sum_{j_1^p,\dots,j_k^p=1}^{p}\prod_{l=1}^{p}\sqrt[p]{\mathbb{E}\left[\left(\partial_{P+\sum_{i'=1}^{k}[(\alpha,\beta_{j^l_{i'}})]}\phi^{m;\mathbb{I}}_{\beta_i}(0)\right)^p\right]}\mathbb{E}\left[\prod_{l=1}^{p}\prod_{i'=1}^{k}\bar{A}^T_{\alpha\beta_{j^l_{i'}}}\right] \leq$$
$$\leq \sum_{j_1^1,\dots,j_k^1=1}^{p}\cdots\sum_{j_1^p,\dots,j_k^p=1}^{p}B_{p,|P|+k}n^{-p(|P|+k)/2}\tilde{B}_p n^{-pk/2} \quad (124)$$

by induction hypothesis; again, the bound is uniform over $\alpha$ by Lemma 14. Abusing notation, since $k\in[p]$ and we can redefine the constants appropriately, and say that the quantity above is bounded by $B_{p,|P|}n^{-p(k+|P|/2)}$.

Let us work out the second multiplicant now:

$$\mathbb{E}\left[\prod_{i\in I}\left(\sum_{k=0}^{p-1}\frac{1}{k!}\partial_s^k\partial_P\phi^{m;\mathbb{I}}_{\beta_i}(0)\right)\right]^2 = \mathbb{E}\left[\sum_{k^{j\in[2]}_{i\in I}=0}^{p-1}\prod_{i\in I,j\in[2]}\left(\frac{1}{k_i^j!}\partial_s^{k_i^j}\partial_P\phi^{m;\mathbb{I}}_{\beta_i}(0)\right)\right] \leq$$
$$\leq \sum_{k^{j\in[2]}_{i\in I}=0}^{p-1}\prod_{i\in I,j\in[2]}\frac{1}{k_i^j!}\sqrt[p]{\mathbb{E}\left[\left(\partial_s^{k_i^j}\partial_P\phi^{m;\mathbb{I}}_{\beta_i}(0)\right)^p\right]} \leq \sum_{k^{j\in[2]}_{i\in I}=0}^{p-1}\prod_{i\in I,j\in[2]}\frac{1}{k_i^j!}B_{p,|P|}n^{-k_i^j-|P|/2}, \quad (125)$$

where we applied Lemma 10. The fastest growing term of the sum is the one with all $k_i^j=0$. Therefore redefining $B_{p,|P|}$ appropriately, we get the quantity to be bounded by $B_{p,|P|}n^{-|P|(p-1)}$.

Going back and using that $|(1-s)^{p-1}| \leq 1$,

$$\mathbb{E}\left|\sum_{\beta_1,\ldots,\beta_p}\left(\prod_{i=1}^{p}\bar{A}^T_{\alpha\beta_i}\right)\left(\prod_{i\in[p]\setminus\{i^c\}}M_i\right)\times(N_{i^c})\right| \leq$$
$$\leq \sum_{j_1,\ldots,j_p=1}^{p}\sup_{s\in[0,1]}\mathbb{E}\left|\sum_{\beta_1,\ldots,\beta_p}\left(\prod_{i=1}^{p}\bar{A}^T_{\alpha\beta_i}\right)\left(\prod_{i\in[p]\setminus\{i^c\}}M_i\right)\times\right.$$
$$\left.\times\left(\prod_{i'=1}^{p}\bar{A}^T_{\alpha\beta_{j_{i'}}}\right)\partial_{P+\sum_{i'=1}^{p}[(\alpha,\beta_{j_{i'}})]^T}\phi^{m;\mathbb{I}}_{\beta_{i^c}}(s)\right| \leq$$
$$\leq \sum_{j_1,\ldots,j_p=1}^{p}\sum_{\beta_1,\ldots,\beta_p}\sqrt{\mathbb{E}\left[\prod_{i\in[p]\setminus\{i^c\}}M_i\right]^2}\times$$
$$\times\sqrt{\sup_{s\in[0,1]}\mathbb{E}\left[\left(\prod_{i=1}^{p}\bar{A}^T_{\alpha\beta_i}\right)\left(\prod_{i'=1}^{p}\bar{A}^T_{\alpha\beta_{j_{i'}}}\right)\partial_{P+\sum_{i'=1}^{p}[(\alpha,\beta_{j_{i'}})]^T}\phi^{m;\mathbb{I}}_{\beta_{i^c}}(s)\right]^2} \leq$$
$$\leq \sum_{\beta_1,\ldots,\beta_p}\sum_{j_1,\ldots,j_p=1}^{p}\sqrt{B^2_{p,|P|}n^{-3p-|P|}n^{-|P|(p-1)}} = \sum_{\beta_1,\ldots,\beta_p}\sum_{k_1,\ldots,k_p=1}^{p}B_{p,|P|}n^{-3p/2}n^{-|P|p/2}. \tag{126}$$

Redefining $B_{p,|P|}$ appropriately, we get the quantity to be bounded by $B_{p,|P|}n^{-p(1+|P|)/2)}$. Hence $\forall I \neq [p]$ the corresponding term is bounded by $B_{p,|P|}n^{-p(1+|P|)/2}$ as well.

As for the case $I \subsetneq [p]\setminus\{i^c\}$, one can follow the same lines as for $I = [p]\setminus\{i^c\}$. An intuitive bound will result in

$$\mathbb{E}\left[\sum_{\beta_1,\ldots,\beta_p}\left(\prod_{i=1}^{p}\bar{A}^T_{\alpha\beta_i}\right)\left(\prod_{i\in I}M_i\right)\times\left(\prod_{i\in I^c}N_i\right)\right] =$$
$$= O(n^p)O(n^{-p/2})O(n^{-|I||P|/2})O(n^{-(p+|P|)(p-|I|)/2})O(n^{-p(p-|I|)/2}) =$$
$$= O(n^{p/2})O(n^{-(p^2+|P|p-|I|p)/2})O(n^{-p(p-|I|)/2}) =$$
$$= O(n^{p/2})O(n^{-p|P|/2})O(n^{-p(p-|I|)}) = O(n^{-p(|P|+1)/2})O(n^{-p(p-|I|-1)}), \tag{127}$$

which is even better than for $I = [p]\setminus\{i^c\}$.

Putting all togeter, we get $\mathbb{E}\left|\sum_\beta \bar{A}^T_{\alpha\beta}\partial_P\phi(\bar{g}^1_\beta,\ldots,\bar{g}^m_\beta,\bar{c}^1,\ldots,\bar{c}^m)\right|^p \leq B_{p,|P|}n^{-p|P|/2}\ \forall P \in ([n]\times[n])^k$ for any even $p$. The same bound for odd $p$ follows from Cauchy-Schwarz.

### H.3 Claim 1$(M_0 : m-1)$ and Claim 2$(M_0 : m-1)$ imply Claim 2$(m)$

We start with the case $|P| = 0$:

$$\begin{aligned}
\mathbb{E}\,|\phi(\bar{g}^1_\alpha, \dots, \bar{g}^m_\alpha, \bar{c}^1, \dots, \bar{c}^m)|^p \le \mathbb{E}\Bigg( & |\phi(\bar{g}^1_\alpha, \dots, \bar{g}^{M_0}_\alpha, 0, \dots, 0, \bar{c}^1, \dots, \bar{c}^{M_0}, 0, \dots, 0)| + \\
& + L \sum_{m'=M_0+1}^{m} \Bigg[ \left| \sum_\beta \bar{A}^{m',T_{m'}}_{\alpha\beta} \phi(\bar{g}^1_\beta, \dots, \bar{g}^{m'-1}_\beta, \bar{c}^1, \dots, \bar{c}^{m'-1}) \right| + \\
& + \left| \frac{1}{n} \sum_\beta \phi(\bar{g}^1_\beta, \dots, \bar{g}^{m'-1}_\beta, \bar{c}^1, \dots, \bar{c}^{m'-1}) \right| \Bigg] \Bigg)^p \le \\
& \le 2^p \mathbb{E}\,|\phi(\bar{g}^1_\alpha, \dots, \bar{g}^{M_0}_\alpha, 0, \dots, 0, \bar{c}^1, \dots, \bar{c}^{M_0}, 0, \dots, 0)|^p + \\
& + 2^p L^p (m - M_0)^p \max_{m' \in [M_0+1:m]} \mathbb{E} \left| \sum_\beta \bar{A}^{m',T_{m'}}_{\alpha\beta} \phi(\bar{g}^1_\beta, \dots, \bar{g}^{m'-1}_\beta, \bar{c}^1, \dots, \bar{c}^{m'-1}) \right|^p + \\
& + 2^p L^p (m - M_0)^p \max_{m' \in [M_0+1:m]} \frac{1}{n} \sum_\beta \mathbb{E} \left| \phi(\bar{g}^1_\beta, \dots, \bar{g}^{m'-1}_\beta, \bar{c}^1, \dots, \bar{c}^{m'-1}) \right|^p \le \\
& \le 2^p \mathbb{E}\,|\phi(\bar{g}^1_\alpha, \dots, \bar{g}^{M_0}_\alpha, 0, \dots, 0, \bar{c}^1, \dots, \bar{c}^{M_0}, 0, \dots, 0)|^p + 2^p L^p (m - M_0)^p B_{p,0}, \qquad (128)
\end{aligned}$$

where $L$ is the Lipschitz constant of $\phi$; redefine $B_{p,0}$ as the above quantity. The bound is uniform over $\alpha$ by the induction hypothesis.

Consider now the case $|P| > 0$. We shall think of $P$ as a multi-set of triples $(\mu, \beta, \gamma)$, where $\mu \in \mathcal{M}$ indicates the "layer", while $\beta$ and $\gamma$ indicate the matrix element. Let $(\mu, \beta, \gamma)^\top = (\mu, \gamma, \beta)$. One can express the derivative wrt weights using the following recurrence:

$$\begin{aligned}
& \partial_P \phi(\bar{g}^1_\alpha, \dots, \bar{g}^m_\alpha, \bar{c}^1, \dots, \bar{c}^m) = \\
& \quad = \sum_{j=1}^{|P|} \sum_{m_1, \dots, m_j = M_0+1}^{m} \sum_{x_1, \dots, x_j \in \{g,c\}} \partial^{x_1}_{m_1} \dots \partial^{x_j}_{m_j} \phi(\bar{g}^1_\alpha, \dots, \bar{g}^m_\alpha, \bar{c}^1, \dots, \bar{c}^m) \times \\
& \qquad \times \frac{1}{j!} \sum_{s:\, P \to [j]} \prod_{i=1}^{j} \begin{cases} \partial_{s^{-1}(i)} \bar{g}^{m_i}_\alpha, & x_i = g \\ \partial_{s^{-1}(i)} \bar{c}^{m_i}, & x_i = c. \end{cases} \qquad (129)
\end{aligned}$$

$$\begin{aligned}
\partial_P \bar{g}^m_\alpha = \partial_P \left( \sum_\beta \bar{A}^{m,T_m}_{\alpha\beta} \phi\left(\bar{g}^1_\beta, \dots, \bar{g}^{m-1}_\beta, \bar{c}^1, \dots, \bar{c}^{m-1}\right) \right) = \\
= \sum_{(\mu,\beta,\gamma) \in P^{T_m}} 1_{m \in \mu} 1_{\alpha = \beta} \partial_{P \setminus \{(\mu,\beta,\gamma)^{T_m}\}} \phi\left(\bar{g}^1_\gamma, \dots, \bar{g}^{m-1}_\gamma, \bar{c}^1, \dots, \bar{c}^{m-1}\right) + \\
+ \sum_\beta \bar{A}^{m,T_m}_{\alpha\beta} \partial_P \phi\left(\bar{g}^1_\beta, \dots, \bar{g}^{m-1}_\beta, \bar{c}^1, \dots, \bar{c}^{m-1}\right). \qquad (130)
\end{aligned}$$

$$\begin{aligned}
\partial_P \bar{c}^m = \partial_P \left( \frac{1}{n} \sum_\beta \phi\left(\bar{g}^1_\beta, \dots, \bar{g}^{m-1}_\beta, \bar{c}^1, \dots, \bar{c}^{m-1}\right) \right) = \\
= \frac{1}{n} \sum_\beta \partial_P \phi\left(\bar{g}^1_\beta, \dots, \bar{g}^{m-1}_\beta, \bar{c}^1, \dots, \bar{c}^{m-1}\right). \qquad (131)
\end{aligned}$$

For even $p$,

$$\mathbb{E}\,|\partial_P \phi(\bar{g}^1_\alpha, \dots, \bar{g}^m_\alpha, \bar{c}^1, \dots, \bar{c}^m)|^p =$$
$$= \mathbb{E}\left(\sum_{j=1}^{|P|} \sum_{m_1,\dots,m_j=M_0+1}^{m} \sum_{x_1,\dots,x_j\in\{g,c\}} \partial^{x_1}_{m_1} \dots \partial^{x_j}_{m_j} \phi(\bar{g}^1_\alpha, \dots, \bar{g}^m_\alpha, \bar{c}^1, \dots, \bar{c}^m) \times \right.$$
$$\left. \times \frac{1}{j!} \sum_{s\colon P \twoheadrightarrow [j]} \prod_{i=1}^{j} \begin{cases} \partial_{s^{-1}(i)} \bar{g}^{m_i}_\alpha, & x_i = g \\ \partial_{s^{-1}(i)} \bar{c}^{m_i}, & x_i = c \end{cases} \right)^p =$$
$$= \sum_{j_1,\dots,j_p=1}^{|P|} \sum_{m^1_1,\dots,m^1_j=M_0+1}^{m} \dots \sum_{m^p_1,\dots,m^p_j=M_0+1}^{m} \sum_{x^1_1,\dots,x^1_j\in\{g,c\}} \dots \sum_{x^p_1,\dots,x^p_j\in\{g,c\}}$$
$$\mathbb{E}\left[\prod_{r=1}^{p} \partial^{x^r_1}_{m^r_1} \dots \partial^{x^r_j}_{m^r_j} \phi(\bar{g}^1_\alpha, \dots, \bar{g}^m_\alpha, \bar{c}^1, \dots, \bar{c}^m) \frac{1}{j_r!} \sum_{s\colon P \twoheadrightarrow [j_r]} \prod_{i=1}^{j_r} \begin{cases} \partial_{s^{-1}(i)} \bar{g}^{m^r_i}_\alpha, & x^r_i = g \\ \partial_{s^{-1}(i)} \bar{c}^{m^r_i}, & x^r_i = c \end{cases}\right]. \quad (132)$$

Since the sums have $O(1)$ terms, it suffices to bound the following expectations:

$$\mathbb{E}\left|\prod_{r=1}^{p} \partial^{x^r_1}_{m^r_1} \dots \partial^{x^r_j}_{m^r_j} \phi(\bar{g}^1_\alpha, \dots, \bar{g}^m_\alpha, \bar{c}^1, \dots, \bar{c}^m) \prod_{i=1}^{j_r} \partial_{s^{-1}(i)} \bar{g}^{m^r_i}_\alpha\right| \leq$$
$$\leq \sqrt{\mathbb{E}\left[\prod_{r=1}^{p} \partial^{x^r_1}_{m^r_1} \dots \partial^{x^r_j}_{m^r_j} \phi(\bar{g}^1_\alpha, \dots, \bar{g}^m_\alpha, \bar{c}^1, \dots, \bar{c}^m)\right]^2 \mathbb{E}\left[\prod_{i=1}^{j_r} \partial_{s^{-1}(i)} \bar{g}^{m^r_i}_\alpha\right]^2}, \quad (133)$$

and

$$\mathbb{E}\left|\prod_{r=1}^{p} \partial^{x^r_1}_{m^r_1} \dots \partial^{x^r_j}_{m^r_j} \phi(\bar{g}^1_\alpha, \dots, \bar{g}^m_\alpha, \bar{c}^1, \dots, \bar{c}^m) \prod_{i=1}^{j_r} \partial_{s^{-1}(i)} \bar{c}^{m^r_i}\right| \leq$$
$$\leq \sqrt{\mathbb{E}\left[\prod_{r=1}^{p} \partial^{x^r_1}_{m^r_1} \dots \partial^{x^r_j}_{m^r_j} \phi(\bar{g}^1_\alpha, \dots, \bar{g}^m_\alpha, \bar{c}^1, \dots, \bar{c}^m)\right]^2 \mathbb{E}\left[\prod_{i=1}^{j_r} \partial_{s^{-1}(i)} \bar{c}^{m^r_i}\right]^2}. \quad (134)$$

Since $j_1, \dots, j_p \geq 1$ and all the derivatives of $\phi$ are bounded, it suffices to bound the second expectations. For this, it suffices to bound the following for any even $p'$, any collecition of weights $P'$, and any $m' \in [M_0 + 1 : m - 1]$:

$$\mathbb{E}\left|\partial_{P'} \bar{c}^{m'}\right|^{p'} = \mathbb{E}\left|\frac{1}{n} \sum_\beta \partial_P \phi\left(\bar{g}^1_\beta, \dots, \bar{g}^{m-1}_\beta, \bar{c}^1, \dots, \bar{c}^{m-1}\right)\right|^{p'} \leq$$
$$\leq \sup_\beta \mathbb{E}\left|\partial_P \phi\left(\bar{g}^1_\beta, \dots, \bar{g}^{m-1}_\beta, \bar{c}^1, \dots, \bar{c}^{m-1}\right)\right|^{p'}, \quad (135)$$

and

$$\mathbb{E}\left|\partial_{P'}\bar{g}_\alpha^{m'}\right|^{p'} =$$

$$= \mathbb{E}\Bigg[\sum_{(\mu,\beta,\gamma)\in P',T_{m'}} 1_{m'\in\mu}1_{\alpha=\beta}\partial_{P'\setminus\{(\mu,\beta,\gamma)^{T_{m'}}\}}\phi\left(\bar{g}_\gamma^1,\ldots,\bar{g}_\gamma^{m'-1},\bar{c}^1,\ldots,\bar{c}^{m'-1}\right) +$$

$$+\sum_\beta \bar{A}_{\alpha\beta}^{m',T_{m'}}\partial_P\phi\left(\bar{g}_\beta^1,\ldots,\bar{g}_\beta^{m'-1},\bar{c}^1,\ldots,\bar{c}^{m'-1}\right)\Bigg]^{p'} \leq$$

$$\leq 2^{p'}\sum_{(\beta,\gamma)\in P',T_{m'}} 1_{m'\in\mu}1_{\alpha=\beta}\mathbb{E}\left[\partial_{P'\setminus\{(\beta,\gamma)^{T_{m'}}\}}\phi\left(\bar{g}_\gamma^1,\ldots,\bar{g}_\gamma^{m'-1},\bar{c}^1,\ldots,\bar{c}^{m'-1}\right)\right]^{p'} +$$

$$+2^{p'}\times\mathbb{E}\left[\sum_\beta \bar{A}_{\alpha\beta}^{m',T_{m'}}\partial_{P'}\phi\left(\bar{g}_\beta^{1:m'-1},\bar{c}^1,\ldots,\bar{c}^{m'-1}\right)\right]^{p'}. \quad (136)$$

$\mathbb{E}\left|\partial_{P'}\bar{c}^{m'}\right|^{p'}$ is bounded by induction. As for $\mathbb{E}\left|\partial_{P'}\bar{g}_\alpha^{m'}\right|^{p'}$, the first expectation is bounded by $B_{p',|P'|}n^{-p'|P'|/2}$ by $2(m'-1)$ while the second one is $B_{p',|P'|}n^{-p'|P'|/2}$ by $2(m')$. This gives $\mathbb{E}\left[\prod_{i=1}^{j_r}\partial_{s^{-1}(i)}\bar{g}_\alpha^{m_i^r}\right]^2 \leq B_{p,|P|}n^{-j_r|P|}$ and $\mathbb{E}\left|\partial_P\phi(\bar{g}_\alpha^1,\ldots,\bar{g}_\alpha^m,\bar{c}^1,\ldots,\bar{c}^m)\right|^p \leq B_{p,|P|}n^{-p|P|/2}$ for appropriately defined $B_{p,|P|}$, as required. As before, uniformity over $\alpha$ comes from the induction hypothesis. The case of odd $p$ follows from Cauchy-Schwarz. □

Now we generalize the above result to polynomially smooth nonlinearities:

**Lemma 15.** *Consider a Tensor Program $\bar{\Pi}$ of width $n$ with matrices satisfying $\mathbb{E}\,\bar{A}_{\beta\gamma}=0$ and $\mathbb{E}\left|\bar{A}_{\beta\gamma}\right|^k \leq \nu_k n^{-k/2}$, $\nu_k\in\mathbb{R}_+\ \forall k\geq 1$, and polynomially smooth nonlinearity $\phi$. Denote the corresponding vectors as $\bar{g}^1,\ldots,\bar{g}^M$ and the corresponding scalars as $\bar{c}^1,\ldots,\bar{c}^M$.*

*Let $P$ be a collection of weights in $\bar{\Pi}$. Then $\forall m\in[M_0:M-1]\ \forall p\geq 1$*

$$\sup_{\alpha\in[n]}\mathbb{E}\left|\partial_P\phi(\bar{g}_\alpha^1,\ldots,\bar{g}_\alpha^m,\bar{c}^1,\ldots,\bar{c}^m)\right|^p \leq B_{p,|P|}n^{-p|P|/2}, \quad (137)$$

*where $B_{p,|P|}$ is a continuous function of a finite number of (scaled) moments $\nu$. Similarly, for a polynomially smooth $\psi$, we have $\forall p\geq 1$*

$$\sup_{\alpha\in[n]}\mathbb{E}\left|\partial_P\psi(\bar{g}_\alpha^1,\ldots,\bar{g}_\alpha^M,\bar{c}^1,\ldots,\bar{c}^M)\right|^p \leq B_{p,|P|}n^{-p|P|/2}. \quad (138)$$

*Proof.* Observe that there were only three places where we have used boundedness of derivatives of $\phi$: they are Eqs. (128), (133) and (134). Let us elaborate the first equation when $\phi$ is bounded with a product of two polynomials

$$\mathcal{P}(x_1,\ldots,x_m) = \sum_{\substack{i_1,\ldots,i_m\geq 0:\\ 0\leq i_1+\ldots+i_m\leq d}} b_{i_{1:m}}x_1^{i_1}\ldots x_m^{i_m}; \quad (139)$$

and

$$\tilde{\mathcal{P}}(x_1,\ldots,x_m) = \sum_{\substack{j_1,\ldots,j_m\geq 0:\\ 0\leq j_1+\ldots+j_m\leq d}} \tilde{b}_{j_{1:m}}x_1^{j_1}\ldots x_m^{j_m}: \quad (140)$$

$$\mathbb{E}\,|\phi(\bar{g}^1_\alpha,\dots,\bar{g}^m_\alpha,\bar{c}^1,\dots,\bar{c}^m)|^p \le \mathbb{E}\,|\mathcal{P}(\bar{g}^1_\alpha,\dots,\bar{g}^m_\alpha)\tilde{\mathcal{P}}(\bar{c}^1,\dots,\bar{c}^m)|^p \le$$

$$\le d^{(2m-M_0)p}\left[\sum_{\substack{i_1,\dots,i_m\ge 0:\\ 0\le i_1+\dots+i_m\le d}} |b_{i_{1:m}}|^p\,\mathbb{E}\left|\left(\bar{g}^1_\alpha\right)^{i_1}\dots\left(\bar{g}^m_\alpha\right)^{i_m}\right|^p\right]\times$$

$$\times\left[\sum_{\substack{j_1,\dots,j_m\ge 0:\\ 0\le j_1+\dots+j_m\le d}} \left|\tilde{b}_{j_{1:m}}\right|^p\,\mathbb{E}\left|\left(\bar{c}^1\right)^{j_1}\dots\left(\bar{c}^m\right)^{j_m}\right|^p\right]. \quad (141)$$

Due to the Cauchy-Schwarz inequality, it suffices to bound $\mathbb{E}\left|g^{m'}_\alpha\right|^{p'}$ for $m'\in[m]$ and $\mathbb{E}\left|c^{m'}\right|^{p'}$ for $m'\in[M_0+1:m]$, for arbitrary $p'\ge 1$. The first one is given by Claim 2 for $|P|=0$ and $\phi(x)=x$ (it is smooth with all the derivatives bounded): $\mathbb{E}\left|g^{m'}_\alpha\right|^{p'}=O(1)$. The second one is given again by our Claim 2 for $|P|=0$:

$$\mathbb{E}\left|c^{m'}\right|^{p'} \le \frac{1}{n^{p'}}\sum_{\beta_1,\dots,\beta_{p'}}\mathbb{E}\left|\prod_{k=1}^{p'}\phi(g^{m'}_{\beta_k})\right| = O(1) \quad (142)$$

by Cauchy-Schwarz. Hence $\mathbb{E}\,|\phi(\bar{g}^1_\alpha,\dots,\bar{g}^m_\alpha)|^p=O(1)$ as before.

The two latter cases, Eqs. (133) and (134), relied on the fact that $\mathbb{E}\left[\prod_{r=1}^p \partial_{m^r_1}\dots\partial_{m^r_j}\phi(\bar{g}^1_\alpha,\dots,\bar{g}^m_\alpha,\bar{c}^1,\dots,\bar{c}^m)\right]^2$ is bounded when $\phi$ has bounded derivatives. Again, using Cauchy-Schwarz, it suffices to bound $\mathbb{E}\left|\partial_{m^r_1}\dots\partial_{m^r_j}\phi(\bar{g}^1_\alpha,\dots,\bar{g}^m_\alpha,\bar{c}^1,\dots,\bar{c}^m)\right|^{p'}$ for arbitrary $p'$. But it follows from the previous speculation since $\partial_{m^r_1}\dots\partial_{m^r_j}\phi$ is smooth and has all the derivatives polynomially bounded. □

### H.4 Proof of Lemma 9

$$\mathbb{E}\left|\partial_P\left[\prod_{i=1}^u f_i(\bar{g}^1_{\alpha_i},\dots,\bar{g}^{m_i}_{\alpha_i},\bar{c}^1,\dots,\bar{c}^{m_i})\right]\right| =$$

$$= \mathbb{E}\left|\sum_{\sqcup_{i=1}^u P_i=P}\prod_{i=1}^u \partial_{P_i} f_i(\bar{g}^1_{\alpha_i},\dots,\bar{g}^{m_i}_{\alpha_i},\bar{c}^1,\dots,\bar{c}^{m_i})\right| \le$$

$$\le \sum_{\sqcup_{i=1}^u P_i=P}\mathbb{E}\left|\prod_{i=1}^u \partial_{P_i} f_i(\bar{g}^1_{\alpha_i},\dots,\bar{g}^{m_i}_{\alpha_i},\bar{c}^1,\dots,\bar{c}^{m_i})\right| \le$$

$$\le \sum_{\sqcup_{i=1}^u P_i=P}\prod_{i=1}^u \sqrt[u]{\mathbb{E}\left[\left|\partial_{P_i} f_i(\bar{g}^1_{\alpha_i},\dots,\bar{g}^{m_i}_{\alpha_i},\bar{c}^1,\dots,\bar{c}^{m_i})\right|^u\right]} \le$$

$$\le \sum_{\sqcup_{i=1}^u P_i=P}\prod_{i=1}^u\left(\sqrt[u]{B_{u,|P_i|}}\,n^{-|P_i|/2}\right) = n^{-|P|/2}\sum_{\sqcup_{i=1}^u P_i=P}\prod_{i=1}^u \sqrt[u]{B_{u,|P_i|}} \quad (143)$$

by Lemma 10 and Lemma 13. Defining $\bar{B}_{u,|P|}=\sum_{\sqcup_{i=1}^u P_i=P}\prod_{i=1}^u \sqrt[u]{B_{u,|P_i|}}$ gives the result.