

CS 380 - GPU and GPGPU Programming

Lecture 9: GPU Architecture, Pt. 7

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Reading Assignment #4 (until Sep 26)



Read (required):

- Get an overview of NVIDIA Ampere (GA102) white paper:

<https://www.nvidia.com/content/PDF/nvidia-ampere-ga-102-gpu-architecture-whitepaper-v2.pdf>

- Get an overview of NVIDIA Ampere (A100) Tensor Core GPU white paper:

<https://www.nvidia.com/content/dam/en-zz/Solutions/Data-Center/nvidia-ampere-architecture-whitepaper.pdf>

- Get an overview of NVIDIA Hopper (H100) Tensor Core GPU white paper:

<https://resources.nvidia.com/en-us-tensor-core>

Read (optional):

- Look at the “Tuning Guides“ for different architectures in the CUDA SDK
- PTX Instruction Set Architecture (8.5): <https://docs.nvidia.com/cuda/parallel-thread-execution/>
Read Chapters 1 – 3; get an overview of Chapter 9;
browse through the other chapters to get a feeling for what PTX looks like
- CUDA SASS ISA (12.6), Chap. 6: https://docs.nvidia.com/cuda/pdf/CUDA_Binary_Utils.pdf



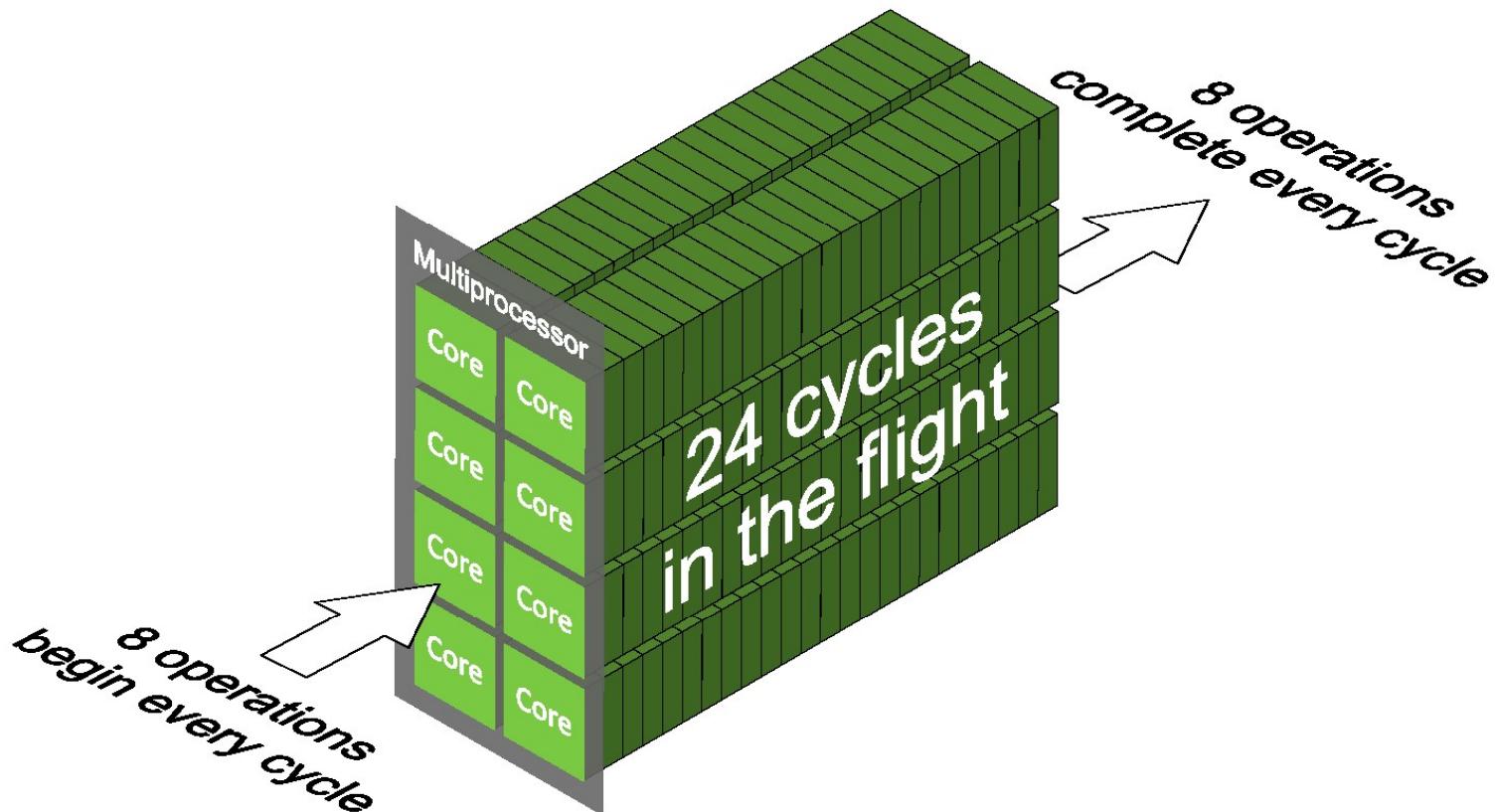
Next Lectures

no lecture on Sep 23 !

Lecture 10: Thu, Sep 26 (Quiz #1)

GPU Architecture: Real Architectures

Use Little's law



Needed parallelism = Latency × Throughput

courtesy of Vasily Volkov

NVIDIA Architectures (since first CUDA GPU)



Tesla [CC 1.x]: 2007-2009

- G80, G9x: 2007 (Geforce 8800, ...)
GT200: 2008/2009 (GTX 280, ...)

Fermi [CC 2.x]: 2010 (2011, 2012, 2013, ...)

- GF100, ... (GTX 480, ...)
GF104, ... (GTX 460, ...)
GF110, ... (GTX 580, ...)

Kepler [CC 3.x]: 2012 (2013, 2014, 2016, ...)

- GK104, ... (GTX 680, ...)
GK110, ... (GTX 780, GTX Titan, ...)

Maxwell [CC 5.x]: 2015

- GM107, ... (GTX 750Ti, ...)
GM204, ... (GTX 980, Titan X, ...)

Pascal [CC 6.x]: 2016 (2017, 2018, 2021, 2022, ...)

- GP100 (Tesla P100, ...)
- GP10x: x=2,4,6,7,8, ...
(GTX 1060, 1070, 1080, Titan X *Pascal*, Titan Xp, ...)

Volta [CC 7.0, 7.2]: 2017/2018

- GV100, ...
(Tesla V100, Titan V, Quadro GV100, ...)

Turing [CC 7.5]: 2018/2019

- TU102, TU104, TU106, TU116, TU117, ...
(Titan RTX, RTX 2070, 2080 (Ti), GTX 1650, 1660, ...)

Ampere [CC 8.0, 8.6, 8.7]: 2020

- GA100, GA102, GA104, GA106, ...
(A100, RTX 3070, 3080, 3090 (Ti), RTX A6000, ...)

Hopper [CC 9.0], Ada Lovelace [CC 8.9]: 2022/23

- GH100, AD102, AD103, AD104, ...
(H100, L40, RTX 4080 (12/16 GB), 4090, RTX 6000, ...)

Blackwell [CC 10.0]: *coming in 2024/25*

- GB200/GB202, GB20x, ...?
(RTX 5080/5090, GB200 NVL72, HGX B100/200, ...?)

ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
# warp sched. / SM	2	2	4	4	2	4	4	4	4
# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L	2L	8L	4L	2L	4L	4L	4L	4L
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP	44 + ILP	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
performance guidelines/multiprocessor level; compute capabilities

ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
# warp sched. / SM	2	2	4	4	2	4	4	4	4
# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L=22	2L=44	8L=88	4L=36	2L=12	4L=24	4L=16	4L=16	4L=16
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP	44 + ILP	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
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ALU Instruction Latencies and Instructs. / SM



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# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L=22	2L=44	8L=88	4L=36	2L=12	4L=24	4L=16	4L=16	4L=16
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22/1	44/2 + ILP	88/2 + ILP	36/1	12/1	24/1	16/1	16/1	16/1

see NVIDIA CUDA C Programming Guides (different versions)
performance guidelines/multiprocessor level; compute capabilities

ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
# warp sched. / SM	2	2	4	4	2	4	4	4	4
# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	$L=22$	$2L=44$	$8L=88$	$4L=36$	$2L=12$	$4L=24$	$4L=16$	$4L=16$	$4L=16$
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22/1	44/2 + ILP	88/2 + ILP	36/1	12/1	24/1	16/1	16/1	16/1

see NVIDIA CUDA C Programming Guides (different versions)
performance guidelines/multiprocessor level; compute capabilities

ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
# warp sched. / SM	2	2	4	4	2	4	4	4	4
# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	22	44	88	36	12	24	16	16	16
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP_(2x)	44 + ILP_(2x)	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
performance guidelines/multiprocessor level; compute capabilities



NVIDIA Fermi Architecture

2010

(compute capability 2.x)

GF100 (cc 2.0), ... (GTX 480, ...)

GF104 (cc 2.1), ... (GTX 460, ...)

GF110 (cc 2.0), ... (GTX 580, ...)

ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
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# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L	2L	8L	4L	2L	4L	4L	4L	4L
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP	44 + ILP	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
 performance guidelines/multiprocessor level; compute capabilities

NVIDIA GF100 SM (2010)

Multiprocessor: SM (CC 2.0)

Streaming processors now called
CUDA cores

32 CUDA cores per Fermi GF100/GF110
streaming multiprocessor (SM)

Example GPU with 15 SMs = 480 CUDA cores (GTX 480)

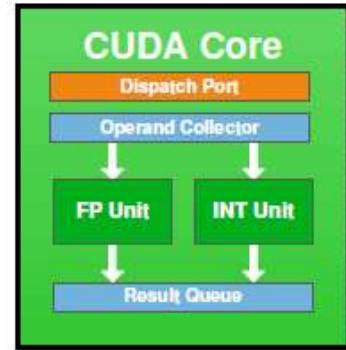
Example GPU with 16 SMs = 512 CUDA cores (GTX 580)

CPU-like cache hierarchy

- L1 cache / shared memory
- L2 cache

Texture units and caches now in SM

(instead of with TPC=multiple SMs in G80/GT200)



ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
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# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L	2L	8L	4L	2L	4L	4L	4L	4L
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP	44 + ILP	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
 performance guidelines/multiprocessor level; compute capabilities

NVIDIA GF104 SM (2010)



Multiprocessor: SM (CC 2.1)

Streaming processors now called
CUDA cores

48 CUDA cores per Fermi GF104
streaming multiprocessor (SM)

Example GPU with 7 SMs = 336 CUDA cores (GTX 460)

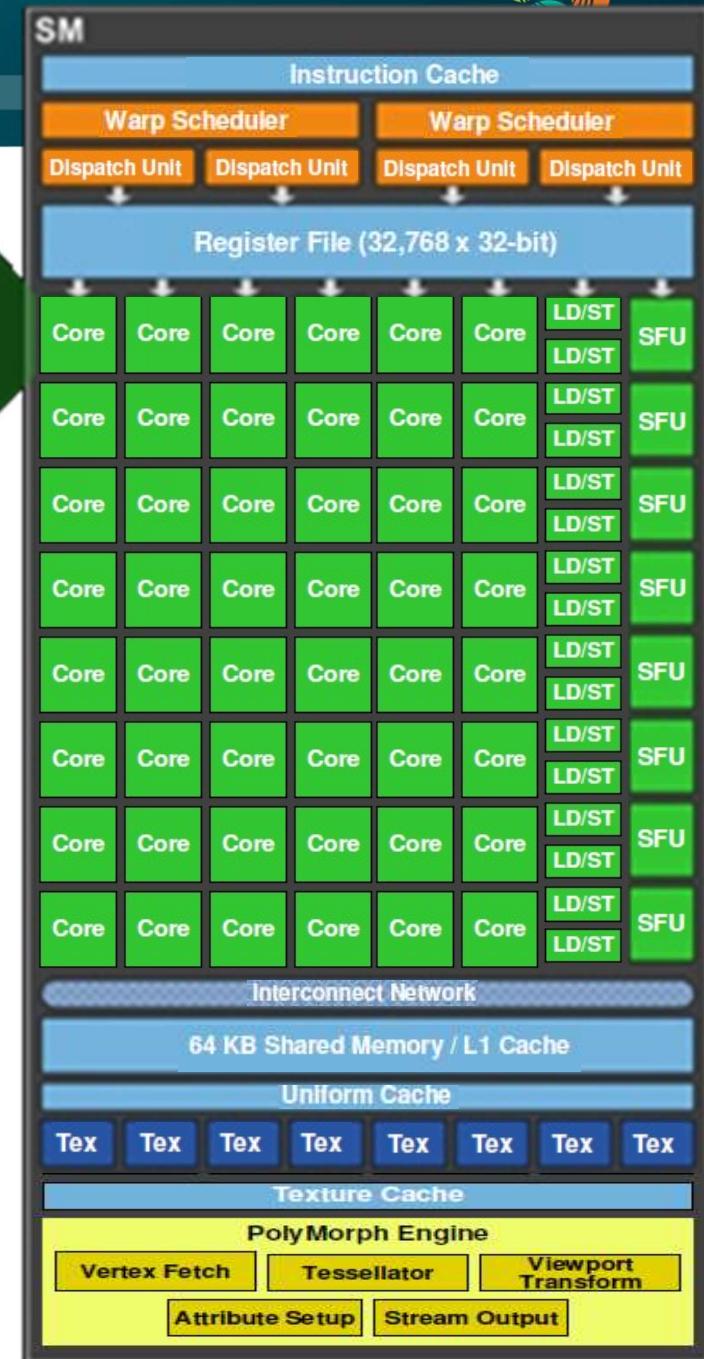
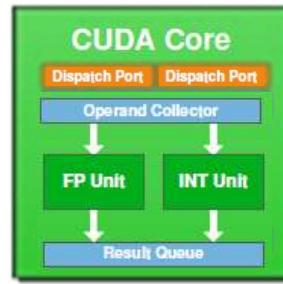
2 dispatch units / warp scheduler: “superscalar”

CPU-like cache hierarchy

- L1 cache / shared memory
- L2 cache

Texture units and caches now in SM

(instead of with TPC=multiple SMs in G80/GT200)

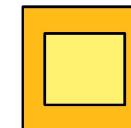
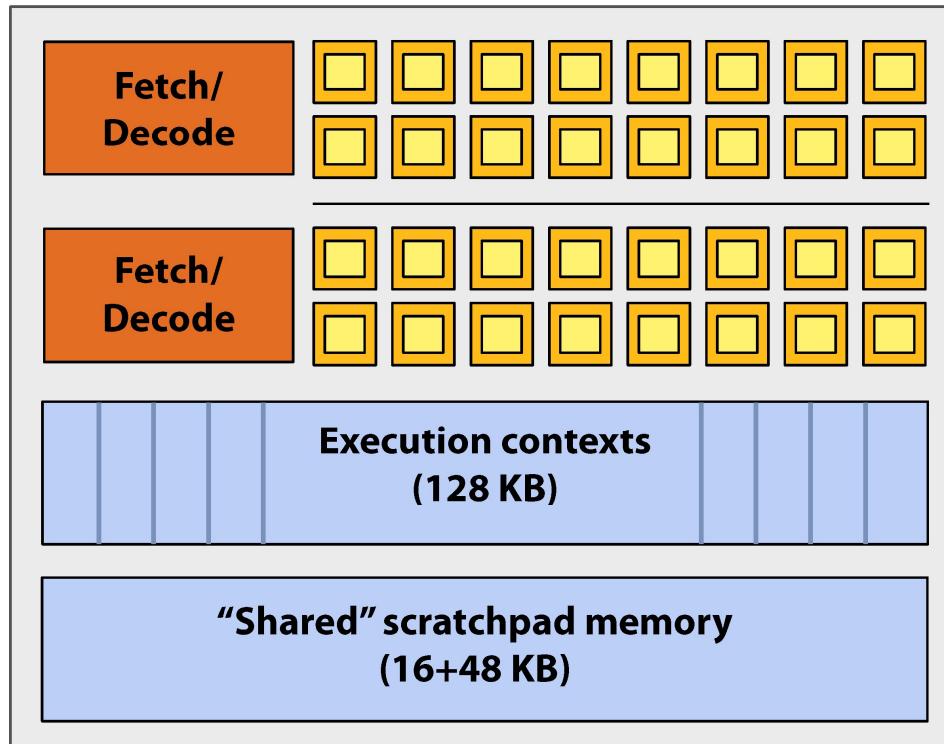


NVIDIA Fermi GF100 Architecture (2010)



NVIDIA GeForce GTX 480 "SM"

CC 2.0, not 2.1 !



= CUDA core
(1 MUL-ADD per clock)

- The **SM** contains 32 **CUDA cores**
- Two **warps** are selected each clock (decode, fetch, and execute two **warps** in parallel)
- Up to 48 warps are interleaved, totaling 1536 **CUDA threads**

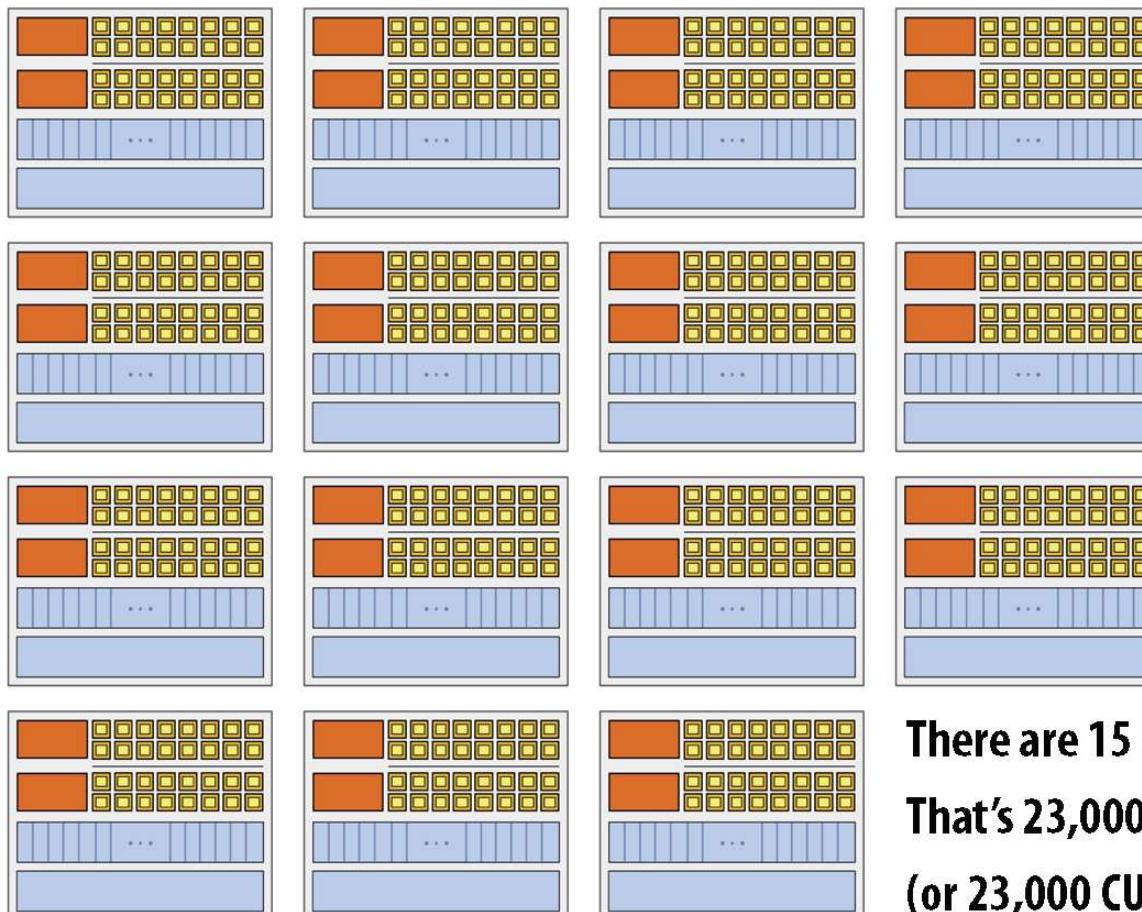
Source: Fermi Compute Architecture Whitepaper
CUDA Programming Guide 3.1, Appendix G

NVIDIA Fermi GF100 Architecture (2010)



NVIDIA GeForce GTX 480

CC 2.0, not 2.1 !



**There are 15 of these things on the GTX 480:
That's 23,000 fragments!
(or 23,000 CUDA threads!)**



NVIDIA Kepler Architecture

2012

(compute capability 3.x)

GK104 (cc 3.0), ... (GTX 680, ...)

GK110 (cc 3.5), ... (GTX 780, GTX Titan (Black), ...)

GK210 (cc 3.7), ... (Tesla K80)



NVIDIA Kepler Architecture (2012)





Instruction Throughput

Instruction throughput numbers in CUDA C Programming Guide (Chapter 5.4)

	Compute Capability										
	3.5, 3.7	5.0, 5.2	5.3	6.0	6.1	6.2	7.x	8.0	8.6	8.9	9.0
16-bit floating-point add, multiply, multiply-add	N/A		256	128	2	256	128	256	128	256	
								128 for __nv_bfloat16		128 for __nv_bfloat16	
32-bit floating-point add, multiply, multiply-add	192		128	64	128		64		128		
64-bit floating-point add, multiply, multiply-add	64		4	32	4		32	32	2	2	64
	8 for GeForce GPUs, except for Titan GPUs						2 for compute capability 7.5 GPUs				

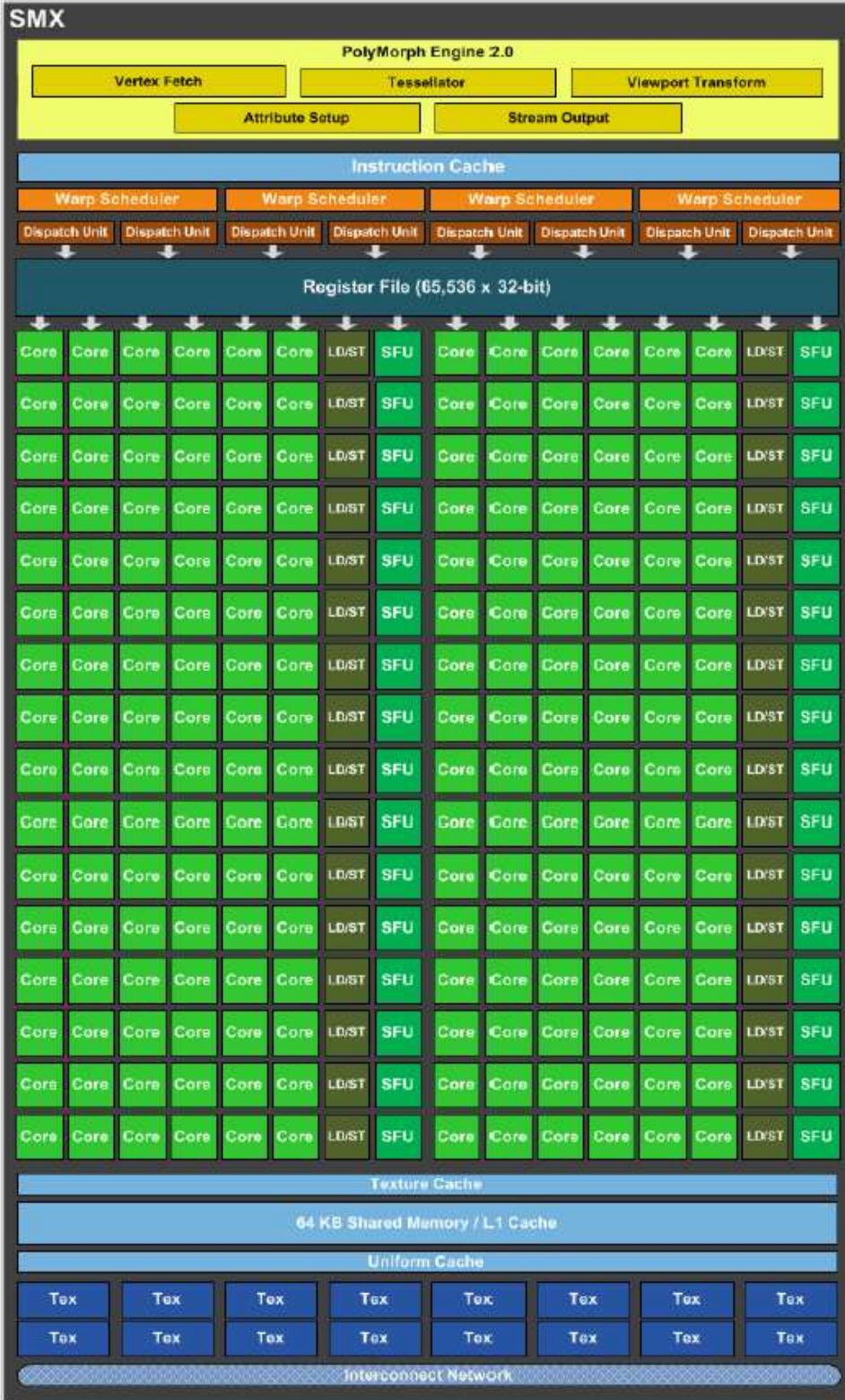
ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
# warp sched. / SM	2	2	4	4	2	4	4	4	4
# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L	2L	8L	4L	2L	4L	4L	4L	4L
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP	44 + ILP	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
 performance guidelines/multiprocessor level; compute capabilities

GK104 SMX



Multiprocessor: SMX (CC 3.0)

- 192 CUDA cores
($192 = 6 * 32$)
- 32 LD/ST units
- 32 SFUs
- 16 texture units

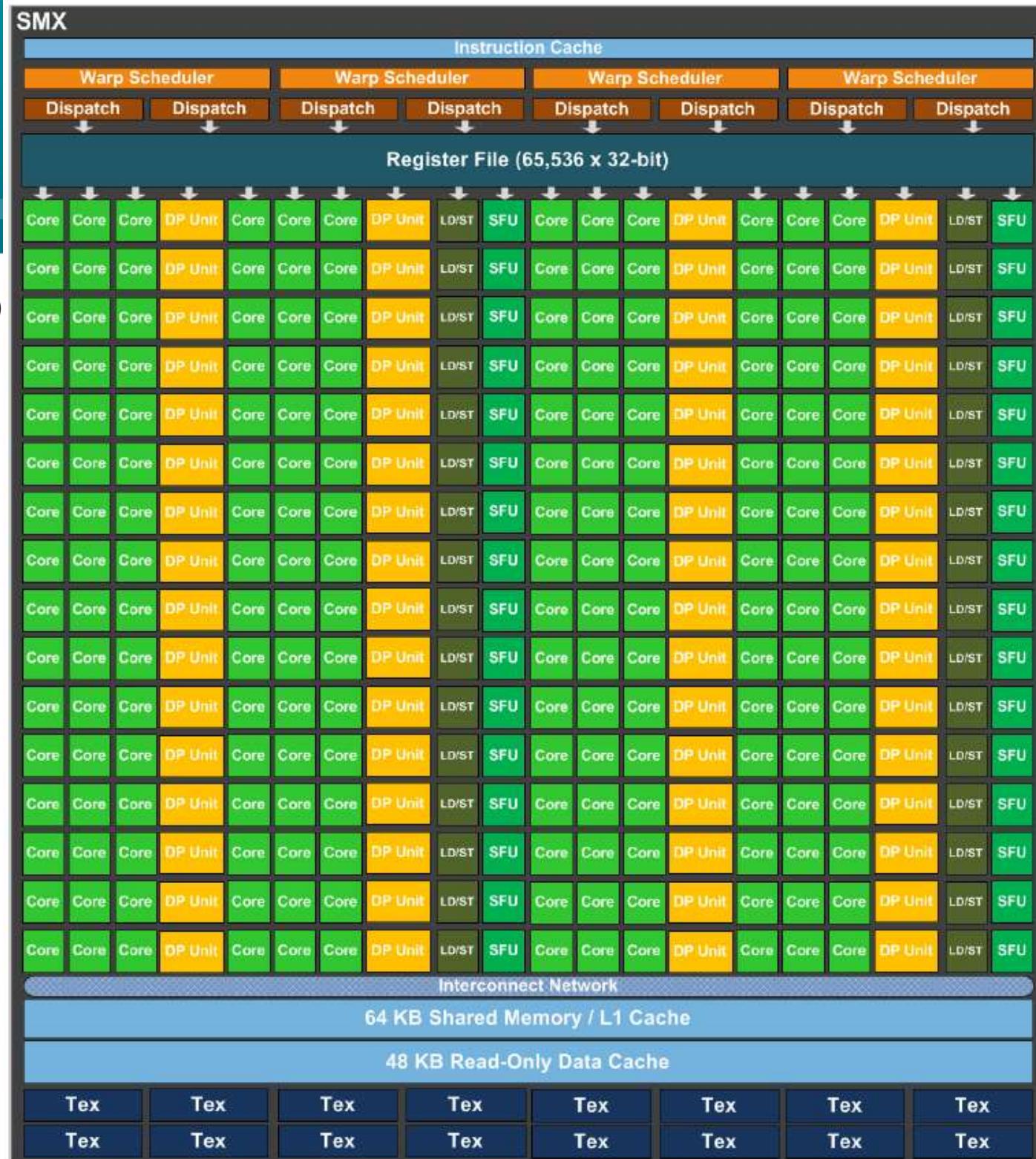
Two dispatch units per warp scheduler exploit ILP
(*instruction-level parallelism*)

Can dual-issue ALU instructions!
("superscalar")

GK110 SMX

Multiprocessor: SMX (CC 3.5)

- 192 CUDA cores
($192 = 6 * 32$)
- 64 DP units
- 32 LD/ST units
- 32 SFUs
- 16 texture units



NVIDIA Kepler Architecture (2012)



Three different versions

- Compute capability 3.0 (GK104)
 - Geforce GTX 680, ...
 - Quadro K5000
 - Tesla K10
- Compute capability 3.5 (GK110)
 - Geforce GTX 780 / Titan / Titan Black
 - Quadro K6000
 - Tesla K20, Tesla K40
- Compute capability 3.7 (GK210)
 - Tesla K80
 - Came out much later (~end of 2014)



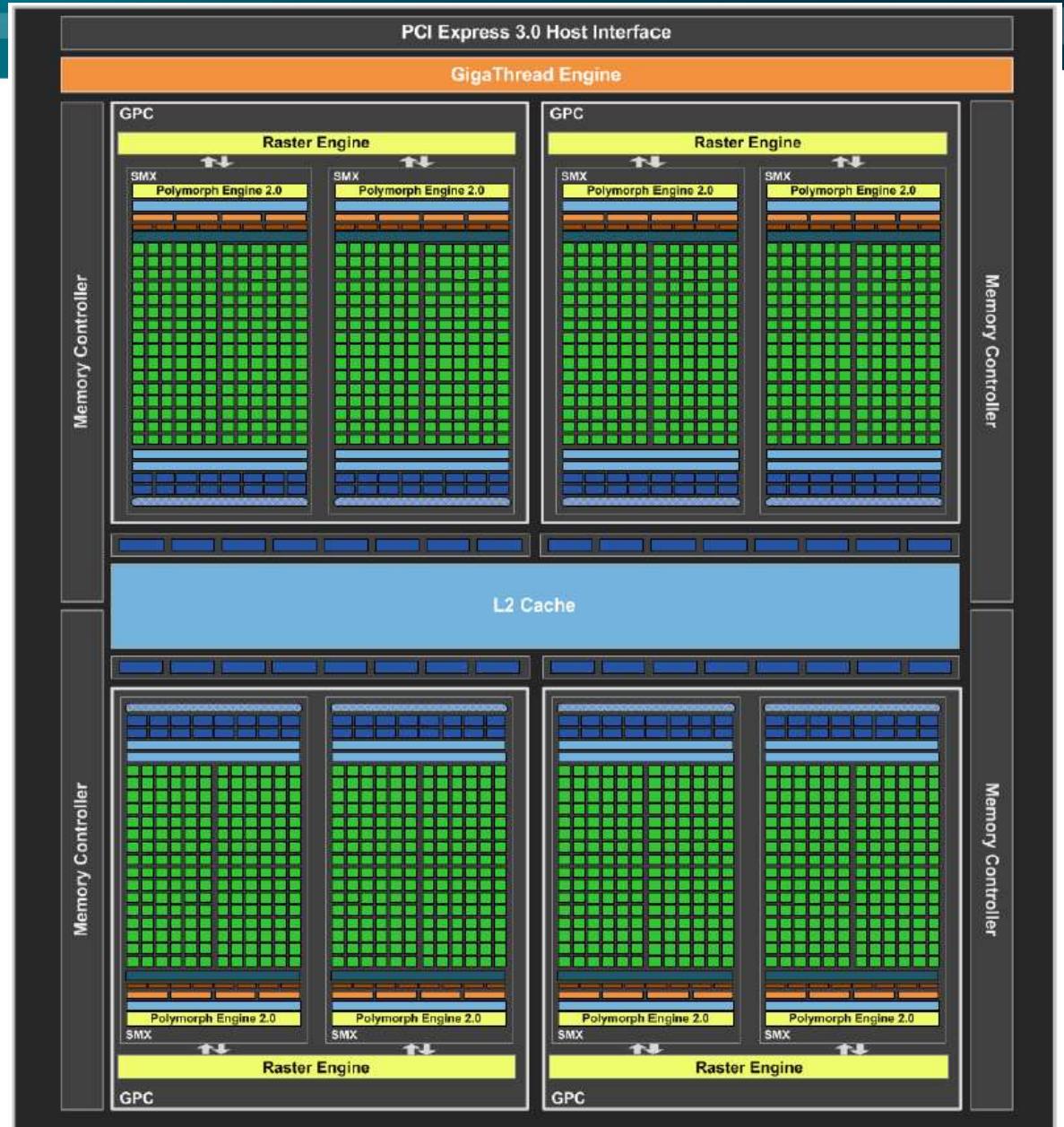


NVIDIA Kepler / GK104 Structure

Full size

- 4 GPCs
- 2 SMXs each

= 8 SMXs,
1536 CUDA cores





NVIDIA Kepler / GK110 Structure (1)

Full size

- 15 SMXs
(Titan Black;
Titan: 14)
- 2880 CUDA
cores
(Titan Black;
Titan: 2688)
- 5 GPCs of
3 SMXs each





NVIDIA Kepler / GK110 Structure (2)

Titan (not Black)

- 14 SMXs

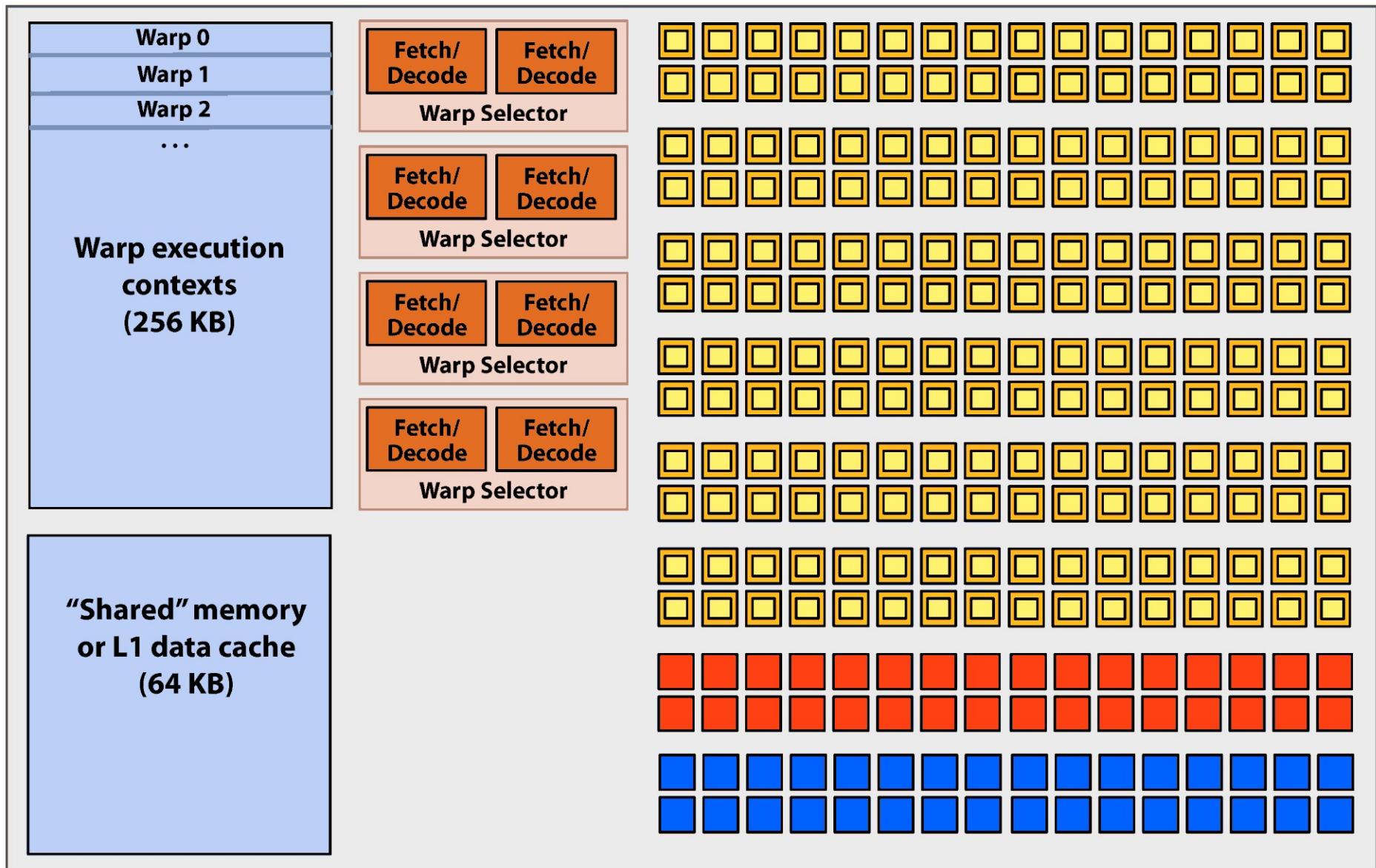
- 2688 CUDA cores

- 5 GPCs with 3 SMXs or 2 SMXs each



Bonus slides: NVIDIA GTX 680 (2012)

NVIDIA Kepler GK104 architecture SMX unit (one “core”)



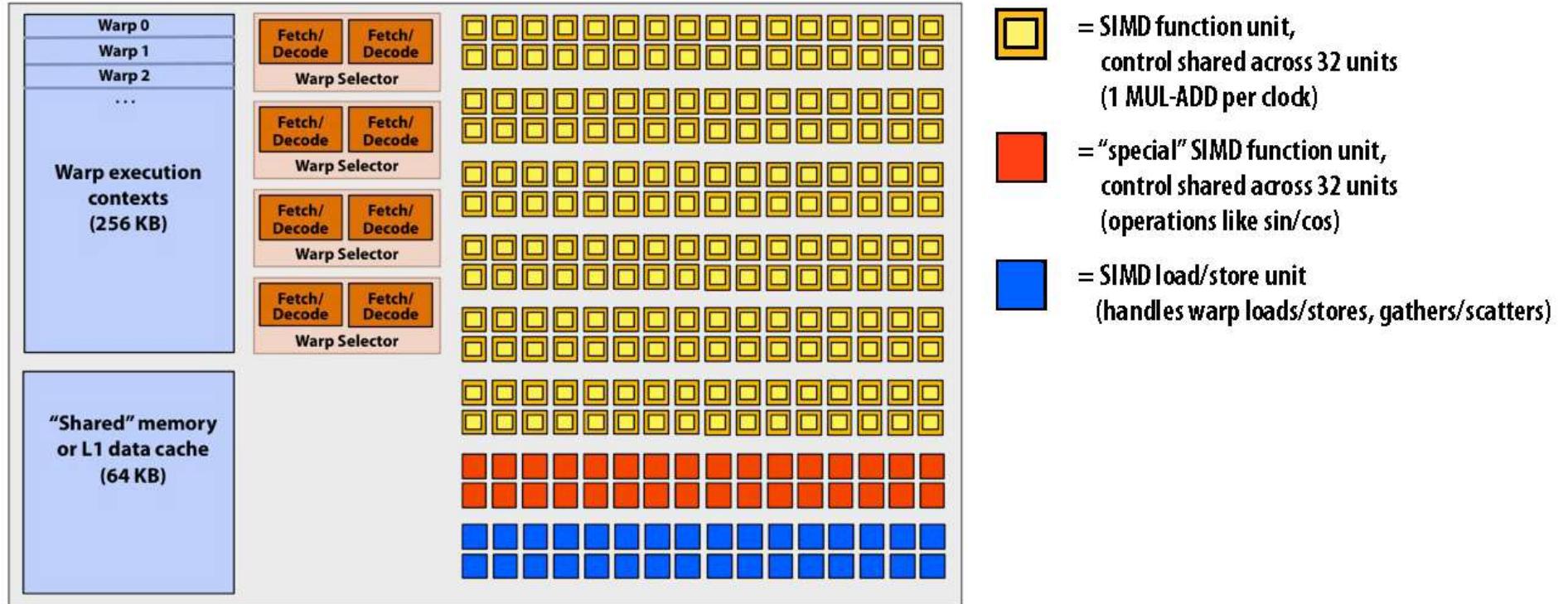
= SIMD function unit,
control shared across 32 units
(1 MUL-ADD per clock)

= “special” SIMD function unit,
control shared across 32 units
(operations like sin/cos)

= SIMD load/store unit
(handles warp loads/stores, gathers/scatters)

Bonus slides: NVIDIA GTX 680 (2012)

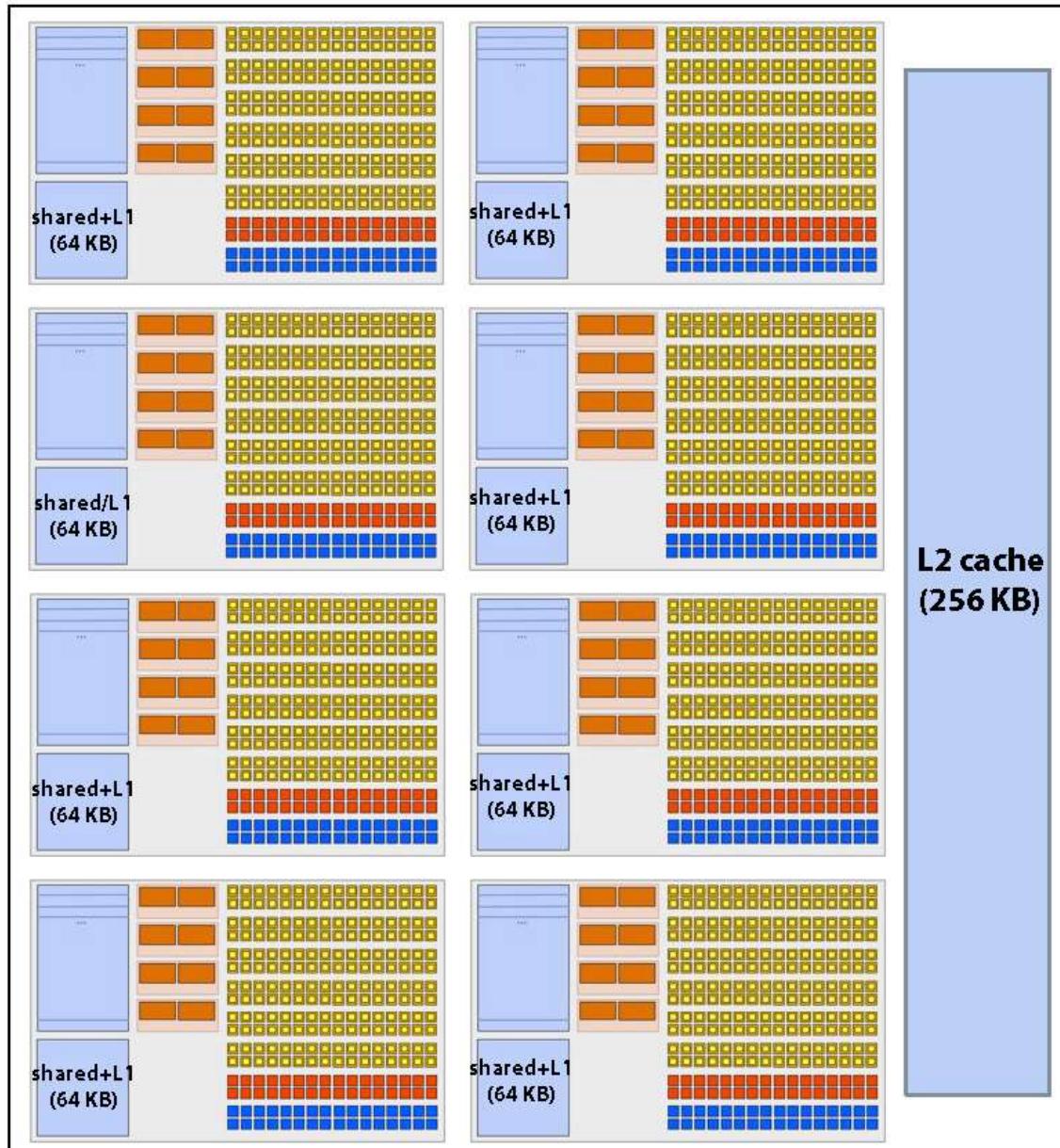
NVIDIA Kepler GK104 architecture SMX unit (one “core”)



- **SMX core resource limits:**
 - Maximum warp execution contexts: 64 (2,048 total CUDA threads)
 - Maximum thread blocks: 16
- **SMX core operation each clock:**
 - Select up to four runnable warps from up to 64 resident on core (thread-level parallelism)
 - Select up to two runnable instructions per warp (instruction-level parallelism)
 - Execute instructions on available groups of SIMD ALUs, special-function ALUs, or LD/ST units

Bonus slides: NVIDIA GTX 680 (2012)

NVIDIA Kepler GK104 architecture



- 1 GHz clock
- Eight SMX cores per chip
- $8 \times 192 = 1,536$ SIMD mul-add ALUs
= 3 TFLOPs
- Up to 512 interleaved warps per chip
(16,384 CUDA threads/chip)
- TDP: 195 watts

Memory
256 bit interface
DDR5 DRAM



NVIDIA Maxwell Architecture

2015

(compute capability 5.x)

GM107 (cc 5.0), ... (GTX 750Ti, ...)

GM204 (cc 5.2), ... (GTX 980, Titan X, ...)

GM20B (cc 5.3), ... (Tegra X1, ...)

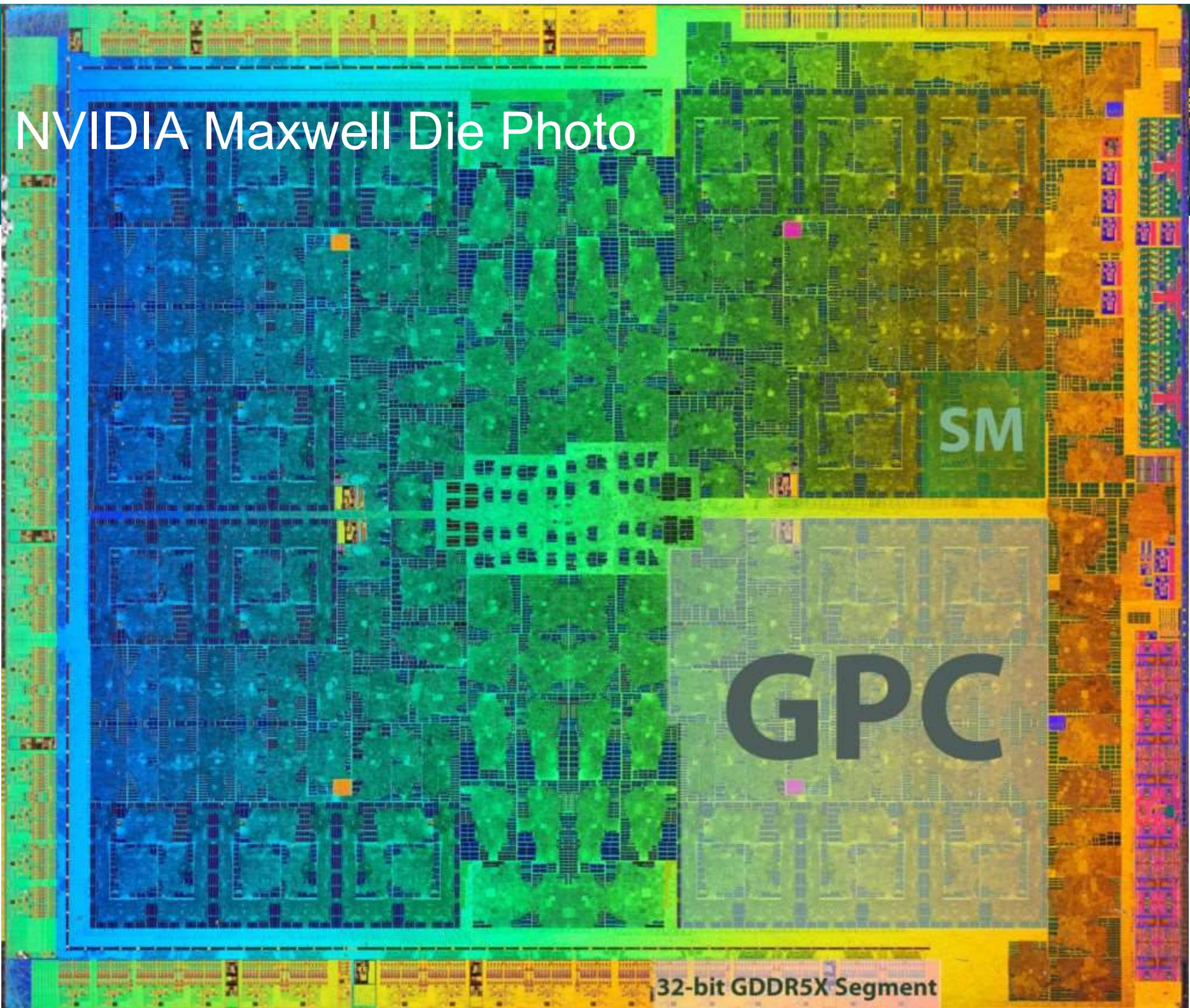
Nintendo Switch/OLED (2017/2021)!



NVIDIA Maxwell Architecture (2015)



NVIDIA Maxwell Die Photo





Instruction Throughput

Instruction throughput numbers in CUDA C Programming Guide (Chapter 5.4)

	Compute Capability										
	3.5, 3.7	5.0, 5.2	5.3	6.0	6.1	6.2	7.x	8.0	8.6	8.9	9.0
16-bit floating-point add, multiply, multiply-add		N/A	256	128	2	256	128	256	128	256	
								128 for __nv_bfloat16		128 for __nv_bfloat16	
32-bit floating-point add, multiply, multiply-add	192	128		64	128		64		128		
64-bit floating-point add, multiply, multiply-add	64	4		32	4		32	32	2	2	64
	8 for GeForce GPUs, except for Titan GPUs						2 for compute capability 7.5 GPUs				

ALU Instruction Latencies and Instructs. / SM



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# warp sched. / SM	2	2	4	4	2	4	4	4	4
# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L	2L	8L	4L	2L	4L	4L	4L	4L
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP	44 + ILP	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
 performance guidelines/multiprocessor level; compute capabilities

Maxwell (GM) Architecture

Multiprocessor: SMM (CC 5.x)

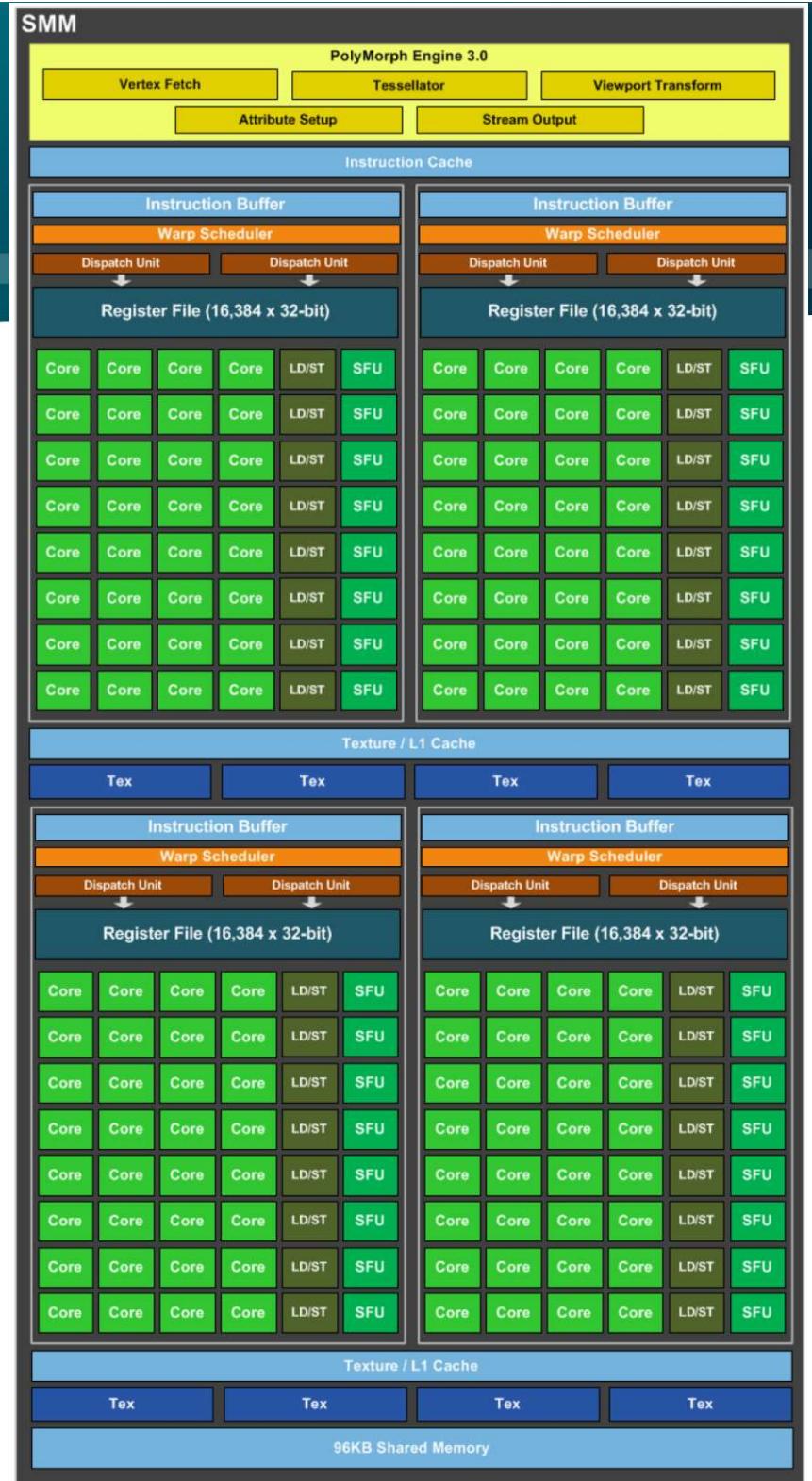
- 128 CUDA cores
- 4 DP units; 32 LD/ST units; 32 SFUs
- 8 texture units

4 partitions inside SMM

- 32 CUDA cores each
- 8 LD/ST units; 8 SFUs each
- Each has its own register file, warp scheduler, two dispatch units (*but cannot dual-issue ALU insts.!*)

Shared memory and L1 cache now separate!

- L1 cache shares with texture cache
- Shared memory is its own space





Maxwell (GM) Architecture

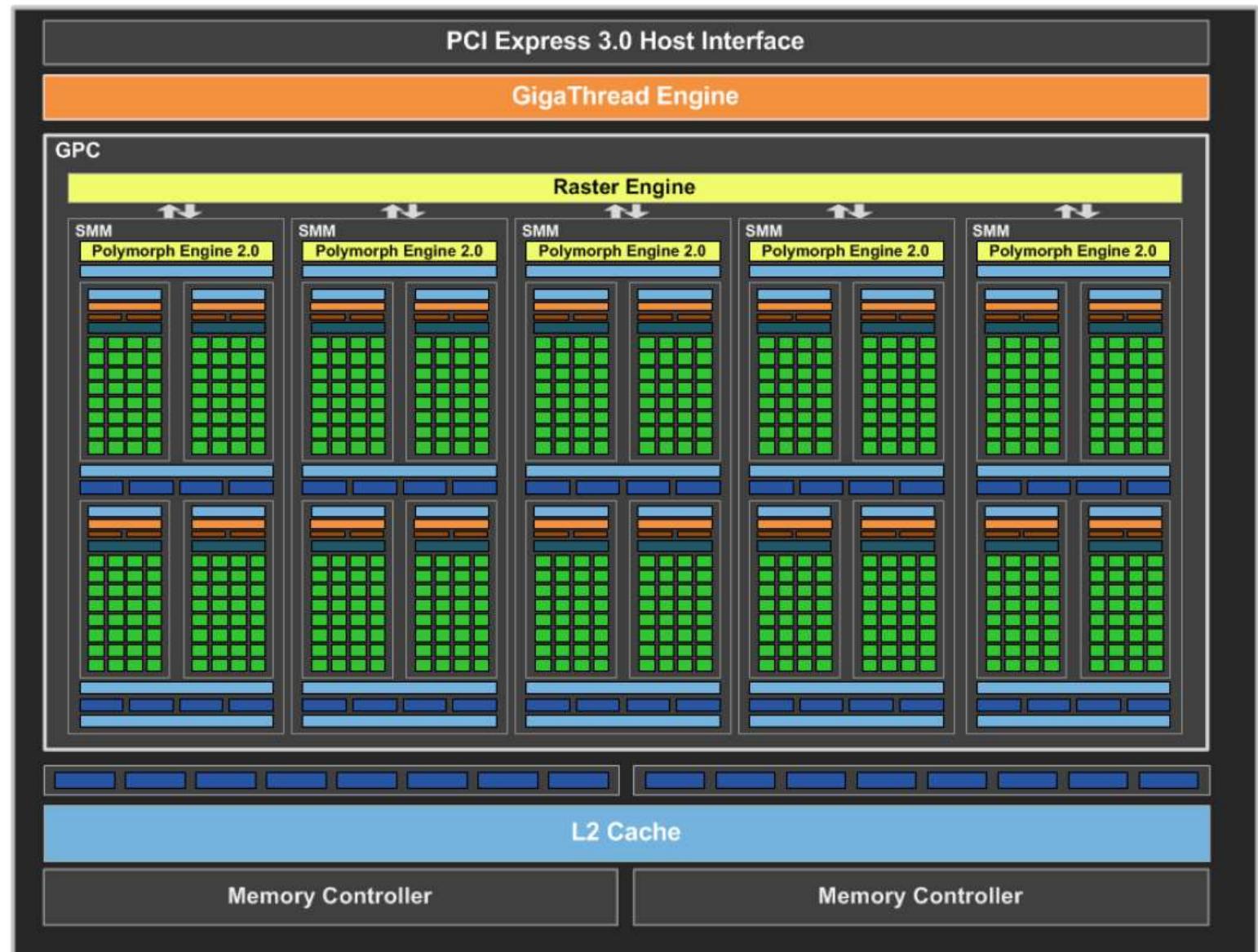
First gen.

GM107

(GTX 750Ti)

5 SMMs

(640 CUDA
cores in
total)





Maxwell (GM) Architecture

Second gen.

GM204
(GTX 980)

16 SMMs
(2048 CUDA
cores in
total)

4 GPCs of 4
SMMs



Maxwell (GM) vs. Kepler (GK) Architecture



GK107 vs. GM107

GPU	GK107 (Kepler)	GM107 (Maxwell)
CUDA Cores	384	640
Base Clock	1058 MHz	1020 MHz
GPU Boost Clock	N/A	1085 MHz
GFLOPs	812.5	1305.6
Texture Units	32	40
Texel fill-rate	33.9 Gigatexels/sec	40.8 Gigatexels/sec
Memory Clock	5000 MHz	5400 MHz
Memory Bandwidth	80 GB/sec	86.4 GB/sec
ROPs	16	16
L2 Cache Size	256KB	2048KB
TDP	64W	60W
Transistors	1.3 Billion	1.87 Billion
Die Size	118 mm ²	148 mm ²
Manufacturing Process	28-nm	28-nm

Maxwell (GM) vs. Kepler (GK) Architecture



GK107 vs. GM204

GPU	GeForce GTX 680 (Kepler)	GeForce GTX 980 (Maxwell)
SMs	8	16
CUDA Cores	1536	2048
Base Clock	1006 MHz	1126 MHz
GPU Boost Clock	1058 MHz	1216 MHz
GFLOPs	3090	4612 ¹
Texture Units	128	128
Texel fill-rate	128.8 Gigatexels/sec	144.1 Gigatexels/sec
Memory Clock	6000 MHz	7000 MHz
Memory Bandwidth	192 GB/sec	224 GB/sec
ROPs	32	64
L2 Cache Size	512KB	2048KB
TDP	195 Watts	165 Watts
Transistors	3.54 billion	5.2 billion
Die Size	294 mm ²	398 mm ²
Manufacturing Process	28-nm	28-nm



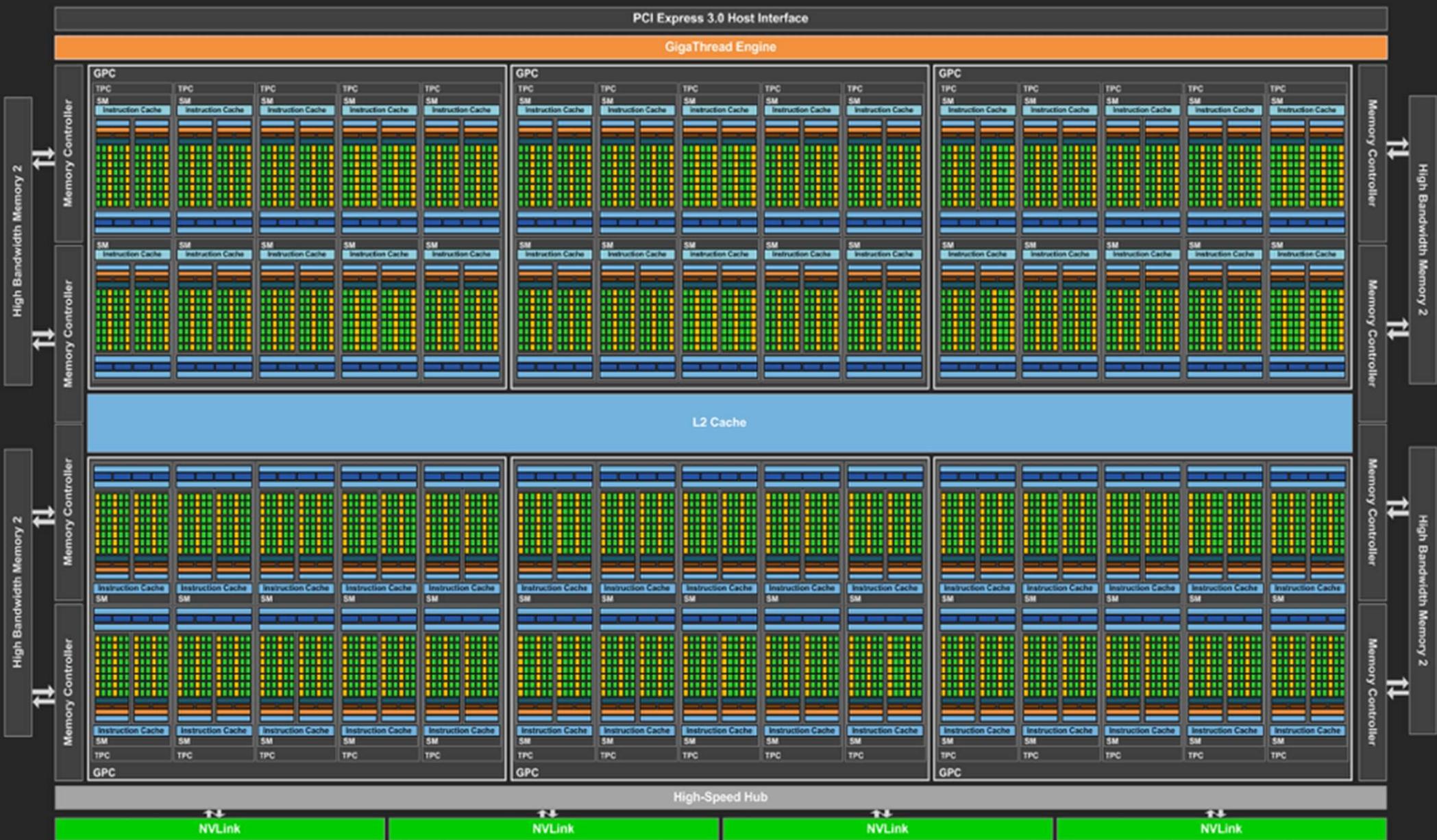
NVIDIA Pascal Architecture

2016

(compute capability 6.x)

- GP100 (cc 6.0), ... (Tesla P100, ...)
- (x=2,4,6,7,8) GP10x (cc 6.1), ... (GTX 1080, Titan X *Pascal/Xp*, Tesla P4/40, ...)
- GM10B (cc 6.2), ... (Tegra X2, ...)

NVIDIA Pascal Architecture (2016)





Instruction Throughput

Instruction throughput numbers in CUDA C Programming Guide (Chapter 5.4)

	Compute Capability										
	3.5, 3.7	5.0, 5.2	5.3	6.0	6.1	6.2	7.x	8.0	8.6	8.9	9.0
16-bit floating-point add, multiply, multiply-add	N/A		256	128	2	256	128	256	128	256	128 for __nv_bfloat16
32-bit floating-point add, multiply, multiply-add	192		128	64	128		64		128		128 for __nv_bfloat16
64-bit floating-point add, multiply, multiply-add	64		4	32	4		32	32	2	2	64

8 for GeForce GPUs, except for Titan GPUs

2 for compute capability 7.5 GPUs

ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
# warp sched. / SM	2	2	4	4	2	4	4	4	4
# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L	2L	8L	4L	2L	4L	4L	4L	4L
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP	44 + ILP	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
 performance guidelines/multiprocessor level; compute capabilities



NVIDIA Pascal GP100 SM

Multiprocessor: SM (CC 6.0)

- 64 CUDA cores
- 32 DP units
- 16 LD/ST units
- 16 SFUs
- 4 texture units



2 partitions inside SM

- 32 CUDA cores each; 16 DP units each; 8 LD/ST units each; 8 SFUs each
- Each has its own register file, warp scheduler, two dispatch units
(but cannot dual-issue ALU (single precision core) insts.!)

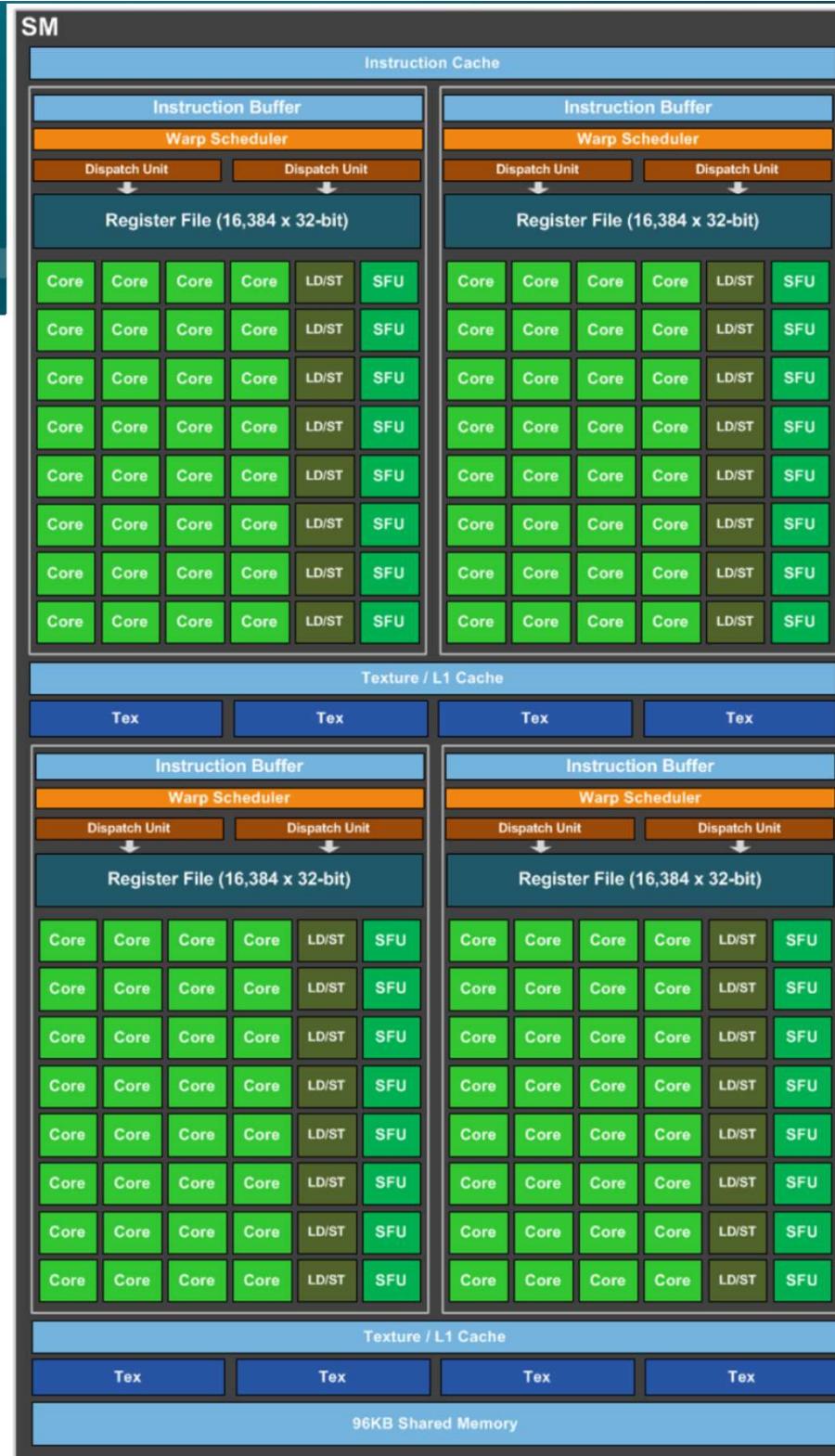
NVIDIA Pascal GP104 SM

Multiprocessor: SM (CC 6.1/6.2)

- 128 CUDA cores
- 32 LD/ST units
- 32 SFUs
- 8 texture units

4 partitions inside SM

- 32 CUDA cores; 8 LD/ST units; 8 SFUs
- Each has its own register file,
warp scheduler, two dispatch units
(but cannot dual-issue ALU insts.!)



NVIDIA Pascal Architecture (2016)



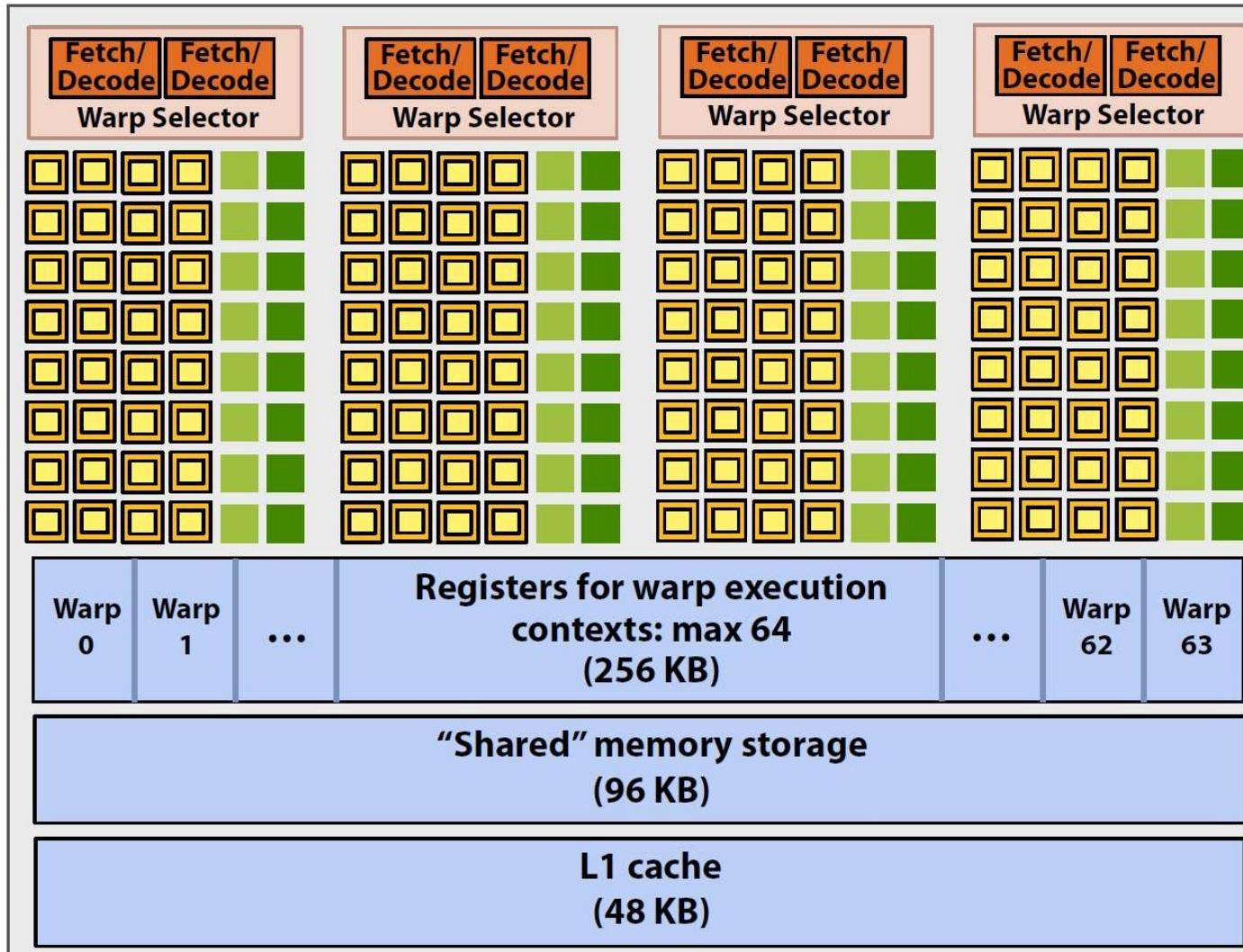
Total chip capacity on Tesla P100 (GP100)

- 56 SMs
 - 64 CUDA cores / SM = 3,584 CUDA cores in total
 - 32 DP units / SM = 1,792 DP units in total
- 28 TPCs (2 SMs per TPC)
- 6 GPCs

Maximum capacity would be 60 SMs and 30 TPCs

NVIDIA GTX 1080 (2016)

This is one NVIDIA Pascal GP104 streaming multi-processor (SM) unit

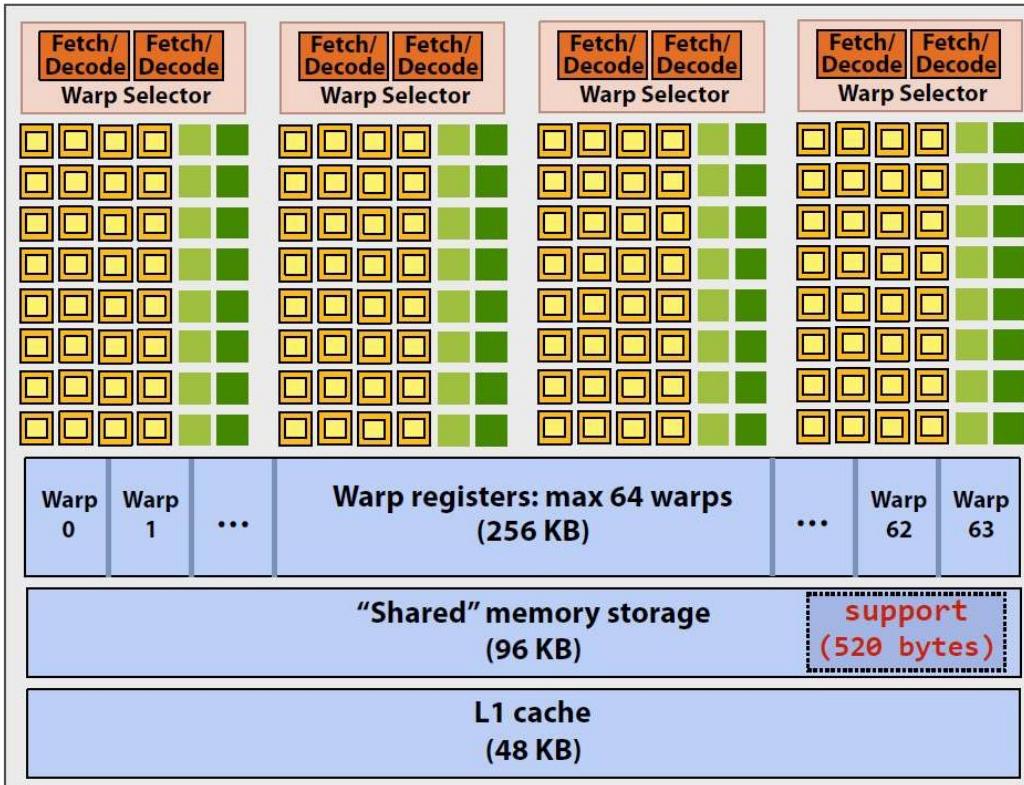


- = SIMD functional unit, control shared across 32 units (1 MUL-ADD per clock)
- = SIMD special function unit (sin, cos, etc.)

SM resource limits:

- Max warp execution contexts: 64 (2,048 total CUDA threads)
- 96 KB of shared memory

Running a single thread block on a SM “core”



```
#define THREADS_PER_BLK 128

__global__ void convolve(int N, float* input,
                        float* output)
{
    __shared__ float support[THREADS_PER_BLK+2];
    int index = blockIdx.x * blockDim.x +
                threadIdx.x;

    support[threadIdx.x] = input[index];
    if (threadIdx.x < 2) {
        support[THREADS_PER_BLK+threadIdx.x]
            = input[index+THREADS_PER_BLK];
    }

    __syncthreads();

    float result = 0.0f; // thread-local
    for (int i=0; i<3; i++)
        result += support[threadIdx.x + i];

    output[index] = result;
}
```

Recall, CUDA kernels execute as SPMD programs

On NVIDIA GPUs groups of 32 CUDA threads share an instruction stream. These groups called “warps”.

A `convolve` thread block is executed by 4 warps (4 warps x 32 threads/warp = 128 CUDA threads per block)

(Warps are an important GPU implementation detail, but not a CUDA abstraction!)

SM core operation each clock:

- Select up to four runnable warps from 64 resident on SM core (thread-level parallelism)
- Select up to two runnable instructions per warp (instruction-level parallelism) *



NVIDIA Volta Architecture

2017/2018

(compute capability 7.0/7.2)

GV100 (cc 7.0), ... (Titan V, Tesla V100, ...)

GV10B, GV11B (cc 7.2), ... (Tegra Xavier, ...)

NVIDIA Volta Architecture (2017/2018)





Instruction Throughput

Instruction throughput numbers in CUDA C Programming Guide (Chapter 5.4)

	Compute Capability										
	3.5, 3.7	5.0, 5.2	5.3	6.0	6.1	6.2	7.x	8.0	8.6	8.9	9.0
16-bit floating-point add, multiply, multiply-add	N/A		256	128	2	256	128	256	128	256	
							128 for __nv_bfloat16		128 for __nv_bfloat16		
32-bit floating-point add, multiply, multiply-add	192	128		64	128		64		128		
64-bit floating-point add, multiply, multiply-add	64		4	32	4	32	32	2	2	64	
	8 for GeForce GPUs, except for Titan GPUs					2 for compute capability 7.5 GPUs					

ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
# warp sched. / SM	2	2	4	4	2	4	4	4	4
# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L	2L	8L	4L	2L	4L	4L	4L	4L
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP	44 + ILP	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
 performance guidelines/multiprocessor level; compute capabilities

NVIDIA Volta SM

Multiprocessor: SM (CC 7.0)

- 64 FP32 + 64 INT32 cores
- 32 FP64 cores
- 32 LD/ST units; 16 SFUs
- 8 tensor cores
(FP16/FP32 mixed-precision)

4 partitions inside SM

- 16 FP32 + 16 INT32 cores each
- 8 FP64 cores each
- 8 LD/ST units; 4 SFUs each
- 2 tensor cores each
- Each has: warp scheduler, dispatch unit, register file





Tensor Cores

Mixed-precision, fast matrix-matrix multiply and accumulate

$$\mathbf{D} = \left(\begin{array}{cccc} \mathbf{A}_{0,0} & \mathbf{A}_{0,1} & \mathbf{A}_{0,2} & \mathbf{A}_{0,3} \\ \mathbf{A}_{1,0} & \mathbf{A}_{1,1} & \mathbf{A}_{1,2} & \mathbf{A}_{1,3} \\ \mathbf{A}_{2,0} & \mathbf{A}_{2,1} & \mathbf{A}_{2,2} & \mathbf{A}_{2,3} \\ \mathbf{A}_{3,0} & \mathbf{A}_{3,1} & \mathbf{A}_{3,2} & \mathbf{A}_{3,3} \end{array} \right) \text{FP16 or FP32} \times \left(\begin{array}{cccc} \mathbf{B}_{0,0} & \mathbf{B}_{0,1} & \mathbf{B}_{0,2} & \mathbf{B}_{0,3} \\ \mathbf{B}_{1,0} & \mathbf{B}_{1,1} & \mathbf{B}_{1,2} & \mathbf{B}_{1,3} \\ \mathbf{B}_{2,0} & \mathbf{B}_{2,1} & \mathbf{B}_{2,2} & \mathbf{B}_{2,3} \\ \mathbf{B}_{3,0} & \mathbf{B}_{3,1} & \mathbf{B}_{3,2} & \mathbf{B}_{3,3} \end{array} \right) \text{FP16} + \left(\begin{array}{cccc} \mathbf{C}_{0,0} & \mathbf{C}_{0,1} & \mathbf{C}_{0,2} & \mathbf{C}_{0,3} \\ \mathbf{C}_{1,0} & \mathbf{C}_{1,1} & \mathbf{C}_{1,2} & \mathbf{C}_{1,3} \\ \mathbf{C}_{2,0} & \mathbf{C}_{2,1} & \mathbf{C}_{2,2} & \mathbf{C}_{2,3} \\ \mathbf{C}_{3,0} & \mathbf{C}_{3,1} & \mathbf{C}_{3,2} & \mathbf{C}_{3,3} \end{array} \right) \text{FP16 or FP32}$$

From this, build larger sizes, higher dimensionalities, ...

[+Tensor cores on later architectures add more data types/precisions!]

NVIDIA Volta Architecture (2017/2018)



Total chip capacity on Tesla V100 (GV100 architecture)

- 80 SMs
 - 64 FP32 cores / SM = 5,120 FP32 cores in total
 - 64 INT32 cores / SM = 5,120 INT32 cores in total
 - 32 FP64 cores / SM = 2,560 FP64 cores in total
 - 4 FP16/FP32 mixed-prec. tensor cores = 650 tensor cores in total
- 40 TPCs (2 SMs per TPC)
- 6 GPCs

Maximum capacity would be 84 SMs and 42 TPCs

Kepler – Volta Specs

Tesla Product	Tesla K40	Tesla M40	Tesla P100	Tesla V100
GPU	GK180 (Kepler)	GM200 (Maxwell)	GP100 (Pascal)	GV100 (Volta)
SMs	15	24	56	80
TPCs	15	24	28	40
FP32 Cores / SM	192	128	64	64
FP32 Cores / GPU	2880	3072	3584	5120
FP64 Cores / SM	64	4	32	32
FP64 Cores / GPU	960	96	1792	2560
Tensor Cores / SM	NA	NA	NA	8
Tensor Cores / GPU	NA	NA	NA	640
GPU Boost Clock	810/875 MHz	1114 MHz	1480 MHz	1455 MHz
Peak FP32 TFLOP/s [*]	5.04	6.8	10.6	15
Peak FP64 TFLOP/s [*]	1.68	.21	5.3	7.5
Peak Tensor Core TFLOP/s [*]	NA	NA	NA	120
Texture Units	240	192	224	320
Memory Interface	384-bit GDDR5	384-bit GDDR5	4096-bit HBM2	4096-bit HBM2
Memory Size	Up to 12 GB	Up to 24 GB	16 GB	16 GB
L2 Cache Size	1536 KB	3072 KB	4096 KB	6144 KB
Shared Memory Size / SM	16 KB/32 KB/48 KB	96 KB	64 KB	Configurable up to 96 KB
Register File Size / SM	256 KB	256 KB	256 KB	256KB
Register File Size / GPU	3840 KB	6144 KB	14336 KB	20480 KB
TDP	235 Watts	250 Watts	300 Watts	300 Watts
Transistors	7.1 billion	8 billion	15.3 billion	21.1 billion
GPU Die Size	551 mm ²	601 mm ²	610 mm ²	815 mm ²
Manufacturing Process	28 nm	28 nm	16 nm FinFET+	12 nm FFN



Turing (vs. Pascal)

Apart from RT cores, Volta and Turing are very similar
(and both have compute capability 7.x: Volta: 7.0, Turing: 7.5)

GPU Features	GeForce GTX 1080	GeForce RTX 2080	Quadro P5000	Quadro RTX 5000
Architecture	Pascal	Turing	Pascal	Turing
GPCs	4	6	4	6
TPCs	20	23	20	24
SMs	20	46	20	48
CUDA Cores / SM	128	64	128	64
CUDA Cores / GPU	2560	2944	2560	3072
Tensor Cores / SM	NA	8	NA	8
Tensor Cores / GPU	NA	368	NA	384
RT Cores	NA	46	NA	48

TU104

TU104



NVIDIA Turing Architecture

2018/2019

(compute capability 7.5)

TU102, TU104, TU106, TU116, ... (cc 7.5)
(Titan RTX, RTX 2070, 2080, 2080Ti, Tesla T4, ...)

NVIDIA Turing Architecture (2018/2019)



TU 102

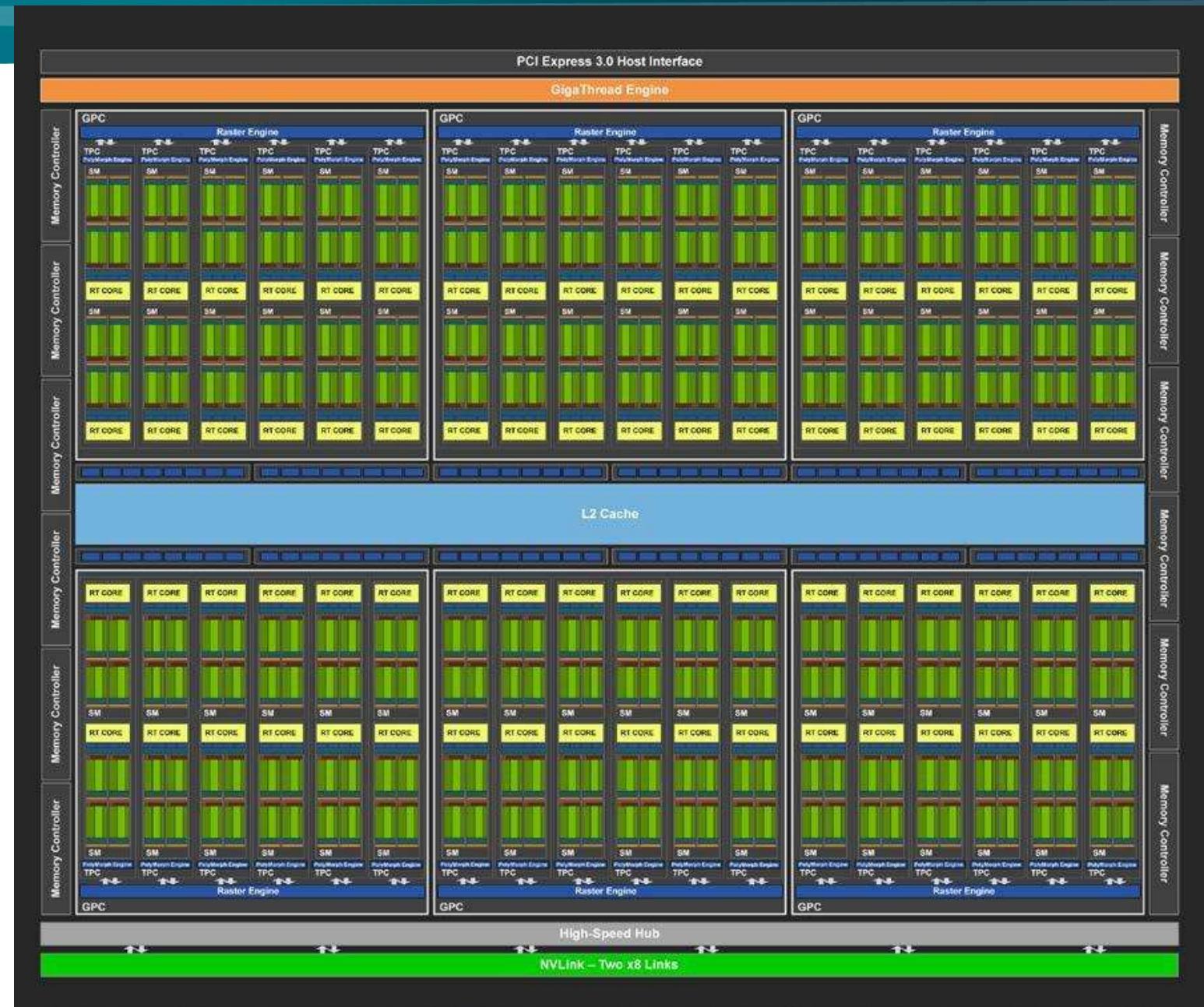
(Geforce:

RTX 2080 Ti,

Quadro:

RTX 6000,

RTX 8000, ...)



NVIDIA Turing Architecture (2018/2019)



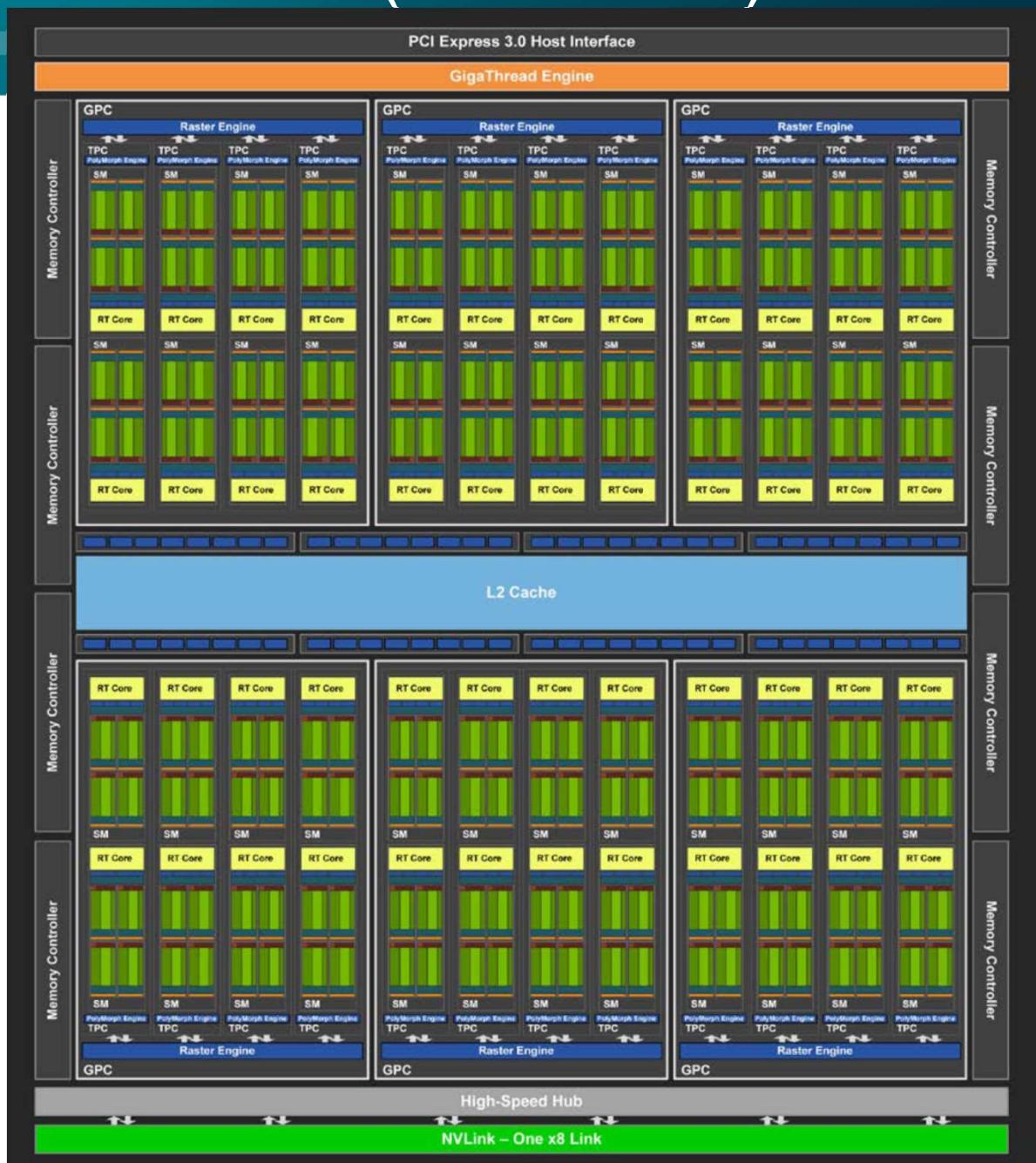
TU 104

(Geforce:

RTX 2080,

Quadro:

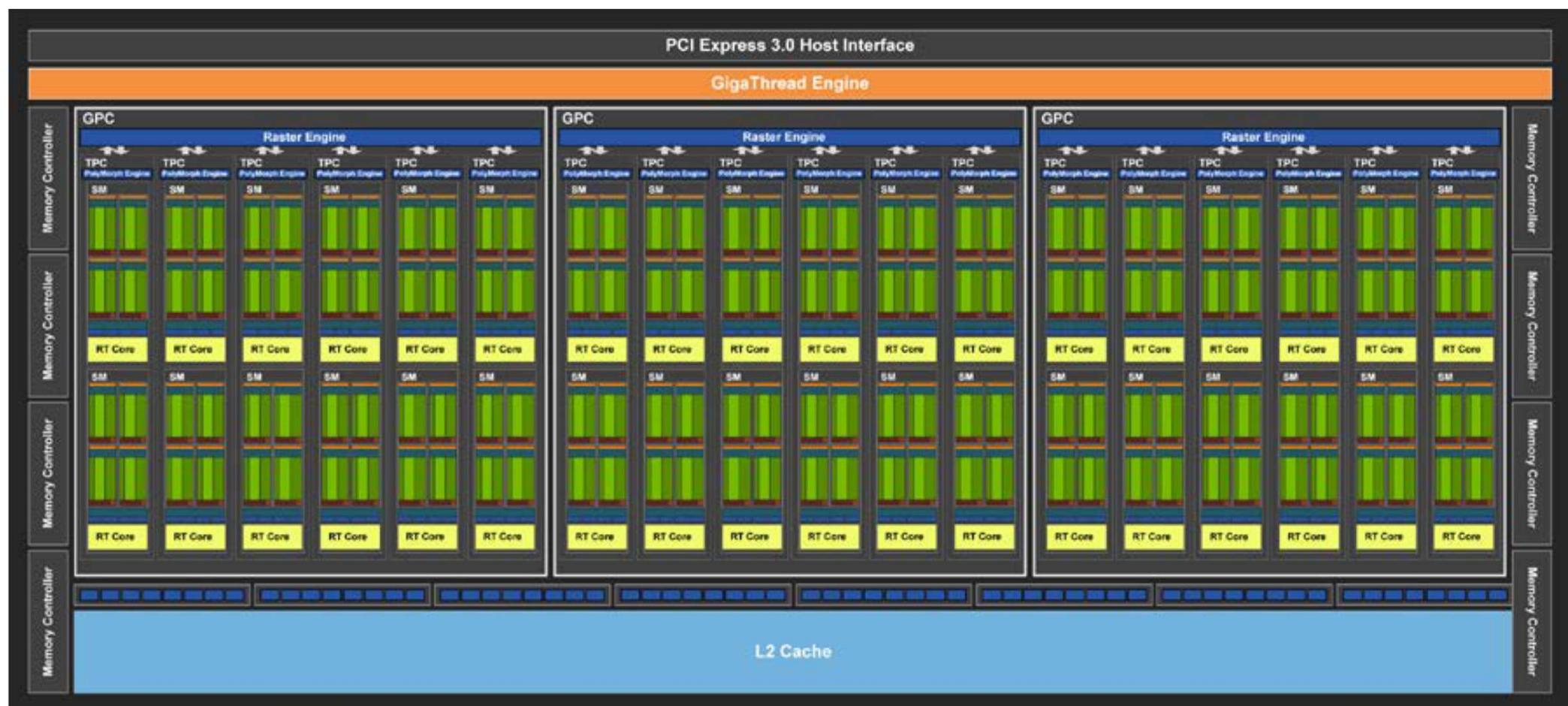
RTX 5000, ...)



NVIDIA Turing Architecture (2018/2019)



TU 106 (Geforce RTX 2070, ...)





Instruction Throughput

Instruction throughput numbers in CUDA C Programming Guide (Chapter 5.4)

	Compute Capability										
	3.5, 3.7	5.0, 5.2	5.3	6.0	6.1	6.2	7.x	8.0	8.6	8.9	9.0
16-bit floating-point add, multiply, multiply-add	N/A		256	128	2	256	128	256	128	256	
							128 for __nv_bfloat16		128 for __nv_bfloat16		
32-bit floating-point add, multiply, multiply-add	192	128		64	128		64		128		
64-bit floating-point add, multiply, multiply-add	64		4	32	4	32	32	2	2	64	
	8 for GeForce GPUs, except for Titan GPUs					2 for compute capability 7.5 GPUs					

ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
# warp sched. / SM	2	2	4	4	2	4	4	4	4
# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L	2L	8L	4L	2L	4L	4L	4L	4L
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP	44 + ILP	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
 performance guidelines/multiprocessor level; compute capabilities

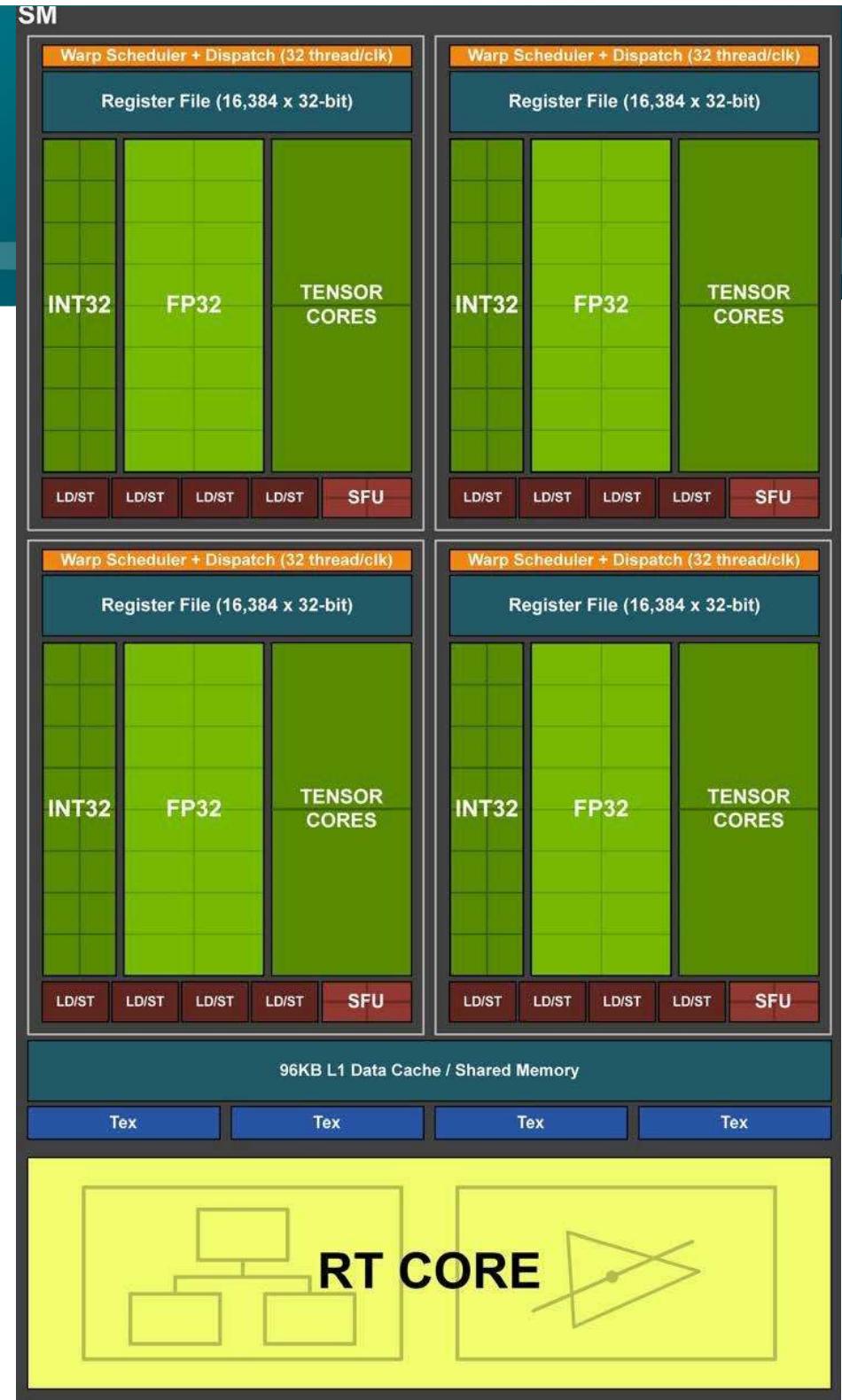
NVIDIA Turing SM

Multiprocessor: SM (CC 7.5)

- 64 FP32 + INT32 cores
- 2 (!) FP64 cores
- 8 Turing tensor cores
(FP16/32, INT4/8 mixed-precision)
- 1 RT (ray tracing) core

4 partitions inside SM

- 16 FP32 + INT32 cores each
- 4 LD/ST units; 4 SFUs each
- 2 Turing tensor cores each
- Each has: warp scheduler,
dispatch unit, 16K register file





NVIDIA Ampere Architecture

2020

(compute capability 8.0/8.6/8.7)

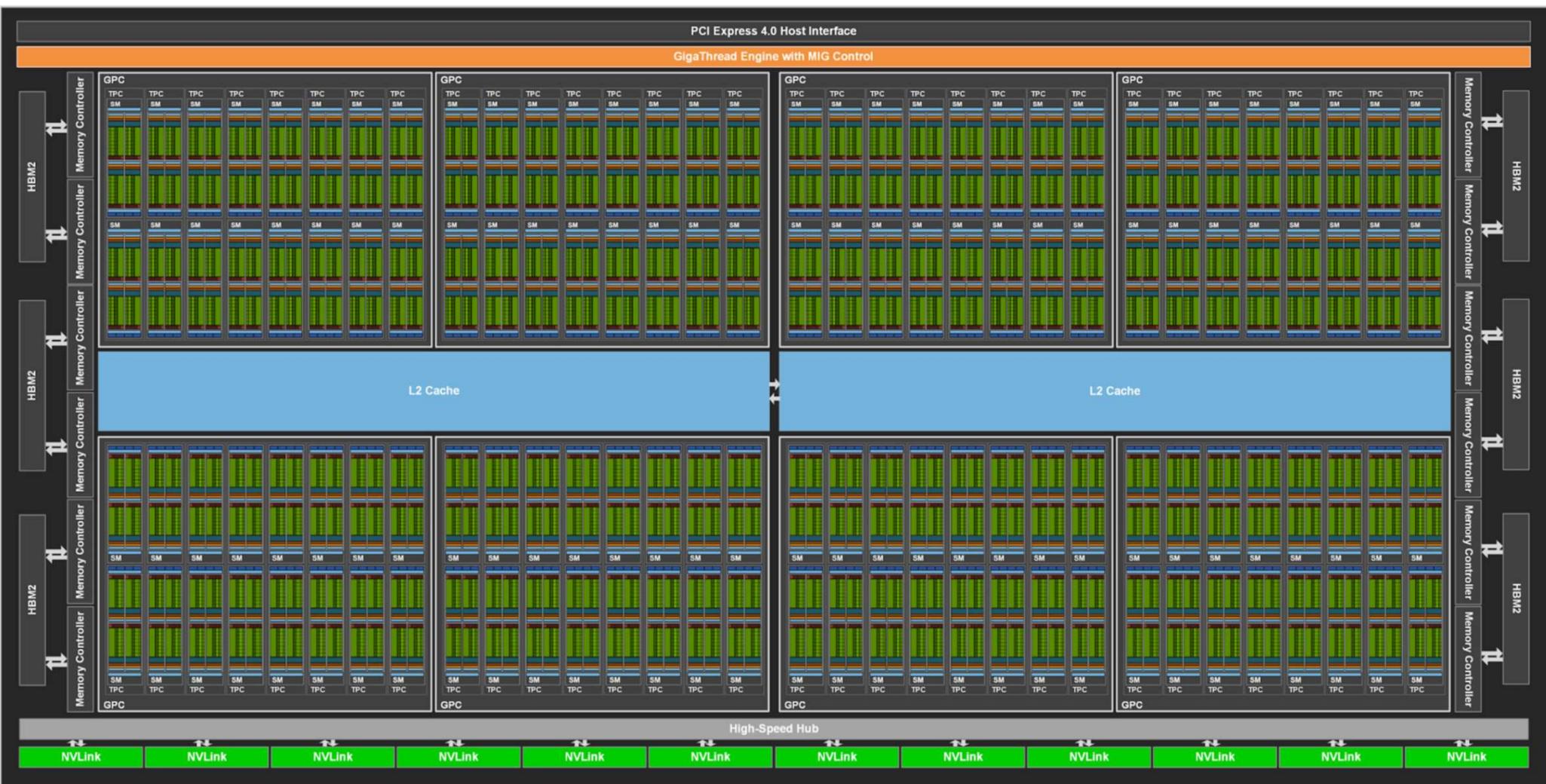
- (x=2,3,4,6,7) GA100 (cc 8.0), ... (A100, ...)
- GA10x (cc 8.6), ... (RTX 3070, RTX 3080, RTX 3090, ...)
- GA10B (cc 8.7), ... (Jetson, DRIVE, ...)

NVIDIA Ampere GA100 Architecture (2020)



GA 100 (A100 Tensor Core GPU)

Full GPU: 128 SMs (in 8 GPCs/64 TPCs)





Instruction Throughput

Instruction throughput numbers in CUDA C Programming Guide (Chapter 5.4)

	Compute Capability										
	3.5, 3.7	5.0, 5.2	5.3	6.0	6.1	6.2	7.x	8.0	8.6	8.9	9.0
16-bit floating-point add, multiply, multiply-add	N/A		256	128	2	256	128	256	128	256	128 for __nv_bfloat16
32-bit floating-point add, multiply, multiply-add	192	128		64	128		64		128		128 for __nv_bfloat16
64-bit floating-point add, multiply, multiply-add	64		4	32	4		32	32	2	2	64

8 for GeForce GPUs, except for Titan GPUs

2 for compute capability 7.5 GPUs

ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
# warp sched. / SM	2	2	4	4	2	4	4	4	4
# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L	2L	8L	4L	2L	4L	4L	4L	4L
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP	44 + ILP	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
 performance guidelines/multiprocessor level; compute capabilities

NVIDIA GA100 SM

Multiprocessor: SM (CC 8.0)

- 64 FP32 + 64 INT32 cores
- 32 FP64 cores
- 4 3rd gen tensor cores
- 1 2nd gen RT (ray tracing) core

4 partitions inside SM

- 16 FP32 + 16 INT32 cores
- 8 FP64 cores
- 8 LD/ST units; 4 SFUs each
- 1 3rd gen tensor core each
- Each has: warp scheduler, dispatch unit, 16K register file



NVIDIA Ampere GA10x Architecture (2020)



GA 102 (RTX 3070, 3080, 3090)

Full GPU: 84 SMs (in 7 GPCs/42 TPCs)



NVIDIA GA10x SM

Multiprocessor: SM (CC 8.6)

- 128₍₆₄₊₆₄₎ FP32 + 64 INT32 cores
- 2 (!) FP64 cores
- 4 3rd gen tensor cores
- 1 2nd gen RT (ray tracing) core

4 partitions inside SM

- 32₍₁₆₊₁₆₎ FP32 + 16 INT32 cores
- 4 LD/ST units; 4 SFUs each
- 1 3rd gen tensor core each
- Each has: warp scheduler, dispatch unit, 16K register file



Specs CC 3.5 – 9.0



Ampere: 8.0, 8.6, 8.7
(8.9 / Ada missing in table)

(CUDA C Programming Guide
11.8, Table 15)

Technical Specifications	Compute Capability														
	3.5	3.7	5.0	5.2	5.3	6.0	6.1	6.2	7.0	7.2	7.5	8.0	8.6	8.7	9.0
Maximum number of resident grids per device <small>[Concurrent Kernel Execution]</small>	32		16	128	32	16	128	16				128			
Maximum dimensionality of grid of thread blocks												3			
Maximum x-dimension of a grid of thread blocks												$2^{31}-1$			
Maximum y- or z-dimension of a grid of thread blocks												65535			
Maximum dimensionality of a thread block												3			
Maximum x- or y-dimension of a block												1024			
Maximum z-dimension of a block												64			
Maximum number of threads per block												1024			
Warp size												32			
Maximum number of resident blocks per SM	16					32						16	32	16	32
Maximum number of resident warps per SM						64						32	64	48	64
Maximum number of resident threads per SM						2048						1024	2048	1536	2048
Number of 32-bit registers per SM	64 K	128 K										64 K			
Maximum number of 32-bit registers per thread block		64 K			32 K	64 K	32 K					64 K			
Maximum number of 32-bit registers per thread												255			

NVIDIA Ampere GA102 Architecture (2020)



GA 102 (RTX 3070, 3080, 3090, A40) Full GPU: 84 SMs (in 7 GPCs/42 TPCs)

- 64K 32-bit registers / SM = 256 KB register storage per SM
- 128 KB shared memory / L1 per SM

For 84 SMs on full GPU [RTX 3090: 82 SMs]

- 21 MB register storage, 10.5 MB shared mem / L1 storage = **31.5 MB context+”shared context” storage !**
- L2 cache size on A40, RTX 3090: 6 MB
- 10,752 FP32 cores (128 FP32 cores per SM) [RTX 3090: 10,496]
- 129,024 max threads in flight (max warps / SM = 48) [RTX 3090: 125,952]

NVIDIA Ampere GA100 Architecture (2020)



GA 100 (A100)

Full GPU: 128 SMs (in 8 GPCs/64 TPCs)

- 64K 32-bit registers / SM = 256 KB register storage per SM
- 192 KB shared memory / L1 per SM

For 128 SMs on full GPU [A100: 108 SMs]

- 32 MB register storage, 24 MB shared mem / L1 storage = **56 MB context+”shared context” storage !**
- L2 cache size on A100: 40 MB
- 8,912 FP32 cores (64 FP32 cores per SM) [A100: 6,912]
- 262,144 max threads in flight (max warps / SM = 64) [A100: 221,184]



Turing vs. Ampere GA102

Graphics Card	GeForce RTX 2080 Founders Edition	GeForce RTX 2080 Super Founders Edition	GeForce RTX 3080 10 GB Founders Edition
GPU Codename	TU104	TU104	GA102
GPU Architecture	NVIDIA Turing	NVIDIA Turing	NVIDIA Ampere
GPCs	6	6	6
TPCs	23	24	34
SMs	46	48	68
CUDA Cores / SM	64	64	128
CUDA Cores / GPU	2944	3072	8704
Tensor Cores / SM	8 (2nd Gen)	8 (2nd Gen)	4 (3rd Gen)
Tensor Cores / GPU	368	384 (2nd Gen)	272 (3rd Gen)
RT Cores	46 (1st Gen)	48 (1st Gen)	68 (2nd Gen)
GPU Boost Clock (MHz)	1800	1815	1710
Peak FP32 TFLOPS (non-Tensor) ¹	10.6	11.2	29.8
Peak FP16 TFLOPS (non-Tensor) ¹	21.2	22.3	29.8
Peak BF16 TFLOPS (non-Tensor) ¹	NA	NA	29.8
Peak INT32 TOPS (non-Tensor) ^{1,3}	10.6	11.2	14.9



Turing vs. Ampere GA102

Peak FP16 Tensor TFLOPS with FP16 Accumulate¹	84.8	89.2	119/238 ²
Peak FP16 Tensor TFLOPS with FP32 Accumulate¹	42.4	44.6	59.5/119 ²
Peak BF16 Tensor TFLOPS with FP32 Accumulate¹	NA	NA	59.5/119 ²
Peak TF32 Tensor TFLOPS¹	NA	NA	29.8/59.5 ²
Peak INT8 Tensor TOPS¹	169.6	178.4	238/476 ²
Peak INT4 Tensor TOPS¹	339.1	356.8	476/952 ²
Frame Buffer Memory Size and Type	8192 MB GDDR6	8192 MB GDDR6	10240 MB GDDR6X
Memory Interface	256-bit	256-bit	320-bit
Memory Clock (Data Rate)	14 Gbps	15.5 Gbps	19 Gbps
Memory Bandwidth	448 GB/sec	496 GB/sec	760 GB/sec
ROPs	64	64	96
Pixel Fill-rate (Gigapixels/sec)	115.2	116.2	164.2
Texture Units	184	192	272
Texel Fill-rate (Gigatexels/sec)	331.2	348.5	465
L1 Data Cache/Shared Memory	4416 KB	4608 KB	8704 KB



Turing vs. Ampere GA102

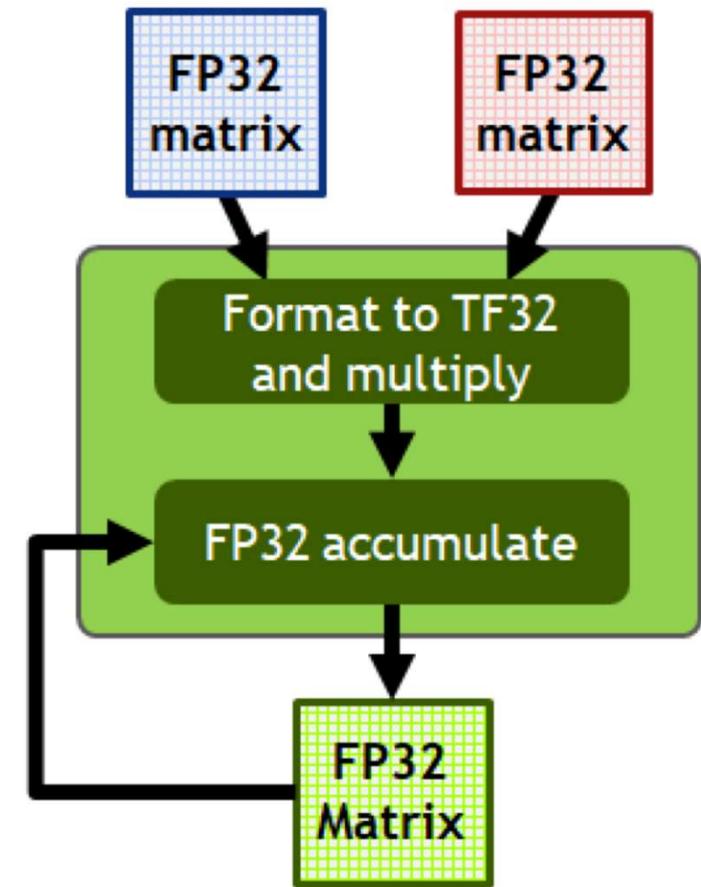
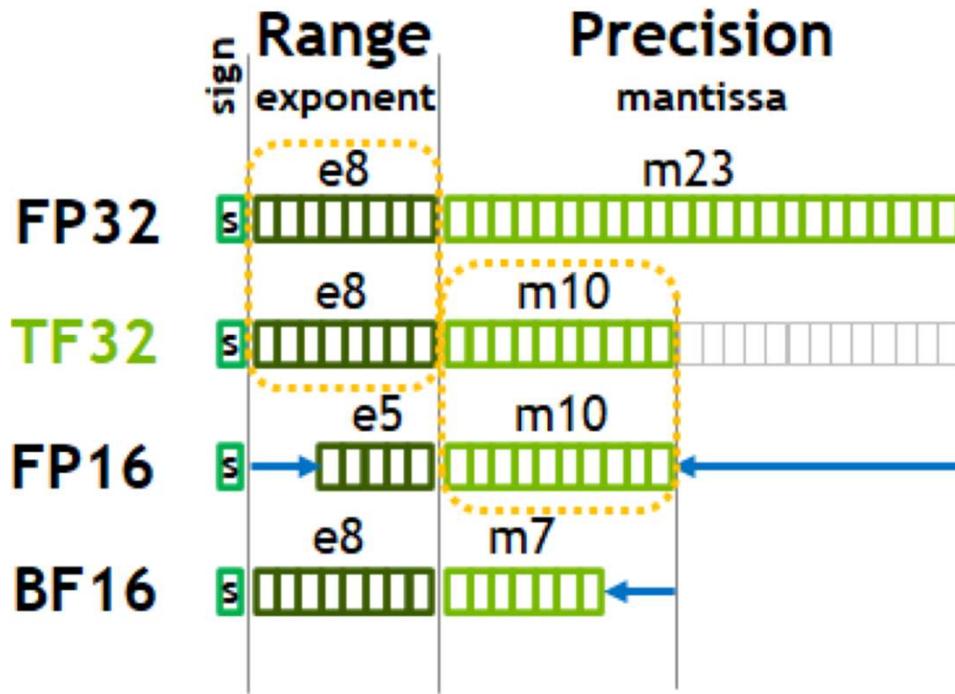
L2 Cache Size	4096 KB	4096 KB	5120 KB
Register File Size	11776 KB	12288 KB	17408 KB
TGP (Total Graphics Power)	225 W	250 W	320W
Transistor Count	13.6 Billion	13.6 Billion	28.3 Billion
Die Size	545 mm ²	545 mm ²	628.4 mm ²
Manufacturing Process	TSMC 12 nm FFN (FinFET NVIDIA)	TSMC 12 nm FFN (FinFET NVIDIA)	Samsung 8 nm 8N NVIDIA Custom Process

1. Peak rates are based on GPU Boost Clock.
2. Effective TOPS / TFLOPS using the new Sparsity Feature
3. TOPS = IMAD-based integer math

Tensor Cores: Many Mixed Precision Options



New in Ampere: TF32, BF16, FP64



plus FP64 (new in Ampere; GA100 only)

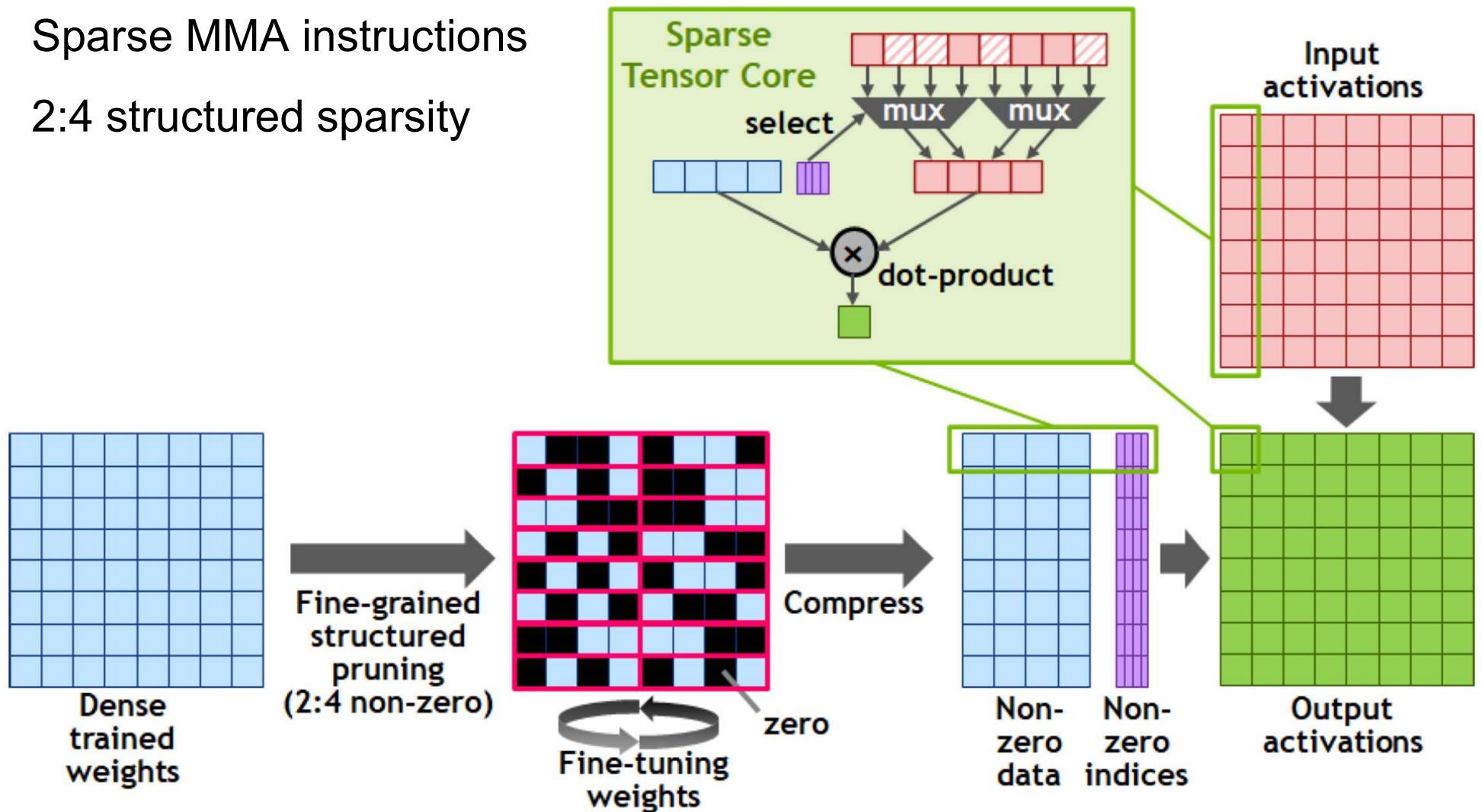
plus INT4/INT8/binary data types (already introduced in Turing)



Tensor Cores: Sparsity Support

Sparse MMA instructions

2:4 structured sparsity





NVIDIA Hopper Architecture

2022

(compute capability 9.0)

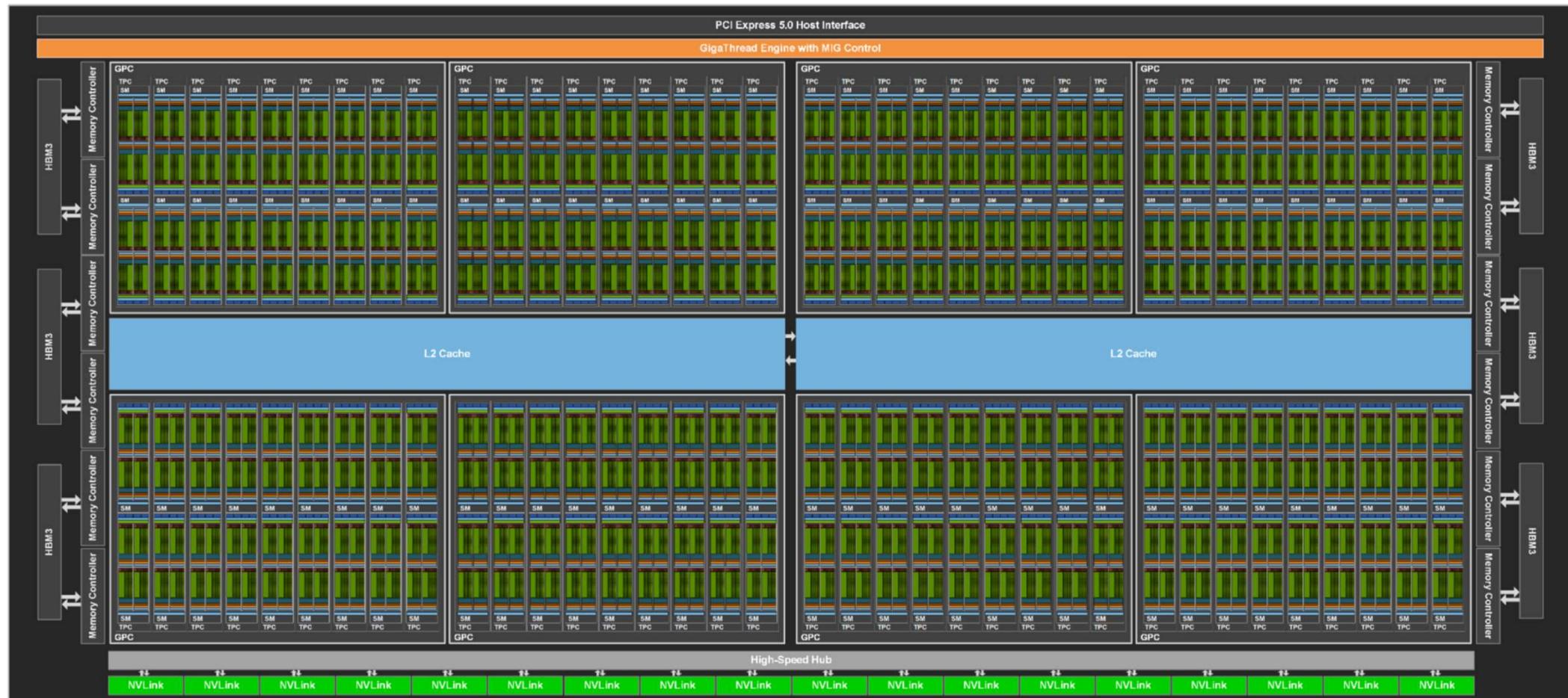
GH100 (cc 9.0), ... (H100, ...)

NVIDIA Hopper GH100 Architecture (2022)



GH 100 (H100 Tensor Core GPU)

Full GPU: 144 SMs (in 8 GPCs/72 TPCs)





Instruction Throughput

Instruction throughput numbers in CUDA C Programming Guide (Chapter 5.4)

	Compute Capability										
	3.5, 3.7	5.0, 5.2	5.3	6.0	6.1	6.2	7.x	8.0	8.6	8.9	9.0
16-bit floating-point add, multiply, multiply-add	N/A		256	128	2	256	128	256	128	256	128 for __nv_bfloat16
32-bit floating-point add, multiply, multiply-add	192		128	64	128		64		128		128 for __nv_bfloat16
64-bit floating-point add, multiply, multiply-add	64		4	32	4		32	32	2	2	64

8 for GeForce GPUs, except for Titan GPUs

2 for compute capability 7.5 GPUs

ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
# warp sched. / SM	2	2	4	4	2	4	4	4	4
# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L	2L	8L	4L	2L	4L	4L	4L	4L
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP	44 + ILP	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
 performance guidelines/multiprocessor level; compute capabilities

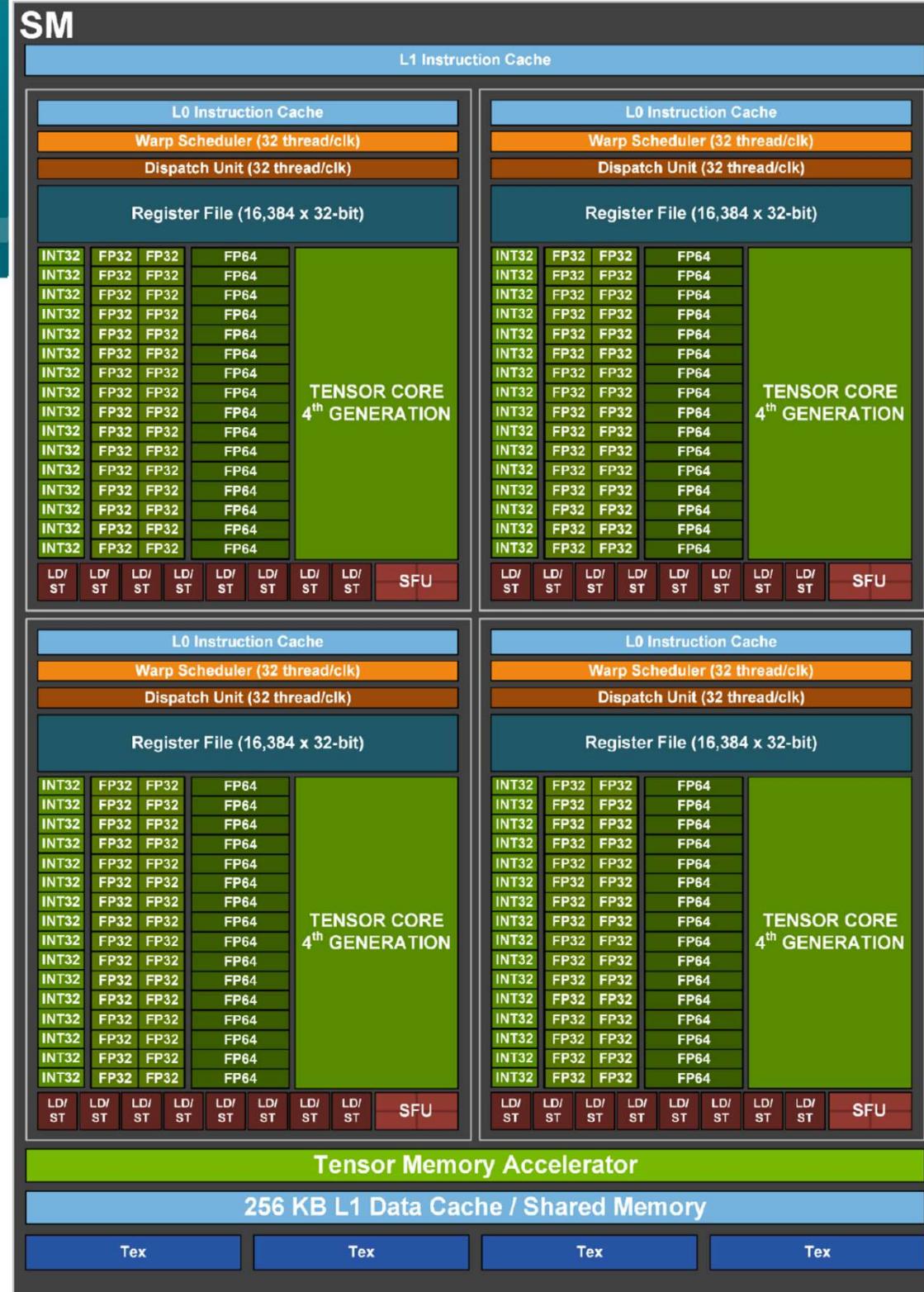
NVIDIA GH100 SM

Multiprocessor: SM (CC 9.0)

- 128 FP32 + 64 INT32 cores
- 64 FP64 cores
- 4x 4th gen tensor cores
- ++ thread block clusters, DPX insts., FP8, TMA

4 partitions inside SM

- 32 FP32 + 16 INT32 cores
- 16 FP64 cores
- 8x LD/ST units; 4 SFUs each
- 1x 4th gen tensor core each
- Each has: warp scheduler, dispatch unit, 16K register file



NVIDIA Hopper GH100 Architecture (2022)



GH 100 (H100)

Full GPU: 144 SMs (in 8 GPCs/72 TPCs)

- 64K 32-bit registers / SM = 256 KB register storage per SM
- 256 KB shared memory / L1 per SM

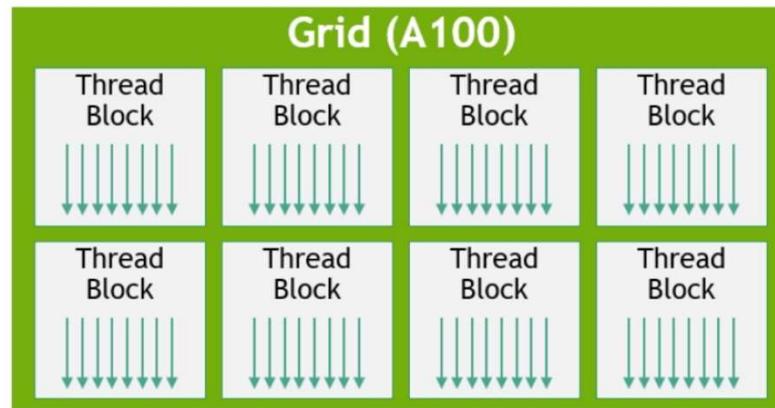
For 144 SMs on full GPU [SXM5: 132; PCIe: 114]

- 36 MB register storage, 36 MB shared mem / L1 storage = **72 MB context+”shared context” storage !**
- L2 cache size on H100: 50 MB
- 18,432 FP32 cores (128 FP32 cores per SM) [SXM5: 16,896]
- 294,912 max threads in flight (max warps / SM = 64) [SXM5: 270,336]

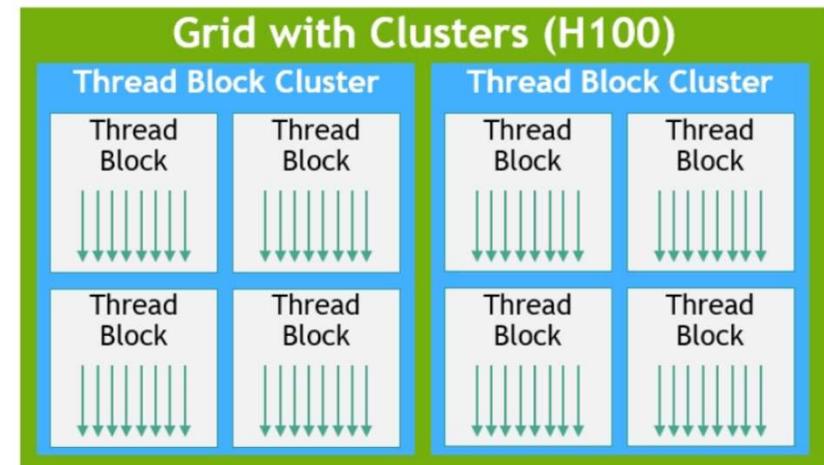
New in CC 9.0: Thread Block Clusters



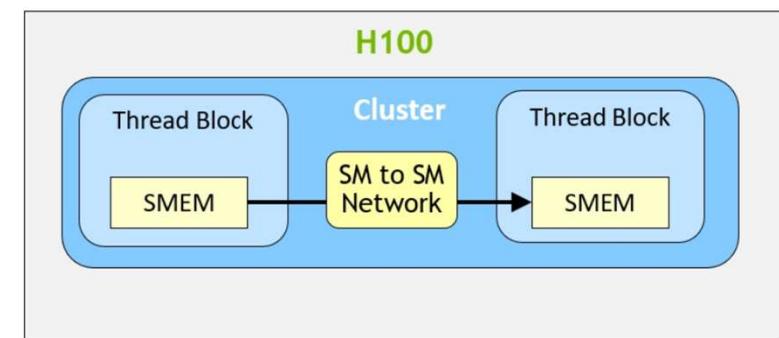
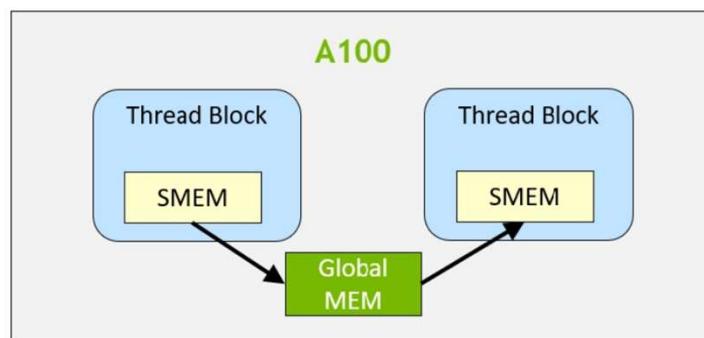
New thread hierarchy level!



all threads of a block are on the same SM !



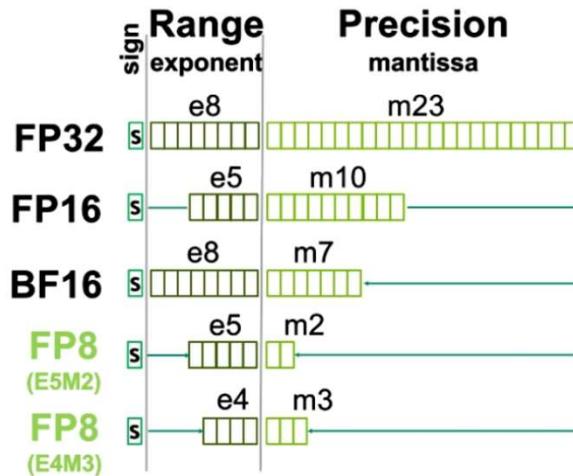
all blocks of a cluster are on the same GPC !



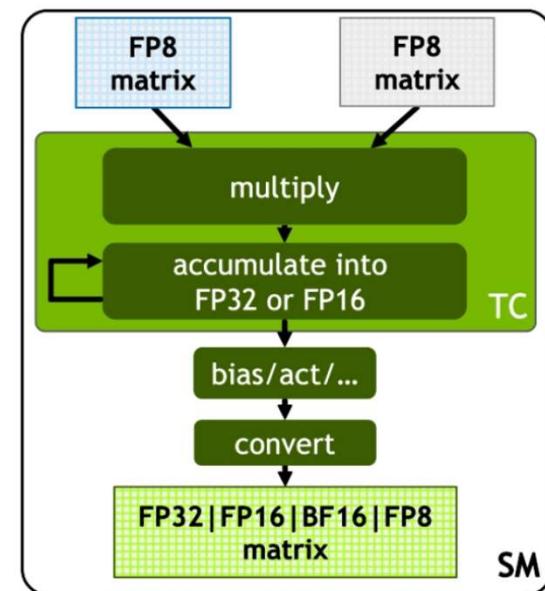
Tensor Cores: More Mixed Precision Options



New in Hopper: FP8



Allocate 1 bit to either range or precision



Support for multiple accumulator and output types

plus other data types from before (INT4/INT8/binary, ...)



Tensor Cores: Hopper vs. Ampere

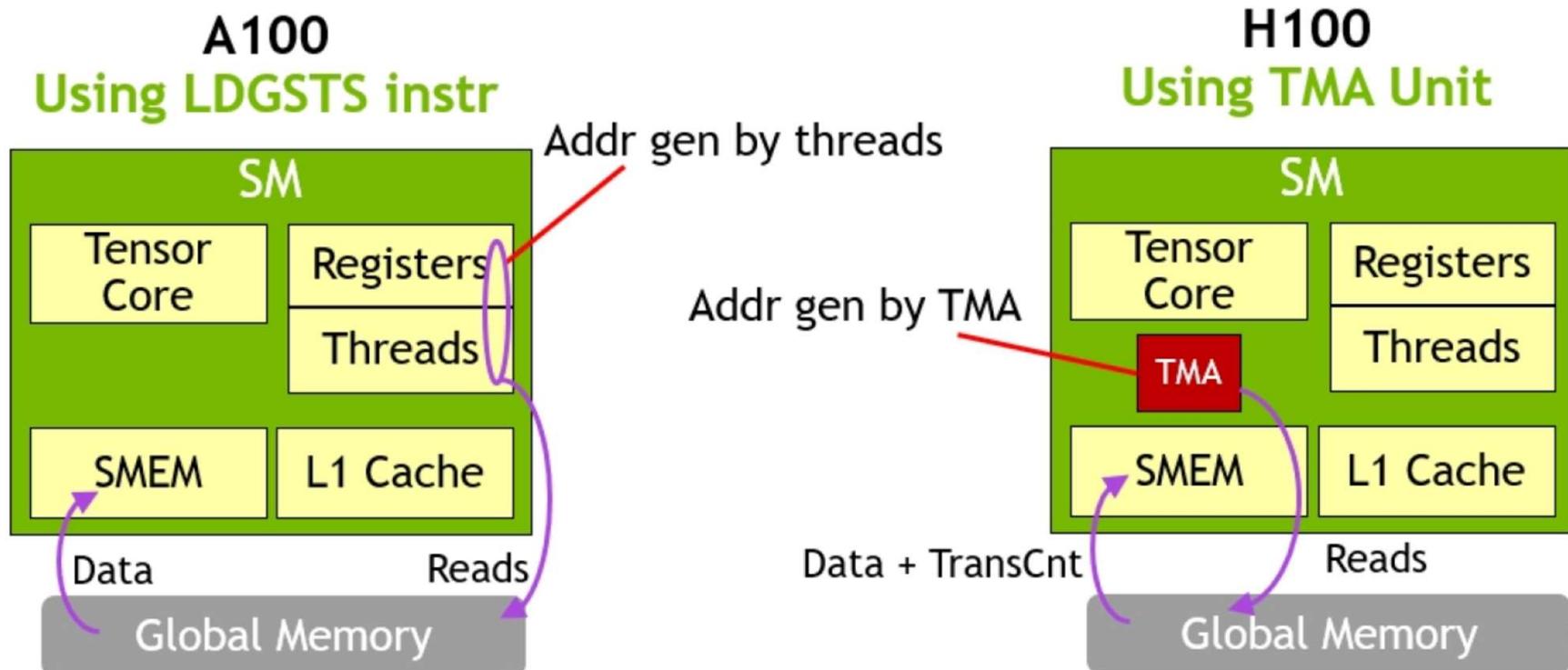
(preliminary)

	A100	A100 Sparse	H100 SXM5 ¹	H100 SXM5 ¹ Sparse	H100 SXM5 ¹ Speedup vs A100
FP8 Tensor Core	NA	NA	2000 TFLOPS	4000 TFLOPS	6.4x vs A100 FP16
FP16	78 TFLOPS	NA	120 TFLOPS	NA	1.5x
FP16 Tensor Core	312 TFLOPS	624 TFLOPS	1000 TFLOPS	2000 TFLOPS	3.2x
BF16 Tensor Core	312 TFLOPS	624 TFLOPS	1000 TFLOPS	2000 TFLOPS	3.2x
FP32	19.5 TFLOPS	NA	60 TFLOPS	NA	3.1x
TF32 Tensor Core	156 TFLOPS	312 TFLOPS	500 TFLOPS	1000 TFLOPS	3.2x
FP64	9.7 TFLOPS	NA	30 TFLOPS	NA	3.1x
FP64 Tensor Core	19.5 TFLOPS	NA	60 TFLOPS	NA	3.1x
INT8 Tensor Core	624 TOPS	1248 TOPS	2000 TFLOPS	4000 TFLOPS	3.2x



Tensor Memory Accelerator (TMA)

Asynchronous transfers





Hopper vs. Ampere (1)

(preliminary)

GPU Features	NVIDIA A100	NVIDIA H100 SXM5 ¹	NVIDIA H100 PCIe ¹
GPU Architecture	NVIDIA Ampere	NVIDIA Hopper	NVIDIA Hopper
GPU Board Form Factor	SXM4	SXM5	PCIe Gen 5
SMs	108	132	114
TPCs	54	66	57
FP32 Cores / SM	64	128	128
FP32 Cores / GPU	6912	16896	14592
FP64 Cores / SM (excl. Tensor)	32	64	64
FP64 Cores / GPU (excl. Tensor)	3456	8448	7296
INT32 Cores / SM	64	64	64
INT32 Cores / GPU	6912	8448	7296
Tensor Cores / SM	4	4	4
Tensor Cores / GPU	432	528	456
GPU Boost Clock (Not Finalized for H100) ³	1410 MHz	Not Finalized	Not Finalized



Hopper vs. Ampere (2)

(preliminary)

GPU Features	NVIDIA A100	NVIDIA H100 SXM ¹	NVIDIA H100 PCIe ¹
Texture Units	432	528	456
Memory Interface	5120-bit HBM2	5120-bit HBM3	5120-bit HBM2e
Memory Size	40 GB	80 GB	80 GB
Memory Data Rate ¹	1215 MHz DDR	Not Finalized	Not Finalized
Memory Bandwidth (Not Finalized for H100) ¹	1555 GB/sec	3000 GB/sec	2000 GB/sec
L2 Cache Size	40 MB	50 MB	50 MB
Shared Memory Size / SM	Configurable up to 164 KB	Configurable up to 228 KB	Configurable up to 228 KB
Register File Size / SM	256 KB	256 KB	256 KB
Register File Size / GPU	27648 KB	33792 KB	29184 KB
TDP ¹	400 Watts	700 Watts	350 Watts
Transistors	54.2 billion	80 billion	80 billion
GPU Die Size	826 mm ²	814 mm ²	814 mm ²
TSMC Manufacturing Process	7 nm N7	4N customized for NVIDIA	4N customized for NVIDIA



Compute Capabilities

Data Center GPU	NVIDIA Tesla V100	NVIDIA A100	NVIDIA H100
GPU Architecture	NVIDIA Volta	NVIDIA Ampere	NVIDIA Hopper
Compute Capability	7.0	8.0	9.0
Threads / Warp	32	32	32
Max Warps / SM	64	64	64
Max Threads / SM	2048	2048	2048
Max Thread Blocks (CTAs) / SM	32	32	32
Max Thread Blocks / Thread Block Clusters	NA	NA	16
Max 32-bit Registers / SM	65536	65536	65536
Max Registers / Thread Block (CTA)	65536	65536	65536
Max Registers / Thread	255	255	255
Max Thread Block Size (# of threads)	1024	1024	1024
FP32 Cores / SM	64	64	128
Ratio of SM Registers to FP32 Cores	1024	1024	512
Shared Memory Size / SM	Configurable up to 96 KB	Configurable up to 164 KB	Configurable up to 228 KB



NVIDIA Ada Lovelace Architecture

2022/2023

(compute capability 8.9)

GA10x (cc 8.9), ... (RTX 4080 12 GB, RTX 4080 16GB,
(x=2,3,4,6,7) RTX 4090, RTX 6000, L40, ...)



NVIDIA Ada Lovelace AD10x Architecture (2022)

Full AD 10x

Full GPU: 144 SMs (in 12 GPCs/72 TPCs)





NVIDIA Ada Lovelace AD102 Architecture (2022)

AD 102 (RTX 4090, ...)

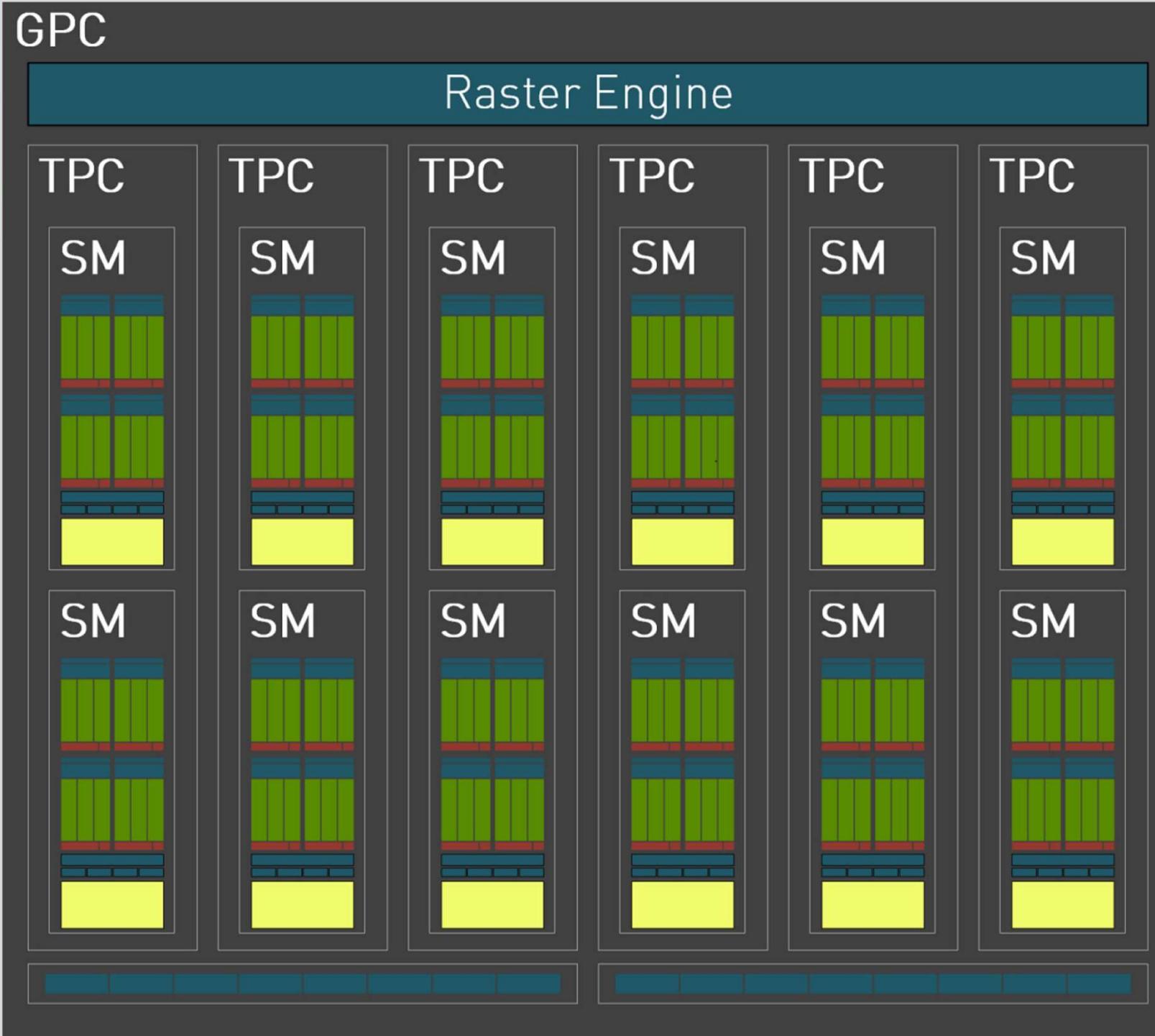
Full RTX 4090: 128 SMs (in 11 GPCs/64 TPCs)



GPC

Full GPC

- 6 TPCs
- 12 SMs
- 16 ROPs





Instruction Throughput

Instruction throughput numbers in CUDA C Programming Guide (Chapter 5.4)

	Compute Capability										
	3.5, 3.7	5.0, 5.2	5.3	6.0	6.1	6.2	7.x	8.0	8.6	8.9	9.0
16-bit floating-point add, multiply, multiply-add	N/A		256	128	2	256	128	256	128	256	128 for __nv_bfloat16
32-bit floating-point add, multiply, multiply-add	192		128	64	128		64		128		128 for __nv_bfloat16
64-bit floating-point add, multiply, multiply-add	64		4	32	4		32	32	2	2	64

8 for GeForce GPUs, except for Titan GPUs

2 for compute capability 7.5 GPUs

ALU Instruction Latencies and Instructs. / SM



CC	2.0 (Fermi)	2.1 (Fermi)	3.x (Kepler)	5.x (Maxwell)	6.0 (Pascal)	6.1/6.2 (Pascal)	7.x (Volta, Turing)	8.0/8.6 (Ampere)	8.9/9.0 (Ada/Hopper)
# warp sched. / SM	2	2	4	4	2	4	4	4	4
# ALU dispatch / warp sched.	1 (over 2 clocks)	2 (over 2 clocks)	2	1	1	1	1	1	1
SM busy with # warps + inst	L	2L	8L	4L	2L	4L	4L	4L	4L
inst. pipe latency (L)	22	22	11	9	6	6	4	4	4
SM busy with # warps	22	22 + ILP	44 + ILP	36	12	24	16	16	16

see NVIDIA CUDA C Programming Guides (different versions)
 performance guidelines/multiprocessor level; compute capabilities

NVIDIA AD102 SM

Multiprocessor: SM (CC 8.9)

- 128 (64+64) FP32 + 64 INT32 cores
- 2 (!) FP64 cores (not in diagram)
- 4x 4th gen tensor cores
- 1x 3rd gen RT (ray tracing) core
- ++ thread block clusters, FP8, ... (?)

4 partitions inside SM

- 32 (16+16) FP32 + 16 INT32 cores
- 4x LD/ST units; 4 SFUs each
- 1x 4th gen tensor core each
- Each has: warp scheduler, dispatch unit, 16K register file



NVIDIA Ada Lovelace AD10x Architecture (2022)



AD 10x / AD 102 (RTX 4090)

Full GPU: 144 SMs (in 12 GPCs/72 TPCs)

- 64K 32-bit registers / SM = 256 KB register storage per SM
- 128 KB shared memory / L1 per SM

For 144 SMs on full GPU [*RTX 4090: 128; RTX 4080 16GB: 76; RTX 4080 12GB: 60*]

- 36 MB register storage, 18 MB shared mem / L1 storage =
54 MB context+”shared context” storage !
- L2 cache size on RTX 4090: 72 MB
- 18,432 FP32 cores (128 FP32 cores per SM) [*RTX 4090: 16,384*]
- 294,912 max threads in flight (max warps / SM = 64) [*RTX 4090: 262,144*]

Comparisons

RTX GPUs



Graphics Card	GeForce RTX 2080 Ti	GeForce RTX 3090 Ti	GeForce RTX 4090
CUDA Cores	4352	10752	16384
GPCs	6	7	11
TPCs	34	42	64
SMs	68	84	128
GPU Boost Clock (MHz)	1635	1860	2520
FP32 TFLOPS	14.2	40	82.6
Tensor Cores	544 (2nd Gen)	336 (3rd Gen)	512 (4th Gen)
Tensor TFLOPS (FP8)	N/A	N/A	660.6/1321.2 ¹
RT Cores	68 (1st Gen)	84 (2nd Gen)	128 (3rd Gen)
RT TFLOPS	42.9	78.1	191
Texture Units	272	336	512
Texture Fill Rate	444.7	625	1290.2
ROPs	88	112	176
Pixel Fill Rate	143.9	208.3	443.5
Memory Size and Type	11 GB GDDR6	24 GB GDDR6X	24 GB GDDR6X
Memory Clock (Data Rate)	14 Gbps	21 Gbps	21 Gbps
Memory Bandwidth	616 GB/sec	1008 GB/sec	1008 GB/sec



Comparisons

RTX GPUs

Graphics Card	GeForce RTX 2080 Ti	GeForce RTX 3090 Ti	GeForce RTX 4090
L1 Cache/Shared Memory	6528 KB	10752 KB	16384 KB
L2 Cache	5632 KB	6144 KB	73728 KB
TGP	260 W	450 W	450 W
Transistor Count	18.6 Billion	28.3 Billion	76.3 Billion
Die Size	754 mm ²	628.4 mm ²	608.5 mm ²
Manufacturing Process	TSMC 12 nm FFN (FinFET NVIDIA)	Samsung 8 nm 8N NVIDIA Custom Process	TSMC 4N NVIDIA Custom Process

1- Using Sparsity feature

Thank you.