BERT Base Uncased Inference Workload Characterization and Microarchitectural Exploration on Intel Skylake Processor

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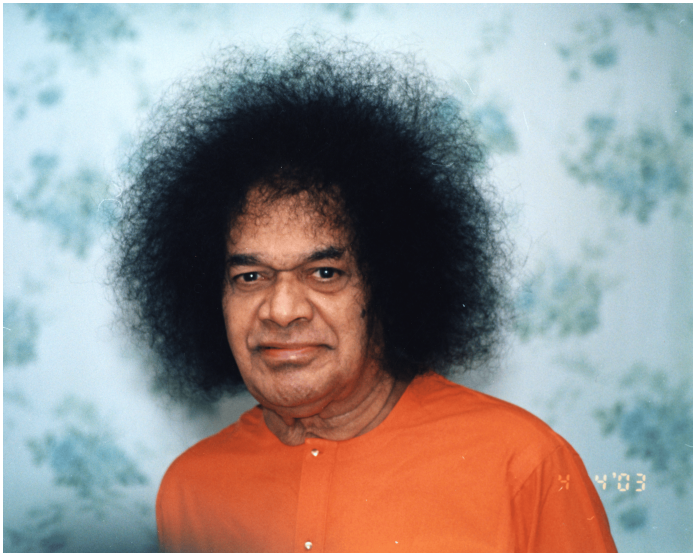

Offering at the Lotus Feet of Bhagawan Sri Sathya Sai Baba

1. Background and Motivation
2. Literature Survey
3. Methodology and Profilers
4. Preliminary Setup
5. Observations and Results
6. Conclusions and Future Works

1 Background and Motivation

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Background and Motivation

- Deep learning models are widely used in domains such as text, image, and speech processing.
- These models are often computationally intensive, which limits their deployment on resource-constrained devices.
- Therefore, it's essential to understand both the software and the underlying hardware.
- This understanding helps identify bottlenecks, enabling optimization and efficient deployment for better performance.

Problem Statement

- **Problem Statement 1**: Microarchitectural Characterization of BERT Base Uncased Model Inference and Exploring Microarchitectural Improvements.
- **Problem Statement 2**: Identify bottlenecks at the Microarchitectural level and suggest improvement opportunities.

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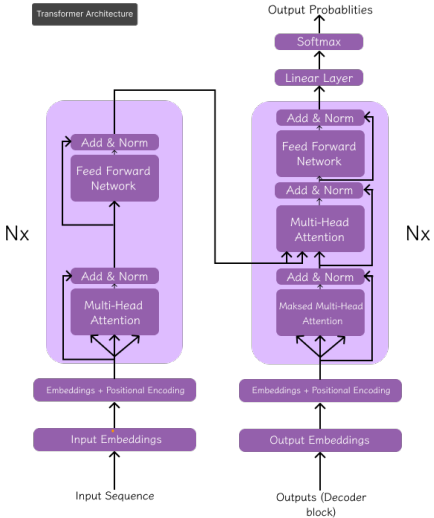
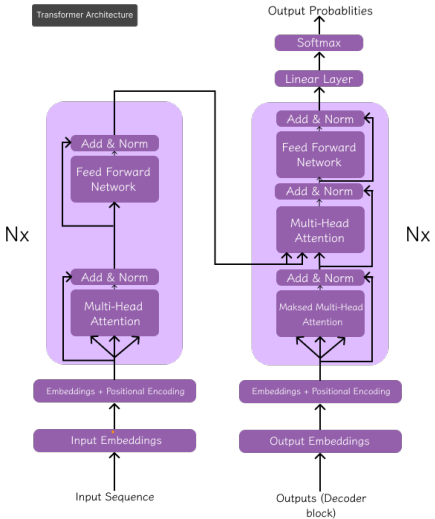
Transformer - Attention is All You Need

- Introduced in 2017.
- Neural network architecture based on a multi-head attention mechanism.
- Used for various NLP tasks.
- Used for image classification - Vision transformer.



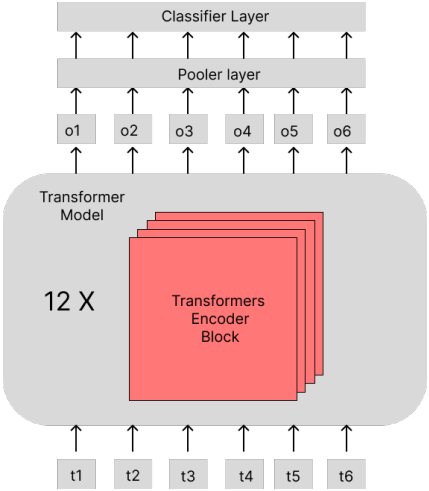
What distinguishes Transformer architecture from other LLM Architectures?

- **Self-Attention Mechanism**
  - Enables parallel processing, unlike RNNs and LSTMs, which are sequential.
  - Leads to faster training and inference.
- **RNNs and LSTMs**
  - RNNs suffer from vanishing gradients, making training slow and unstable.
  - LSTMs introduced memory cells and gating mechanisms to reduce this issue.
  - However, they still process inputs sequentially, limiting speed.
- **Transformers**
  - Use residual connections: input is added to the output of sublayers. Helps in better gradient flow and model convergence.



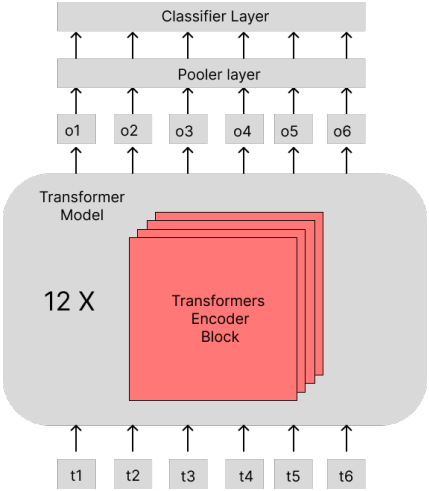
BERT Base Uncased

- BERT - Bidirectional Encoder Representations from Transformers.
- Introduced by Google in 2018.
- Uses the transformer neural network architecture.
- It is an encoder-based model.
- Captures full context for better language understanding (Bidirectional).
- **Different types**:
  - BERT Base (Cased and Uncased).
  - BERT Large (Cased and Uncased).
  - Others: Robustly Optimized BERT, SpanBERT, etc.



Why BERT Base Uncased Model?

- Faster in training and inference.
- Less computationally expensive.
- For many NLP tasks, it is a starting point.
- Since it is an uncased version, it helps with tasks that are case-insensitive.
- Transfer learning.



Micro-architecture of a Processor

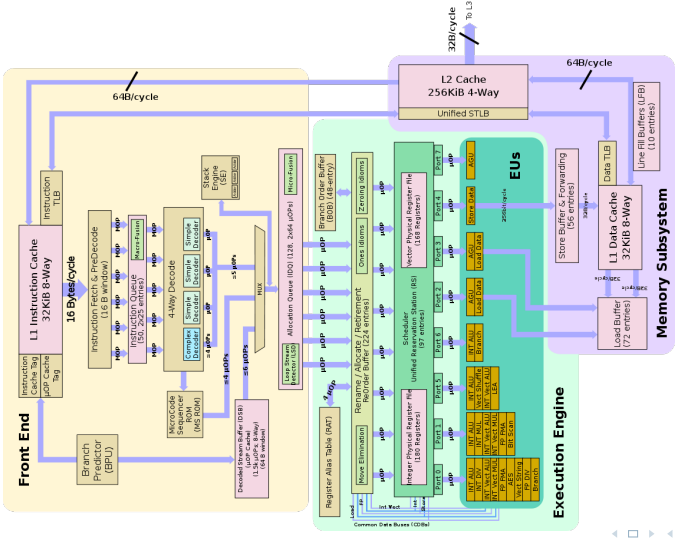
- **Computer Architecture** refers to the design of a processor including Instruction Set Architecture (ISA), supported data types, memory addressing, and I/O mechanisms.
- **Microarchitecture**, also known as Computer Organization, deals with the internal implementation of the architecture.
- It defines how the processor executes instructions including pipelining, execution units, cache hierarchy, branch prediction, and speculative execution.
- While architecture is about **what** a computer can do, microarchitecture is about **how** it does it.

Pipeline of Intel Core CPU

Simple Five-Stage Pipeline

Instructions	Clock Cycles								
	1	2	3	4	5	6	7	8	9
Instruction X	IF	ID	EXE	MEM	WB				
Instruction X+1		IF	ID	EXE	MEM	WB			
Instruction X+2			IF	ID	EXE	MEM	WB		
Instruction X +3				IF	ID	EXE	MEM	WB	
Instruction X+4					IF	ID	EXE	MEM	WB

Intel Skylake Micro-Architecture



Intel Skylake Micro-Architecture

- **4 per cycle:**
  - Front-End can allocate up to 4 uOps per cycle and Back-End can retire up to 4 uOps per cycle.
- **Pipline slots will be:**
  - Front-End
  - Back-End
  - Bad Speculation
  - Retirement

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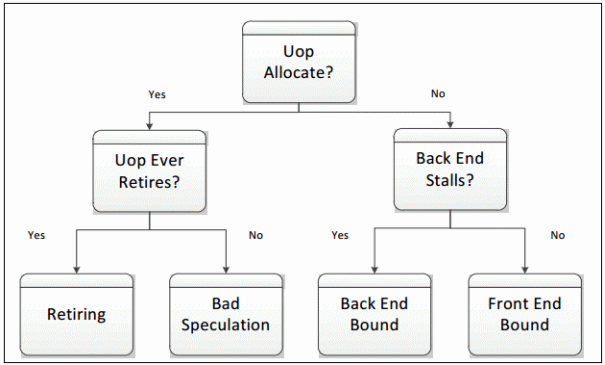
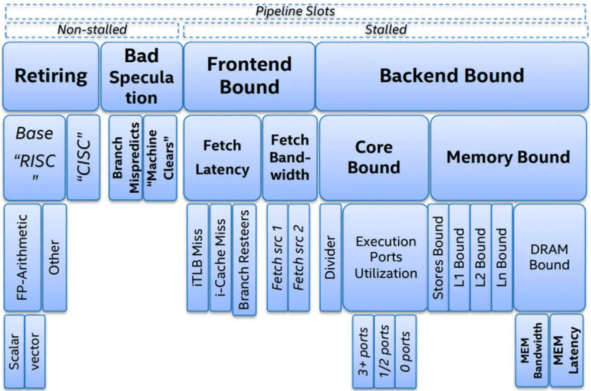
Top-Down Methodology

- **Top-Down Analysis**
  - It helps us to find the high-level causes of program execution.
  - Main categories are Front-End Bound, Back-End Bound, Retiring, or Bad Speculation.



Top-Down Methodology



Intel's VTune Profiler

- A performance profiling tool from Intel for analyzing code on Intel's CPU and GPU.
- CPU Metrics: Cpu utilization, Cache misses, Port utilization.
- Identify the Hotspots of our applications.

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System and Model Details

Parameter	**Value**
Processor	Intel(R) Core(TM) i5-8350U CPU @ 1.70GHz
Microarchitecture	Skylake
OS	Pop!_OS 22.04
Profiler	Intel VTune Profiler 2024.0.0
Framework	PyTorch
Model	BERT Base Uncased
Parameters	110M
Optimizer	AdamW
Number of Tokens (Input)	512
Hidden States	768

Table: System and Model Details

Hyperthreading Disabled

- Threads compete for the same physical core resources.
- Leads to contention and delays.
- Hence, some operations will be bottlenecked.
- `do_spin`: busy-waiting threads.
- Threads constantly check for control.
- Hotspot Analysis: consumes a lot of time.

Function	Module	CPU Time	% of CPU Time
[MKL BLAS]@avx2_sgemm_kernel_0	libmkl_avx2.so.2	35.953s	59.4%
do_spin	libgomp.so.1.0.0	4.173s	6.9%
[MKL BLAS]@avx2_sgemm_scopy_right4_ea	libmkl_avx2.so.2	1.942s	3.2%
[MKL BLAS]@avx2_sgemm_kernel_0_b0	libmkl_avx2.so.2	1.888s	3.1%
at::vec::AVX2::Vectorized<float>::exp_u20	libtorch_cpu.so	1.501s	2.5%
[Others]	N/A*	15.088s	24.9%

*N/A is applied to non-summable metrics

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Microarchitecture Exploration

Top-Down Performance analysis of BERT Base Uncased Model - 1

Elapsed Time: 40.767s

Clockticks:	135,019,100,000	
Instructions Retired:	382,173,600,000	
CPI Rate:	0.353	
Retiring:	69.0%	of Pipeline Slots
Front-End Bound:	6.1%	of Pipeline Slots
Bad Speculation:	1.5%	of Pipeline Slots
Back-End Bound:	23.5%	of Pipeline Slots

Microarchitecture Exploration

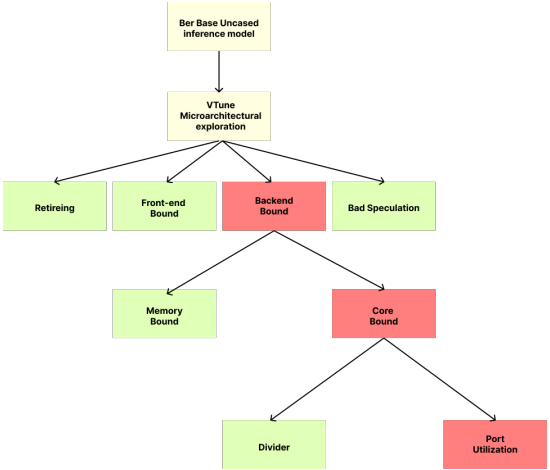
Top-Down Performance analysis of BERT Base Uncased Model - 2

Elapsed Time: 40.767s

Clockticks:	135,019,100,000	
Instructions Retired:	382,173,600,000	
CPI Rate:	0.353	
Retiring:	69.0%	of Pipeline Slots
Front-End Bound:	6.1%	of Pipeline Slots
Bad Speculation:	1.5%	of Pipeline Slots
Back-End Bound:	23.5%	of Pipeline Slots
Memory Bound:	7.8%	of Pipeline Slots
Core Bound:	15.7%	of Pipeline Slots
Divider:	0.4%	of Clockticks
Port Utilization:	15.6%	of Clockticks
Cycles of 0 Ports Utilized:	4.3%	of Clockticks
Cycles of 1 Port Utilized:	5.4%	of Clockticks
Cycles of 2 Ports Utilized:	13.1%	of Clockticks
Cycles of 3+ Ports Utilized:	68.3%	of Clockticks
Vector Capacity Usage (FPU):	100.0%	
Average CPU Frequency:	3.4 GHz	
Total Thread Count:	8	
Paused Time:	0s	

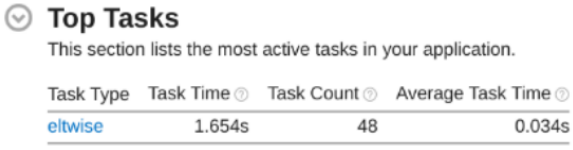
Microarchitecture Exploration

Top-Down Performance analysis Summary



Hotspot Analysis

- Top Task - eltwise.
- Helps in doing element-wise operations.
- for our model in Gelu activation function, Layer normalization.



Top Tasks

This section lists the most active tasks in your application.

Task Type	Task Time	Task Count	Average Task Time
eltwise	1.654s	48	0.034s

Hotspot Analysis

- Hotspot function - General matrix multiplication, Takes about **60%** of the CPU time while running the BERT Base Uncased.
- Which does:

$$C := \alpha \cdot \mathrm{op}(A) \cdot \mathrm{op}(B) + \beta \cdot C \qquad (1)$$

Function	Module	CPU Time	% of CPU Time
[MKL BLAS]@avx2_sgemm_kernel_0	libmkl_avx2.so.2	26.002s	65.8%
[MKL BLAS]@avx2_sgemm_kernel_0_b0	libmkl_avx2.so.2	1.438s	3.6%
at::vec::AVX2::Vectorized<float>::exp_u20	libtorch_cpu.so	1.109s	2.8%
[MKL BLAS]@avx2_sgemm_scopy_right4_ea	libmkl_avx2.so.2	0.906s	2.3%
[MKL BLAS]@avx2_sgemm_kernel_nocopy_NN_b1	libmkl_avx2.so.2	0.838s	2.1%
[Others]	N/A*	9.252s	23.4%

Port Utilization and Its Relation with the Hot Loop

Ports on Skylake Processor

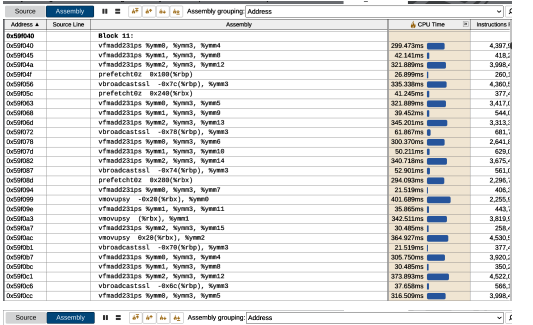
Skylake Execution Units and Ports							
Port 0	Port 1	Port 2	Port 3	Port 4	Port 5	Port 6	Port 7
INT ALU	INT ALU	AGU	AGU	STORE Data	INT ALU	INT ALU	AGU
INT DIV	INT MUL	LOAD Data	LOAD Data		VECT Shuffle	Branch	
INT Vect ALU	INT Vect ALU				INT Vect ALU		
INT Vect MUL	INT Vect MUL				LEA		
FP FMA	FP FMA						
AES	Bit Scan						
VECT String							
FP DIV							
Branch							

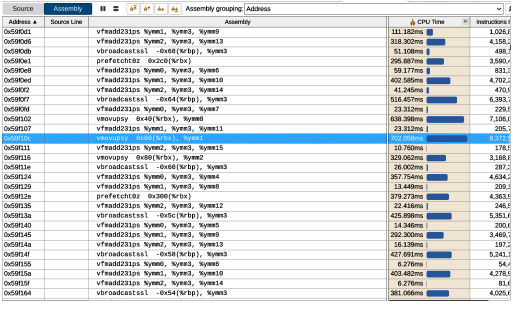
Port Utilization and Its Relation with the Hot Loop

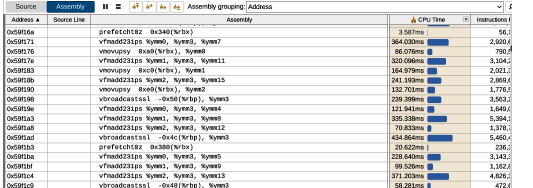
Cycles of 2-Ports

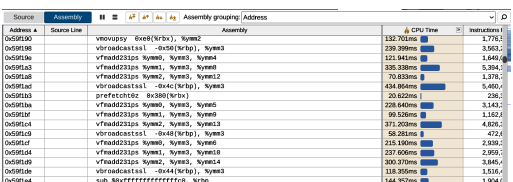
- Represents the percentage of the total number of cycles where only 2 ports were utilized.
- running only 2 uOps per cycle on all execution port.
- But we issue 4 uOps per cycle.
- **Possible reasons for 2-ports utilization:**
  - Raw Data Dependencies.
  - Insufficient number of execution ports.
  - Vector Pipe Usage (100%) means that the floating point instructions are vectorized properly.

Hotloop Pattern of Hotspot Function









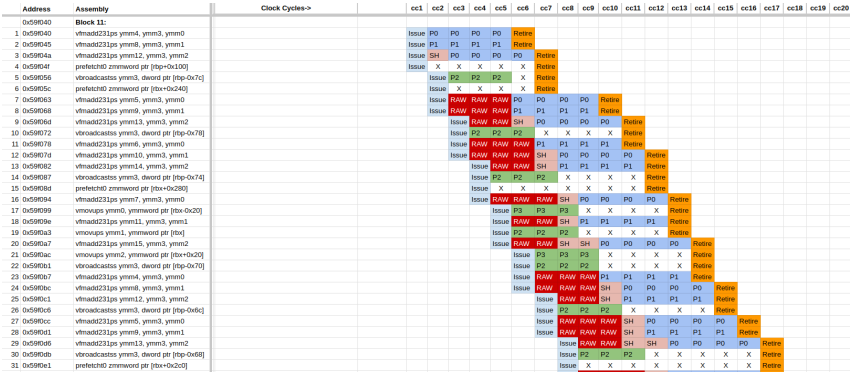
Pipeline View for Hot Loop

Instruction Details

Instructions	Operands	Execution Units	Port Number	Latency
VFMADD231PS	ymm1,ymm2, ymm3	FP FMA	P0, P1	4
PREFETCHT0	-	-	-	-
VBROADCASTSS	ymm,m32	LOAD	P2, P3	3
VMOVUPS	y, m256	LOAD	P2, P3	3

Pipeline View for Hot Loop

Pipeline view 1



	Address	Assembly	Clock Cycles->	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc9	cc10	cc11	cc12	cc13	cc14	cc15	cc16	cc17	cc18	cc19	cc20
	0x59f040	**Block 11:**																					
1	0x59f040	vfmadd231ps ymm4, ymm3, ymm0		Issue	P0	P0	P0	P0	Retire														
2	0x59f045	vfmadd231ps ymm8, ymm3, ymm1		Issue	P1	P1	P1	P1	Retire														
3	0x59f04a	vfmadd231ps ymm12, ymm3, ymm2		Issue	SH	P0	P0	P0	P0	Retire													
4	0x59f04f	prefetcht0 zmmword ptr [rbp+0x100]		Issue	X	X	X	X	X	Retire													
5	0x59f056	vbroadcastss ymm3, dword ptr [rbp-0x7c]			Issue	P2	P2	P2	X	Retire													
6	0x59f05c	prefetcht0 zmmword ptr [rbx+0x240]			Issue	X	X	X	X	Retire													
7	0x59f063	vfmadd231ps ymm5, ymm3, ymm0			Issue	RAW	RAW	RAW	P0	P0	P0	P0	P0	Retire									
8	0x59f068	vfmadd231ps ymm9, ymm3, ymm1			Issue	RAW	RAW	RAW	P1	P1	P1	P1	P1	Retire									
9	0x59f06d	vfmadd231ps ymm13, ymm3, ymm2				Issue	RAW	RAW	SH	P0	P0	P0	P0	P0	Retire								
10	0x59f072	vbroadcastss ymm3, dword ptr [rbp-0x78]				Issue	P2	P2	P2	X	X	X	X	X	Retire								
11	0x59f078	vfmadd231ps ymm6, ymm3, ymm0				Issue	RAW	RAW	RAW	P1	P1	P1	P1	P1	Retire								
12	0x59f07d	vfmadd231ps ymm10, ymm3, ymm1				Issue	RAW	RAW	RAW	SH	P0	P0	P0	P0	P0	Retire							
13	0x59f082	vfmadd231ps ymm14, ymm3, ymm2					Issue	RAW	RAW	SH	P1	P1	P1	P1	P1	Retire							
14	0x59f087	vbroadcastss ymm3, dword ptr [rbp-0x74]					Issue	P2	P2	P2	X	X	X	X	X	Retire							
15	0x59f08d	prefetcht0 zmmword ptr [rbx+0x280]					Issue	X	X	X	X	X	X	X	X	Retire							
16	0x59f094	vfmadd231ps ymm7, ymm3, ymm0					Issue	RAW	RAW	RAW	SH	P0	P0	P0	P0	Retire							
17	0x59f099	vmovups ymm0, ymmword ptr [rbx-0x20]						Issue	P3	P3	P3	X	X	X	X	Retire							
18	0x59f09e	vfmadd231ps ymm11, ymm3, ymm1						Issue	RAW	RAW	SH	P1	P1	P1	P1	Retire							
19	0x59f0a3	vmovups ymm1, ymmword ptr [rbx]						Issue	P2	P2	P2	X	X	X	X	Retire							
20	0x59f0a7	vfmadd231ps ymm15, ymm3, ymm2						Issue	RAW	RAW	SH	SH	P0	P0	P0	P0	Retire						
21	0x59f0ac	vmovups ymm2, ymmword ptr [rbx+0x20]							Issue	P3	P3	P3	X	X	X	X	Retire						
22	0x59f0b1	vbroadcastss ymm3, dword ptr [rbp-0x70]							Issue	P2	P2	P2	X	X	X	X	Retire						
23	0x59f0b7	vfmadd231ps ymm4, ymm3, ymm0							Issue	RAW	RAW	RAW	P1	P1	P1	P1	Retire						
24	0x59f0bc	vfmadd231ps ymm8, ymm3, ymm1							Issue	RAW	RAW	RAW	SH	P0	P0	P0	P0	Retire					
25	0x59f0c1	vfmadd231ps ymm12, ymm3, ymm2								Issue	RAW	RAW	SH	P1	P1	P1	P1	Retire					
26	0x59f0c6	vbroadcastss ymm3, dword ptr [rbp-0x6c]								Issue	P2	P2	P2	X	X	X	X	Retire					
27	0x59f0cc	vfmadd231ps ymm5, ymm3, ymm0								Issue	RAW	RAW	RAW	SH	P0	P0	P0	P0	Retire				
28	0x59f0d1	vfmadd231ps ymm9, ymm3, ymm1								Issue	RAW	RAW	RAW	SH	P1	P1	P1	P1	Retire				
29	0x59f0d6	vfmadd231ps ymm13, ymm3, ymm2									Issue	RAW	RAW	SH	SH	P0	P0	P0	P0	Retire			
30	0x59f0db	vbroadcastss ymm3, dword ptr [rbp-0x68]									Issue	P2	P2	P2	X	X	X	X	X	Retire			
31	0x59f0e1	prefetcht0 zmmword ptr [rbx+0x2c0]									Issue	X	X	X	X	X	X	X	X	Retire			

Pipeline View for Hot Loop

Pipeline view 2

	Address	Assembly	7	cc8	cc9	cc10	cc11	cc12	cc13	cc14	cc15	cc16	cc17	cc18	cc19	cc20	cc21	cc22	cc23	cc24	cc25	cc26
32	0x59f0e8	vfmadd231ps ymm6, ymm3, ymm0		Issue	RAW	RAW	RAW	SH	P1	P1	P1	P1	Retire									
33	0x59f0ed	vfmadd231ps ymm10, ymm3, ymm1			Issue	RAW	RAW	SH	SH	P0	P0	P0	P0	Retire								
34	0x59f0f2	vfmadd231ps ymm14, ymm3, ymm2			Issue	RAW	RAW	SH	SH	P1	P1	P1	P1	Retire								
35	0x59f0f7	vbroadcastss ymm3, dword ptr [rbp-0x64]			Issue	P2	P2	P2	X	X	X	X	X	Retire								
36	0x59f0fd	vfmadd231ps ymm7, ymm3, ymm0			Issue	RAW	RAW	RAW	SH	SH	P0	P0	P0	P0	Retire							
37	0x59f102	vmovups ymm0, ymmword ptr [rbx+0x40]				Issue	P2	P2	P2	X	X	X	X	X	Retire							
38	0x59f107	vfmadd231ps ymm11, ymm3, ymm1				Issue	RAW	RAW	SH	SH	P1	P1	P1	P1	Retire							
39	0x59f10c	vmovups ymm1, ymmword ptr [rbx+0x60]				Issue	P3	P3	P3	X	X	X	X	X	Retire							
40	0x59f111	vfmadd231ps ymm15, ymm3, ymm2				Issue	RAW	RAW	SH	SH	SH	P0	P0	P0	P0	Retire						
41	0x59f116	vmovups ymm2, ymmword ptr [rbx+0x80]					Issue	P2	P2	P2	X	X	X	X	X	Retire						
42	0x59f11e	vbroadcastss ymm3, dword ptr [rbp-0x60]					Issue	P3	P3	P3	X	X	X	X	X	Retire						
43	0x59f124	vfmadd231ps ymm4, ymm3, ymm0					Issue	RAW	RAW	RAW	SH	P1	P1	P1	P1	Retire						
44	0x59f129	vfmadd231ps ymm8, ymm3, ymm1					Issue	RAW	RAW	RAW	SH	SH	P0	P0	P0	P0	Retire					
45	0x59f12e	prefetcht0 zmmword ptr [rbx+0x300]						Issue	X	X	X	X	X	X	X	X	Retire					
46	0x59f135	vfmadd231ps ymm12, ymm3, ymm2						Issue	RAW	RAW	SH	SH	P1	P1	P1	P1	Retire					
47	0x59f13a	vbroadcastss ymm3, dword ptr [rbp-0x5c]						Issue	P2	P2	P2	X	X	X	X	X	Retire					
48	0x59f140	vfmadd231ps ymm5, ymm3, ymm0						Issue	RAW	RAW	RAW	SH	SH	P0	P0	P0	P0	Retire				
49	0x59f145	vfmadd231ps ymm9, ymm3, ymm1							Issue	RAW	RAW	SH	SH	P1	P1	P1	P1	Retire				
50	0x59f14a	vfmadd231ps ymm13, ymm3, ymm2							Issue	RAW	RAW	SH	SH	SH	P0	P0	P0	P0	Retire			
51	0x59f14f	vbroadcastss ymm3, dword ptr [rbp-0x58]							Issue	P2	P2	P2	X	X	X	X	X	X	Retire			
52	0x59f155	vfmadd231ps ymm6, ymm3, ymm0							Issue	RAW	RAW	RAW	SH	SH	P1	P1	P1	P1	Retire			
53	0x59f15a	vfmadd231ps ymm10, ymm3, ymm1								Issue	RAW	RAW	SH	SH	SH	P0	P0	P0	P0	Retire		
54	0x59f15f	vfmadd231ps ymm14, ymm3, ymm2								Issue	RAW	RAW	SH	SH	SH	P1	P1	P1	P1	Retire		
55	0x59f164	vbroadcastss ymm3, dword ptr [rbp-0x54]								Issue	P2	P2	P2	X	X	X	X	X	X	Retire		
56	0x59f16a	prefetcht0 zmmword ptr [rbx+0x340]								Issue	X	X	X	X	X	X	X	X	X	Retire		
57	0x59f171	vfmadd231ps ymm7, ymm3, ymm0									Issue	RAW	RAW	SH	SH	SH	P0	P0	P0	P0	Retire	
58	0x59f176	vmovups ymm0, ymmword ptr [rbx+0xa0]									Issue	P2	P2	P2	X	X	X	X	X	X	Retire	
59	0x59f17e	vfmadd231ps ymm11, ymm3, ymm1									Issue	RAW	RAW	SH	SH	SH	P1	P1	P1	P1	Retire	
60	0x59f183	vmovups ymm1, ymmword ptr [rbx+0xc0]									Issue	P3	P3	P3	X	X	X	X	X	X	Retire	
61	0x59f18b	vfmadd231ps ymm15, ymm3, ymm2										Issue	RAW	SH	SH	SH	P0	P0	P0	P0	Retire	
62	0x59f190	vmovups ymm2, ymmword ptr [rbx+0xe0]										Issue	P2	P2	P2	X	X	X	X	X	X	Retire
63	0x59f198	vbroadcastss ymm3, dword ptr [rbp-0x50]										Issue	P3	P3	P3	X	X	X	X	X	X	Retire

Pipeline View for Hot Loop

Pipeline view 3

	Address	Assembly	cc13	cc14	cc15	cc16	cc17	cc18	cc19	cc20	cc21	cc22	cc23	cc24	cc25	cc26	cc27	cc28	cc29	cc30	cc31	cc32	cc33
64	0x59f19e	vfmadd231ps ymm4, ymm3, ymm0				Issue	RAW	RAW	RAW	SH	SH	P1	P1	P1	P1	Retire							
65	0x59f1a3	vfmadd231ps ymm8, ymm3, ymm1					Issue	RAW	RAW	SH	SH	SH	P0	P0	P0	P0	Retire						
66	0x59f1a8	vfmadd231ps ymm12, ymm3, ymm2					Issue	RAW	RAW	SH	SH	SH	P1	P1	P1	P1	Retire						
67	0x59f1ad	vbroadcastss ymm3, dword ptr [rbp-0x4c]					Issue	P2	P2	P2	X	X	X	X	X	X	Retire						
68	0x59f1b3	prefetcht0 zmmword ptr [rbx+0x380]					Issue	X	X	X	X	X	X	X	X	X	Retire						
69	0x59f1ba	vfmadd231ps ymm5, ymm3, ymm0						Issue	RAW	RAW	SH	SH	SH	P0	P0	P0	P0	Retire					
70	0x59f1bf	vfmadd231ps ymm9, ymm3, ymm1						Issue	RAW	RAW	SH	SH	SH	P1	P1	P1	P1	Retire					
71	0x59f1c4	vfmadd231ps ymm13, ymm3, ymm2						Issue	RAW	RAW	SH	SH	SH	SH	P0	P0	P0	P0	Retire				
72	0x59f1c9	vbroadcastss ymm3, dword ptr [rbp-0x48]						Issue	P2	P2	P2	X	X	X	X	X	X	X	Retire				
73	0x59f1cf	vfmadd231ps ymm6, ymm3, ymm0							Issue	RAW	RAW	SH	SH	SH	P1	P1	P1	P1	Retire				
74	0x59f1d4	vfmadd231ps ymm10, ymm3, ymm1							Issue	RAW	RAW	SH	SH	SH	SH	P0	P0	P0	P0	Retire			
75	0x59f1d9	vfmadd231ps ymm14, ymm3, ymm2							Issue	RAW	RAW	SH	SH	SH	SH	P1	P1	P1	P1	Retire			
76	0x59f1de	vbroadcastss ymm3, dword ptr [rbp-0x44]							Issue	P2	P2	P2	X	X	X	X	X	X	X	Retire			
77	0x59f1e4	sub rbp, 0xffffffffffffffc0								Issue	P5	X	X	X	X	X	X	X	X	Retire			
78	0x59f1e8	vfmadd231ps ymm7, ymm3, ymm0								Issue	RAW	RAW	SH	SH	SH	SH	P0	P0	P0	P0	Retire		
79	0x59f1ed	vmovups ymm0, ymmword ptr [rbx+0x100]								Issue	P2	P2	P2	X	X	X	X	X	X	X	Retire		
80	0x59f1f5	vfmadd231ps ymm11, ymm3, ymm1								Issue	RAW	RAW	SH	SH	SH	SH	P1	P1	P1	P1	Retire		
81	0x59f1fa	vmovups ymm1, ymmword ptr [rbx+0x120]									Issue	P2	P2	P2	X	X	X	X	X	X	Retire		
82	0x59f202	vfmadd231ps ymm15, ymm3, ymm2									Issue	RAW	SH	SH	SH	SH	P0	P0	P0	P0	Retire		
83	0x59f207	vmovups ymm2, ymmword ptr [rbx+0x140]									Issue	P3	P3	P3	X	X	X	X	X	X	Retire		
84	0x59f20f	sub rbx, 0xffffffffffffff80									Issue	P5	X	X	X	X	X	X	X	X	Retire		
85	0x59f216	vbroadcastss ymm3, dword ptr [rbp-0x80]										Issue	P2	P2	P2	X	X	X	X	X	Retire		
86	0x59f21c	sub rax, 0x1										Issue	P5	X	X	X	X	X	X	X	X	X	Retire
87	0x59f220	hint-taken jnle 0x59f040 <Block 11>										Issue	P6	X	X	X	X	X	X	X	X	X	Retire

Summary of Pipeline View for Hot Loop

Too Many Structural Hazards

Total number of RAW Stalls	104
Total number of Strucutral hazard(SH) stalls	98
Total Number of Stall X	231
Ratio of Raw stall	0.2401847575
% of RAW stalls	24.01847575
Ratio of SH stalls	0.2263279446
% of SH stalls	22.63279446
IPC(No of Instruction / No of Clock cycle)	2.636363636

Proposed Soultion

Pipeline View 1 - adding FP FMA at Port. No 8

	Address	Assembly	Clock Cycles->	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc9	cc10	cc11	cc12	cc13	cc14	cc15	cc16
	0x59f040	**Block 11:**																	
1	0x59f040	vfmadd231ps ymm4, ymm3, ymm0		Issue	P0	P0	P0	P0	Retire										
2	0x59f045	vfmadd231ps ymm8, ymm3, ymm1		Issue	P1	P1	P1	P1	Retire										
3	0x59f04a	vfmadd231ps ymm12, ymm3, ymm2		Issue	P8	P8	P8	P8	Retire										
4	0x59f04f	prefetcht0 zmmword ptr [rbp+0x100]		Issue	X	X	X	X	Retire										
5	0x59f056	vbroadcastss ymm3, dword ptr [rbp-0x7c]			Issue	P2	P2	P2	X	Retire									
6	0x59f05c	prefetcht0 zmmword ptr [rbx+0x240]			Issue	X	X	X	X	Retire									
7	0x59f063	vfmadd231ps ymm5, ymm3, ymm0			Issue	RAW	RAW	RAW	P0	P0	P0	P0	Retire						
8	0x59f068	vfmadd231ps ymm9, ymm3, ymm1			Issue	RAW	RAW	RAW	P1	P1	P1	P1	Retire						
9	0x59f06d	vfmadd231ps ymm13, ymm3, ymm2				Issue	RAW	RAW	P8	P8	P8	P8	Retire						
10	0x59f072	vbroadcastss ymm3, dword ptr [rbp-0x78]				Issue	P2	P2	P2	X	X	X	Retire						
11	0x59f078	vfmadd231ps ymm6, ymm3, ymm0				Issue	RAW	RAW	RAW	P0	P0	P0	P0	Retire					
12	0x59f07d	vfmadd231ps ymm10, ymm3, ymm1				Issue	RAW	RAW	RAW	P1	P1	P1	P1	Retire					
13	0x59f082	vfmadd231ps ymm14, ymm3, ymm2					Issue	RAW	RAW	P8	P8	P8	P8	Retire					
14	0x59f087	vbroadcastss ymm3, dword ptr [rbp-0x74]					Issue	P2	P2	P2	X	X	X	Retire					
15	0x59f08d	prefetcht0 zmmword ptr [rbx+0x280]					Issue	X	X	X	X	X	X	X	Retire				
16	0x59f094	vfmadd231ps ymm7, ymm3, ymm0					Issue	RAW	RAW	RAW	P0	P0	P0	P0	Retire				
17	0x59f099	vmovups ymm0, ymmword ptr [rbx-0x20]						Issue	P3	P3	P3	X	X	X	Retire				
18	0x59f09e	vfmadd231ps ymm11, ymm3, ymm1						Issue	RAW	RAW	P1	P1	P1	P1	Retire				
19	0x59f0a3	vmovups ymm1, ymmword ptr [rbx]						Issue	P2	P2	P2	X	X	X	X	Retire			
20	0x59f0a7	vfmadd231ps ymm15, ymm3, ymm2						Issue	RAW	RAW	P8	P8	P8	P8	X	Retire			
21	0x59f0ac	vmovups ymm2, ymmword ptr [rbx+0x20]							Issue	P3	P3	P3	X	X	X	Retire			
22	0x59f0b1	vbroadcastss ymm3, dword ptr [rbp-0x70]							Issue	P2	P2	P2	X	X	X	Retire			
23	0x59f0b7	vfmadd231ps ymm4, ymm3, ymm0							Issue	RAW	RAW	RAW	P0	P0	P0	P0	Retire		
24	0x59f0bc	vfmadd231ps ymm8, ymm3, ymm1							Issue	RAW	RAW	RAW	P1	P1	P1	P1	Retire		
25	0x59f0c1	vfmadd231ps ymm12, ymm3, ymm2								Issue	RAW	RAW	P8	P8	P8	P8	Retire		
26	0x59f0c6	vbroadcastss ymm3, dword ptr [rbp-0x6c]								Issue	P2	P2	P2	X	X	X	Retire		
27	0x59f0cc	vfmadd231ps ymm5, ymm3, ymm0								Issue	RAW	RAW	RAW	P0	P0	P0	P0	Retire	
28	0x59f0d1	vfmadd231ps ymm9, ymm3, ymm1								Issue	RAW	RAW	RAW	P1	P1	P1	P1	Retire	
29	0x59f0d6	vfmadd231ps ymm13, ymm3, ymm2									Issue	RAW	RAW	P8	P8	P8	P8	Retire	
30	0x59f0db	vbroadcastss ymm3, dword ptr [rbp-0x68]									Issue	P2	P2	P2	X	X	X	Retire	
31	0x59f0e1	prefetcht0 zmmword ptr [rbx+0x2c0]									Issue	X	X	X	X	X	X	X	Retire

Proposed Soultion

Pipeline View 2 - adding FP FMA at Port. No 8

	Address	Assembly	cc8	cc9	cc10	cc11	cc12	cc13	cc14	cc15	cc16	cc17	cc18	cc19	cc20	cc21	cc22	cc23	cc24
32	0x59f0e8	vfmadd231ps ymm6, ymm3, ymm0	Issue	RAW	RAW	RAW	P0	P0	P0	P0	Retire								
33	0x59f0ed	vfmadd231ps ymm10, ymm3, ymm1		Issue	RAW	RAW	P1	P1	P1	P1	Retire								
34	0x59f0f2	vfmadd231ps ymm14, ymm3, ymm2		Issue	RAW	RAW	P8	P8	P8	P8	Retire								
35	0x59f0f7	vbroadcastss ymm3, dword ptr [rbp-0x64]		Issue	P2	P2	P2	X	X	X	X	Retire							
36	0x59f0fd	vfmadd231ps ymm7, ymm3, ymm0		Issue	RAW	RAW	RAW	P0	P0	P0	P0	Retire							
37	0x59f102	vmovups ymm0, ymmword ptr [rbx+0x40]			Issue	P2	P2	P2	X	X	X	Retire							
38	0x59f107	vfmadd231ps ymm11, ymm3, ymm1			Issue	RAW	RAW	P1	P1	P1	P1	Retire							
39	0x59f10c	vmovups ymm1, ymmword ptr [rbx+0x60]			Issue	P3	P3	P3	X	X	X	X	Retire						
40	0x59f111	vfmadd231ps ymm15, ymm3, ymm2			Issue	RAW	RAW	P8	P8	P8	P8	X	Retire						
41	0x59f116	vmovups ymm2, ymmword ptr [rbx+0x80]				Issue	P2	P2	P2	X	X	X	Retire						
42	0x59f11e	vbroadcastss ymm3, dword ptr [rbp-0x60]				Issue	P3	P3	P3	X	X	X	Retire						
43	0x59f124	vfmadd231ps ymm4, ymm3, ymm0				Issue	RAW	RAW	RAW	P0	P0	P0	P0	Retire					
44	0x59f129	vfmadd231ps ymm8, ymm3, ymm1				Issue	RAW	RAW	RAW	P1	P1	P1	P1	Retire					
45	0x59f12e	prefetcht0 zmmword ptr [rbx+0x300]					Issue	X	X	X	X	X	X	Retire					
46	0x59f135	vfmadd231ps ymm12, ymm3, ymm2					Issue	RAW	RAW	P8	P8	P8	P8	Retire					
47	0x59f13a	vbroadcastss ymm3, dword ptr [rbp-0x5c]					Issue	P2	P2	P2	X	X	X	X	Retire				
48	0x59f140	vfmadd231ps ymm5, ymm3, ymm0					Issue	RAW	RAW	RAW	P0	P0	P0	P0	Retire				
49	0x59f145	vfmadd231ps ymm9, ymm3, ymm1						Issue	RAW	RAW	P1	P1	P1	P1	Retire				
50	0x59f14a	vfmadd231ps ymm13, ymm3, ymm2						Issue	RAW	RAW	P8	P8	P8	P8	Retire				
51	0x59f14f	vbroadcastss ymm3, dword ptr [rbp-0x58]						Issue	P2	P2	P2	X	X	X	X	Retire			
52	0x59f155	vfmadd231ps ymm6, ymm3, ymm0						Issue	RAW	RAW	RAW	P0	P0	P0	P0	Retire			
53	0x59f15a	vfmadd231ps ymm10, ymm3, ymm1							Issue	RAW	RAW	P1	P1	P1	P1	Retire			
54	0x59f15f	vfmadd231ps ymm14, ymm3, ymm2							Issue	RAW	RAW	P8	P8	P8	P8	Retire			
55	0x59f164	vbroadcastss ymm3, dword ptr [rbp-0x54]							Issue	P2	P2	P2	X	X	X	X	Retire		
56	0x59f16a	prefetcht0 zmmword ptr [rbx+0x340]							Issue	X	X	X	X	X	X	X	Retire		
57	0x59f171	vfmadd231ps ymm7, ymm3, ymm0								Issue	RAW	RAW	P0	P0	P0	P0	Retire		
58	0x59f176	vmovups ymm0, ymmword ptr [rbx+0xa0]								Issue	P2	P2	P2	X	X	X	Retire		
59	0x59f17e	vfmadd231ps ymm11, ymm3, ymm1								Issue	RAW	RAW	P1	P1	P1	P1	X	Retire	
60	0x59f183	vmovups ymm1, ymmword ptr [rbx+0xc0]								Issue	P3	P3	P3	X	X	X	X	Retire	
61	0x59f18b	vfmadd231ps ymm15, ymm3, ymm2									Issue	RAW	P8	P8	P8	P8	X	Retire	
62	0x59f190	vmovups ymm2, ymmword ptr [rbx+0xe0]									Issue	P2	P2	P2	X	X	X	Retire	

Proposed Soultion

Pipeline View 3 - adding FP FMA at Port. No 8

	Address	Assembly	:15	cc16	cc17	cc18	cc19	cc20	cc21	cc22	cc23	cc24	cc25	cc26	cc27	cc28	cc29	cc30
64	0x59f19e	vfmadd231ps ymm4, ymm3, ymm0		Issue	RAW	RAW	RAW	P0	P0	P0	P0	Retire						
65	0x59f1a3	vfmadd231ps ymm8, ymm3, ymm1			Issue	RAW	RAW	P1	P1	P1	P1	Retire						
66	0x59f1a8	vfmadd231ps ymm12, ymm3, ymm2			Issue	RAW	RAW	P8	P8	P8	P8	Retire						
67	0x59f1ad	vbroadcastss ymm3, dword ptr [rbp-0x4c]			Issue	P2	P2	P2	X	X	X	X	Retire					
68	0x59f1b3	prefetcht0 zmmword ptr [rbx+0x380]			Issue	X	X	X	X	X	X	X	Retire					
69	0x59f1ba	vfmadd231ps ymm5, ymm3, ymm0				Issue	RAW	RAW	P0	P0	P0	P0	Retire					
70	0x59f1bf	vfmadd231ps ymm9, ymm3, ymm1				Issue	RAW	RAW	P1	P1	P1	P1	Retire					
71	0x59f1c4	vfmadd231ps ymm13, ymm3, ymm2				Issue	RAW	RAW	P8	P8	P8	P8	X	Retire				
72	0x59f1c9	vbroadcastss ymm3, dword ptr [rbp-0x48]				Issue	P2	P2	P2	X	X	X	X	Retire				
73	0x59f1cf	vfmadd231ps ymm6, ymm3, ymm0					Issue	RAW	RAW	P0	P0	P0	P0	Retire				
74	0x59f1d4	vfmadd231ps ymm10, ymm3, ymm1					Issue	RAW	RAW	P1	P1	P1	P1	Retire				
75	0x59f1d9	vfmadd231ps ymm14, ymm3, ymm2					Issue	RAW	RAW	P8	P8	P8	P8	X	Retire			
76	0x59f1de	vbroadcastss ymm3, dword ptr [rbp-0x44]					Issue	P2	P2	P2	X	X	X	X	Retire			
77	0x59f1e4	sub rbp, 0xffffffffffffffc0						Issue	P5	X	X	X	X	X	Retire			
78	0x59f1e8	vfmadd231ps ymm7, ymm3, ymm0						Issue	RAW	RAW	P0	P0	P0	P0	Retire			
79	0x59f1ed	vmovups ymm0, ymmword ptr [rbx+0x100]						Issue	P2	P2	P2	X	X	X	X	Retire		
80	0x59f1f5	vfmadd231ps ymm11, ymm3, ymm1						Issue	RAW	RAW	P1	P1	P1	P1	X	Retire		
81	0x59f1fa	vmovups ymm1, ymmword ptr [rbx+0x120]							Issue	P2	P2	P2	X	X	X	Retire		
82	0x59f202	vfmadd231ps ymm15, ymm3, ymm2							Issue	RAW	P8	P8	P8	P8	X	Retire		
83	0x59f207	vmovups ymm2, ymmword ptr [rbx+0x140]							Issue	P3	P3	P3	X	X	X	X	Retire	
84	0x59f20f	sub rbx, 0xffffffffffffff80							Issue	P5	X	X	X	X	X	X	Retire	
85	0x59f216	vbroadcastss ymm3, dword ptr [rbp-0x80]								Issue	P2	P2	P2	X	X	X	Retire	
86	0x59f21c	sub rax, 0x1								Issue	P5	X	X	X	X	X	Retire	
87	0x59f220	hint-taken jnle 0x59f040 <Block 11>								Issue	P6	X	X	X	X	X	X	Retire

Summary of Pipeline View for Hot Loop after new addition

We have got an IPC gain of 10%. The Total Number of clock cycles is 30. For the hotspot function, we got an IPC gain of 6.59%

Total number of RAW Stalls	104
Total number of Strucutral hazard(SH) stalls	0
Total Number of Stall X	167
Ratio of Raw stall	0.3837638376
% of RAW stalls	38.37638376
Ratio of SH stalls	0
% of SH stalls	0
IPC(No of Instruction / No of Clock cycle)	2.9
IPC gain	0.1000000002
Hotspot %CPUTime	0.659
Application IPC gain	0.0659
IPC gain in %	10.00000002
Application IPC gain %	6.59

1 Background and Motivation

2 Literature Survey

3 Methodology and Profilers

4 Preliminary Setup

5 Observations and Results

6 Conclusions and Future Works

Conclusions

- Insufficient port utilization is the primary bottleneck for the BERT base uncased model.
- The Introduction of extra units can give us a good improvement in the inference task.

Future Works

- Since multithreading was disabled for our experiments, we shall enable it and repeat the same microarchitecture analysis and confirm if the results that we got holds.
- Use a trace-based simulator like Champsim, DynamoRio, or GEM5 to confirm that the improvement persists.

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Thank you!