

# SageAttention3: Microscaling FP4 Attention for Inference and An Exploration of 8-bit Training

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## Abstract

The efficiency of attention is important due to its quadratic time complexity. We enhance the efficiency of attention through two key contributions: First, we leverage the new FP4 Tensor Cores in Blackwell GPUs to accelerate attention computation. Our implementation achieves **1038** TOPS on RTX5090, which is a **5 $\times$**  speedup over the fastest FlashAttention on RTX5090. Experiments show that our FP4 attention can accelerate inference of various models in a plug-and-play way. Second, we pioneer low-bit attention to training tasks. Existing low-bit attention works like FlashAttention3 and SageAttention focus only on inference. However, the efficiency of training large models is also important. To explore whether low-bit attention can be effectively applied to training tasks, we design an accurate and efficient 8-bit attention for both forward and backward propagation. Experiments indicate that 8-bit attention achieves lossless performance in fine-tuning tasks but exhibits slower convergence in pretraining tasks. The code is available at <https://github.com/thu-ml/SageAttention>.

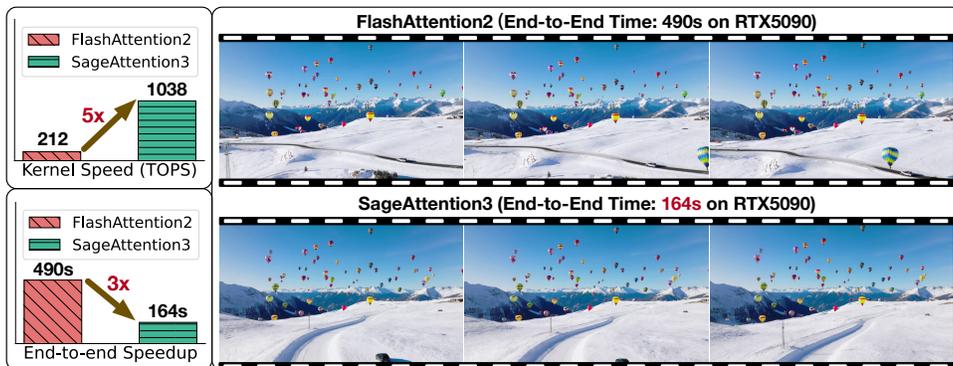


Figure 1: The upper left figure shows the kernel speedup on RTX5090. The other two figures show the end-to-end inference speedup of generating a video using HunyuanVideo on RTX5090. Note that FlashAttention3 can only run on Hopper GPUs, so FlashAttention2 is already the fastest on RTX5090.

## 1 Introduction

**Motivation.** The efficiency of attention is critical for generation models, especially given their quadratic time complexity with longer sequences [1, 2]. Quantization offers an effective way to

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accelerate inference by utilizing low-bit Tensor Cores in GPUs [3, 4, 5, 6]. The new FP4 Tensor Cores in Blackwell GPUs deliver significantly faster performance compared to FP16 [7]. We want to propose a novel FP4 attention implementation that provides plug-and-play compatibility for inference acceleration. Beyond inference, training efficiency is equally important. However, no prior work has explored low-bit attention for training large models. To address this gap, we design a trainable 8-bit attention to explore its feasibility in training tasks.

To the best of our knowledge, we are the first work that designs FP4 attention for inference and the first work to explore the feasibility of low-bit attention for training large models.

**Challenges.** There are two primary obstacles for FP4 attention and one key difficulty for 8-bit trainable attention. First, **(C1)** FP4 quantization suffers from severe value limitations (only 15 representable values), making both per-tensor and per-token quantization approaches inadequate for preserving model accuracy. Second, **(C2)** The attention map  $P$  consists primarily of small values in the range  $[0, 1]$ . When directly quantized to FP4, these values force the scaling factors into an extremely narrow dynamic range. However, hardware requires the quantization factors to be in FP8 data type. This leads to significant accuracy loss when presenting these scale factors in FP8. Third, **(C3)** When employing 8-bit attention during training, we find that the attention map gradients are particularly vulnerable to quantization errors, resulting in accumulated errors in the input gradients.

**Our Method.** To address **(C1)**, we propose to use FP4 microscaling quantization for the two matrix multiplications in attention, i.e.,  $QK^T$  and  $PV$ . By constraining the quantization group size to  $1 \times 16$  (instead of per-tensor or per-channel), our method effectively contains outlier effects within each block while improving FP4 quantization accuracy. To overcome **(C2)**, we propose a two-level quantization method for  $P$  to fully utilize the presentative range of the FP8 scaling factor, enhancing the quantization accuracy of  $P$ . Specifically, this approach first normalizes each token’s range to  $[0, 448 \times 6]$  through per-token quantization, then applies FP4 microscaling quantization for enhanced precision. To address **(C3)**, we identify the most accuracy-sensitive matrix multiplication among the five in backpropagation and maintain its accuracy in FP16.

**Result.** Our FP4 attention, named SageAttention3, could achieve **1038** TOPS on RTX5090, which is a  $5 \times$  speedup than FlashAttention. Furthermore, we demonstrate that 8-bit trainable attention, named SageBwd, could achieve lossless performance when fine-tuning base models for instruction-following tasks, but is not suitable for pretraining tasks.

**Contribution.** Our work makes the following key contributions:

- (1) We design the first FP4 attention to accelerate inference, achieving **1000+** TOPS on RTX5090.
- (2) We propose the first trainable low-bit attention, enabling accelerated training with lossless fine-tuning performance, while revealing key insights for low-bit attention in training.

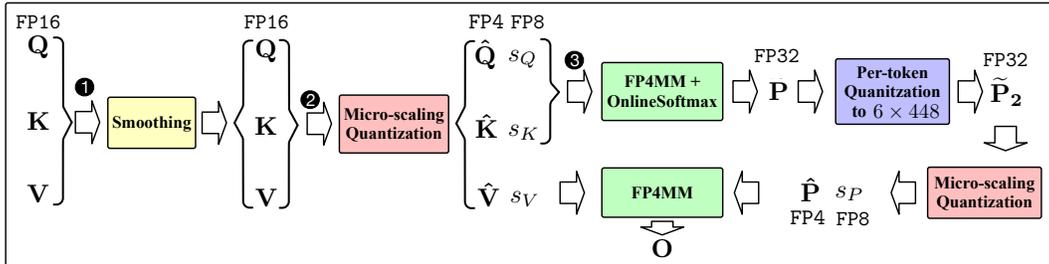


Figure 2: Workflow of microscaling FP4 attention.

## 2 Preliminary

**FlashAttention.** The attention computation contains two matrix multiplications and one softmax calculation:  $S = QK^T$ ,  $P = \text{Softmax}(S)$ ,  $O = PV$ . The  $Q, K, V$  are in the shape of  $N \times D$ , where  $N$  means the sequence length and  $D$  means the dimension of an attention head.  $P, S$  are in the shape of  $N \times N$ . FlashAttention divides  $Q$  to blocks  $\{Q_i\}$  in the shape of  $B_q \times D$ , and divides  $K, V$  to  $\{K_i\}, \{V_i\}$  in the shape of  $B_{kv} \times D$ . Then it uses online softmax to avoid the large memory IO for  $S$  and  $P$ :  $S_{ij} = Q_i K_j^T$ ,  $P_{ij} = \text{OnlineSoftmax}(S_{ij})$ ,  $O_{ij} = P_{ij} V_j$ .

**Notation.** For simplicity, we omit subscripts and use  $\mathbf{Q}, \mathbf{K}, \mathbf{V}, \mathbf{S}, \mathbf{P}, \mathbf{O}$  to denote the matrix blocks in FlashAttention, while retaining full subscript notation in Algorithm 1, 2, and 3.

**Quantization.** Quantization is used to accelerate Matmul by converting two matrices from high-bit to low-bit with scale factors. Take INT8 quantization for Matmul  $AB$  as an example, where  $A$  and  $B$  are in FP16 data type. It can be formulated:  $s_A = \max(|A|)/127$ ,  $\hat{A} = \lceil A/s_A \rceil$ ,  $s_B = \max(|B|)/127$ ,  $\hat{B} = \lceil B/s_B \rceil$ , where  $\hat{A}, \hat{B}$  are in INT8 and the others are in FP32. Then,  $AB \approx \hat{A}\hat{B} \times s_A \times s_B$ , which can be accelerated by the INT8 Tensor Core. The granularity of quantization is determined by the dimensions reduced by the max operation. For example, in *per-token quantization*, the max is computed along each row of a matrix. In *per-block quantization*, the max is computed on a block of a matrix, which in our paper means a FlashAttention block.

### 3 FP4 Attention for Inference Acceleration

This section presents our microscaling FP4 attention through three key components: (1) the fundamental workflow for applying microscaling FP4 quantization to attention in Section 3.1, (2) the two-level quantization approach for the attention map in Section 3.2, and (3) critical hardware implementation optimization in Section 3.3.

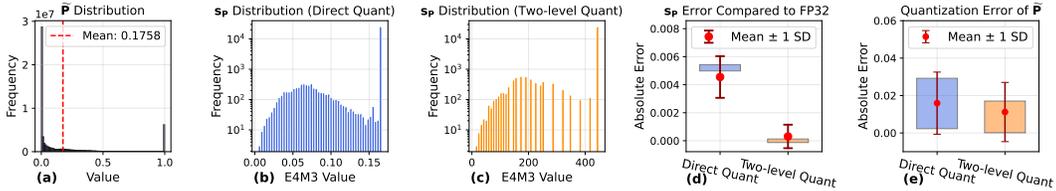


Figure 3: Analysis of the benefit of two-level quantization. (a) shows the distribution of  $\tilde{\mathbf{P}}$ . (b) and (c) show the distribution of  $s_{\mathbf{P}}$  using direct quantization and two-level quantization. (d) and (e) show the error of  $s_{\mathbf{P}}$  and  $\tilde{\mathbf{P}}$  using direct quantization and two-level quantization.

#### 3.1 Microscaling FP4 Attention

**FP4 microscaling quantization.** Given a matrix  $X \in \mathbb{R}^{N \times d}$ , we quantize it to  $\hat{X}$  in FP4 data type with a scale factor matrix  $s_X$  in FP8 data type. Specifically,  $X$  is partitioned into  $X_{ij} \in \mathbb{R}^{1 \times n}$  blocks, where each  $1 \times n$  block corresponds to one scale factor  $s_{ij}$ . The FP4 microscaling quantization ( $[\hat{X}, s_X = \phi(X)]$ ) and dequantization ( $X' = \phi^{-1}(\hat{X}, s_X)$ ) can be formulated as follows.

$$\text{Quantization } \phi: s_{ij} = \max(|X|)/6, \quad \hat{X}_{ij} = \lceil X_{ij}/s_{ij} \rceil \quad (1)$$

$$\text{Dequantization } \phi^{-1}: X'_{ij} = s_{ij} \times \hat{X}_{ij} \quad (2)$$

Where the  $\lceil \cdot \rceil$  means FP4 rounding.

**FP4 microscaling quantization Matmul.** Consider a matrix multiplication  $AB$ , where  $A$  and  $B$  are in FP16 precision. The speed of the Matmul is about 200 TOPS on RTX5090. In contrast, the speed of the FP4 microscaling Matmul is about 1600 TOPS, which is an 8x speedup. The FP4 microscaling Matmul instruction (FP4MM) takes four inputs, i.e.,  $\hat{A}, s_A, \hat{B}, s_B$ , and the output  $C$  equals to the Matmul result between  $\phi^{-1}(\hat{A}, s_A)$  and  $\phi^{-1}(\hat{B}, s_B)$ :

$$C = \text{FP4MM}(\hat{A}, s_A, \hat{B}, s_B) \quad (3)$$

**Attention computation.** We accelerate attention computation by applying FP4 microscaling quantization to both matrix multiplications:  $\mathbf{QK}^\top$  and  $\mathbf{PV}$ .

$$\begin{aligned} \hat{\mathbf{Q}}, s_{\mathbf{Q}} &= \phi(\mathbf{Q}), & \hat{\mathbf{K}}, s_{\mathbf{K}} &= \phi(\mathbf{K}^\top), & \mathbf{S} &= \text{FP4MM}(\hat{\mathbf{Q}}, s_{\mathbf{Q}}, \hat{\mathbf{K}}, s_{\mathbf{K}}) \\ & & \tilde{\mathbf{P}} &= \text{OnlineSoftmax}(\mathbf{S}) \\ \hat{\mathbf{P}}, s_{\mathbf{P}} &= \phi(\tilde{\mathbf{P}}), & \hat{\mathbf{V}}, s_{\mathbf{V}} &= \phi(\mathbf{V}), & \mathbf{O} &= \text{FP4MM}(\hat{\mathbf{P}}, s_{\mathbf{P}}, \hat{\mathbf{V}}, s_{\mathbf{V}}) \end{aligned} \quad (4)$$

It is important to note that our hardware implementation builds on FlashAttention, where the matrices  $\mathbf{Q}$ ,  $\mathbf{K}$ ,  $\tilde{\mathbf{P}}$ , and  $\mathbf{V}$  in our formulation correspond to FlashAttention’s tiled  $Q$ ,  $K$ ,  $\tilde{P}$ , and  $V$  blocks as described in Section 2. Additionally, to enhance the attention accuracy, we adopt the smoothing  $Q$  and  $K$  in SageAttention2 [4]. The complete algorithm is presented in Algorithm 1.

**Data type determination.** There are two choices for the FP4 data type [8]. The first one is the NVFP4, which is in E2M1 data type and its quantization block size is  $1 \times 16$  and its scale factor is in E4M3 data type. The second one is the MXFP4, which is also in E2M1 data type. However, its quantization block size is  $1 \times 32$  and its scale factor is in E8M0 data type. We choose NVFP4 because the accuracy of NVFP4 is much higher than that of MXFP4 in attention quantization. Empirical results: Table 1(a) shows the accuracy of MXFP4 and NVFP4 using real  $\mathbf{Q}$ ,  $\mathbf{K}$ ,  $\mathbf{V}$  across all layers of CogVideoX. Results indicate that the accuracy of NVFP4 outperforms that of MXFP4.

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**Algorithm 1:** Implementation of the microscaling FP4 attention.

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1: Input: Matrices  $Q(\text{FP16}), K(\text{FP16}), V(\text{FP16}) \in \mathbb{R}^{N \times d}$ , block size  $B_q, B_{kv}$ .
2: Preprocessing:  $K = K - \text{mean}(K)$  // Smoothing K of SageAttention.
3: Divide  $Q$  to  $T_m = N/B_q$  blocks  $\{\mathbf{Q}_i\}$ ; divide  $K$ , and  $V$  to  $T_n = N/B_{kv}$  blocks  $\{\mathbf{K}_i\}, \{\mathbf{V}_i\}$ ;
4: for  $i = 1$  to  $T_m$  do
5:    $\bar{q}_i = \text{mean}(\mathbf{Q}_i)$ ,  $(\mathbf{s}_Q, \hat{\mathbf{Q}}_i) = \phi(\mathbf{Q}_i - \bar{q}_i)$ ; // Smoothing Q of SageAttention2.
6:   for  $j$  in  $[1, T_n]$  do
7:      $(\mathbf{s}_K, \hat{\mathbf{K}}_j) = \phi(\mathbf{K}_j^\top)$ ,  $(\mathbf{s}_V, \hat{\mathbf{V}}_j) = \phi(\mathbf{V}_j)$ ;
8:      $\mathbf{S}_{ij} = \text{FP4MM}(\hat{\mathbf{Q}}_i, \mathbf{s}_Q, \hat{\mathbf{K}}_j, \mathbf{s}_K) + \text{GEMV}(\bar{q}_i, \hat{\mathbf{K}}_j^\top)$ ; // Smoothing Q.
9:      $m_{ij} = \max(m_{i,j-1}, \text{rowmax}(\mathbf{S}_{ij}))$ ,  $\tilde{\mathbf{P}}_{ij} = \exp(\mathbf{S}_{ij} - m_{ij})$ ,
        $l_{ij} = e^{m_{i,j-1} - m_{ij}} l_{i,j-1} + \text{rowsum}(\tilde{\mathbf{P}}_{ij})$ ;
10:     $\mathbf{s}_{P_1} = \text{rowmax}(\tilde{\mathbf{P}}_{ij}) / (448 \times 6)$ ,  $\hat{\mathbf{P}}_{ij} = \tilde{\mathbf{P}}_{ij} / \mathbf{s}_{P_1}$ ,  $\mathbf{s}_{P_2}, \hat{\mathbf{P}}_{ij} = \phi(\hat{\mathbf{P}}_{ij})$ ; // two-level quantization
11:     $\mathbf{O}_{ij} = \text{diag}(e^{m_{i,j-1} - m_{ij}}) \mathbf{O}_{i,j-1} + \text{FP4MM}(\hat{\mathbf{P}}_{ij}, \mathbf{s}_{P_2}, \hat{\mathbf{V}}_j, \mathbf{s}_V) \times \mathbf{s}_{P_1}$ 
12:  end for
13:   $\mathbf{O}_i = \text{diag}(l_{i,T_n})^{-1} \mathbf{O}_{i,T_n}$ ;
14: end for
15: return  $O = \{\mathbf{O}_i\}$ 

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### 3.2 Two-level Scaling for $\tilde{\mathbf{P}}$

Applying microscaling FP4 quantization for  $\tilde{\mathbf{P}}$  presents a challenge to attention accuracy. For example, Fig. 12(c) shows direct quantization severely degrades output quality, producing results substantially different from full-precision outputs. Our analysis reveals that the issue occurs because microscaling NVFP4 quantization requires the scale factor to be represented in E4M3 FP8 format [9], rather than the FP32 data type typically used for scale factors. This causes accuracy loss when the scale factor is directly converted to E4M3 format. To better understand this accuracy loss, we analyze the data distribution of  $\tilde{\mathbf{P}}$  and its scale factors in Fig. 3. Since  $\tilde{\mathbf{P}}$  is computed using online softmax [10], the values in each microscaling block  $\tilde{\mathbf{P}}_{ij}$  fall  $[0, 1]$ . Consequently, the scale factor (scale factor =  $\max(\tilde{\mathbf{P}}_{ij})/6$ ) ranges between 0 and 0.167. This narrow range leads to inefficient usage of E4M3’s representable range, increasing accuracy loss. To reduce accuracy loss by fully utilizing E4M3’s range, we propose a two-level quantization method for the  $\tilde{\mathbf{P}}$  matrix. Specifically, we first quantize each row of  $\tilde{\mathbf{P}}$  to  $[0, 448 \times 6]$ . Then we apply the standard FP4 quantization  $\phi$  for the quantized  $\tilde{\mathbf{P}}$ . The two-level quantization can be formulated as follows:

$$\begin{aligned}
\mathbf{s}_{P_1} &= \text{rowmax}(\tilde{\mathbf{P}}) / (448 \times 6), \quad \tilde{\mathbf{P}}_2 = \tilde{\mathbf{P}} / \mathbf{s}_{P_1}, \quad \mathbf{s}_{P_2}, \hat{\mathbf{P}}_2 = \phi(\tilde{\mathbf{P}}_2) \\
(\tilde{\mathbf{P}} &\approx \hat{\mathbf{P}}_2 \times \mathbf{s}_{P_2} \times \mathbf{s}_{P_1}), \quad \mathbf{O} = \text{FP4MM}(\hat{\mathbf{P}}_2, \mathbf{s}_{P_2}, \hat{\mathbf{V}}, \mathbf{s}_V) \times \mathbf{s}_{P_1}
\end{aligned} \tag{5}$$

Where  $\tilde{\mathbf{P}}$ ,  $\tilde{\mathbf{P}}_2$ , and  $\mathbf{s}_{P_1}$  are in FP32 data type.  $\mathbf{s}_{P_2}$  and  $\mathbf{s}_V$  are in FP8 data type.  $\hat{\mathbf{P}}_2$  and  $\hat{\mathbf{V}}$  are in FP4 data type.

Empirical results: As shown in Fig. 3, our two-level quantization maximizes the E4M3 range utilization for  $\mathbf{s}_P$ , thereby reducing both the numerical representation error of  $\mathbf{s}_P$  and the quantization error of  $\tilde{\mathbf{P}}$ . A more formal theoretical analysis is provided in Appendix A.5. Table 1(b) shows the accuracy of

two-level quantization against naive direct quantization, using real Q, K, V from layers of CogVideoX. Results indicate that two-level quantization boosts the accuracy.

### 3.3 Implementation and Optimization on Hardware

**Permutation for K.** Unlike FP16, the FP32 accumulator’s memory layout in FP4 MatMul [11] differs from its operand A’s register layout (shown in Fig. 20 and 19). Performing thread shuffles to match operand A’s layout would degrade kernel performance. Our solution transforms the accumulator layout (Fig. 21) by permuting the P tile’s columns. To maintain correct MatMul, we correspondingly rearrange K’s columns, which can be fused with the quantization kernel.

**Reuse shuffle.** The in-kernel micro-scaling quantization of  $\tilde{\mathbf{P}}$  requires finding the max value of 16 consecutive row elements. However, as shown in Fig. 21, these 16 elements are distributed across four threads, necessitating intra-thread max reduction followed by inter-thread shuffling, significantly slowing down the kernel. We optimize this by fusing quantization with online softmax, which also computes row-wise maxima. First, we compute the max over 16 elements in  $S$  and reuse it in the subsequent softmax max-reduction. This fusion reduces redundant shuffles and max operations by 50%, yielding about 10% whole kernel speedup.

**Producer warp epilogue.** In conventional warp-specialized kernels, consumer warps typically handle both MatMul and store operations while producers merely load inputs, with ping-pong scheduling between consumers enabling stage overlap [12]. However, register constraints make this approach infeasible for our FP4 attention kernel. Instead, we implement ping-pong scheduling between producer warps: while one producer loads inputs for the next MatMul operation, another concurrently stores outputs to global memory, with consumer warps solely responsible for transferring MatMul results from registers to shared memory. This novel design overlaps MatMul and global memory stores within register constraints, boosting throughput.

## 4 INT8 Attention for Training

Low-bit quantization attention works, such as FlashAttention3 and SageAttention, are only for inference. In this section, we propose an INT8 attention for training, named SageBwd, which quantizes six of seven matrix multiplications in attention to INT8, achieving no performance degradation in fine-tuning tasks. Besides, we implement both INT8 SageBwd and FP8 SageBwd and conduct comparison experiments, proving INT8 SageBwd is superior to FP8 SageBwd in Section 5.4.

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**Algorithm 2:** Forward pass of the 8-bit attention.

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1: Input: FP16 matrices  $Q, K, V \in \mathbb{R}^{N \times d}$ , and block size  $B_q, B_{kv}$ .
2:  $K_m = \text{mean}(K)$ ;  $K \leftarrow K - K_m$ ; // Smooth-k technique.
3: Divide  $Q$  to  $T_m = N/B_q$  blocks  $\{\mathbf{Q}_i\}$ ; divide  $K$ , and  $V$  to  $T_n = N/B_{kv}$  blocks  $\{\mathbf{K}_i\}, \{\mathbf{V}_i\}$ ;
4: Quantization:  $\{\mathbf{s}_Q, \hat{\mathbf{Q}}_i\} = \{\psi(\mathbf{Q}_i)\}$ ,  $\{\mathbf{s}_K, \hat{\mathbf{K}}_i\} = \{\psi(\mathbf{K}_i^\top)\}$ ,  $\{\mathbf{s}_V, \hat{\mathbf{V}}_i\} = \{\psi(\mathbf{V}_i)\}$ ; // Per-block.
5: for  $i = 1$  to  $T_m$  do
6:    $\mathbf{O}_i \in \mathbb{R}^{B_q \times D} = (0)$ ,  $\mathbf{L}_i \in \mathbb{R}^{B_q} = (0)$ ,  $m_i \in \mathbb{R}^{B_{kv}} = (0)$ ;
7:   for  $j$  in  $[1, T_n]$  do
8:      $\mathbf{S}_{ij} = \text{MM}(\hat{\mathbf{Q}}_i, \hat{\mathbf{K}}_j) \times \mathbf{s}_Q \times \mathbf{s}_K$ ;
9:      $m_{ij} = \max(m_{i,j-1}, \text{rowmax}(\mathbf{S}_{ij}))$ ,  $\tilde{\mathbf{P}}_{ij} = \exp(\mathbf{S}_{ij} - m_{ij})$ ,
        $l_{ij} = e^{m_{i,j-1} - m_{ij}} l_{i,j-1} + \text{rowsum}(\tilde{\mathbf{P}}_{ij})$ ;
10:     $\mathbf{s}_P = \exp(\text{rowmax}(\mathbf{S}_{ij}) - m_{ij})/127$ ,  $\hat{\mathbf{P}}_{ij} = \tilde{\mathbf{P}}_{ij}/\mathbf{s}_P$ ; // Per-token quantization.
11:     $\mathbf{O}_{ij} = \text{diag}(e^{m_{i,j-1} - m_{ij}}) \mathbf{O}_{i,j-1} + \text{MM}(\hat{\mathbf{P}}_{ij}, \hat{\mathbf{V}}_j) \times \mathbf{s}_P \times \mathbf{s}_V$ 
12:  end for
13:   $\mathbf{O}_i = \text{diag}(l_{i,T_n})^{-1} \mathbf{O}_{i,T_n}$ ;
14:   $\mathbf{L}_i = m_{i,T_n} + \log(l_{i,T_n})$ ;
15: end for
16: return  $\mathbf{O} = \{\mathbf{O}_i\}$ ,  $\mathbf{L} = \{\mathbf{L}_i\}$ ;

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## 4.1 Forward

There are two matrix multiplications in the forward pass of attention:

$$\mathbf{S} = \mathbf{Q}\mathbf{K}^\top, \quad \mathbf{O} = \mathbf{P}\mathbf{V} \quad (6)$$

**Per-token quantization for  $\mathbf{P}$ .** Following SageAttention [3], we apply smoothing  $\mathbf{K}$  and per-block INT8 quantization for the  $\mathbf{Q}\mathbf{K}^\top$ . However, for the  $\tilde{\mathbf{P}}\mathbf{V}$ , a static per-block INT8 quantization with a static scale factor of  $1/127$  for  $\tilde{\mathbf{P}}$  is inaccurate [3]. Fortunately, we find applying per-token INT8 quantization for  $\tilde{\mathbf{P}}\mathbf{V}$  and per-block INT8 quantization for  $\mathbf{V}$  can enhance the attention accuracy. Furthermore, we eliminate the need for explicit max operations on  $\mathbf{P}$  by reusing both global and local maximum values from the online softmax computation (Line 9 in Algorithm 2). The algorithm for the forward is shown in Algorithm 2.

Given our extensive use of INT8 per-block quantization in trainable attention, we formalize the process as follows. For each FlashAttention block  $\mathbf{X}$ , the quantization process  $\mathbf{s}_\mathbf{X}, \hat{\mathbf{X}} = \psi(\mathbf{X})$  can be formulated as:

$$\mathbf{s}_\mathbf{X} = \max(|\mathbf{X}|)/127, \quad \hat{\mathbf{X}} = \mathbf{X}/\mathbf{s}_\mathbf{X} \quad (7)$$

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**Algorithm 3:** Backward pass of the 8-bit attention.

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1: Input:  $\{\mathbf{s}_\mathbf{Q}, \hat{\mathbf{Q}}_i\}, \{\mathbf{s}_\mathbf{K}, \hat{\mathbf{K}}_i\}, \{\mathbf{s}_\mathbf{V}, \hat{\mathbf{V}}_i\}, K_m, O, \{\mathbf{L}_i\}$  from forward,  $dO \in \mathbb{R}^{N \times d}$ , block size  $B_q, B_{kv}$ ;
2:  $D = \text{rowsum}(dO \circ O)$ , divide  $D$  to  $T_m = N/B_q$  blocks  $\{\mathbf{D}_i\}$ ;
3: for  $j = 1$  to  $T_n$  do
4:   for  $i$  in  $[1, T_m]$  do
5:      $\mathbf{S}_{ij} = \text{MM}(\mathbf{Q}_i, \hat{\mathbf{K}}_j) \times \mathbf{s}_\mathbf{Q} \times \mathbf{s}_\mathbf{K}$ ;  $\mathbf{P}_{ij} = \exp(\mathbf{S}_{ij} - \mathbf{L}_i)$ ;
6:      $\mathbf{s}_\mathbf{P}, \hat{\mathbf{P}}_{ij} = \psi(\mathbf{P}_{ij})$ ,  $\mathbf{s}_{dO}, \hat{dO}_i = \psi(dO_i)$ ; // INT8 per-block quantization.
7:      $d\mathbf{V}_j \leftarrow d\mathbf{V}_j + \text{MM}(\hat{\mathbf{P}}_{ij}^\top, \hat{dO}_i) \times \mathbf{s}_\mathbf{P} \times \mathbf{s}_{dO}$ ;
8:      $d\mathbf{P}_{ij} = \text{MM}(dO, \mathbf{V}_j^\top)$ ; // Keep in FP16.
9:      $d\mathbf{S}_{ij} = \mathbf{P}_{ij} \circ (d\mathbf{P}_{ij} - \mathbf{D}_i)$ ;  $\mathbf{s}_{dS}, \hat{dS}_{ij} = \psi(d\mathbf{S}_{ij})$ ; // INT8 per-block quantization.
10:     $d\mathbf{Q}_i \leftarrow d\mathbf{Q}_i + \text{MM}(\hat{dS}_{ij}, \hat{\mathbf{K}}_j) \times \mathbf{s}_{dS} \times \mathbf{s}_\mathbf{K} + \text{rowsum}(d\mathbf{S}_{ij})K_m$ ; // Backward for smooth-k.
11:     $d\mathbf{K}_j \leftarrow d\mathbf{K}_j + \text{MM}(\hat{dS}_{ij}, \hat{\mathbf{Q}}_i) \times \mathbf{s}_{dS} \times \mathbf{s}_\mathbf{Q}$ ;
12:   end for
13: end for
14: return  $dQ, dK, dV$ ;

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## 4.2 Backward

There are five matrix multiplications in the backward pass of attention:

$$\mathbf{S} = \mathbf{Q}\mathbf{K}^\top, \quad d\mathbf{V} = \tilde{\mathbf{P}}^\top d\mathbf{O}, \quad d\mathbf{P} = d\mathbf{O}\mathbf{V}^\top, \quad d\mathbf{Q} = d\mathbf{S}\mathbf{K}, \quad d\mathbf{K} = d\mathbf{S}^\top\mathbf{Q} \quad (8)$$

We observe that whether applying quantizing to  $d\mathbf{O}\mathbf{V}^\top$  has a significant impact on the accuracy of the gradient of  $Q, K$ . This is because the accuracy of  $d\mathbf{O}\mathbf{V}^\top$  directly determines the accuracy of  $d\mathbf{P}$  and  $d\mathbf{S}$  (see computational dependencies in Algorithm 3). The accuracy loss in  $d\mathbf{S}$  will continuously accumulate errors into  $d\mathbf{Q}$  and  $d\mathbf{K}$  during the recurrent process along the sequence length in FlashAttention’s backward pass, meaning longer sequences lead to greater error accumulation. Therefore, we maintain  $d\mathbf{O}\mathbf{V}^\top$  in FP16 while accelerating the other four matrix multiplications using INT8 per-block quantization. The algorithm for the forward is shown in Algorithm 3. Empirical results: Table 1 (c) shows the accuracy of the  $d\mathbf{Q}$  with and without quantization of  $d\mathbf{O}\mathbf{V}^\top$ . We find that the accuracy of  $d\mathbf{Q}$  is significantly improved when keeping  $d\mathbf{O}\mathbf{V}^\top$  in FP16.

Table 1: Accuracy ablation using different quantization strategies.

(a) Different FP4 choices				(b) Different scale strategies for $\tilde{\mathbf{P}}$				(c) Different data types for $d\mathbf{O}\mathbf{V}^\top$			
Type	CosSim $\uparrow$	L1 $\downarrow$	RMSE $\downarrow$	Method	CosSim	L1	RMSE	Method	CosSim	L1	RMSE
MXFP4	98.37%	0.294	0.994	Direct	93.32%	0.193	1.103	INT8	97.47%	0.171	2.440
NVFP4	<b>99.52%</b>	<b>0.077</b>	<b>0.201</b>	Two-level	<b>99.52%</b>	<b>0.077</b>	<b>0.201</b>	FP16	<b>99.77%</b>	<b>0.039</b>	<b>0.692</b>

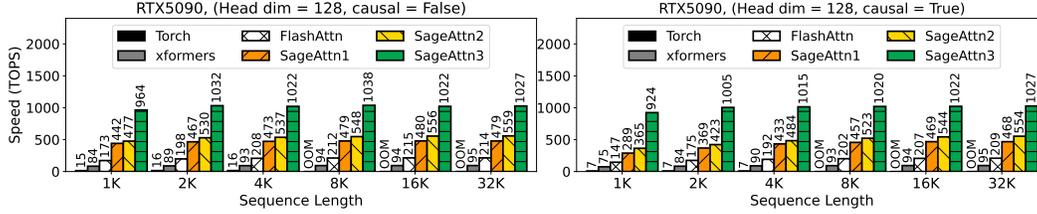


Figure 4: Speed comparison between SageAttention3 and Baselines (RTX5090, headdim=128).

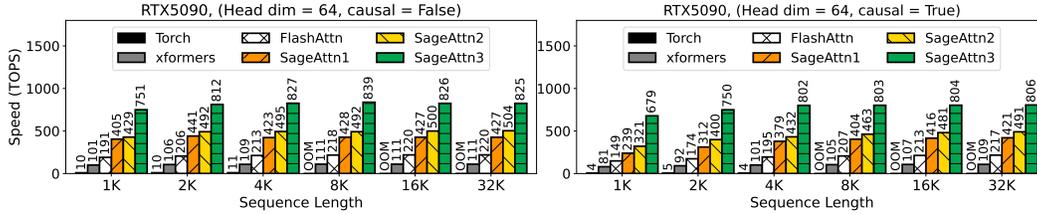


Figure 5: Speed comparison between SageAttention3 and Baselines (RTX5090, headdim=64).

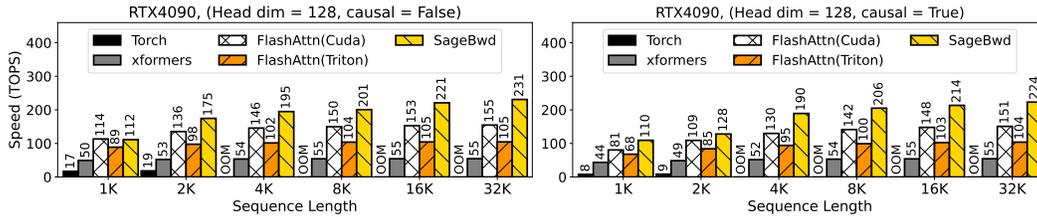


Figure 6: Speed comparison between SageBwd and Baselines (RTX4090, headdim=128).

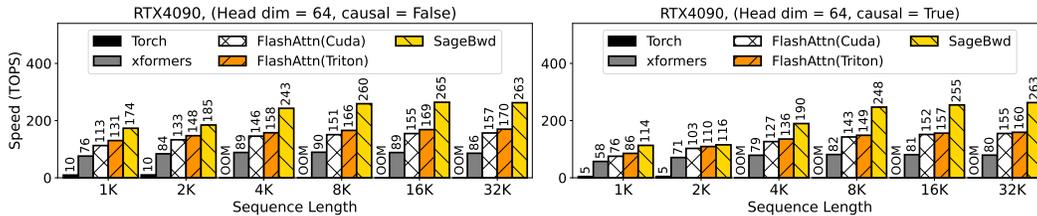


Figure 7: Speed comparison between SageBwd and Baselines (RTX4090, headdim=64).

Table 2: End-to-end metrics comparison on various models.

Model	Attention	CLIPSIM $\uparrow$	CLIP-T $\uparrow$	VQA-a $\uparrow$	VQA-t $\uparrow$	FScore $\uparrow$
CogvideoX	Full-Precision (16bit)	0.1865	0.9968	70.476	69.875	4.780
	SageAttention2 (8bit)	0.1880	0.9969	69.414	70.750	4.534
	SageAttention3 (4bit)	<b>0.1881</b>	<b>0.9969</b>	<b>69.860</b>	<b>70.364</b>	<b>4.035</b>
Hunyuan Video	Full-Precision (16bit)	0.1838	0.9993	68.998	78.891	1.4793
	SageAttention2 (8bit)	0.1836	0.9993	69.497	77.019	1.4741
	SageAttention3 (4bit)	<b>0.1866</b>	<b>0.9993</b>	<b>70.552</b>	<b>75.440</b>	<b>1.232</b>
Mochi	Full-Precision (16bit)	0.1828	0.9990	61.9840	61.0000	1.8042
	SageAttention2 (8bit)	0.1819	0.9990	61.0093	60.3732	1.7539
	SageAttention3 (4bit)	<b>0.1800</b>	<b>0.9993</b>	<b>61.863</b>	<b>59.429</b>	<b>1.649</b>
Model	Attention	FID $\downarrow$	sFID $\downarrow$	CLIP $\uparrow$	IR $\uparrow$	
Flux	Full-Precision (16bit)	162.812	146.980	31.409	0.91	
	SageAttention2 (8bit)	163.107	146.213	31.436	0.90	
	SageAttention3 (4bit)	<b>162.121</b>	<b>142.839</b>	<b>31.450</b>	<b>0.94</b>	
Stable-Diffusion3.5	Full-Precision (16bit)	166.421	146.379	31.93	0.93	
	SageAttention2 (8bit)	164.986	148.557	32.01	0.93	
	SageAttention3 (4bit)	<b>166.102</b>	<b>145.587</b>	<b>32.01</b>	<b>0.92</b>	

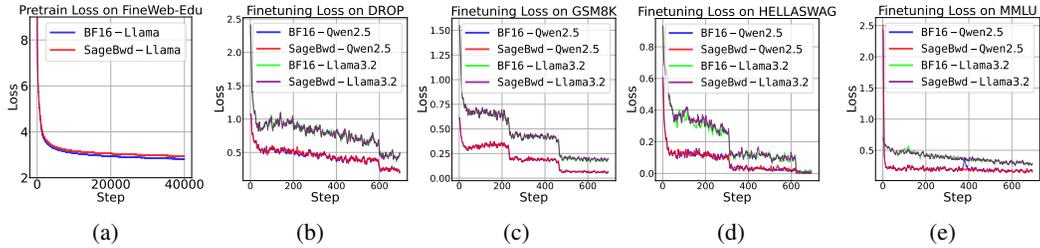


Figure 8: Pretraining and Finetuning loss curves of BF16 and 8-bit attention.

Table 3: 8-bit attention finetune results on Qwen2.5 and Llama3.2 models.

Model	Method	GSM8K <sub>(Acc↑)</sub>	DROP <sub>(F1↑)</sub>	MMLU <sub>(Acc↑)</sub>	HELLASWAG <sub>(Acc↑)</sub>
Qwen2.5 (1.5B)	BF16	0.521	0.733	0.569	0.905
	SageBwd	0.520	<b>0.734</b>	<b>0.574</b>	<b>0.911</b>
Qwen2.5 (3B)	BF16	0.601	0.785	0.640	0.944
	SageBwd	<b>0.607</b>	0.782	<b>0.653</b>	0.943
Llama3.2 (1B)	BF16	0.259	0.641	0.464	0.828
	SageBwd	<b>0.268</b>	0.637	0.458	0.823

## 5 Experiments

**Main results.** SageAttention3 is faster than FlashAttention and xformers by  $5\times$  and  $11\times$  on RTX5090, and maintains end-to-end metrics across various models. Furthermore, SageBwd is faster than FlashAttention and xformers by  $1.67\times$  and  $3\times$  on RTX4090, and achieves no measurable degradation in fine-tuning tasks.

### 5.1 Setup

**Models and attentions.** We validate the effectiveness of SageAttention3 and SageBwd across a diverse set of representative models from language, image, and video generation. Specifically, we conduct experiments on: Qwen2.5 [13] and Llama3.2 [14] for text2text, CogvideoX [15], HunyuanVideo [16], and Mochi [17] for text2video, Flux [18], and Stable-Diffusion3.5 [19] for text2image. We compare our method with FlashAttention2 [20], xformers [21], SageAttention [3], and SageAttention2 [4]. Please **note** that FlashAttention3 can only run on Hopper GPUs, so FlashAttention2 is already the fastest version for RTX5090 and RTX4090.

**Datasets, metrics, and hyperparameters.** For the details about the datasets, metrics, and hyperparameters we used, please refer to Appendix A.3.

**Implementation.** We implement SageAttention3 using CUTLASS [22] and CUDA, and implement SageBwd using OpenAI Triton [23].



Figure 9: Visible examples of video generation on HunyuanVideo (left) and image generation on Stable-Diffusion3.5 (right).

Table 4: End-to-end speedup performance using SageAttention3 and SageBwd.

(a) Inference latency using SageAttention3.					(b) One iteration training latency using SageBwd.		
Model	Original	Sage1	Sage2	Sage3	Model	Original	SageBwd
CogvideoX (2B)	64 s	55 s	46 s	<b>27 s</b>	Llama (8K)	2.1 s	<b>1.9 s</b>
HunyuanVideo	489 s	257 s	240 s	<b>164 s</b>	Llama (16K)	6.0 s	<b>5.2 s</b>

## 5.2 Efficiency and Effectiveness

**Kernel Speed.** Fig. 4 and 5 show the kernel speed of SageAttention3 and baselines on RTX5090. We can see that SageAttention3 achieves 4~5 $\times$  speedup over FlashAttention2 and 8~11 $\times$  speedup over xformers. Fig. 6 and 7 show the forward+backward speed of SageBwd and baselines on RTX4090. It shows that SageBwd achieves 1.67 $\times$  speedup at most than FlashAttention2 and a higher speedup than FlashAttention2 implemented in Triton and xformers.

**End-to-end metrics loss of SageAttention3.** In Table 2, we compare the end-to-end quality metrics on various models using SageAttention3 and other attention methods. The results demonstrate that SageAttention3 almost incurs almost no end-to-end quality loss across these models.

**End-to-end metrics loss of SageBwd.** To evaluate the effectiveness of SageBwd on training tasks, we conduct two experiments. First, we fine-tune the base models of Qwen2.5 (3B) and Llama3.2 (1B) on GSM8K [24], DROP [25], MMLU [26], and HELLASWAG [27] datasets. Fig. 8 (b-e) shows the fine-tuning loss results, indicating that SageBwd perfectly aligns with BF16. Moreover, our evaluation of the fine-tuned models’ answer quality across multiple test datasets (Table 3) demonstrates that SageBwd achieves the same performance as BF16. Second, we conduct pre-training tasks on FineWebEdu [28] using a Llama (400M) [29] model. Fig. 8 (a) shows the loss curve, indicating that while SageBwd can achieve loss convergence, its convergence speed is relatively slow. This limitation restricts its applicability in pretraining tasks.

**Visible example.** Fig. 9 visualizes some comparative examples of video generation on HunyuanVideo and image generation on Stable-diffusion3.5 using SageAttention3. The results demonstrate that SageAttention3 maintains full generation quality. Additional visible examples are provided in Fig. 10, 11, 13, and 14 in the Appendix.

**End-to-end speedup.** Table 4(a) and 4(b) summarize end-to-end inference and training latency improvements. The results show that SageAttention3 (Table 4(a)) achieved about 3 $\times$  (HunyuanVideo) and 2.4 $\times$  (CogVideoX) end-to-end inference generation speedups on RTX5090. Furthermore, SageBwd (Table 4(b)) accelerates the training of Llama (1B) by about 1.15 $\times$  using 8K/16K token micro-batches on RTX4090.

## 5.3 Benefit of Using Both SageAttention3 and SageBwd

Table 5: Comparison between BF16 and INT8 fine-tuning followed by FP4 inference.

(a) Qwen2.5-1.5B results.			(b) Qwen2.5-3B results.		
Method	GSM8k $\uparrow$	MMLU $\uparrow$	Method	GSM8k $\uparrow$	MMLU $\uparrow$
BF16 Fine-tuning	0.4912	0.4688	BF16 Fine-tuning	0.5860	0.6000
SageBwd <b>Fine-tuning</b>	<b>0.5232</b>	<b>0.4934</b>	SageBwd <b>Fine-tuning</b>	<b>0.5945</b>	<b>0.6032</b>

We first apply SageBwd during fine-tuning, followed by SageAttention3 during inference. Specifically, we fine-tuned Qwen2.5 for 1,000 steps using either BF16 or SageBwd, and then evaluated inference performance using SageAttention3. The results on GSM8k and MMLU are shown in Table 5, INT8 SageBwd fine-tuning followed by FP4 SageAttention3 inference achieves higher accuracy on GSM8k and MMLU, suggesting the approaches are complementary. This improvement is likely because INT8 and FP4 share a more similar representable data distribution, reducing the mismatch error compared to BF16.

## 5.4 INT8 SageBwd vs FP8 SageBwd

We choose INT8 for SageBwd for two key reasons: (1) Higher gradient accuracy in attention backward. The backward of INT8 attention yields more accurate gradients for  $Q$ ,  $K$ , and  $V$  compared to FP8. We evaluate all layers of CogVideoX-2B and report the L1 error and cosine similarity of the gradients in Table 6 and Table 7. For fairness,  $dOV^\top$  is kept in FP16 for both methods. As shown in the results, INT8 SageBwd achieves lower L1 error and higher cosine similarity than FP8 SageBwd. (2) Wider hardware support. INT8 is supported on almost all modern GPUs, including NVIDIA A100 and many non-NVIDIA devices (e.g., AMD MI250 [30], Ascend 910B [31]), while FP8 support remains limited to newer architectures. Additionally, we fine-tune Qwen2.5-1.5B and Qwen2.5-3B for 1,000 steps using either INT8 or FP8 SageBwd (both with  $dOV^\top$  kept in FP16 for fairness), and then inference with FP4 SageAttention3. As shown in Table 8, models fine-tuned with INT8 attention achieve higher accuracy on both GSM8K and MMLU benchmarks.

Table 6: L1 error of  $Q$ ,  $K$ , and  $V$  gradients.

Method	$dQ \downarrow$	$dK \downarrow$	$dV \downarrow$
INT8 SageBwd	<b>0.0290</b>	<b>0.0317</b>	<b>0.0423</b>
FP8 SageBwd	0.0696	0.0999	0.0873

Table 7: Cos similarity of  $Q$ ,  $K$ , and  $V$  gradients.

Method	$dQ \uparrow$	$dK \uparrow$	$dV \uparrow$
INT8 SageBwd	<b>0.9987</b>	<b>0.9993</b>	<b>0.9995</b>
FP8 SageBwd	0.9880	0.9910	0.9955

Table 8: Comparison of INT8 and FP8 SageBwd fine-tuning on Qwen2.5 models.

(a) Qwen2.5-1.5B

Method	GSM8K $\uparrow$	MMLU $\uparrow$
INT8 Fine-tuning	<b>0.5232</b>	<b>0.4934</b>
FP8 Fine-tuning	0.5031	0.4689

(b) Qwen2.5-3B

Method	GSM8K $\uparrow$	MMLU $\uparrow$
INT8 Fine-tuning	<b>0.5945</b>	<b>0.6032</b>
FP8 Fine-tuning	0.5868	0.5907

## 6 Related Work

Recent efficient attention works [2] that utilize hardware features to accelerate attention computation methods mainly include the following: FlashAttention [32] introduces tiling to reduce the GPU memory I/O between global memory and on-chip SRAM, achieving significant speedup. FlashAttention2 [20] improves the parallelism and warp partition strategies. FlashAttention3 [33] exclusively optimizes the kernel speed on the Hopper GPUs. xformers [21] accelerates attention using dedicated CUDA kernels. SageAttention [3] and SageAttention2 [4, 34] accelerate attention using quantization and some novel outlier smoothing techniques. RingAttention [35] extends FlashAttention to multi-GPU/Node environments. In these works, although FlashAttention3 proposes a version of FP8 attention, it has failed to be applied to video generation models in a plug-and-play way [4]. Moreover, the FP8 attention in FlashAttention3 does not support the backward pass, limiting its applicability to training tasks. Additionally, numerous efficient attention variants have emerged, including linear attention [36, 37, 38, 39, 40, 41] and sparse attention [42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54]. Although these works represent promising research directions, they are orthogonal to our work.

## 7 Conclusions

In this paper, we make two key contributions. Firstly, we design SageAttention3, the first microscaling FP4 attention for inference acceleration, achieving **1038** TOPS on RTX5090, which is a  $5\times$  speedup than the fastest FlashAttention on RTX5090. Experiments show that SageAttention3 could accelerate various models with no end-to-end quality metrics degradation. Secondly, we introduce the first trainable 8-bit attention (SageBwd) for training acceleration and explore its feasibility in training tasks. We find that the 8-bit attention could achieve lossless performance in fine-tuning tasks, but currently has some limitations in pertaining tasks.

**Future Work.** First, while SageBwd demonstrates faster performance than FP16 implementation, we observe a noticeable gap between its current speed and theoretical upper bounds. This gap may be caused by suboptimal Triton kernel implementations, which we plan to further optimize. Second, and more importantly, investigating the application of low-bit attention in pretraining tasks presents a promising research direction worthy of exploration.

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## A Appendix

### A.1 Visible Comparison Examples



Figure 10: Visible examples of image generation on Stable-Diffusion3.5.



Figure 11: Visible examples of image generation on Flux.



(a) Full-Precision

(b) Two-level quantization

(c) Direct quantization

Figure 12: Visual comparison of different scale strategies for  $\tilde{P}$  from CogVideoX.



Figure 13: Visible examples of video generation on CogVideoX.

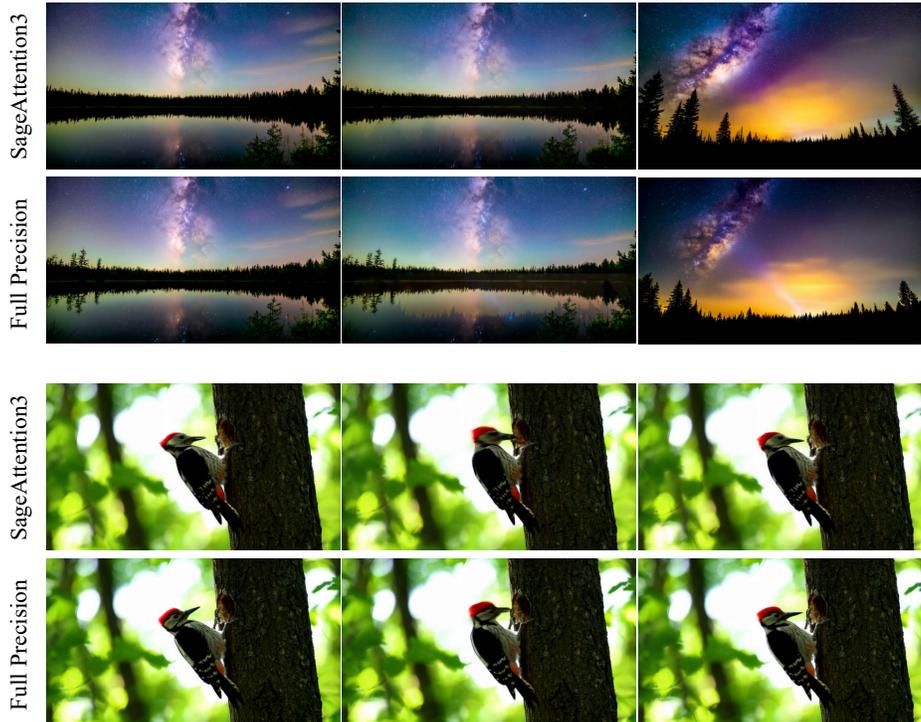


Figure 14: Visible examples of video generation on HunyuanVideo.

Fig. 10 and Fig. 11 show additional visual comparison examples of image generation tasks. Fig. 13 and Fig. 14 show more visual comparison examples of video generation tasks.

## A.2 Additional Kernel Speed Comparison

Fig. 15 and Fig. 16 show the forward kernel speed of SageBwd. Fig. 17 and Fig. 18 show the backward kernel speed of SageBwd. SageBwd achieved a **2x** speed up than FlashAttention in the forward propagation. SageBwd achieved a 1.2~1.6x speed up than FlashAttention in the backward propagation.

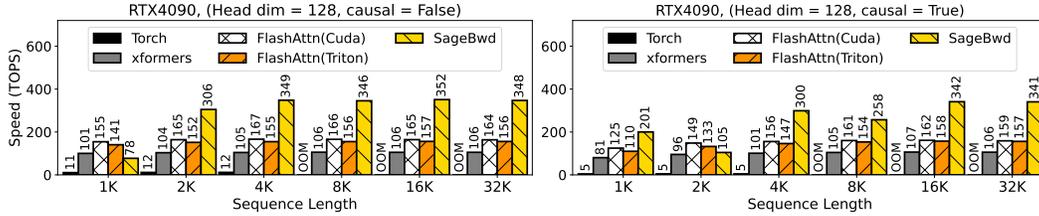


Figure 15: Forward speed comparison between SageBwd and Baselines (RTX4090, headdim=128).

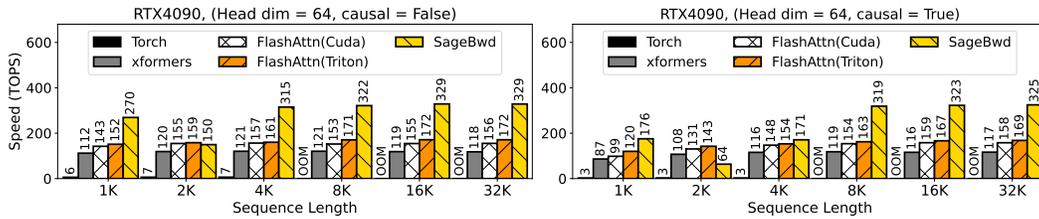


Figure 16: Forward speed comparison between SageBwd and Baselines (RTX4090, headdim=64).

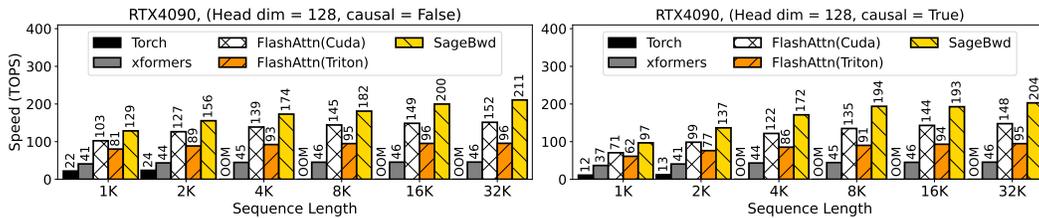


Figure 17: Backward speed comparison between SageBwd and Baselines (RTX4090, headdim=128).

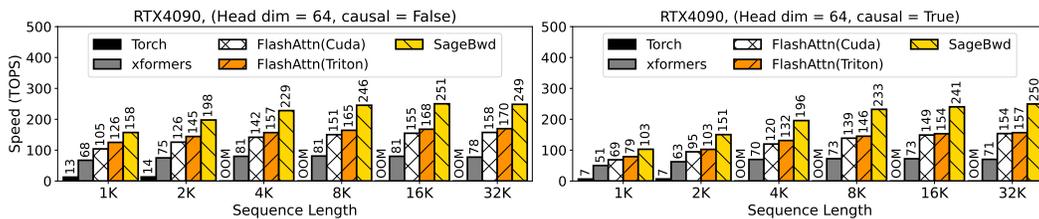


Figure 18: Backward speed comparison between SageBwd and Baselines (RTX4090, headdim=64).

### A.3 Datasets, Metrics, and Hyperparameters

**Datasets.** Text-to-video models are evaluated using the open-sora [55] prompt sets. Text-to-image models are assessed on COCO annotations [56]. Language models are evaluated on GSM8K [24], DROP [25], MMLU [26], and HELLASWAG [27] datasets.

**End-to-end metrics.** For text-to-text models, we use Accuracy (Acc.) and F1-Score (F1). For text-to-video models, we evaluate the quality of generated videos on five metrics: CLIPSIM and CLIP-Temp (CLIP-T) [57] to measure the text-video alignment; (VQA-a) and (VQA-t) to assess the video aesthetic and technical quality, respectively; and Flow-score (FScore) for temporal consistency [58]. For text-to-image models, generated images are evaluated in three aspects: FID [59] and sFID [60] for fidelity evaluation, *Clipscore* (CLIP) [61] for text-image alignment, and *ImageReward* (IR) [62] for human preference.

**Accuracy metrics.** We use three metrics to assess the accuracy of quantized attention output  $O'$  compared to attention output in full-precision  $O$ : First, we flatten  $O'$  and  $O$  into vectors in the shape of  $1 \times n$ . Then, Cosine similarity:  $CosSim = \sum OO' / \sqrt{\sum O^2} \sqrt{\sum O'^2}$ , Relative L1 distance:  $L1 = \sum |O - O'| / \sum |O|$ , Root mean square error:  $RMSE = \sqrt{(1/n) \sum (O - O')^2}$ .

**Hyperparameters.** For pretraining tasks, we use a 400M model with a hidden size of 1024, 20 layers, an intermediate size of 3072, and 16 attention heads. The training uses a learning rate of 1e-3 with linear decay over 1000 warmup steps, and each step processes 2M tokens. For finetuning tasks, we train for 700 steps using a learning rate of 3e-5 with linear decay and 100 warmup steps with a batch size of 32 on GSM8K dataset and 128 on MMLU, DROP, and HELLASWAG datasets.

T0(v0, v1)	T0(v2, v3)	T0(v4, v5)	T0(v6, v7)	T1(v0, v1)	T1(v2, v3)	T1(v4, v5)	T1(v6, v7)	T2(v0, v1)	T2(v2, v3)	T2(v4, v5)	T2(v6, v7)	T3(v0, v1)	T3(v2, v3)	T3(v4, v5)	T3(v6, v7)
T0(v8, v9)	T0(v10, v11)	T0(v12, v13)	T0(v14, v15)	T1(v8, v9)	T1(v10, v11)	T1(v12, v13)	T1(v14, v15)	T2(v8, v9)	T2(v10, v11)	T2(v12, v13)	T2(v14, v15)	T3(v8, v9)	T3(v10, v11)	T3(v12, v13)	T3(v14, v15)

Figure 19: FP4 operand A register layout - rows 0 and 8, thread 0-3, entries 0-15.

T0(v0, v1)	T1(v0, v1)	T2(v0, v1)	T3(v0, v1)	T0(v4, v5)	T1(v4, v5)	T2(v4, v5)	T3(v4, v5)	T0(v8, v9)	T1(v8, v9)	T2(v8, v9)	T3(v8, v9)	T0(v12, v13)	T1(v12, v13)	T2(v12, v13)	T3(v12, v13)
T0(v8, v9)	T1(v8, v9)	T2(v8, v9)	T3(v8, v9)	T0(v6, v7)	T1(v6, v7)	T2(v6, v7)	T3(v6, v7)	T0(v10, v11)	T1(v10, v11)	T2(v10, v11)	T3(v10, v11)	T0(v14, v15)	T1(v14, v15)	T2(v14, v15)	T3(v14, v15)

Figure 20: FP32 accumulator register layout - rows 0 and 8, thread 0-3, entries 0-15.

T0(v0, v1)	T1(v0, v1)	T2(v0, v1)	T3(v0, v1)	T0(v2, v3)	T1(v2, v3)	T2(v2, v3)	T3(v2, v3)	T0(v4, v5)	T1(v4, v5)	T2(v4, v5)	T3(v4, v5)	T0(v6, v7)	T1(v6, v7)	T2(v6, v7)	T3(v6, v7)
T0(v8, v9)	T1(v8, v9)	T2(v8, v9)	T3(v8, v9)	T0(v10, v11)	T1(v10, v11)	T2(v10, v11)	T3(v10, v11)	T0(v12, v13)	T1(v12, v13)	T2(v12, v13)	T3(v12, v13)	T0(v14, v15)	T1(v14, v15)	T2(v14, v15)	T3(v14, v15)

Figure 21: Permuted FP32 accumulator register layout - rows 0 and 8, thread 0-3, entries 0-15.

### A.4 Additional Experiments of using SageBwd

Table 9–14 show Qwen2.5 (1.5B), Qwen2.5 (3B), and Llama3.2 (3B) fine-tuning results on four datasets with five different random seeds. The average and standard deviation show SageBwd is highly consistent with BF16 across various random seeds.

Table 9: Comparison of SageBwd and BF16 performance on GSM8K and DROP across different seeds on Qwen2.5 (1.5B).

Seed	GSM8K		DROP	
	SageBwd	BF16	SageBwd	BF16
42	0.5133	0.5125	0.7316	0.7364
233	0.5027	0.5042	0.7269	0.7295
1234	0.4973	0.4973	0.7329	0.7342
5678	0.5201	0.5208	0.7340	0.7332
1	0.5049	0.5057	0.7278	0.7404
<b>Avg</b>	0.5077	0.5081	0.7307	0.7348
<b>Std</b>	0.0090	0.0089	0.0032	0.0040

Table 10: Comparison of SageBwd and BF16 performance on MMLU and HellaSwag across different seeds on Qwen2.5 (1.5B).

Seed	MMLU		HellaSwag	
	SageBwd	BF16	SageBwd	BF16
42	0.5814	0.5873	0.9089	0.9065
233	0.5746	0.5785	0.9082	0.9049
1234	0.5805	0.5836	0.9025	0.9047
5678	0.5736	0.5693	0.9112	0.9053
1	0.5830	0.5823	0.9058	0.9075
<b>Avg</b>	0.5786	0.5802	0.9073	0.9058
<b>Std</b>	0.0043	0.0069	0.0033	0.0012

Table 11: Comparison of SageBwd and BF16 performance on GSM8K and DROP across different seeds on Qwen2.5 (3B).

Seed	GSM8K		DROP	
	SageBwd	BF16	SageBwd	BF16
42	0.5982	0.6232	0.7800	0.7812
233	0.5997	0.5974	0.7786	0.7812
1234	0.6156	0.6103	0.7786	0.7824
5678	0.6065	0.6012	0.7816	0.7853
1	0.6171	0.6073	0.7813	0.7832
<b>Avg</b>	0.6074	0.6079	0.7800	0.7827
<b>Std</b>	0.0001	0.0001	0.0000	0.0000

Table 12: Comparison of SageBwd and BF16 performance on MMLU and HellaSwag across different seeds on Qwen2.5 (3B).

Seed	MMLU		HellaSwag	
	SageBwd	BF16	SageBwd	BF16
42	0.6434	0.6425	0.9419	0.9402
233	0.6431	0.6437	0.9405	0.9402
1234	0.6492	0.6492	0.9414	0.9429
5678	0.6531	0.6400	0.9430	0.9440
1	0.6510	0.6454	0.9446	0.9434
<b>Avg</b>	0.6480	0.6442	0.9423	0.9421
<b>Std</b>	0.0000	0.0000	0.0000	0.0000

Table 13: Comparison of SageBwd and BF16 performance on GSM8K and DROP across different seeds on Llama3.2 (1B).

Seed	GSM8K		DROP	
	SageBwd	BF16	SageBwd	BF16
42	0.2722	0.2547	0.6367	0.6447
233	0.2661	0.2570	0.6456	0.6424
1234	0.2616	0.2873	0.6439	0.6352
5678	0.2684	0.2585	0.6372	0.6409
1	0.2646	0.2335	0.6393	0.6441
<b>Avg</b>	0.2666	0.2582	0.6405	0.6414
<b>Std</b>	0.0000	0.0003	0.0000	0.0000

Table 14: Comparison of SageBwd and BF16 performance on MMLU and HellaSwag across different seeds on Llama3.2 (3B).

Seed	MMLU		HellaSwag	
	SageBwd	BF16	SageBwd	BF16
42	0.4665	0.4705	0.8230	0.8319
233	0.4646	0.4560	0.8327	0.8256
1234	0.4702	0.4757	0.8202	0.8243
5678	0.4580	0.4639	0.8232	0.8276
1	0.4666	0.4691	0.8218	0.8236
<b>Avg</b>	0.4652	0.4670	0.8242	0.8266
<b>Std</b>	0.0000	0.0000	0.0000	0.0000

### A.5 Transposing $V$ .

Performing the forward propagation of attention in full FP4 precision poses additional challenges compared to FP16. The input tensors  $Q$ ,  $K$ , and  $V$  are typically contiguous in the head dimensions. However, the row-major constraints on FP4 MMA for the second GEMM necessitate  $V$  to be contiguous in the sequence length dimension. Calling a standalone pre-processing transpose kernel for this purpose incurs excessive overhead, particularly during inference, which is often a memory-bound situation. We address the problem by kernel fusion. For the first problem, we fuse the transpose of  $V$  into the quantization kernel, thereby avoiding additional I/O overhead.

### A.6 Accumulated Quantization Error Analysis.

Table 15: Layer-wise L1 error analysis of SageAttention3 on CogVideoX-2B. The second row shows the results by retaining the three most sensitive layers in FP16.

Method	Layer1 ↓	Layer10 ↓	Layer20 ↓	Layer30 ↓
Use SageAttention3 directly	0.0076	0.0922	0.1146	0.0571
Keep 3 most sensitive layers in FP16	0.0076	<b>0.0447</b>	<b>0.0773</b>	<b>0.0429</b>

To explore the issue of accumulated quantization error across layers, we conduct an analysis using SageAttention3 on CogVideoX-2B and report the per-layer L1 error in Table 15. We observe that the accumulated error generally increases with layer depth, though it occasionally decreases in deeper layers, suggesting partial error cancellation. To mitigate this drift, we apply a simple yet effective strategy: keeping the three layers with the largest observed error growth in FP16 precision. As shown in the table, this adjustment significantly reduces the overall error accumulation across layers.

### A.7 Ablation of Smoothing Techniques.

Table 16: Ablation of attention accuracy with different smoothing methods on CogVideoX-2B. Smoothing K and Smoothing Q are techniques from SageAttention and SageAttention2.

Method	Cossim $\uparrow$	L1 Error $\downarrow$	RMSE $\downarrow$
None	0.915642	0.335867	0.303483
SmoothQuant	0.930125	0.267617	0.252883
Hadamard	0.941222	0.262047	0.223970
<b>Smoothing_Q</b>	<b>0.982848</b>	<b>0.115658</b>	<b>0.125862</b>
<b>Smoothing_K</b>	<b>0.991176</b>	<b>0.094832</b>	<b>0.097668</b>

To investigate the impact of different smoothing strategies on attention accuracy, we compare several existing techniques, including SmoothQuant [63] and Hadamard transformations, which provide per-token or per-tensor scaling control. However, we find these methods less effective in our setting. SageAttention3 inherits the smoothing Q and smoothing K mechanisms introduced in SageAttention2. We conduct an ablation study on all layers of CogVideoX-2B to evaluate their effects. As shown in Table 16, both smoothing Q and smoothing K yield substantially higher cosine similarity and lower reconstruction errors, demonstrating their effectiveness in stabilizing quantized attention computation.

### A.8 Theoretical Speed Comparison.

Table 17: Theoretical throughput comparison between FlashAttention3 and SageAttention3 across different GPUs.

Method	B300 TOPS $\uparrow$	B200 TOPS $\uparrow$	RTX5090 TOPS $\uparrow$
FlashAttention3	2500	2500	209.5
FlashAttention3 (FP8)	5000	5000	419
SageAttention3 (FP4)	<b>15000</b>	<b>10000</b>	<b>1676</b>

To provide a theoretical comparison with FlashAttention3, we refer to NVIDIA’s official documentation on throughput (TOPS) across different precisions. Since FlashAttention3 is currently only supported on H100 GPUs, a direct empirical comparison is not feasible. Instead, we estimate the theoretical compute throughput of both FlashAttention3 and our SageAttention3 on GPUs that support FP4 Tensor Cores (B300, B200, and RTX5090). As summarized in Table 17, SageAttention3 achieves substantially higher theoretical peak throughput, highlighting its potential for further accelerating attention computation beyond FlashAttention-3.

### A.9 FlashAttentions vs SageAttentions.

Table 18: Speed–accuracy trade-off of different attention methods.

Method	TOPS on 5090 $\uparrow$	TOPS on H100 $\uparrow$	Accuracy (CosSim) $\uparrow$
FlashAttention2	214	338	100.000%
FlashAttention3 (16bit)	N/A	470	100.000%
FlashAttention3 (8bit)	N/A	890	98.570%
SageAttention1	479	518	99.996%
SageAttention2 (8bit)	643	885	99.995%
SageAttention3 (4bit)	<b>1038</b>	N/A	<b>99.551%</b>

To illustrate the trade-off between accuracy and speed, we recorded the accuracy (Cosine similarity) of various attention methods across all layers of CogVideoX-2B, along with their theoretical throughput on RTX5090 and H100 GPUs. These results are summarized in the Table 18.

### A.10 Analysis of Two-Level Quantization.

*Proof.* We analyze the relative quantization error of  $\tilde{\mathbf{P}}$  using both direct quantization and two-level quantization as follows:

For direct quantization, the relative quantization error, denoted as  $E_1$ , is defined as:

$$\mathbf{s}_{\mathbf{P}}, \hat{\mathbf{P}} = \phi(\tilde{\mathbf{P}}), \quad E_1 = \frac{|\mathbf{s}_{\mathbf{P}} \times \hat{\mathbf{P}} - \tilde{\mathbf{P}}|}{|\tilde{\mathbf{P}}|} \quad (9)$$

For two-level quantization, the first level proceeds as:

$$\mathbf{s}_{\mathbf{P}_1} = \text{rowmax}(\tilde{\mathbf{P}})/(448 \times 6), \quad \tilde{\mathbf{P}}_2 = \tilde{\mathbf{P}}/\mathbf{s}_{\mathbf{P}_1},$$

The quantization error introduced in this first step is negligible because  $\tilde{\mathbf{P}}$ ,  $\tilde{\mathbf{P}}_2$ , and  $s_{P_1}$  are all represented in FP32 format.

We focus primarily on the second-level quantization, where the relative quantization error  $E_2$  is given by:

$$\mathbf{s}_{\mathbf{P}_2}, \hat{\mathbf{P}}_2 = \phi(\tilde{\mathbf{P}}_2), \quad E_2 = \frac{|\mathbf{s}_{\mathbf{P}_2} \times \hat{\mathbf{P}}_2 - \tilde{\mathbf{P}}_2|}{|\tilde{\mathbf{P}}_2|} \quad (10)$$

The key difference between Equation 9 and 10 lies in the range of the FP8 scale factor.

Let  $\{X\}_n$  denote the number of distinct representable values in the set  $X$ . Then:

in direct quantization:

$$0 \leq \mathbf{s}_{\mathbf{P}} \leq 0.167, \quad \mathbf{s}_{\mathbf{P}} \in \mathbf{E4M3}, \quad \{\mathbf{s}_{\mathbf{P}}\}_n = 35$$

In two-level quantization:

$$0 \leq \mathbf{s}_{\mathbf{P}_2} \leq 448.0, \quad \mathbf{s}_{\mathbf{P}_2} \in \mathbf{E4M3}, \quad \{\mathbf{s}_{\mathbf{P}_2}\}_n = 127$$

Since  $\{\mathbf{E2M1}\}_n = 8$ , the number of unique outputs after dequantization is:

For direct quantization:

$$\tilde{\mathbf{P}}' = \mathbf{s}_{\mathbf{P}} \times \hat{\mathbf{P}}, \quad \{\tilde{\mathbf{P}}'\}_n = 35 \times 8 = 280$$

For two-level quantization:

$$\tilde{\mathbf{P}}'_2 = \mathbf{s}_{\mathbf{P}_2} \times \hat{\mathbf{P}}_2, \quad \{\tilde{\mathbf{P}}'_2\}_n = 127 \times 8 = 1016$$

Let  $\Delta(p_i)$  denote the interval between the two nearest quantization levels surrounding the value  $p_i \in \tilde{\mathbf{P}}$ . Then the absolute quantization error satisfies:

$$|\hat{p}_i - p_i| \leq \frac{\Delta(p_i)}{2}$$

The relative error  $\varepsilon$  satisfies:

$$\varepsilon_i \leq \frac{\Delta(p_i)}{2 \times p_i}$$

Given that  $\{\tilde{\mathbf{P}}'_2\}_n > \{\tilde{\mathbf{P}}'\}_n$ , the quantization intervals in the two-level scheme are finer:

$$\frac{\Delta(\tilde{\mathbf{P}}_2)}{\tilde{\mathbf{P}}_2} < \frac{\Delta(\tilde{\mathbf{P}})}{\tilde{\mathbf{P}}}$$

Thus, the relative quantization error satisfies:

$$\frac{|\tilde{\mathbf{P}}'_2 - \tilde{\mathbf{P}}_2|}{\tilde{\mathbf{P}}_2} < \frac{|\mathbf{P}' - \tilde{\mathbf{P}}|}{\tilde{\mathbf{P}}}$$

Which leads to the conclusion:

$$E_2 < E_1$$

□

### A.11 Analysis of the Benefit of Keeping $d\mathbf{O}_i \mathbf{V}_j^\top$ in FP16 in SageBwd.

The backward pass of SageBwd involves 5 MatMuls. The accuracy of  $\mathbf{S}_{ij} = \mathbf{Q}_i \mathbf{K}_j^\top$  is fully addressed in SageAttention2. The remaining four are as follows:

- (1)  $d\mathbf{P}_{ij} = d\mathbf{O}_i \mathbf{V}_j^\top$ .
- (2)  $d\mathbf{Q}_i \leftarrow d\mathbf{Q}_i + d\mathbf{S}_{ij} \mathbf{K}_j$
- (3)  $d\mathbf{K}_j \leftarrow d\mathbf{K}_j + d\mathbf{S}_{ij}^\top \mathbf{Q}_i$
- (4)  $d\mathbf{V}_j \leftarrow d\mathbf{V}_j + \mathbf{P}_{ij}^\top d\mathbf{O}_i$

We choose to keep (1) in FP16, while quantizing others to INT8. This choice can be formally justified:

*Proof.* Following [64], we assume that any matrix  $\mathbf{X} \in \mathbb{R}^{n \times d}$  (e.g.  $\mathbf{Q}, \mathbf{K}, \mathbf{V}, d\mathbf{O}$ ) satisfies:

- The entries in  $\mathbf{X}$  are mutually independent.
- $\mathbf{X}_{ij} \sim N(\mu_{\mathbf{X},j}, \sigma_{\mathbf{X},j}^2)$ , i.e. the distribution of each token is identical.

The quantization error of a matrix  $\mathbf{X}$  is denoted as:

$$\Delta \mathbf{X} := s_{\mathbf{X}} \hat{\mathbf{X}} - \mathbf{X}, \quad \text{where } s_{\mathbf{X}}, \hat{\mathbf{X}} = \psi(\mathbf{X}).$$

For example, consider the error in  $d\mathbf{Q}$ . Neglecting second-order error terms, we have:

$$\Delta d\mathbf{Q} = \underbrace{(\mathbf{P} \circ (d\mathbf{O} \Delta \mathbf{V}^\top + \Delta d\mathbf{O} \mathbf{V}^\top)) \mathbf{K}}_{\Delta d\mathbf{Q}^{(1)} \text{ from (1)}} + \underbrace{\Delta d\mathbf{S} \mathbf{K} + d\mathbf{S} \Delta \mathbf{K}}_{d\mathbf{Q}^{(2)} \text{ from (2)}}.$$

Here,  $d\mathbf{S} = \mathbf{P} \circ (d\mathbf{P} - D) = \mathbf{P} \circ (d\mathbf{O} \mathbf{V}^\top - D)$ , where  $D = d\mathbf{O} \odot \mathbf{O}$ . In element-wise terms (the subscript denotes a single element):

$$d\mathbf{S}_{ij} = \mathbf{P}_{ij} \sum_k d\mathbf{O}_{ik} (\mathbf{V}_{jk} - \mathbf{O}_{ik}) = \mathbf{P}_{ij} \sum_k d\mathbf{O}_{ik} \left( \mathbf{V}_{jk} - \sum_\ell \mathbf{P}_{i\ell} \mathbf{V}_{\ell k} \right)$$

Since  $\mathbf{V}$  is independent of other variables, by linearity of expectation:

$$\mathbb{E}[d\mathbf{S}_{ij}] = \mathbb{E} \left[ \mathbf{P}_{ij} \sum_k d\mathbf{O}_{ik} \left( \mu_{\mathbf{V},k} - \sum_\ell \mathbf{P}_{i\ell} \mu_{\mathbf{V},k} \right) \right] = 0.$$

Moreover, as negating  $\mathbf{V}$  flips the sign of  $d\mathbf{S}_{ij}$ , the PDF of  $d\mathbf{S}_{ij}$  is symmetric. Using a "round-to-nearest" quantization policy, we have  $\mathbb{E}[\Delta d\mathbf{S}] = 0$ . Thus

$$\mathbb{E} [d\mathbf{Q}^{(2)}] = \mathbb{E}[\Delta d\mathbf{S} \mathbf{K} + d\mathbf{S} \Delta \mathbf{K}] = 0,$$

while  $\mathbb{E} [\Delta d\mathbf{Q}^{(1)}]$  is generally non-zero (e.g. when distributions have non-zero means), indicating that  $d\mathbf{Q}$ 's error is dominated by  $\Delta d\mathbf{Q}^{(1)}$ . □

### A.12 Broader Impact

This paper presents work that aims to advance the field of efficient machine learning systems. It can be used to accelerate the inference and training processes of various models. None of the negative impacts we feel must be specifically highlighted here.

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