

Recipes for Pre-training LLMs with MXFP8

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Abstract

Using fewer bits to represent model parameters and related tensors during pre-training has become a required technique for improving GPU efficiency without sacrificing accuracy. Microscaling (MX) formats [1] introduced in NVIDIA Blackwell generation of GPUs [2] represent a major advancement of this technique, making it practical to combine narrow floating-point data types with finer granularity per-block scaling factors. In turn, this enables both quantization of more tensors than previous approaches and more efficient execution of operations on those tensors.

Effective use of MX-formats requires careful choices of various parameters. In this paper we review these choices and show how MXFP8-E4M3 datatype and a specific number conversion algorithm result in training sessions that match those carried out in BF16. We present results using models with up to 8B parameters, trained on high-quality datasets of up to 15T tokens.

1 Introduction

Scaling the number of parameters of deep learning models, especially large generative models, has intensified the need for more efficient compute and memory solutions. Reducing the number of bits to represent a data type (sometimes referred to as reducing precision) is a successful strategy to improve performance while lowering memory requirements. However, maintaining model accuracy while reducing precision remains a key challenge.

Microscaling (MX) formats, specified by an Open Compute Project working group (OCP) [1], combine narrow floating-point types with fine-grained scaling factors to deliver a balance of dynamic range, precision, and hardware efficiency. OCP v1.0 specification [1] and research works like [3, 4, 5] have shown a fine-grained scaling approach to be an effective strategy compared to granular (e.g., per-tensor) scaling approaches, especially in sub-8-bit pre-training regimes.

NVIDIA’s latest GPU generation, Blackwell [2], adds native MX data type support to Tensor Cores. Blackwell supports MX data for 8-bit (MXFP8), 6-bit (MXFP6) and 4-bit (MXFP4) floating-point types. This paper focuses on MXFP8 pre-training of large language models (LLMs), demonstrating two key factors needed for successful pre-training (no accuracy degradation compared to BF16 sessions):

- First, MXFP8-E4M3 datatype should be used for all tensor types, including activation gradients.
- Second, careful consideration of rounding is needed when converting from high-precision formats to MXFP8, resulting in an algorithm different from the one suggested in OCP v1.0 specification.

For each design choice, we present ablation studies on small models (e.g. 100s of millions of parameters) pretrained on short (e.g. 100s of billions) token horizons. We then apply the findings to large multi-billion-parameter models trained on trillion token horizons.

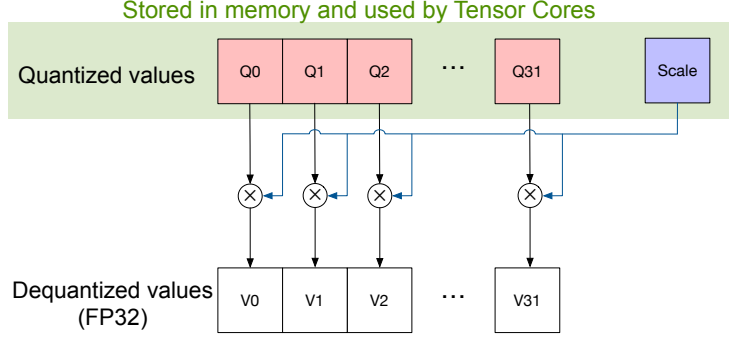


Figure 1: A single MXFP block (in green box) and interpretation of MXFP format.

2 Microscaling format support in NVIDIA Blackwell

Background: An MX-format is specified by the block size K , a shared scaling factor per block, X , and the data-type of elements in the block. A block is a contiguous sequence of K elements. $K = 32$ for all MX types. The data-type of X is UE8M0 and X encodes either NaN or any power-of-two¹ value in the range 2^{-127} to 2^{127} .

Given K input elements in a source-format, V_i (typically FP32); $1 \leq i \leq K$, conversion to MX-format consists of computing X and Q_i such that $Q_i \times X$ is the decoded value corresponding to V_i . X and Q_i are stored in memory instead of V_i . Thus, X serves as the decoding scale factor to decode quantized values back to their high-precision counterparts. This is depicted in Figure 1.

A tensor in source-format is sub-divided into blocks of K elements and converted into MX-format to be stored in memory and/or processed by math units in hardware. Tensor Cores in Blackwell consume X and Q_i to compute the dot product of two MX-formatted blocks. If the accumulated output of a dot-product operation in Tensor Cores is FP32, then this output is thereafter quantized to MX-format if a subsequent operation consuming the output needs it in that format. The conversion process is, $Q_i = \text{Quantize_to_fp8}(V_i/X)$. Section 3 describes the conversion details. Fine-grained scaling helps each MX block independently align to the needed range of input values before quantization.

Table 1: MX-format support in Blackwell

Format	Data type	Max. normal	Min. subnorm.	Binades	Relative speed vs BF16 (Tensor Core math)
MXFP8	E4M3	$1.75 * 2^8$	2^{-9}	17.8	2x
	E5M2	$1.75 * 2^{15}$	2^{-16}	31.8	2x
MXFP6	E2M3	$1.875 * 2^2$	2^{-3}	5.9	2x
	E3M2	$1.75 * 2^4$	2^{-3}	8.8	2x
MXFP4	E2M1	$1.5 * 2^2$	2^{-1}	3.6	4x

Table 1 shows the MX-formats supported in Blackwell. The data type column uses the convention ExMy to denote x-bit for floating-point exponent and y-bit for mantissa. For a fixed bit-width, floating-point numbers trade-off exponent width with mantissa width. Thus, MXFP8 E4M3 is a 8-bit data type with 1 sign bit, 4-bit for FP exponent and 3-bit of mantissa. Similarly, E5M2 is an 8-bit type with 5-bit for exponent and 2-bit for mantissa. Compared to E4M3, E5M2 can represent a larger dynamic range, but with less precision. E5M2 follows IEEE 754 conventions [6] for representation of special values, whereas the remaining data types extend the dynamic range by not representing Infinity and NaN (E4M3 has only one bit-pattern for NaN [7]). More bits in the exponent field translates to a larger range while more bits in the mantissa field translates to more precision within a given range. Every floating-point type has a dynamic range that it can represent — we denote this range in terms of *binades* which is the \log_2 -ratio of the maximum to the minimum finite representable in that format.

¹Power-of-two is a number of the form 2^n where n is a positive integer, negative integer, or zero.



Figure 2: Pre-training a 8B LLM on 15T tokens. **Top:** Training behavior of BF16 vs MXFP8. **Bottom:** Comparing BF16, FP8 and MXFP8’s downstream task scores on MMLU and a set of 9 reasoning tasks. MXFP8 numerics use our proposed rounding method and E4M3 for all quantized tensors.

3 Pre-training with MXFP8

In this section we review MXFP8 training results, training recipe, and the algorithm for converting to MXFP8 used for training. Ablation studies explain the recipe and conversion algorithm choices.

3.1 Training Results

To establish the equivalence of MXFP8 and BF16 for model accuracy we pretrain an 8B parameter model on 15T tokens. We observe:

- Validation perplexity when using MXFP8 matches that of BF16 (top plot in Figure 2). There is less than 0.50% difference between MXFP8 and BF16 validation perplexity values throughout the pre-training run.
- Downstream task evaluation scores match between MXFP8 and BF16 sessions (bottom plots in Figure 2).

The same equivalence is also observed for smaller models or smaller datasets, making MXFP8 a preferred option to efficiently train LLMs. The 8B parameter model [8] consists of 32 transformer

blocks, 32 attention heads. Hidden size is 4096, GQA group size is 8, KV-channels count is 128, sequence length during pre-training is 8192. Initial learning rate is $6e-4$ that cosine decays to $6e-6$. A phased data-blending approach is used to train the model: in the first phase, a data mixture that promotes diversity in data is used and in the second phase high-quality datasets (e.g., Wikipedia) are used. We switch to the second phase at the 60% point of training. This blend style has also been used in other large scale pre-training setups [9].

Training was carried out using Megatron-LM software [10] on 3072 Hopper GPUs using batch size 768. MX operations were simulated by converting BF16 inputs to MXFP8 and back to BF16 prior to GEMM operations.

Evaluation scores are measured on two sets of downstream tasks: (1) 5-shot score on MMLU [11] and (2) Averaged 1-shot score across 9 general reasoning benchmarks: ARC-Challenge and ARC-Easy [12], Race [13], PIQA [14], Winogrande [15], Hellaswag [16], OpenBookQA [17], Social IQA [18] and Commonsense QA [19].

In summary, we find MXFP8 maintains accuracy compared to BF16 or FP8 pre-trained models. On Blackwell GPU-based systems, MXFP8 has $2\times$ higher throughput than BF16 making end-to-end MXFP8 pre-training faster than BF16 pre-training. We also find the MXFP8 recipe to be simpler to use when compared to FP8 (all layers can be quantized and scaling is handled in the hardware) while allowing for equal or better throughput.

3.2 MXFP8 Training Recipe

The recipe is defined by two choices: which tensors to quantize to MXFP8 and which FP8 binary encoding to use for different tensors.

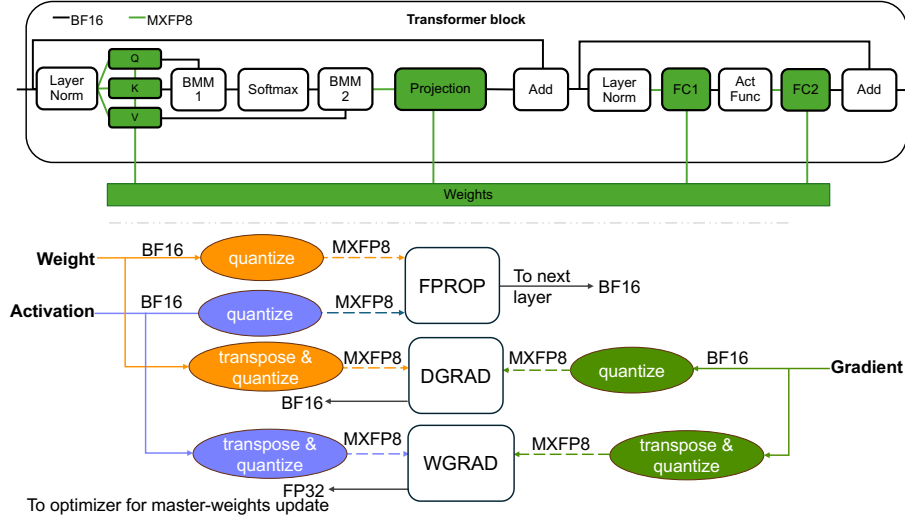


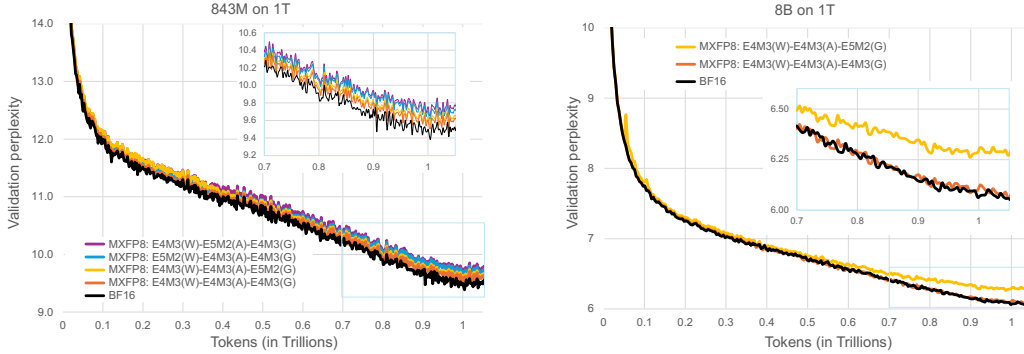
Figure 3: **Top:** Transformer layers quantized to MXFP8 inside a single transformer block. **Bottom:** Training workflow for a single layer during forward-pass (FPROP), error-gradient pass (DGRAD) and weight-gradient pass (WGRAD).

3.2.1 Tensors to Quantize

We execute GEMMs with weights (i.e. QKV and Proj in attention and FFN, as shown in Figure 3) in MXFP8. Therefore, activation, weight, as well as activation gradient input tensors for these GEMMs are converted to MXFP8. The Batch-Matrix Multiplications (BMM1, the query-key dot product and BMM2, the attention score-value product) in the self-attention layer, along with operations like Softmax, Act-func and residual-add are in high-precision. The input embedding layer and the final output-projection layer are also in BF16 or FP16. We leave it to future work to explore reducing the precision of these operations.

The aforementioned tensors are quantized to MXFP8 for all transformer blocks of a model, in contrast to per-tensor [9] or per-row quantization [20] for FP8, where some transformer layers were left in BF16. As a result, MXFP8 due to its fine-granularity scaling factors enables accelerating more of an LLM’s layers.

During training, with MXFP quantization, the training framework keeps two copies of each tensor, each copy is quantized along the axes of dot-product reduction (row and column). Figure 3 shows how each tensor is used in forward (FPROP), weight-gradient (WGRAD) and activation-gradient (DGRAD) computation during the training loop. Since each tensor is used in non-transposed and transposed form, quantization needs to occur along two separate axes (row and column).



(a) Validation perplexity curves for 843M parameter model trained on 1T tokens.

(b) Validation perplexity curves for 8B parameter model trained on 1T tokens.

Figure 4: Pre-training loss curves comparing E4M3 and E5M2 when used across different tensor types: weights (W), activation (A) and gradients (G). The inset shows a zoomed-in view of the loss at the end of training.

3.2.2 FP8 Encoding Choice

Our MXFP8 recipe uses E4M3 encoding for all tensor types - weights, activations, and activation gradients. This is in contrast to coarser-scaled FP8 training [9, 7, 21, 22], which used E4M3 for weights and activations but E5M2 for gradients. With fine-grained scaling of MXFP8, the dynamic range requirement at a 32-element block size is sufficiently captured by 17.8 binades of E4M3 type. Once the range requirements are met, precision (or sampling) becomes important. We demonstrate this recipe choice with an empirical study on an 843M and 8B parameter models. Figure 4a shows that E4M3 is the preferred choice for weights and activations, as using E5M2 for these tensor types (the blue and purple curves, respectively) results in a worse perplexity. While either E5M2 or E4M3 encodings are comparably good for the 843M parameter model, in Figure 4b we see that the larger 8B parameter model requires the higher precision of E4M3 for activation gradients (orange curve), as E5M2 gradients (yellow curve) lead to a substantial degradation in perplexity.

3.3 Conversion from FP32 to MXFP8

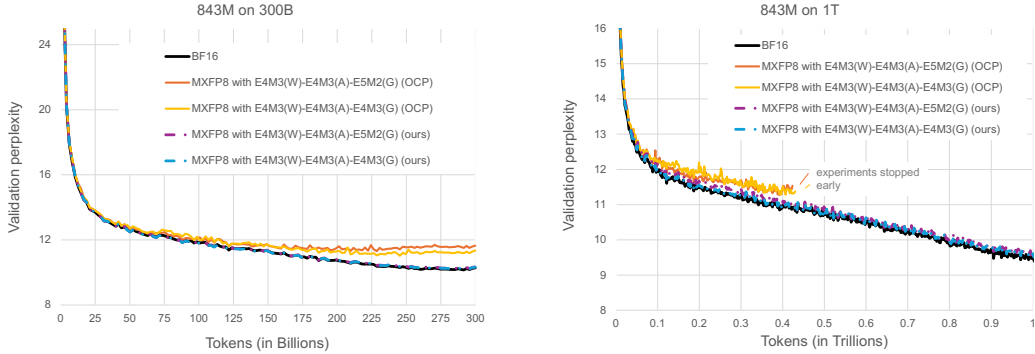
Often the original high precision (for example, FP32 or BF16) values within a block are outside the representable range for the target MX format, both underflowing the minimum and overflowing the maximum representable magnitude. To address this, prior to conversion all values are multiplied with a scale factor so that no value overflows the MX format range, while minimizing flushes to 0. The shared per-block scale factor, X , is computed based on the maximum absolute value (amax) among the 32 high-precision input values, i.e. $\text{amax} = \max \|V_i\|; 1 \leq i \leq 32$. The goal is to map this amax in the input-format to be the largest representable value in the desired MX-format. Once X is computed, V_i is divided by X and the resulting value is quantized to a FP8-representable number using Round-to-nearest-ties-to-even (RN) rounding. Furthermore, saturating conversion mode is used (as described in OCP FP8 specification [23]) i.e. magnitudes exceeding FP8-maximum are clamped to respective maximum representative magnitude in quantized format. Special care is taken if some or all elements in the input are Infinity and/or not-a-number (NaN).

Algorithm 1 Our proposal for computing scale factor, X (simplified method)

$X_{\text{float}} \leftarrow \text{amax}/\text{destmax}$ $\text{exp}X_{\text{float}} \leftarrow \log_2(X_{\text{float}})$ $\text{exp}X_{\text{int}} \leftarrow \text{ceil}(\text{exp}X_{\text{float}})$ $X \leftarrow \text{clamp}(\text{exp}X_{\text{int}}, -127, 127)$ $X \leftarrow X + 127$ return 2^X	$\triangleright \text{destmax}$ is max representable in MX-format \triangleright extract the exponent of X (de-biased form) \triangleright round-up \triangleright clamp to min/max E8M0 representable \triangleright add bias \triangleright store X
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Algorithm 1 outlines the scale-factor computation used by training sessions in Section 3.1. Step 3 is the key part, *rounding-up the scale factor towards positive infinity*, when converting X to a power-of-2 value. This is different from the scheme suggested by OCP v1 specification, which effectively rounds down the scale factor. Since during quantization to MXFP8, high precision values are divided by X , rounding up X ensures that after scaling no V/X value exceeds the maximum magnitude representable in the destination format. Conversely, rounding down, as in OCP v1 suggestion, will lead to scaled values overflowing the representable range, introducing more quantization noise.

We hypothesize this aspect leading to MXFP8 training issues when using OCP v1 conversion scheme as shown in Figure 5. As can be seen in the figure, these issues are eliminated when using our proposal in Algorithm1. A more detailed description of conversion workflow is provided in Appendix Sec. A.1.



(a) Validation perplexity curves for 843M parameter model trained on 300B tokens.

(b) Validation perplexity curves for 843M parameter model trained on 1T tokens.

Figure 5: Comparing scale factor rounding modes suggested in the OCP v1.0 specification and our work. E4M3 and E5M2 are MXFP8 formats; notation E4M3(W) denotes E4M3 data type for Weights. Similarly, E4M3(A) and E4M3(G) refer to activations and gradients, respectively.

4 Related work

Low-precision training and inference is a widely studied topic in deep learning literature. While significant progress has been made in low-precision inference [24, 25, 26, 27], there are relatively fewer studies demonstrating low-precision techniques for pre-training LLMs, especially large-scale pre-training on a large token horizon. Our work primarily focuses on 8-bit pre-training and prior work on related low-precision LLM pre-training can be grouped into the following two categories:

- **LLM pre-training using FP8 formats:** [7] proposes an FP8 binary interchange format, consisting of E4M3 and E5M2 encodings, and a per-tensor scaling approach — an entire tensor is scaled to capture the maximum number of tensor values in the representable range in FP8. [28] discusses FP8 pre-training challenges and proposes model-level modifications to train a 7B parameter model. Recently, per-tensor scaled FP8 was used to train the Nemotron-H family of LLMs [9] and the Llama-4 family of models also used FP8 [29]. Both of these approaches mention the need to keep a few transformer blocks in high-precision. Instead of per-tensor scaling, DeepSeek-V3 family of models [22] use block-scaled FP8, this helps to better capture outliers and minimize quantization errors. With block-scaling setup, certain tensors require vector 1x128

scaling and certain tensors require per-block (e.g. 128x128) software scaling. Native support for MXFP8 simplifies this — fine-grained scaling provides better numerical robustness and hardware support for scaling avoids any tradeoff between smaller block sizes and hardware speed.

- **Pre-training using MXFP formats:** [3] presents empirical data on pre-training models with MXFP formats. They show cast-only inference results for MXFP8 and pre-training results for MXFP6 and MXFP4-weights. [30] studies MXFP4 backward-pass quantization and [31] investigates MXFP4 weight quantization on relatively small token horizon.

5 Conclusions and future work

We present studies on several aspects of MXFP8-formats and their usage in pre-training models, e.g. scale computation, data format of specific tensors, numerical aspects of quantization, model layers that could be quantized for maximizing training throughput. We discuss recipes for pre-training LLMs with MXFP8-formats. The MXFP8 pre-training recipe is implemented in Transformer Engine [32] and the conversion numerics in cuDNN and cuBLAS libraries.

As part of our future work, we plan to extend our study to post-training phases (e.g. phases that perform reinforcement learning (RL)-based policy optimizations and their variants [33] as well as supervised fine-tuning stages). Additionally, from a hardware systems performance perspective, since tensors have to be quantized along two separate axes with MX-formats, the training framework needs to store two copies for each tensor (we discussed this in section 3.2). We plan to study scaling methods that would lower the storage overhead.

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A Appendix

A.1 UE8M0 rounding

Computation described in Algorithm 1 is a simplification. The simplification comes from storing the output of $\log_2(\text{float } x)$ in FP32. \log_2 function on device internally performs a round-to-nearest of the resulting return value and thus the result of $\text{ceil}(\log_2(x))$ can be different if the output of \log_2 is not stored in a sufficiently large data-type. Hence, for emulation purposes we work directly with the bit representation of the ratio of `amax` and `destmax`. We, next, describe the computation flow.

Background: As a reminder, the quantization process from 32 high-precision values, V_i , to quantized values, Q_i ; $1 \leq i \leq 32$, is given by: $Q_i = \text{Quantize_to_fp8}(V_i/X)$. X is the scale factor; the exponent of X is stored in an 8bit integer container in memory and interpreted as 2 raised to this exponent value by the hardware (after a bias correction). This scale factor *decodes* Q_i back to V_i (with quantization loss).

Value of scale factor (X) = `float_to_8bits(amax/destmax)`, where `amax` is absolute maximum in input/source block (of 32 elements) and `destmax` is the largest positive number in the destination (MX) number system. `float_to_8bits` converts a floating-point number to a power-of-two number.

A float (FP32) number can be represented in IEEE convention as $2^E \times 1.\text{mantissa}$ (normal) or $2^{-126} \times 0.\text{mantissa}$ (subnormal). E can lie between -127 to 127 (or 0 to 254 with the exponent bias) and can be represented in the 8-bit container for scale factor. -126 (or 1 with the exponent bias) is also representable by 8-bit container. `mantissa` lies between $[0, 1)$. So, the question is: should `mantissa` bits be rounded-up, rounded-down, round-to-nearest, discarded, etc. to create a power-of-two number? We find round-up to be the best choice for pre-training with MX-formats.

Rounding: For `float_to_8bits()`, the recommended order of computation is:

1. Compute the decoding scale as: `decode_scale = block_amax/destmax`
2. if `decode_scale` is below 2^{-127} , then set it to 2^{-127} (which is the smallest value representable in UE8M0)
3. For all other values that are not powers of 2, *round-up* to the closest representable UE8M0 value.

By construction `amax/destmax` never exceeds 2^{127} (which is the largest value representable in UE8M0) with FP8, FP6 or FP4 formats. The above computations are done in the bit-space in emulation.

A.2 MX-format conversion

Section 2 relies on the standard MX-format conversion algorithm defined in [3], but for completeness we show it here given a shared scaling exponent X as computed in 3.3.

Quantizing FP32 values to MX type: After X is computed, V_i/X is computed and the resulting value is quantized to a FP8-representable number (`Quantize_to_fp8()`). Round-to-nearest-ties-to-even (RN) rounding is used during this quantization step. The conversion process is saturating, i.e. if after rounding the resulting value exceeds FP8 max or is less than FP8 min value, then the result is clamped to respective max or min value.

Quantization operations add computation overhead — Blackwell has hardware support for rounding the scale (using our proposed method) and quantizing values to lower this overhead.

A.3 Why is special hardware needed for MX-formats?

Computing the matrix-product of two tensors involves performing dot-products between sub-vectors of the two tensors. Therefore, scaling factors need to be processed once per group of values that share the scale. Since MX-formats have fine-grained scaling, scale factors are processed once after each block's dot-product is computed, thus, many times per tensor-wide dot-product. This is expensive to do in software, so hardware needs to add support for accelerating tensor operations involving MX-formats (e.g. Blackwell).

A.4 MXFP8 pre-training for a mixture-of-experts model

Section 3.1 discusses empirical data that shows MXFP8 matches BF16 accuracy (both training loss as well as downstream task accuracy). Transformer based mixture-of-experts (MoE) models are popular in literature. Figure 6 shows that MXFP8 pre-training also matches BF16 pre-training loss curve for a MoE setup that we experimented with. The MoE model has 16 billion total parameters and ~ 2.5 billion active parameters and we train the model on 1 trillion tokens. We follow the same guidelines discussed in section 3.2 for pre-training the MoE model. The pre-training phase uses a WSD [34] learning rate schedule. The final loss of the MXFP8-trained MoE model is within 0.1% of BF16-training.

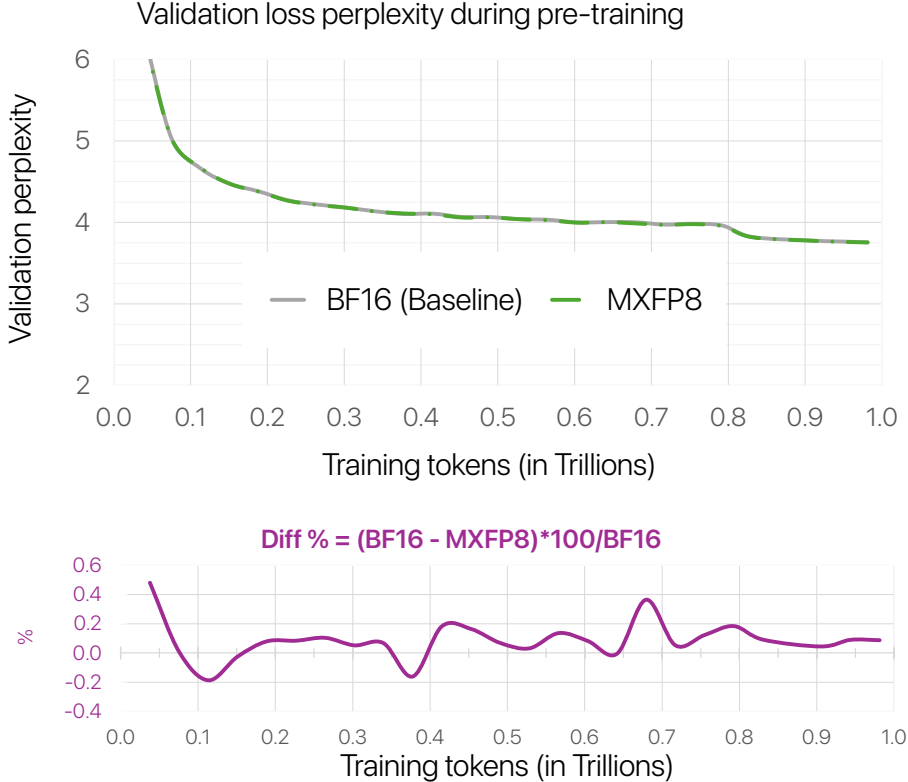


Figure 6: MXFP8 versus BF16 for a MoE model

A.5 Model configurations

We conduct numerical experiments on LLM pre-training with variants of Nemotron-4 [8] models. Training and model details are described below. The 1T and 300B tokens dataset are a subset of the 17T data set discussed in [35]. Table 2 details the parameters for the various models that were used.

Table 2: Configuration for the LLM models.

Model	Layers	Hidden Size	Attention Heads	Sequence Length	Batch Size	Initial LR	Final LR
843M	24	1024	16	4096	256	2.5e-4	2.5e-7
8B	32	4096	32	4096	1024	3e-4	3e-7