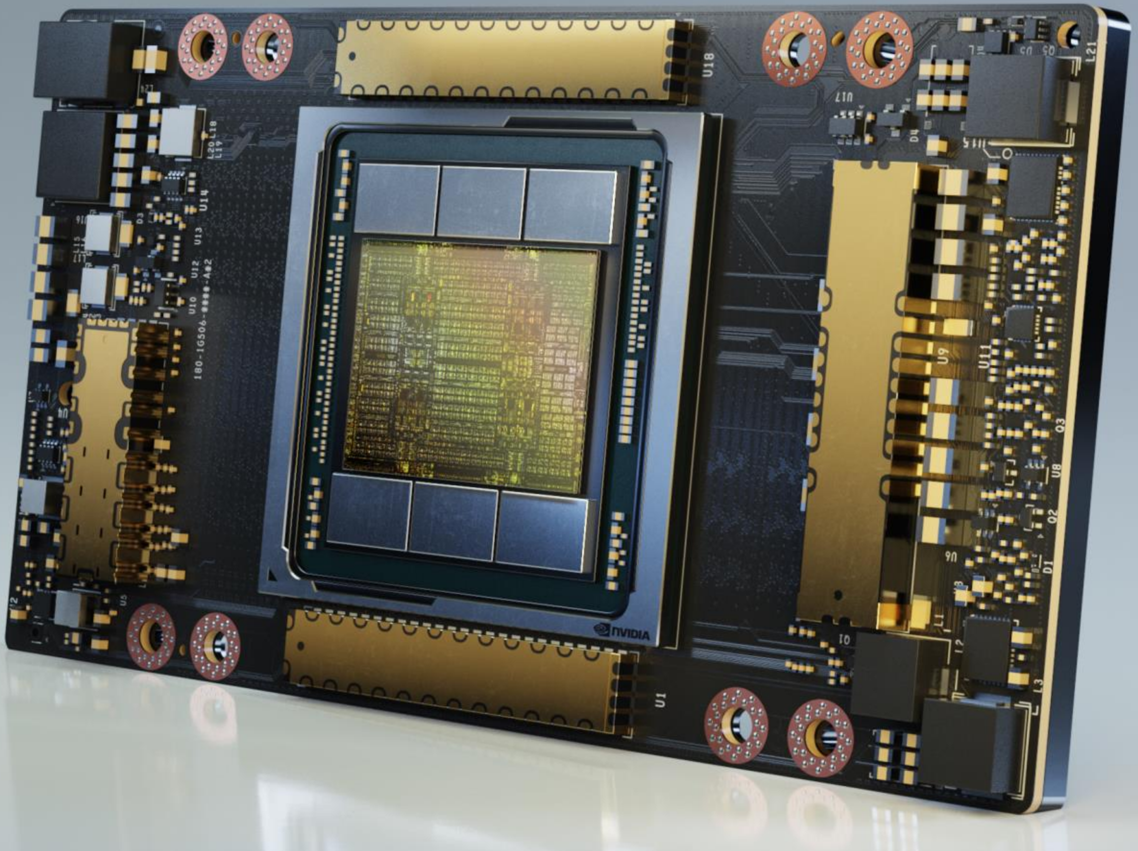
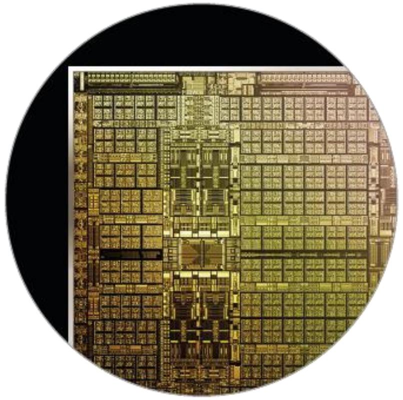
Inside the NVIDIA Ampere Architecture

Ronny Krashinsky, Olivier Giroux
GPU Architects

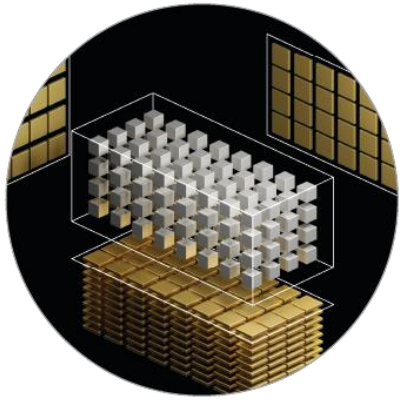
GTC 2020



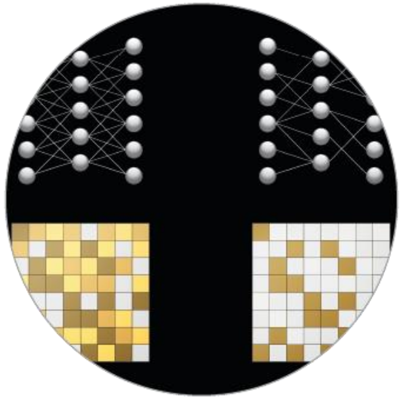
UNPRECEDENTED ACCELERATION AT EVERY SCALE



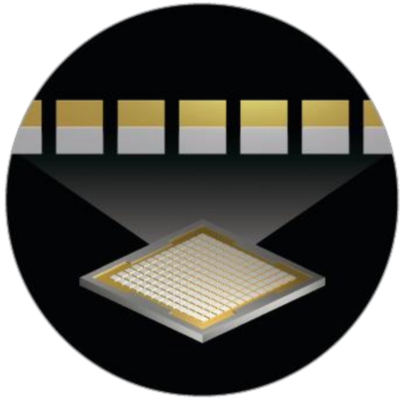
54 BILLION XTORS



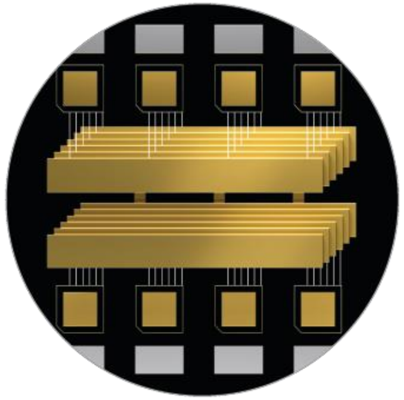
3rd GEN TENSOR CORES



SPARSITY ACCELERATION



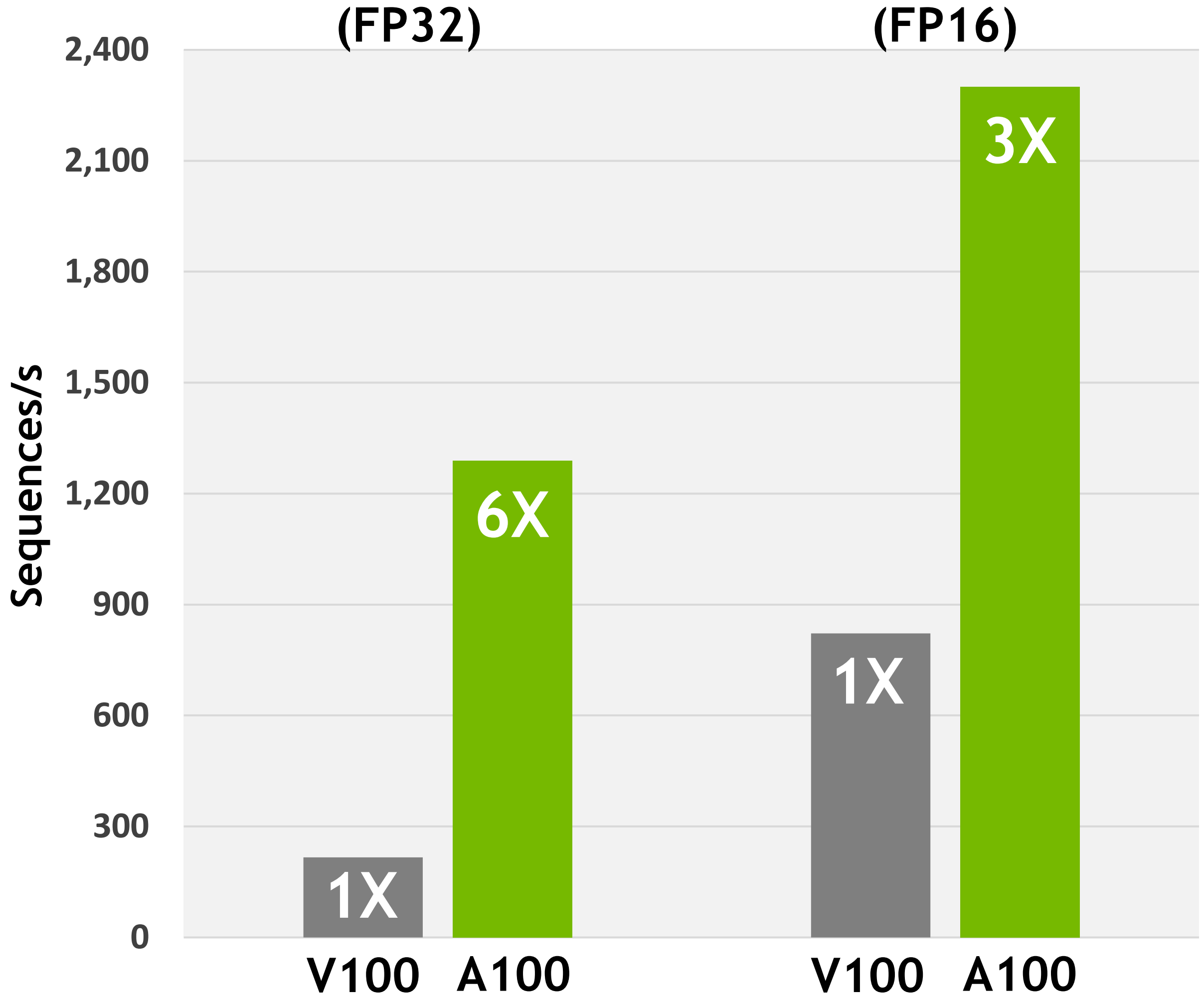
MIG



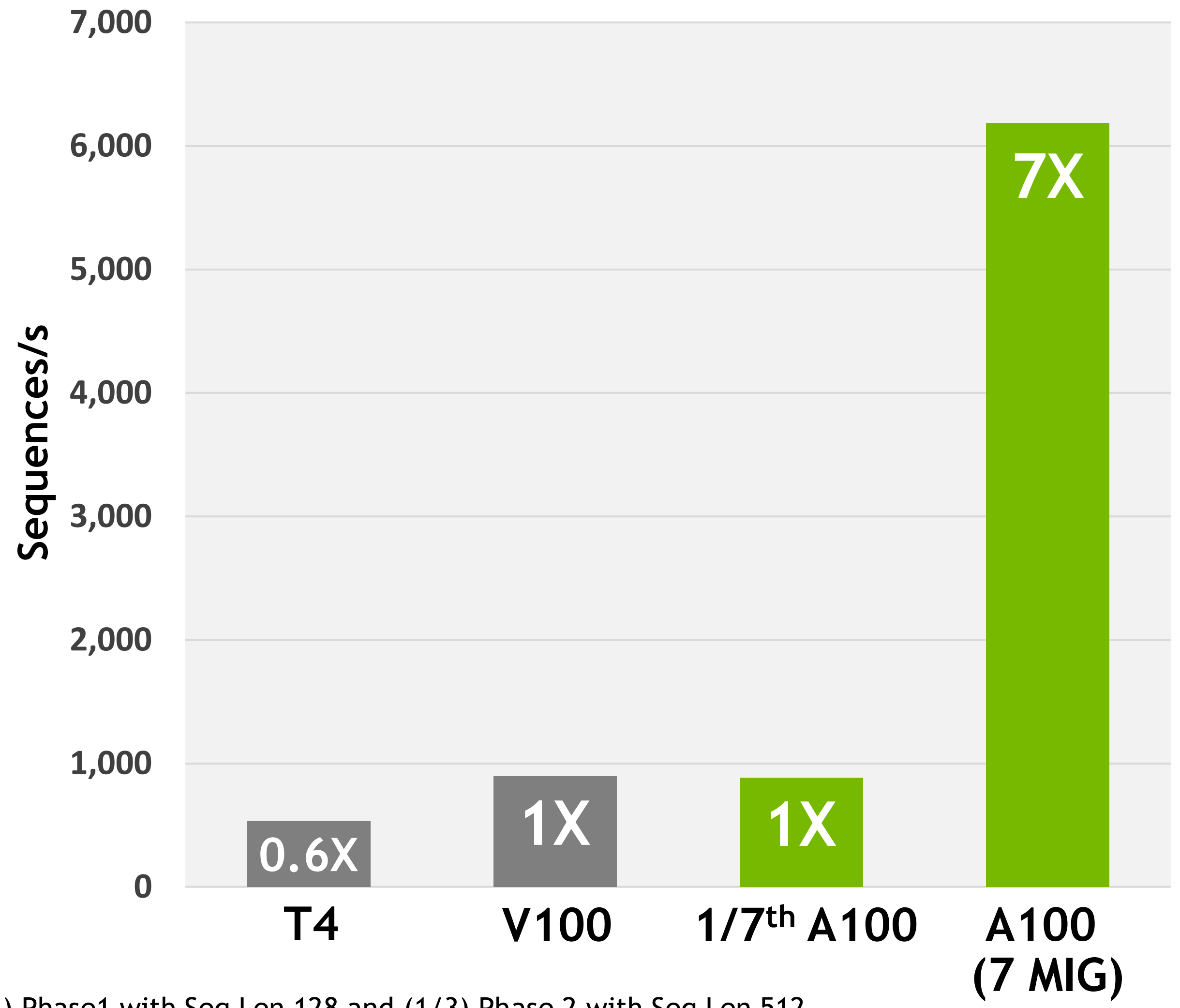
3rd GEN NVLINK & NVSWITCH

UNIFIED AI ACCELERATION

BERT-LARGE TRAINING

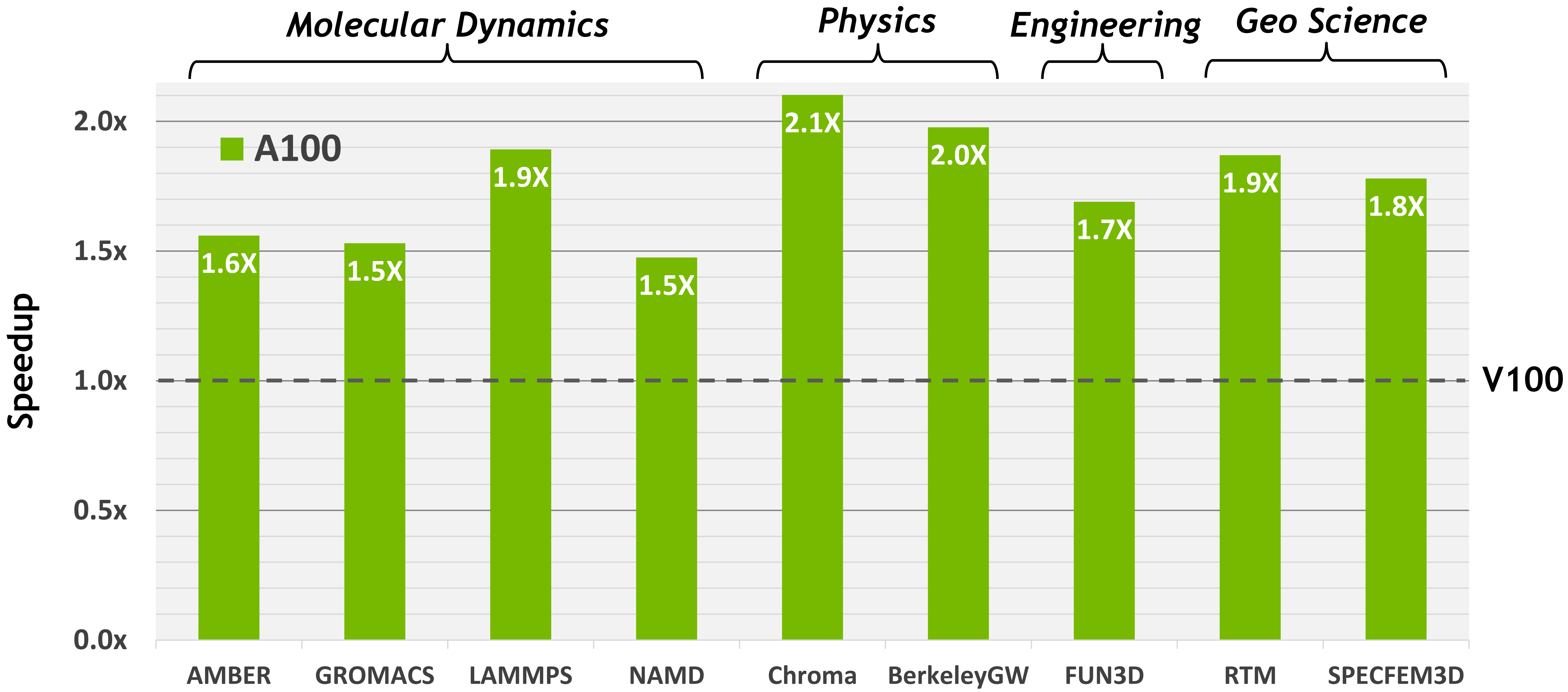


BERT-LARGE INFERENCE



All results are measured
BERT Large Training (FP32 & FP16) measures Pre-Training phase, uses PyTorch including (2/3) Phase1 with Seq Len 128 and (1/3) Phase 2 with Seq Len 512,
V100 is DGX1 Server with 8xV100, A100 is DGX A100 Server with 8xA100, A100 uses TF32 Tensor Core for FP32 training
BERT Large Inference uses TRT 7.1 for T4/V100, with INT8/FP16 at batch size 256. Pre-production TRT for A100, uses batch size 94 and INT8 with sparsity

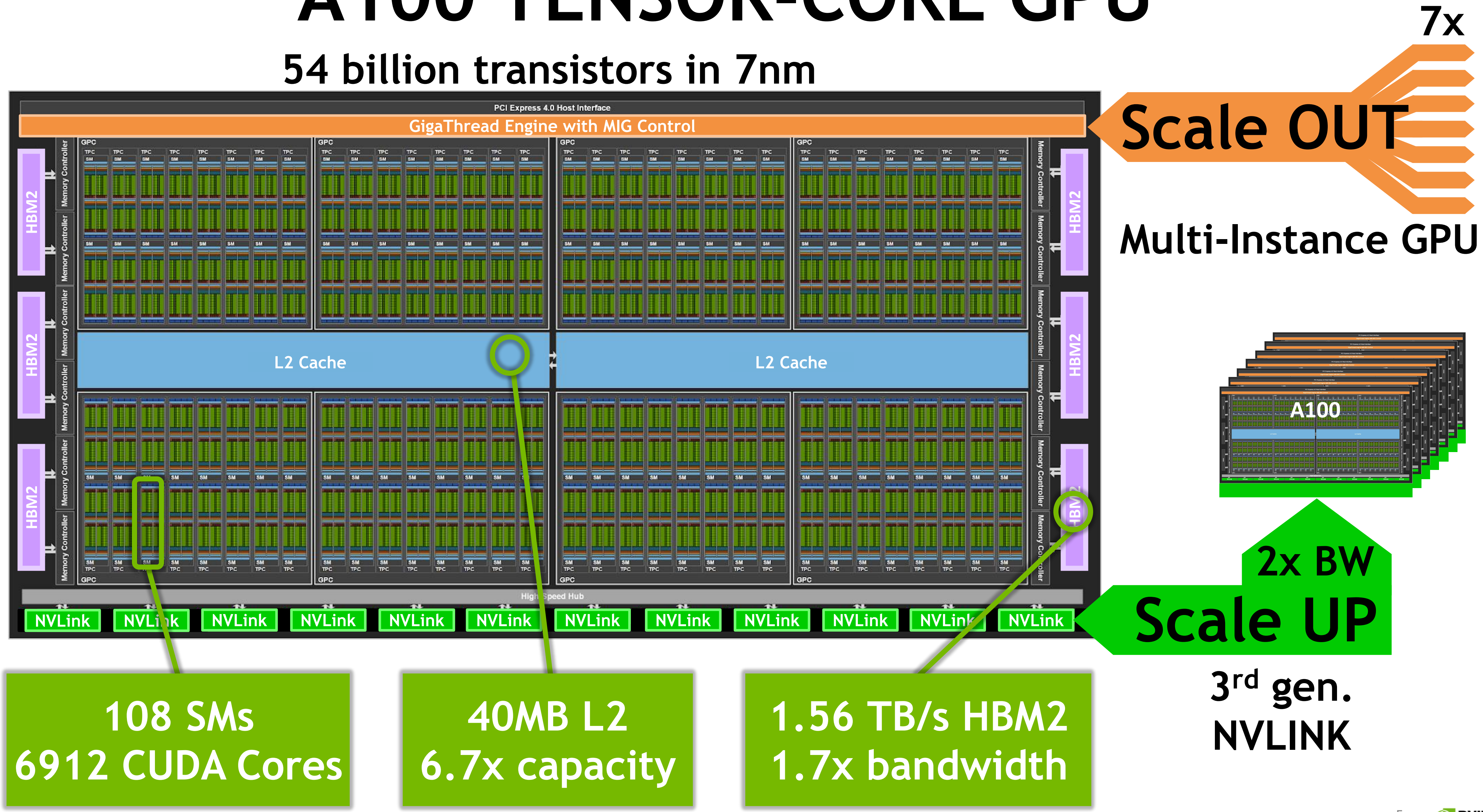
ACCELERATING HPC



All results are measured
Except BerkeleyGW, V100 used is single V100 SXM2. A100 used is single A100 SXM4
More apps detail: AMBER based on PME-Cellulose, GROMACS with STMV (h-bond), LAMMPS with Atomic Fluid LJ-2.5, NAMD with v3.0a1 STMV_NVE
Chroma with szscl21_24_128, FUN3D with dpw, RTM with Isotropic Radius 4 1024^3, SPECFEM3D with Cartesian four material model
BerkeleyGW based on Chi Sum and uses 8xV100 in DGX-1, vs 8xA100 in DGX A100

A100 TENSOR-CORE GPU

54 billion transistors in 7nm



A100 SM

Third-generation Tensor Core

Faster and more efficient

Comprehensive data types

Sparsity acceleration

Asynchronous data movement and synchronization

Increased L1/SMEM capacity

1. New Tensor Core
2. Strong Scaling
3. Elastic GPU
4. Productivity

1. **New Tensor Core**
2. Strong Scaling
3. Elastic GPU
4. Productivity

V100 TENSOR CORE

	INPUT OPERANDS	ACCUMULATOR	TOPS	X-factor vs. FFMA
V100	FP32	FP32	15.7	1x
	FP16	FP32	125	8x

V100

125 TOPS

FF16/FP32 Mixed-precision

8x vs. FFMA

NVIDIA

A100 TENSOR CORE

	INPUT OPERANDS	ACCUMULATOR	TOPS	X-factor vs. FFMA
V100	FP32	FP32	15.7	1x
	FP16	FP32	125	8x
A100	FP32	FP32	19.5	1x
	FP16	FP32	312	16x

V100→A100

2.5x TOPS
FF16/FP32 Mixed-precision

2x TOPS/SM

NVIDIA

A100 TENSOR CORE

	INPUT OPERANDS	ACCUMULATOR	TOPS	X-factor vs. FFMA
V100	FP32	FP32	15.7	1x
	FP16	FP32	125	8x
A100	FP32	FP32	19.5	1x
	TF32	FP32	156	8x
	FP16	FP32	312	16x
	BF16	FP32	312	16x

TF32 accelerates FP32 in/out data → 10x vs. V100 FP32

BFloat16 (BF16) at same rate as FP16

A100 TENSOR CORE

	INPUT OPERANDS	ACCUMULATOR	TOPS	X-factor vs. FFMA
V100	FP32	FP32	15.7	1x
	FP16	FP32	125	8x
A100	FP32	FP32	19.5	1x
	TF32	FP32	156	8x
	FP16	FP32	312	16x
	BF16	FP32	312	16x
	FP16	FP16	312	16x
	INT8	INT32	624	32x
	INT4	INT32	1248	64x
	BINARY	INT32	4992	256x

½ ½ ¼

2x 2x 4x

TOPS track operand width

Inference data types

A100 TENSOR CORE

	INPUT OPERANDS	ACCUMULATOR	TOPS	X-factor vs. FFMA	SPARSE TOPS	SPARSE X-factor vs. FFMA
V100	FP32	FP32	15.7	1x	-	-
	FP16	FP32	125	8x	-	-
A100	FP32	FP32	19.5	1x	-	-
	TF32	FP32	156	8x	312	16x
	FP16	FP32	312	16x	624	32x
	BF16	FP32	312	16x	624	32x
	FP16	FP16	312	16x	624	32x
	INT8	INT32	624	32x	1248	64x
	INT4	INT32	1248	64x	2496	128x
	BINARY	INT32	4992	256x	-	-

With Sparsity *another* 2x, INT8/INT4 reach *petaops*

A100 TENSOR CORE

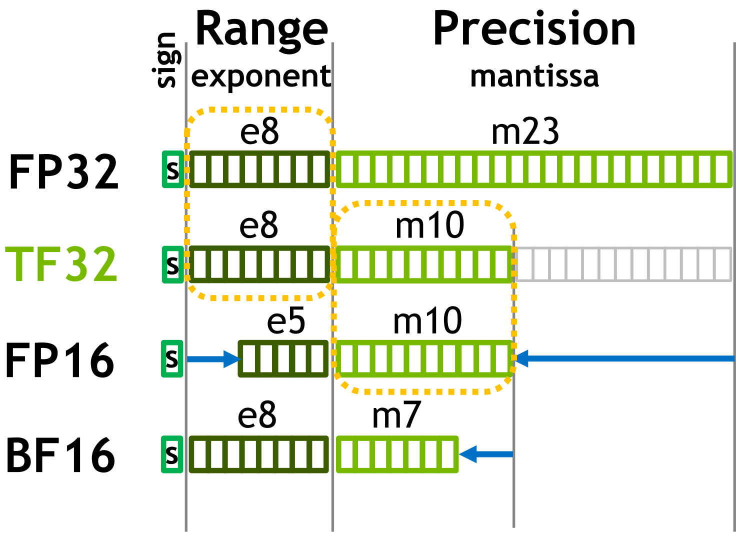
	INPUT OPERANDS	ACCUMULATOR	TOPS	X-factor vs. FFMA	SPARSE TOPS	SPARSE X-factor vs. FFMA
V100	FP32	FP32	15.7	1x	-	-
	FP16	FP32	125	8x	-	-
A100	FP32	FP32	19.5	1x	-	-
	TF32	FP32	156	8x	312	16x
	FP16	FP32	312	16x	624	32x
	BF16	FP32	312	16x	624	32x
	FP16	FP16	312	16x	624	32x
	INT8	INT32	624	32x	1248	64x
	INT4	INT32	1248	64x	2496	128x
	BINARY	INT32	4992	256x		
	IEEE FP64		19.5	1x		

V100→A100
2.5x FLOPS for HPC

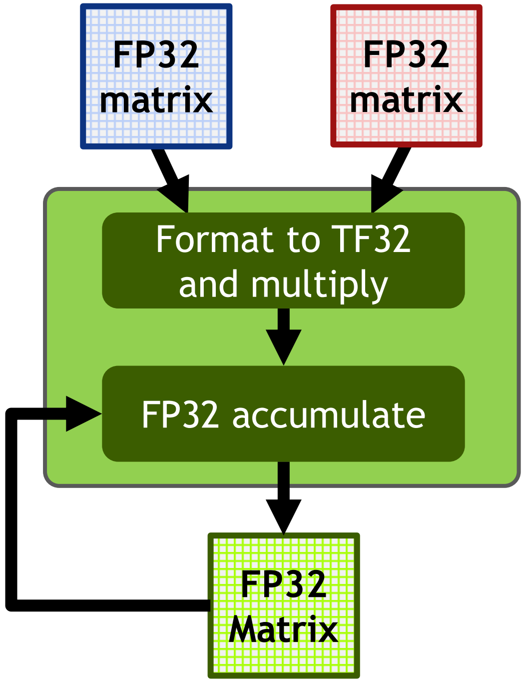
A100 TENSOR CORE

	INPUT OPERANDS	ACCUMULATOR	TOPS	X-factor vs. FFMA	SPARSE TOPS	SPARSE X-factor vs. FFMA
V100	FP32	FP32	15.7	1x	-	-
	FP16	FP32	125	8x	-	-
A100	FP32	FP32	19.5	1x	-	-
	TF32	FP32	156	8x	312	16x
	FP16	FP32	312	16x	624	32x
	BF16	FP32	312	16x	624	32x
	FP16	FP16	312	16x	624	32x
	INT8	INT32	624	32x	1248	64x
	INT4	INT32	1248	64x	2496	128x
	BINARY	INT32	4992	256x	-	-
	IEEE FP64		19.5	1x	-	-

INSIDE A100 TensorFloat-32 (TF32)



Range of FP32 with precision of FP16



FP32 input/output

FP32 storage and math for all activations, gradients, …
everything outside tensor cores

Out-of-the-box tensor core acceleration for DL

Easy step towards maximizing tensor core performance with mixed-precision (FP16, BF16)

Up to 4x speedup on linear solvers for HPC

→S22082: Mixed-Precision Training of Neural Networks, 5/20 2:45pm PDT

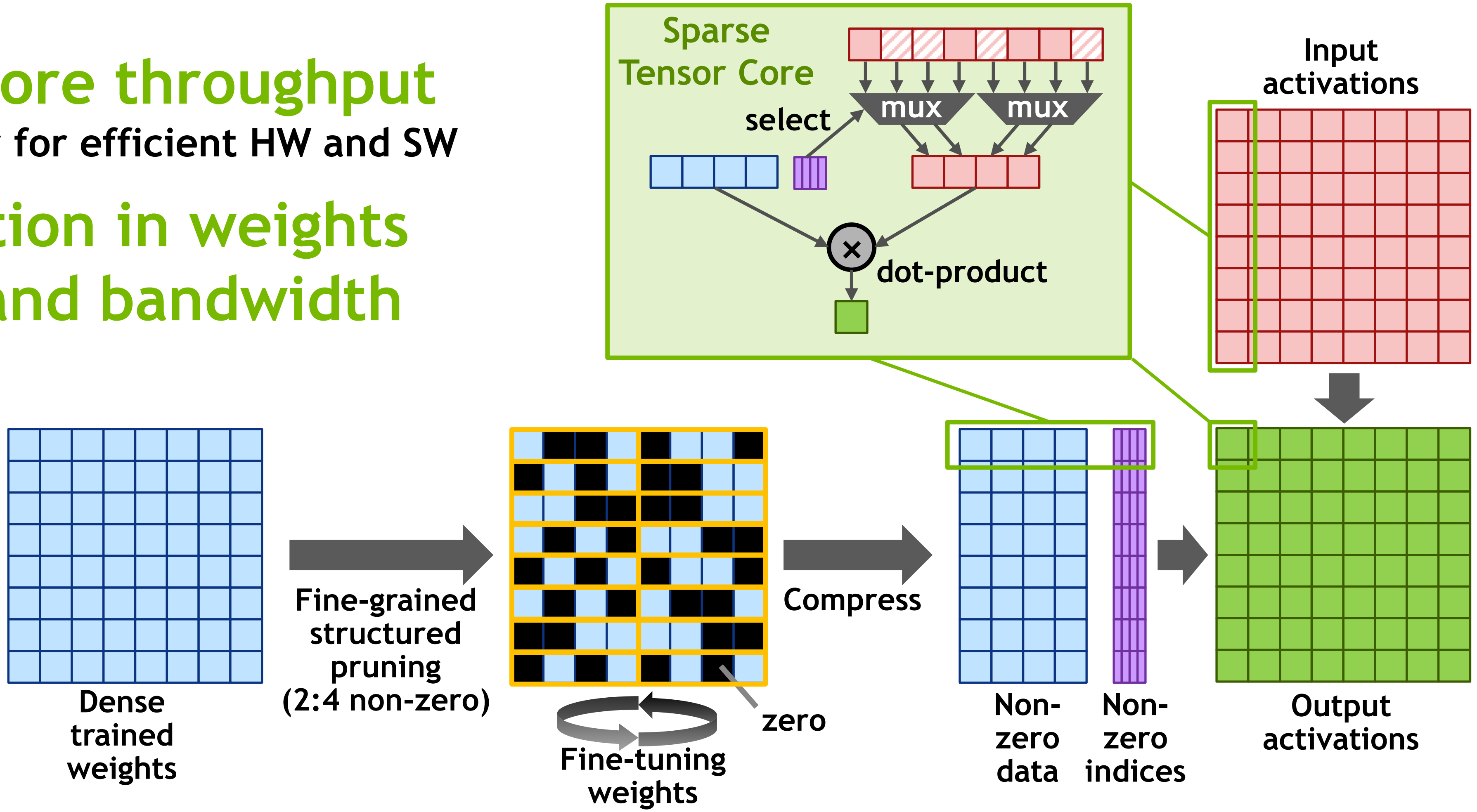
→S21681: How CUDA Math Libraries can help you unleash the power of the new NVIDIA A100 GPU (recording available)

INSIDE A100 SPARSE TENSOR CORE

2x Tensor Core throughput

Structured-sparsity for efficient HW and SW

~2x reduction in weights footprint and bandwidth



~No loss in inferencing accuracy

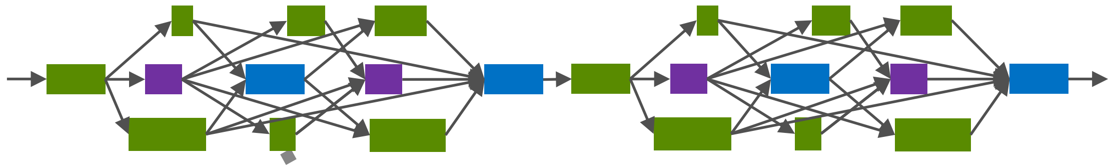
Evaluated across dozens of networks: vision, object detection, segmentation, natural language modeling, translation

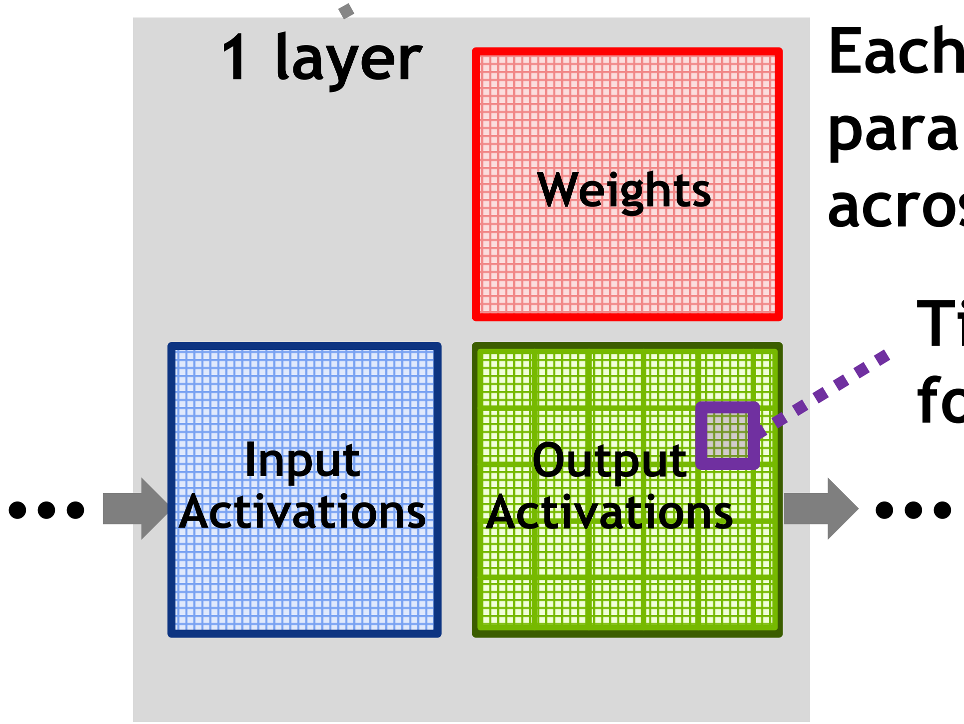
→ S22085: Accelerating Sparsity in the NVIDIA Ampere Architecture, 5/20 1:30pm PDT

1. New Tensor Core
2. **Strong Scaling**
3. Elastic GPU
4. Productivity

DL STRONG SCALING

DL networks:
Long chains of sequentially-dependent compute-intensive layers

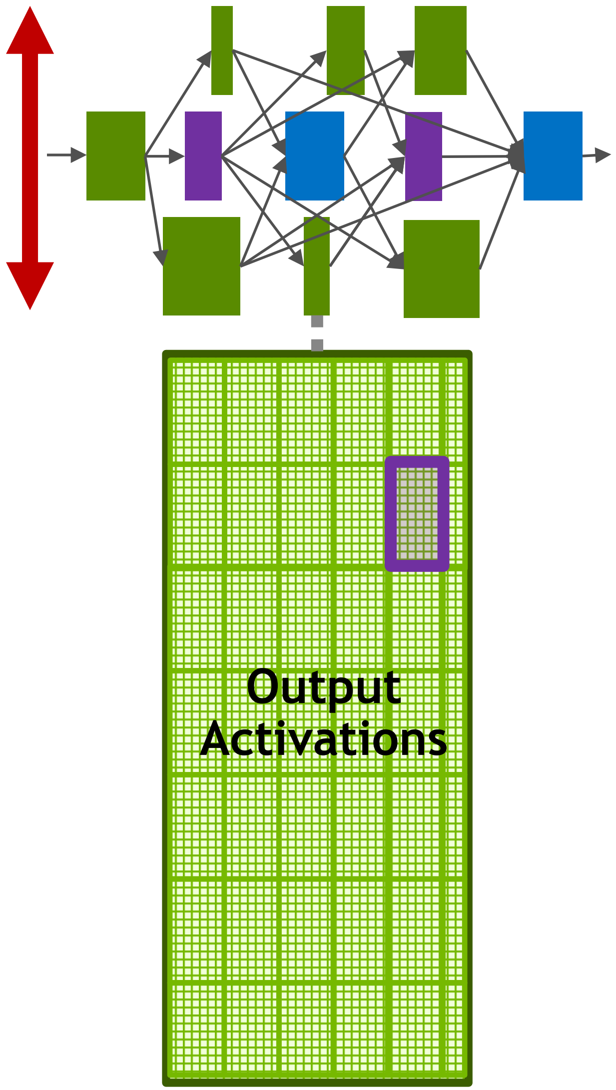




Each layer is parallelized across GPU

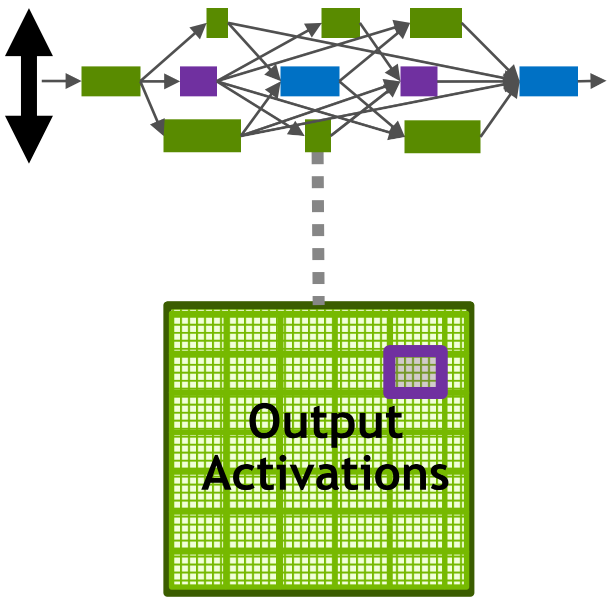
Tile: work for 1 SM

Weak scaling



~2.5x larger network runs in same time

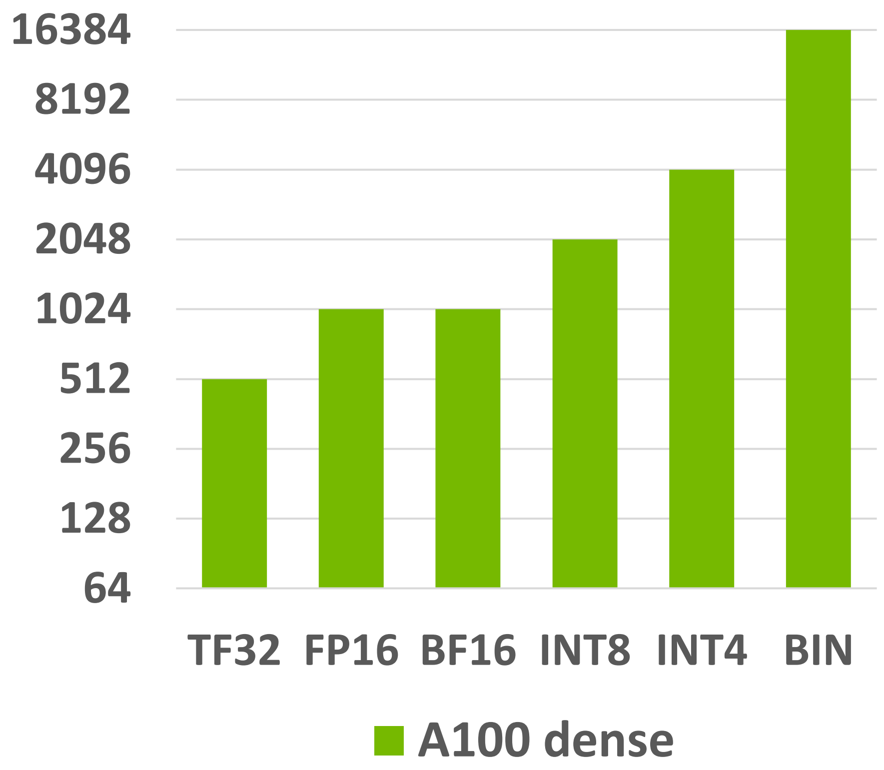
Strong scaling



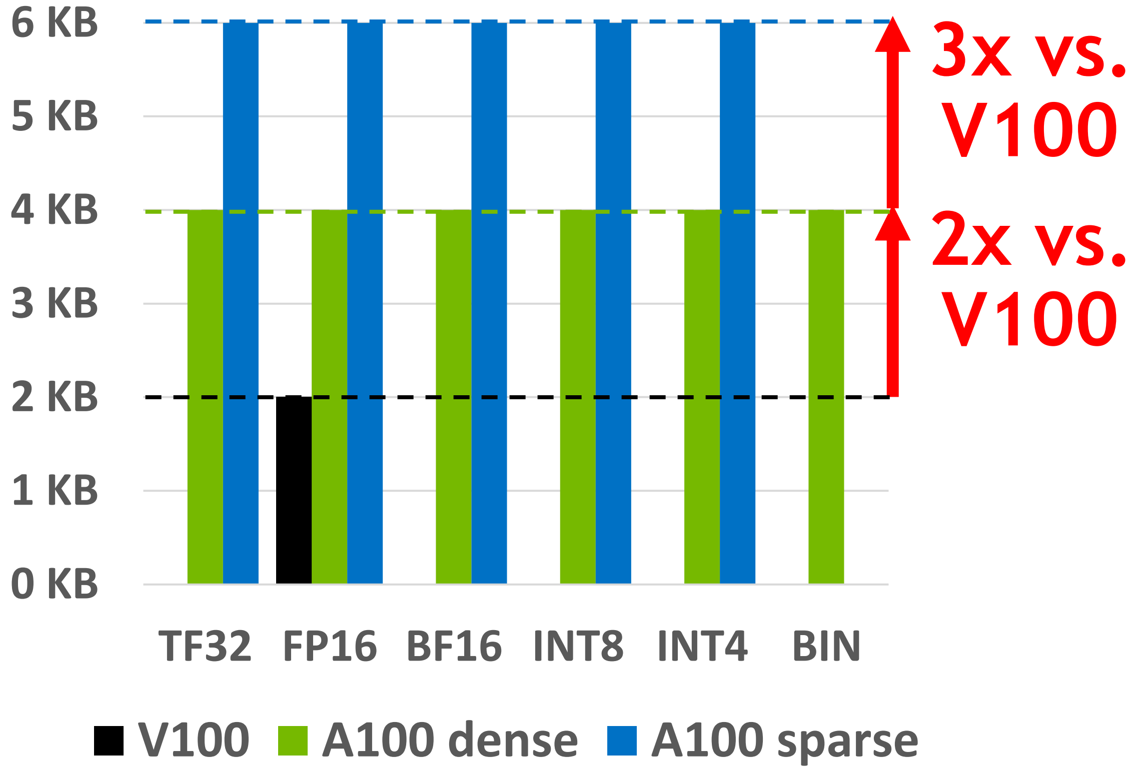
Fixed network runs ~2.5x faster

HOW TO KEEP TENSOR CORES FED?

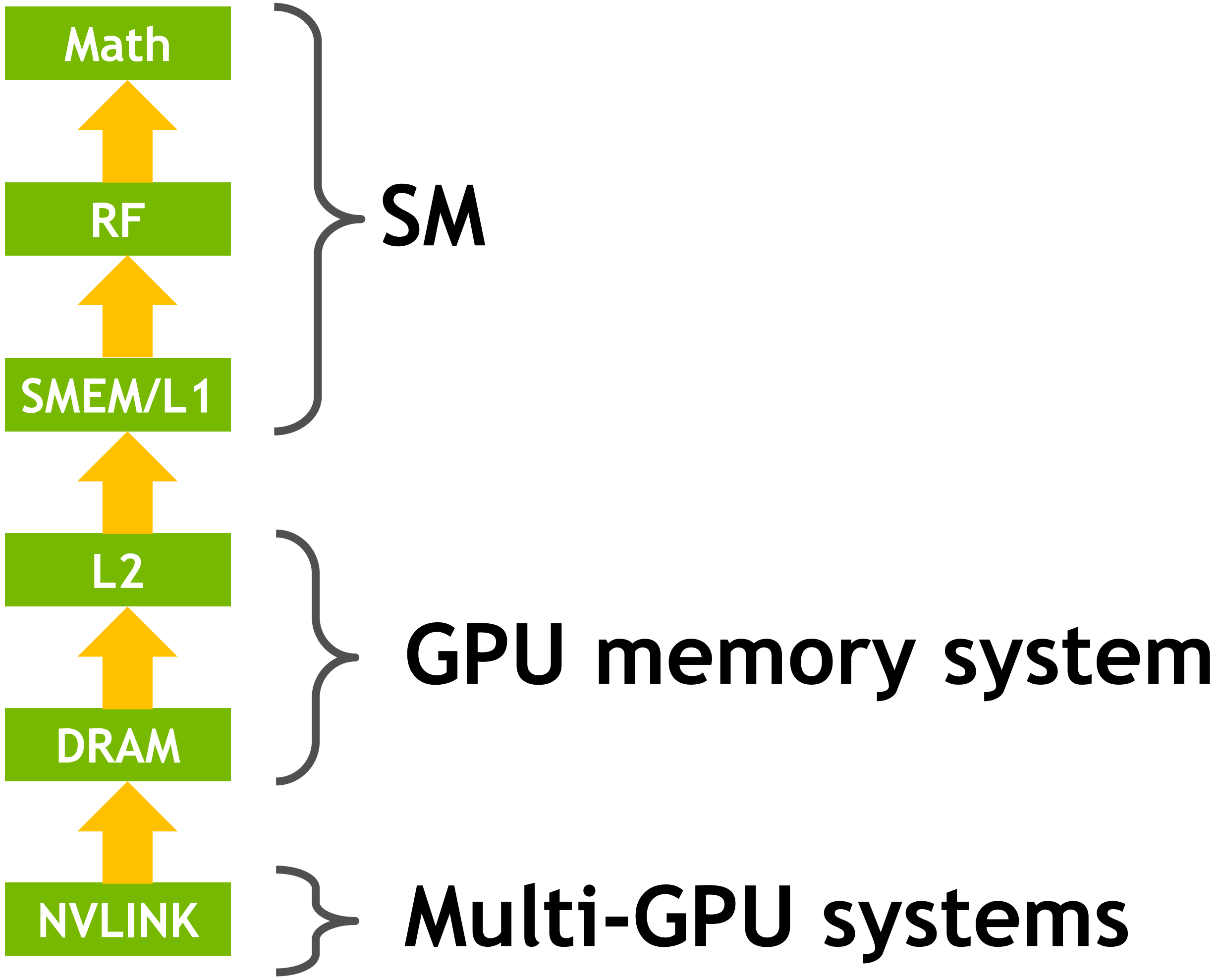
Math bandwidth
(MACs/clock/SM)



Required data bandwidth
(A+B operands, B/clock/SM)



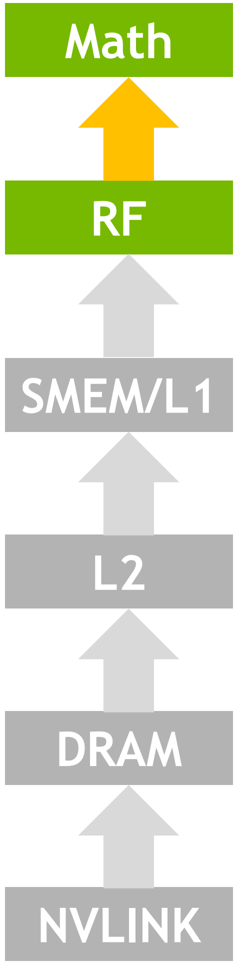
A100 STRONG SCALING INNOVATIONS

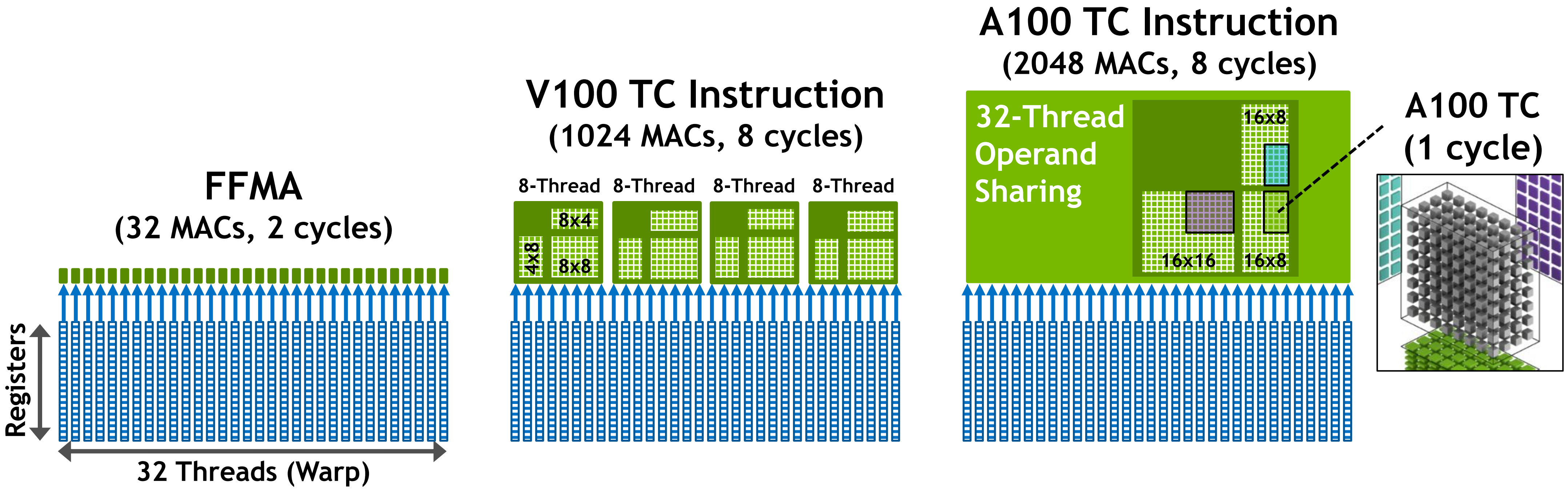


Improve speeds & feeds and efficiency across all levels of compute and memory hierarchy

A100 TENSOR CORE

2x throughput vs. V100, >2x efficiency



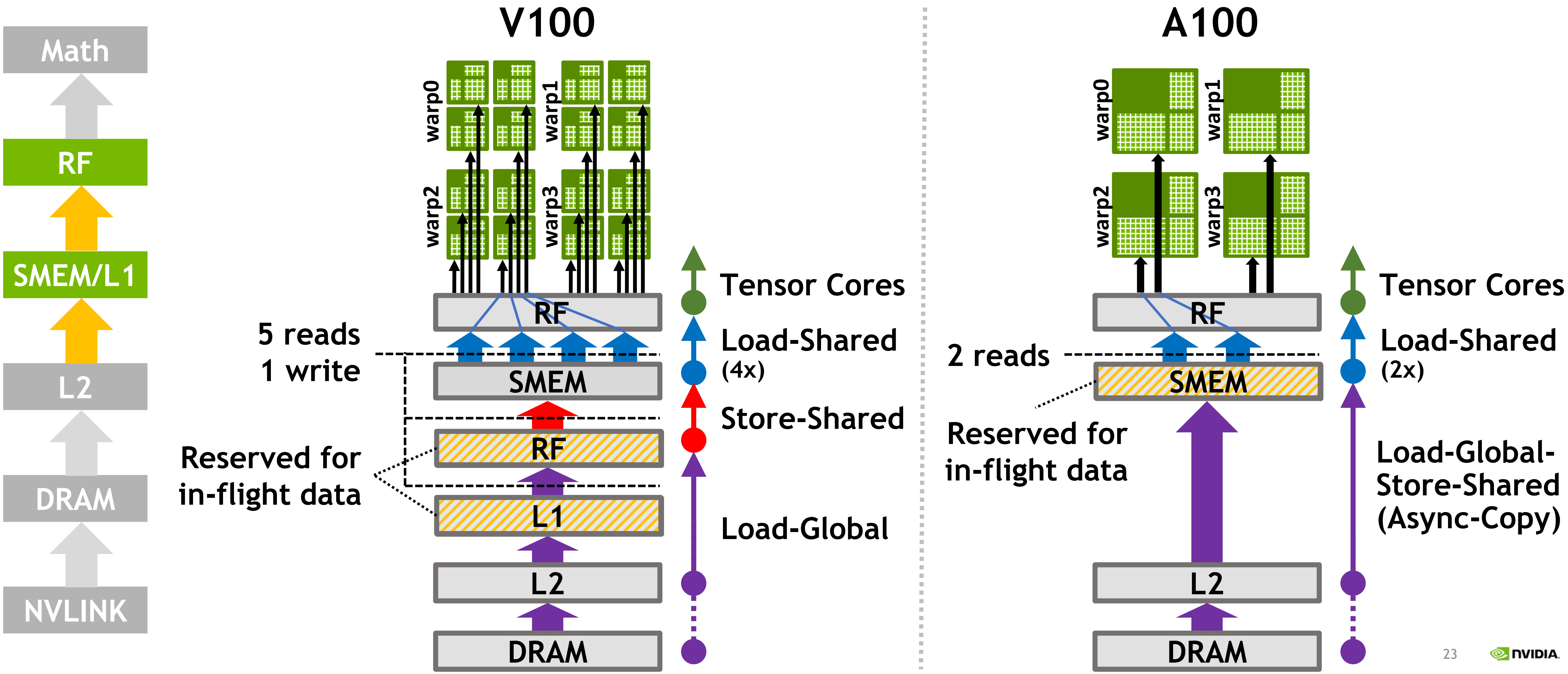


16x16x16 matrix multiply	FFMA	V100 TC	A100 TC	A100 vs. V100 (improvement)	A100 vs. FFMA (improvement)
Thread sharing	1	8	32	4x	32x
Hardware instructions	128	16	2	8x	64x
Register reads+writes (warp)	512	80	28	2.9x	18x
Cycles	256	32	16	2x	16x

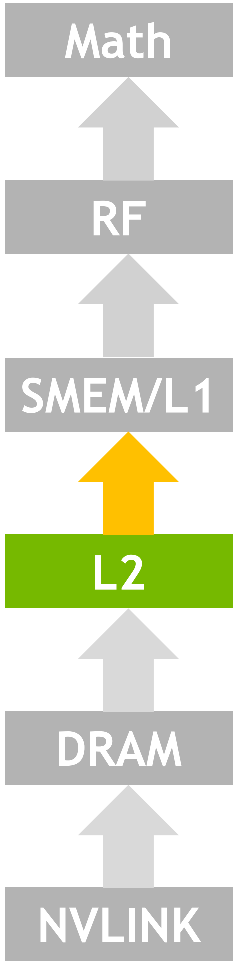
Tensor Cores assume FP16 inputs with FP32 accumulator, V100 Tensor Core instruction uses 4 hardware instructions

A100 SM DATA MOVEMENT EFFICIENCY

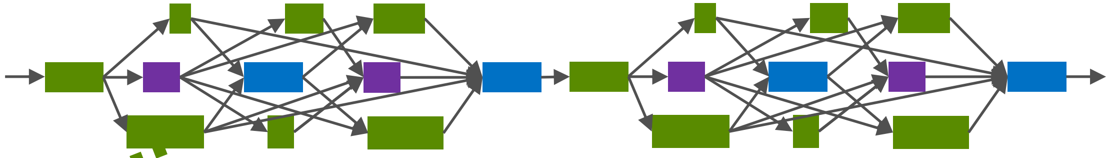
3x SMEM/L1 bandwidth, 2x in-flight capacity

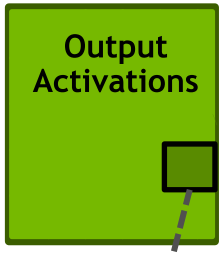


A100 L2 BANDWIDTH

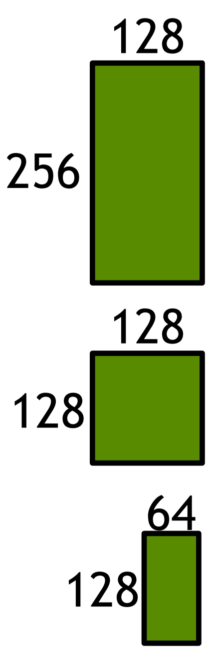


Parallelize across GPU



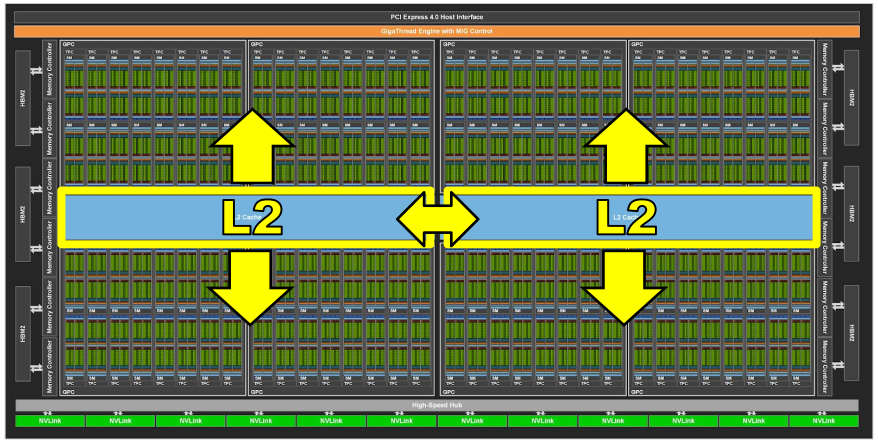


Tile: work for 1 SM



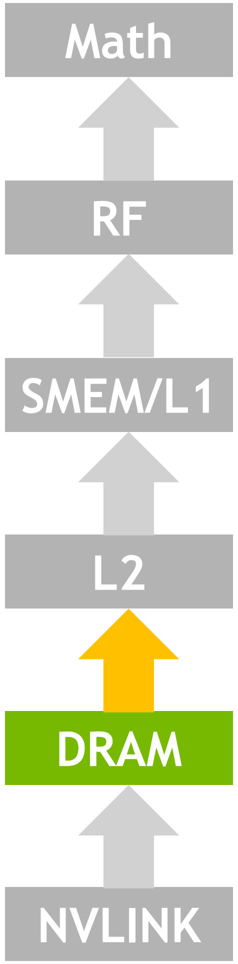
	V100	V100++ (hypothetical)	A100
	80 SMs V100 TC 64 L2 slices 32 B/clk/slice	108 SMs A100 TC 64 L2 slices 32 B/clk/slice	108 SMs A100 TC 80 L2 slices 64 B/clk/slice
256 × 128	12 B/clk/SM 47%	24 B/clk/SM 127%	24 B/clk/SM 51%
128 × 128	16 B/clk/SM 63%	32 B/clk/SM 169%	32 B/clk/SM 68%
128 × 64	24 B/clk/SM 94%	48 B/clk/SM 253%	48 B/clk/SM 101%

Split L2 with hierarchical crossbar - 2.3x increase in bandwidth over V100, lower latency



NVIDIA

A100 DRAM BANDWIDTH



Faster HBM2

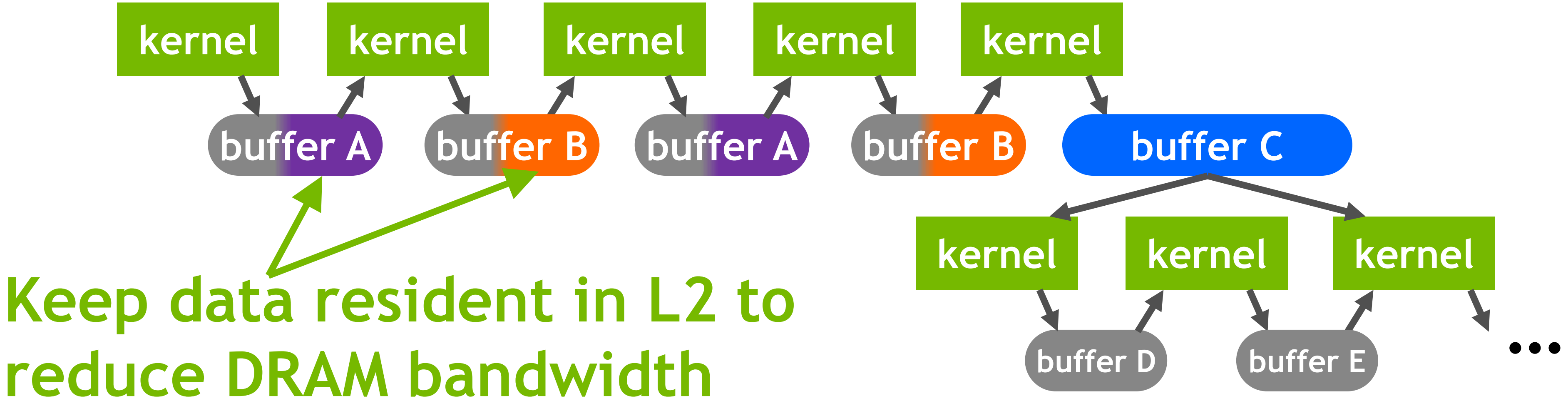
25% more pins, 38% faster clocks

→ 1.6 TB/s, 1.7x vs. V100

Larger and smarter L2

40MB L2, 6.7x vs. V100

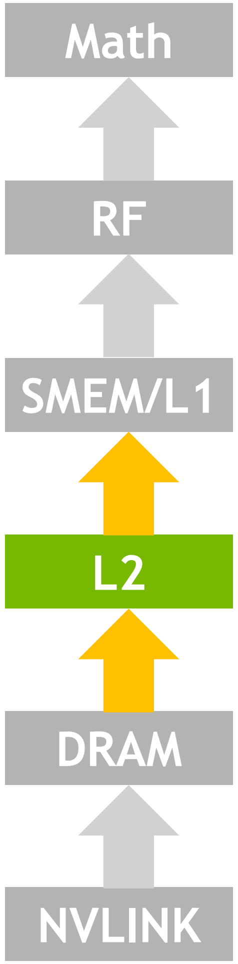
L2-Residency controls



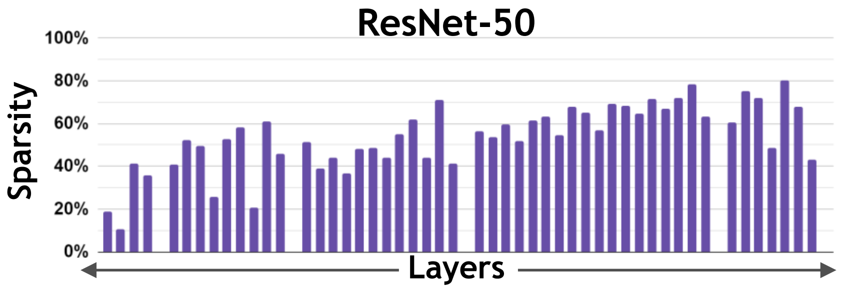
→ S21819: Optimizing Applications for NVIDIA Ampere GPU Architecture, 5/21 10:15am PDT

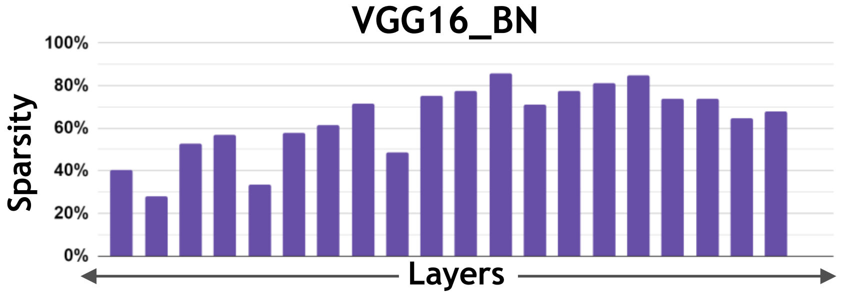
NVIDIA

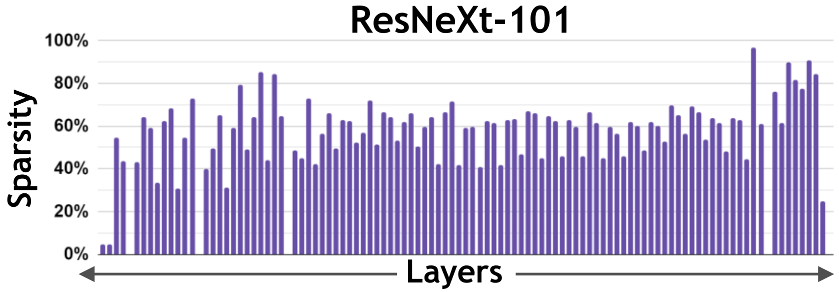
A100 COMPUTE DATA COMPRESSION



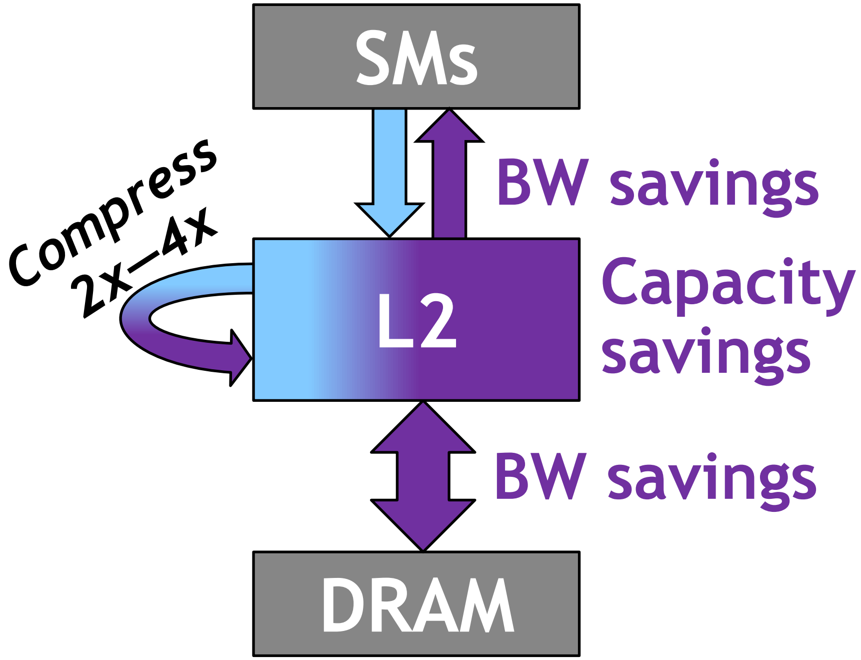
Activation sparsity due to ReLU







Up to 4x DRAM+L2 bandwidth and 2x L2 capacity for fine-grained unstructured sparsity



→ S21819: Optimizing Applications for NVIDIA Ampere GPU Architecture, 5/21 10:15am PDT

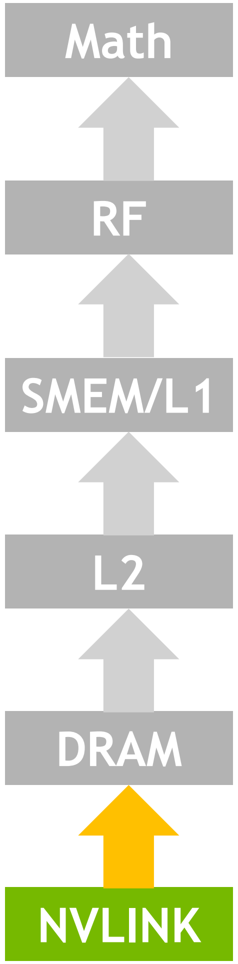
A100 NVLINK BANDWIDTH

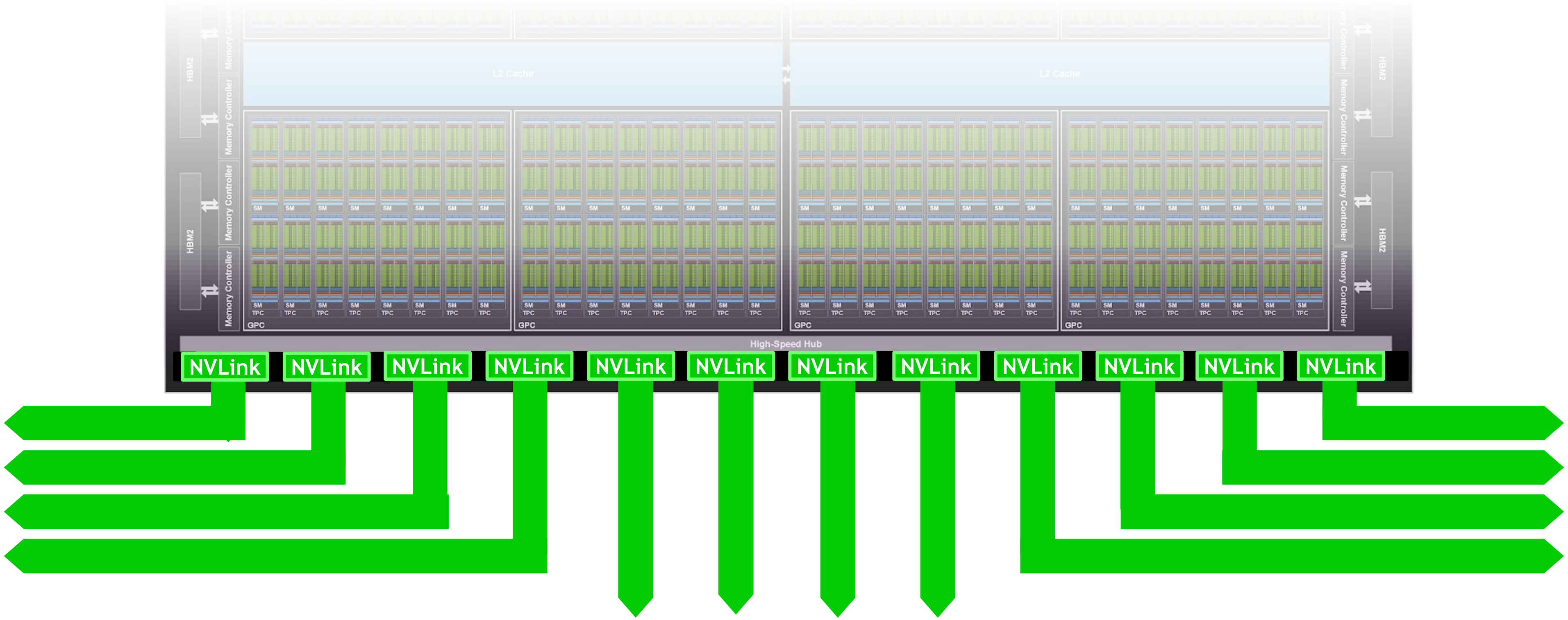
Third Generation NVLink

50 Gbit/sec per signal pair

12 links, 25 GB/s in/out, 600 GB/s total

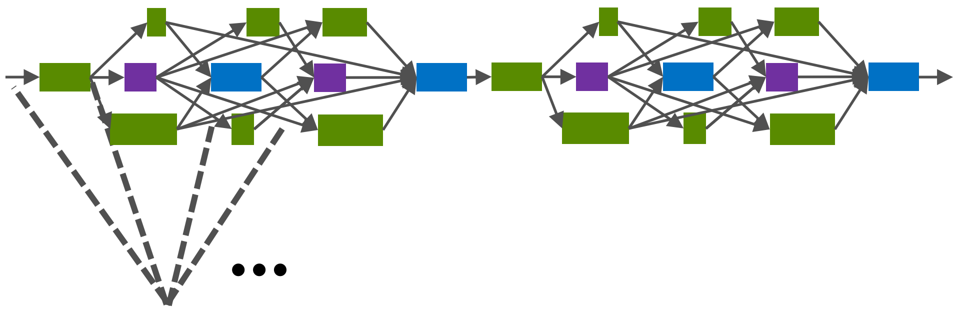
2x vs. V100





→S21884: Under the Hood of the new DGX A100 System Architecture (recording available soon)

A100 ACCELERATES CUDA GRAPHS

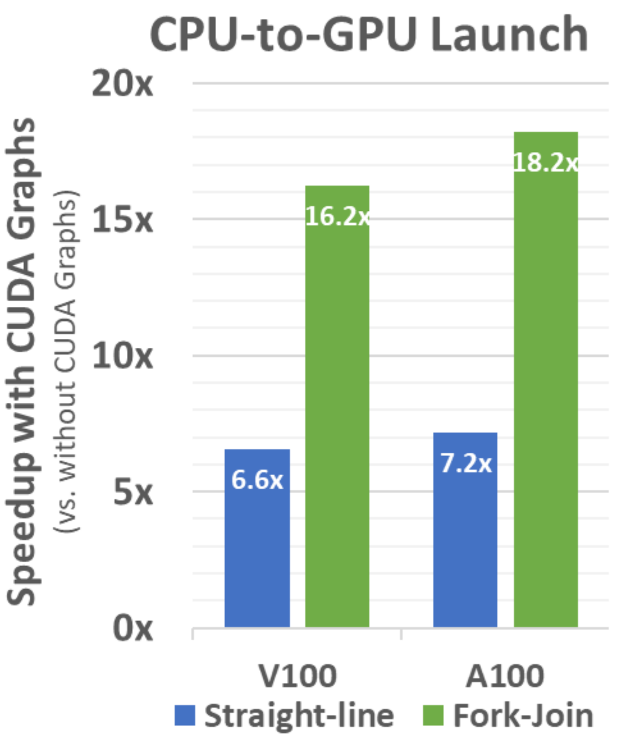


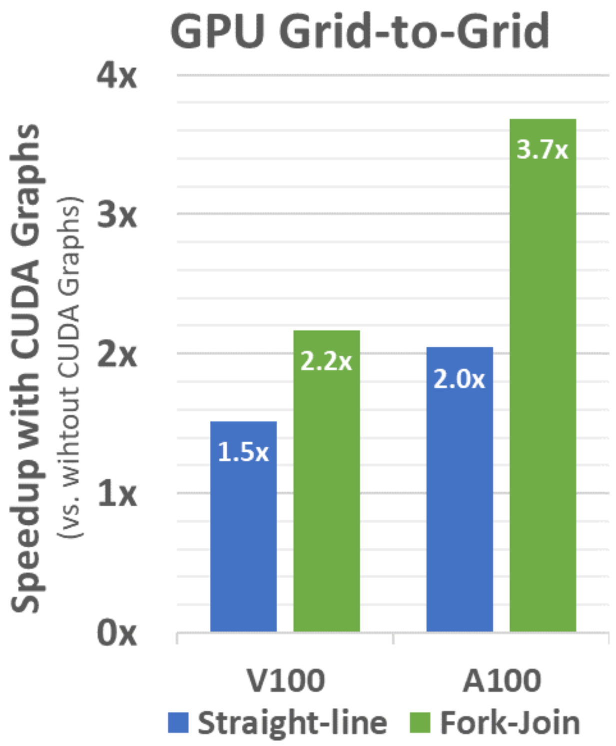
Grid launches:

- *CPU-to-GPU*
- *GPU grid-to-grid*

With strong scaling CPU and grid launch overheads become increasingly important

(Amdahl's law)





32-node graphs of empty grids, DGX1-V, DGX-A100

One-shot CPU-to-GPU graph submission and graph reuse

Microarchitecture improvements for grid-to-grid latencies

→S21760: CUDA New Features And Beyond, 5/19 10:15am PDT

NVIDIA

A100 STRONG SCALING INNOVATIONS

Delivering unprecedented levels of performance

A100 improvements over V100

Math	2.5x	Tensor Core math BW (FP16)
	2.9x	Effective RF BW with A100 Tensor Core
RF	2.8x	Effective RF capacity with Async-Copy bypassing RF
	3.0x	Effective SMEM BW with A100 Tensor Core and Async-Copy
SMEM/L1	2.3x	SMEM capacity
	2.3x	L2 BW
L2	6.7x	L2 capacity, +Residency Control
	1.7x	DRAM BW
DRAM	1.3x	DRAM capacity
	2.0x	NVLINK BW
NVLINK		

A100 STRONG SCALING INNOVATIONS

Delivering unprecedented levels of performance

A100 improvements over V100

Math
2.5x Tensor Core math BW (FP16) 5.0x Sparse Tensor Core (FP16)
2.9x Effective RF BW with A100 Tensor Core

RF
2.8x Effective RF capacity with Async-Copy bypassing RF
3.0x Effective SMEM BW with A100 Tensor Core and Async-Copy

SMEM/L1
2.3x SMEM capacity
2.3x L2 BW

L2
6.7x L2 capacity, +Residency Control
1.7x DRAM BW

9.2x
13.3x Compute Data Compression *(max)*
6.8x

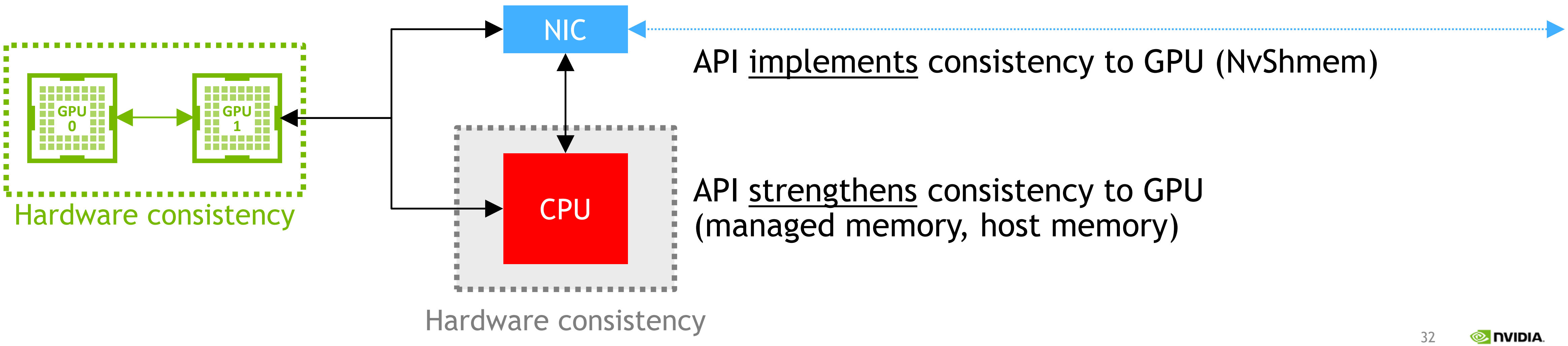
DRAM
1.3x DRAM capacity
2.0x NVLINK BW

NVLINK

1. New Tensor Core
2. Strong Scaling
3. **Elastic GPU**
4. Productivity

NVLINK: ONE BIG GPU

- **InfiniBand/Ethernet**: travels a long distance, consistency is the responsibility of software
- **PCI Express**: hardware consistency for I/O, not for programming language memory models
- **NVLINK**: hardware consistency for programming language memory models, like system bus

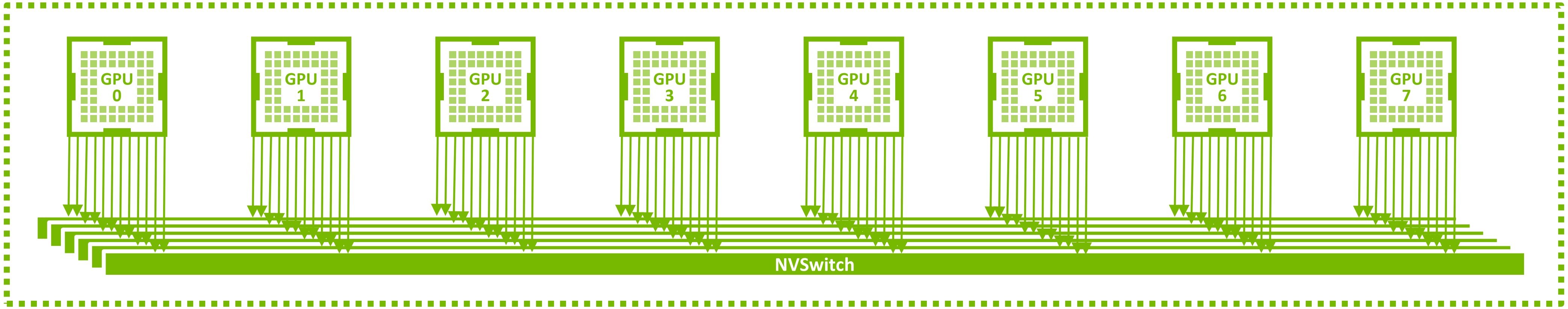


HGX A100: 3RD GEN NVLINK

- **HGX A100 4-GPU:** fully-connected system with 100GB/s all-to-all BW

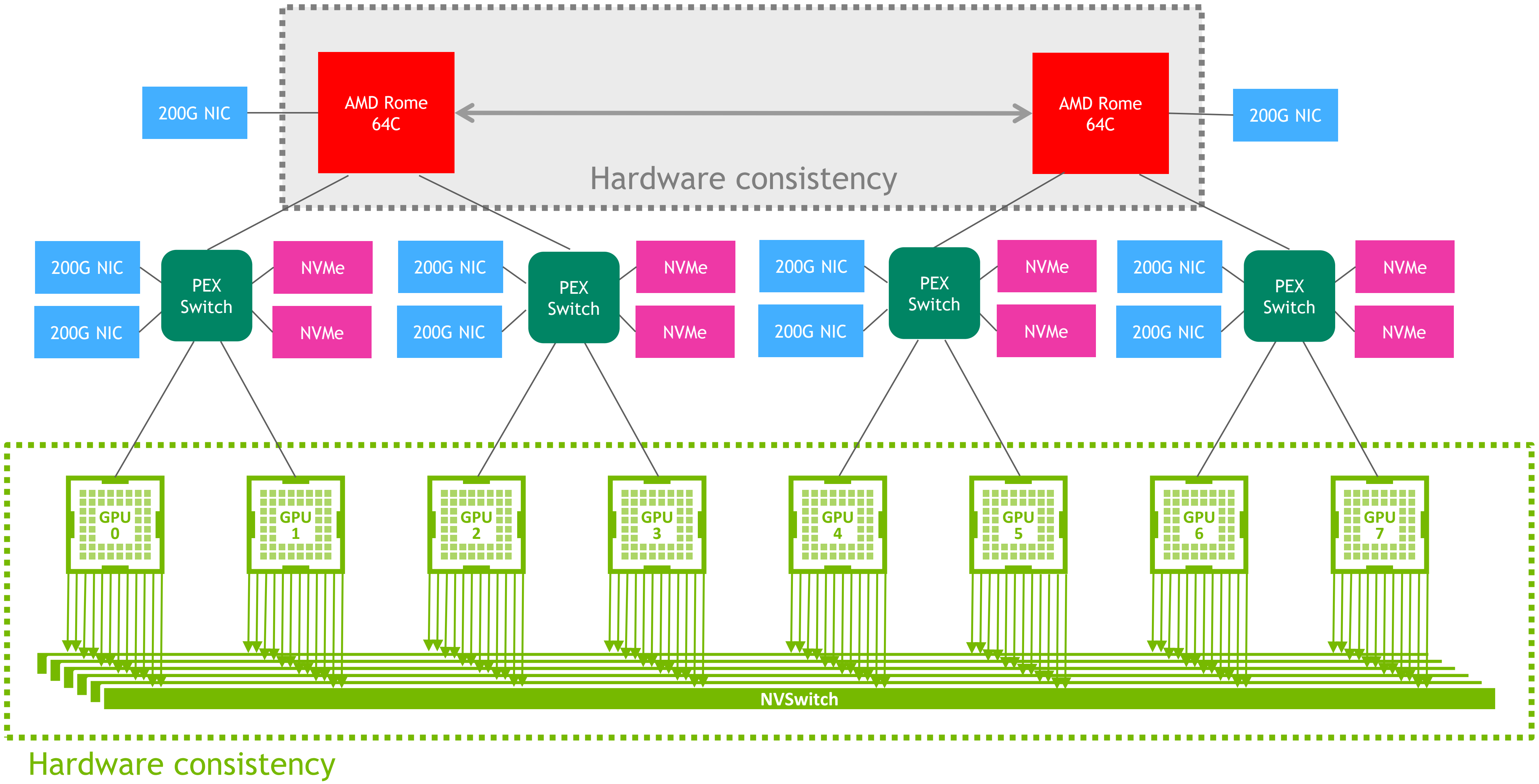
HGX A100: 3RD GEN NVLINK & SWITCH

- **HGX A100 4-GPU**: fully-connected system with 100GB/s all-to-all BW
- **New NVSwitch**: 6B transistors in TSMC 7FF, 36 ports, 25GB/s each, per direction
- **HGX A100 8-GPU**: 6x NVSwitch in a fat tree topology, 2.4TB/s full-duplex bandwidth



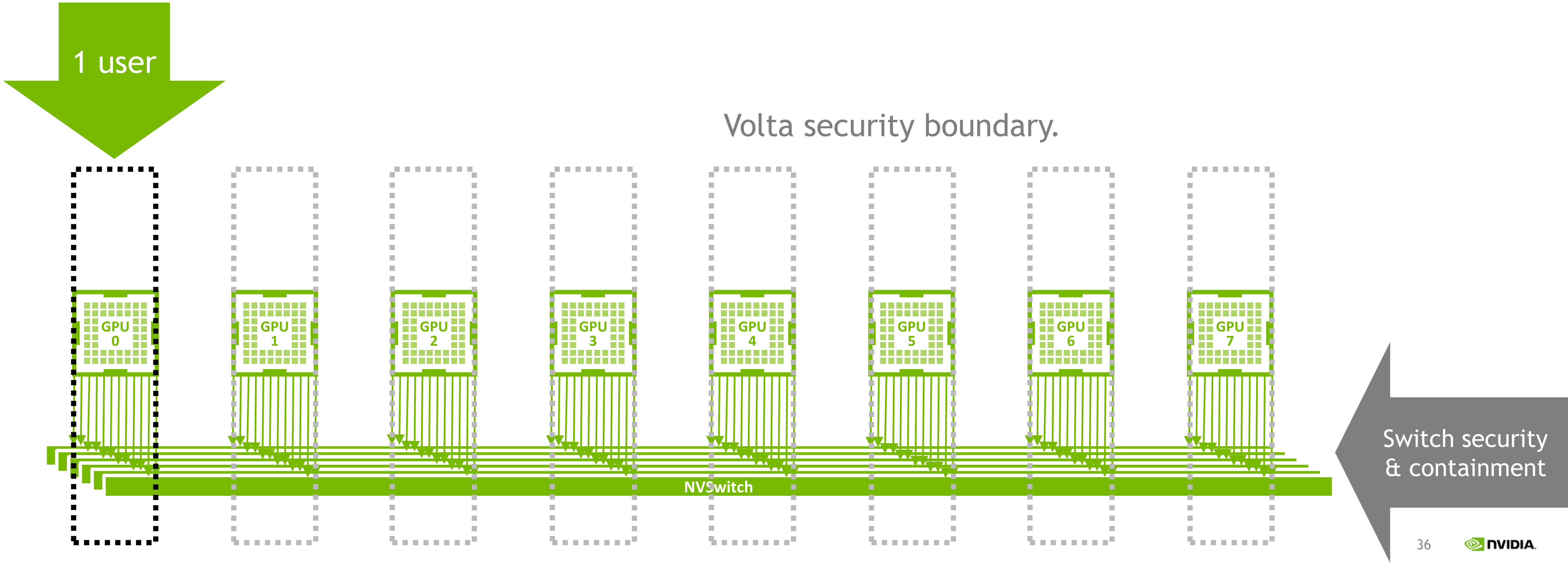
Hardware consistency

DGX A100: PCIE4 CONTROL & I/O



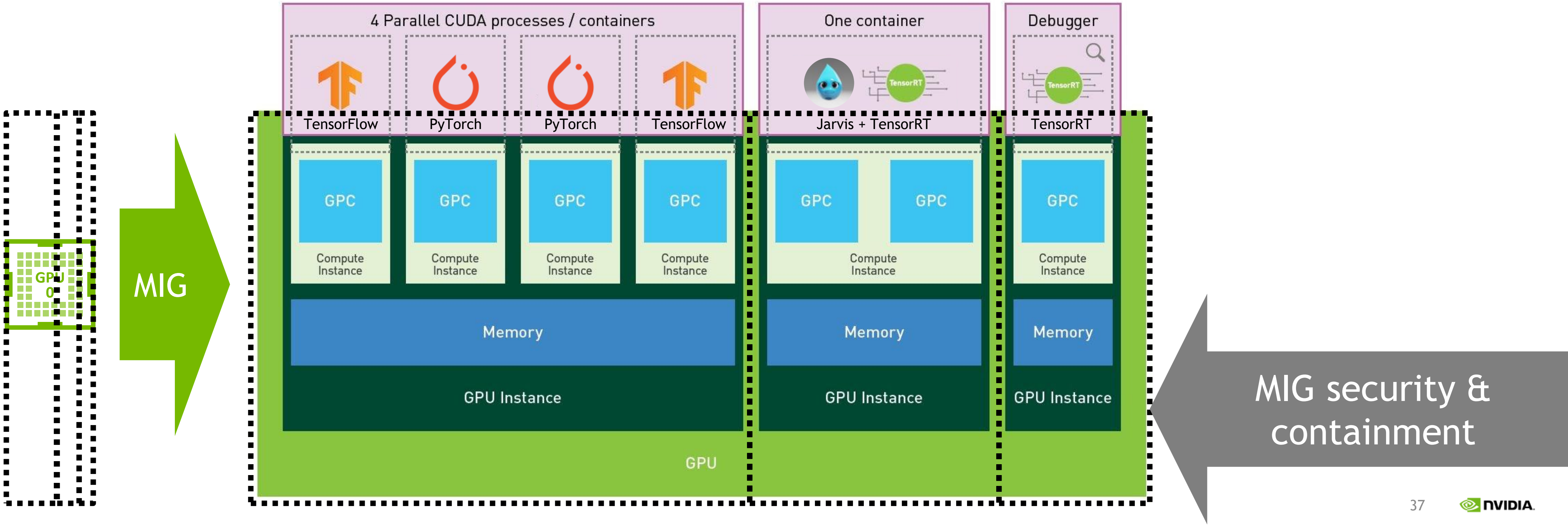
CLOUD SMALL INSTANCE USAGE

- Small workloads can under-utilize GPU cloud instances, provisioned at whole GPU level
- CSPs can't use MPS for GPU space-sharing, because it doesn't provide enough isolation



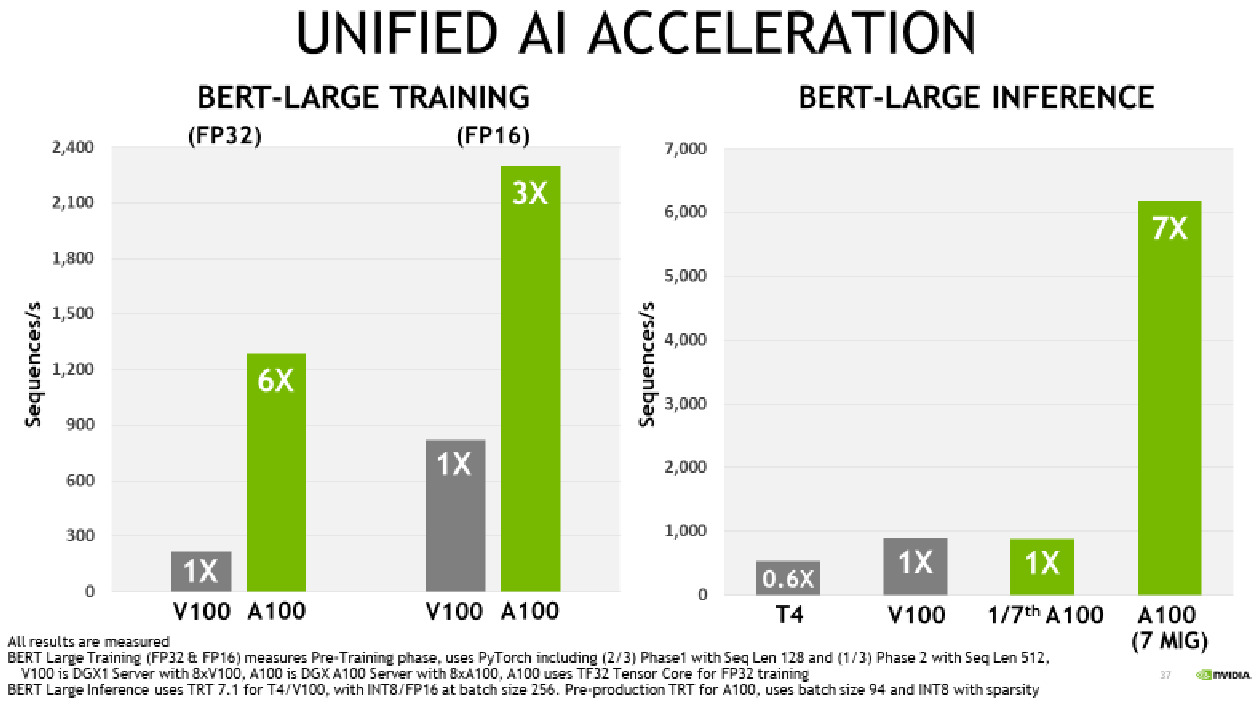
NEW: MULTI-INSTANCE GPU (MIG)

- Up to 7 instances total, dynamically reconfigurable
- **Compute instances:** compute/fault isolation, but share/compete for memory
- **GPU instances:** separate and isolated paths through the entire memory system



ELASTIC GPU COMPUTING

- Each A100 is 1 to 7 GPUs
- Each DGX A100 is 1 to 56 GPUs
- Each GPU can serve a different user, with full memory isolation and QoS

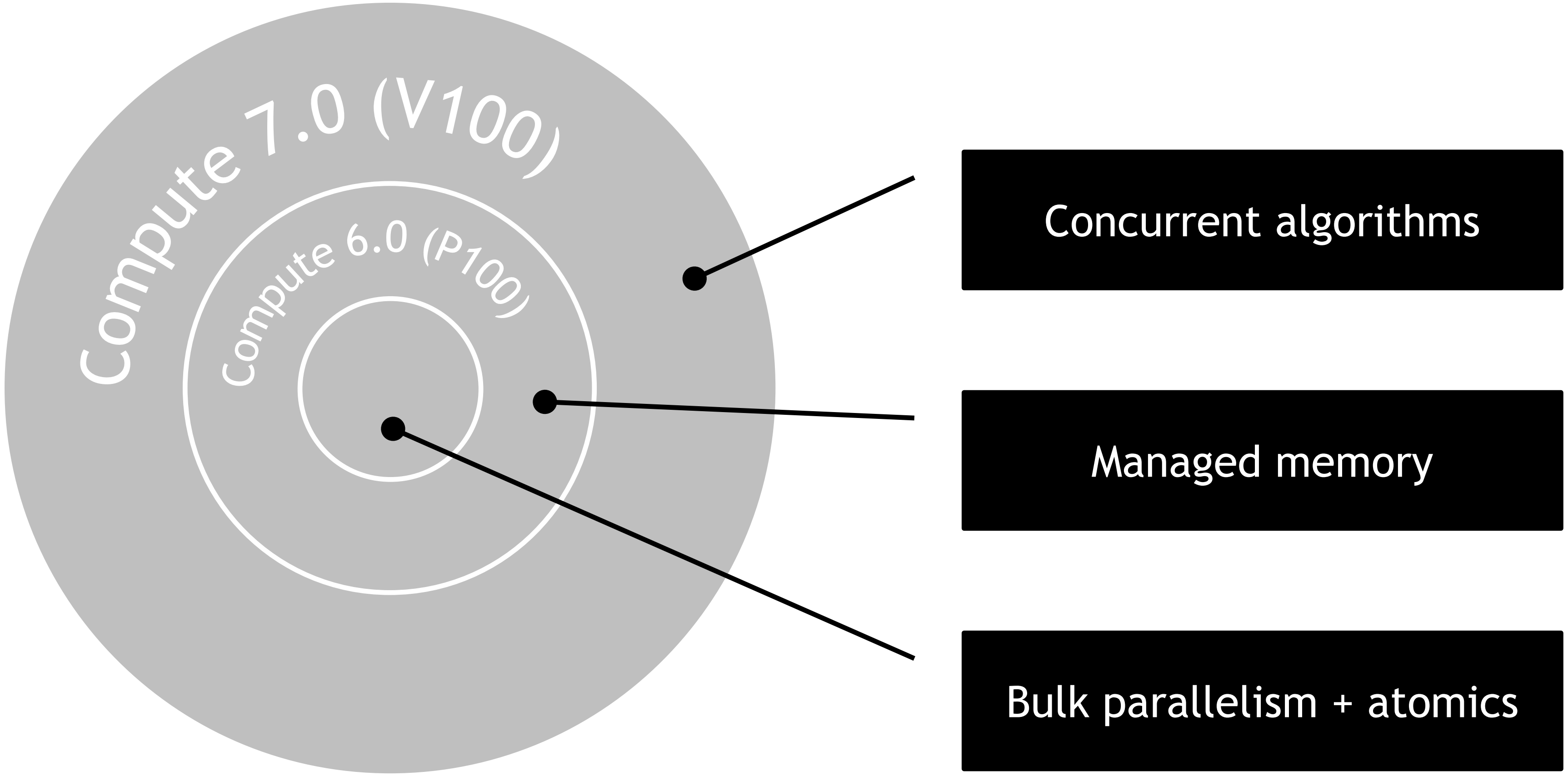


→S21975: Inside NVIDIA's Multi-Instance GPU Feature (recording available)
→S21884: Under the Hood of the new DGX A100 System Architecture (recording available soon)
→S21702: Introducing NVIDIA DGX A100: The Universal AI System for Enterprise, 5/20 9:00am PDT

1. New Tensor Core
2. Strong Scaling
3. Elastic GPU
4. **Productivity**

COMPUTE CAPABILITY

Programming Model Development at NVIDIA



GPU PROGRAMMING IN 2020 AND BEYOND

Math Libraries | Standard Languages | Directives | CUDA

```
std::transform(par, x, x+n, y, y,
    [=](float x, float y){
        return y + a*x;
});
```

```
do concurrent (i = 1:n)
   y(i) = y(i) + a*x(i)
enddo
```

GPU Accelerated C++ and Fortran

```
#pragma acc data copy(x,y)
{

...

std::transform(par, x, x+n, y, y,
    [=](float x, float y){
        return y + a*x;
});

...

}
```

Incremental Performance Optimization with Directives

```
__global__
void saxpy(int n, float a,
           float *x, float *y) {
  int i = blockIdx.x*blockDim.x +
          threadIdx.x;
  if (i < n) y[i] += a*x[i];
}

int main(void) {
  ...
  cudaMemcpy(d_x, x, ...);
  cudaMemcpy(d_y, y, ...);

  saxpy<<<(N+255)/256,256>>>(...);

  cudaMemcpy(y, d_y, ...);
```

Maximize GPU Performance with CUDA C++/Fortran

GPU Accelerated Math Libraries

→S21766 Inside the NVIDIA HPC SDK: the Compilers, Libraries and Tools for Accelerated Computing, 5/19 1:30PM PST

PROGRAMMING MODEL WANTED

Software pipelining to hide latency is hard.

```
__device__ void exhibit_A1()
{
  memcpy(/* ... */); //< blocks here
  /* more work */

  compute();         //< needed here
  /* more work */
}
```

Data

```
__device__ void exhibit_B1()
{
  compute_head();
  __syncthreads(); //< blocks here
  /* more work */

  compute_tail();  //< needed here
  /* more work */
}
```

Compute

PROGRAMMING MODEL WANTED

Software pipelining to hide latency is hard.

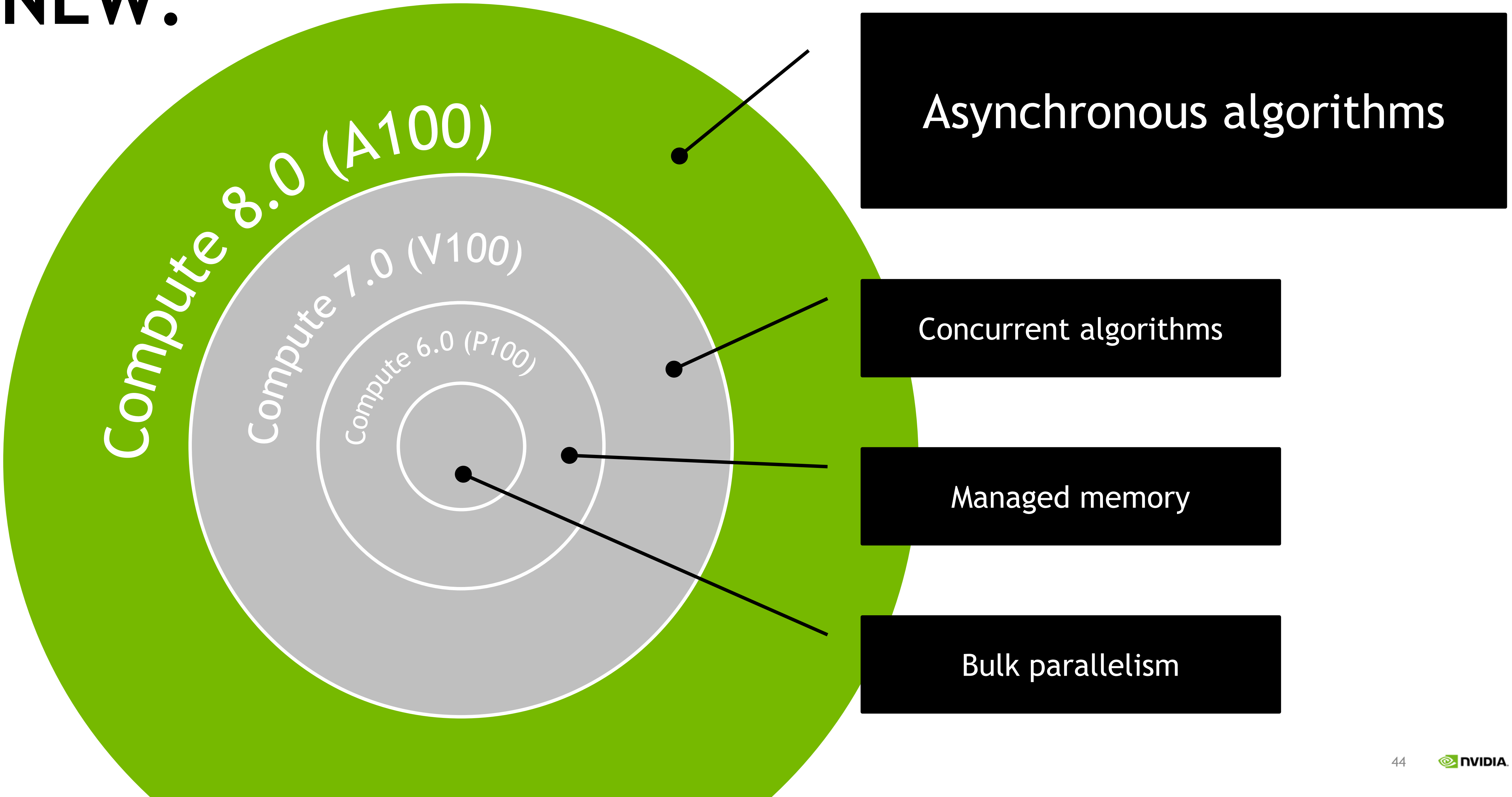
```
__device__ void exhibit_A2()
{
  memcpy(/* ... */); //< blocks here
  /* memcpy( ... ); */

  compute();         //< needed here
  /* compute(); */
}
```

Data

```
__device__ void exhibit_B2()
{
  compute_head();
  __syncthreads(); //< blocks here
  /* compute_head();
     __syncthreads(); */
  compute_tail();  //< needed here
  /* compute_tail(); */
}
```

Compute

NEW:



Compute 8.0 (A100)
Compute 7.0 (V100)
Compute 6.0 (P100)
Asynchronous algorithms
Concurrent algorithms
Managed memory
Bulk parallelism

CO-DESIGNED: A100 & C++20 barrier

Key to asynchronous programming in compute_80

```
#include <cuda/barrier> // ISO C++20 conforming extension
using barrier = cuda::barrier<cuda::thread_scope_block>;
```

```
class barrier {  // synopsis
  //...
  void arrive_and_wait();
  arrival_token arrive(ptrdiff_t = 1);
  void wait(arrival_token &&) const;
  //...
};
```

Nonblocking

ASYNCHRONOUS COPY + BARRIER

Capability	PTX ISA	CUDA C++ API
Asynchronous barrier	mbarrier.{*<basis functions>*}	`cuda::barrier<…>`
Asynchronous copy	`cp.async.ca +` `cp.async.mbarrier.arrive`	`cuda::memcpy_async(…)`
+Cache-bypass	`cp.async.cg`	CUDA 11 preview library in `experimental::` namespace
+Zero-fill ragged edge	`cp.async.* … wr-size, rd-size;`	
+User-level tracking	`cp.async.mbarrier.arrive.noinc`	
+Single-threaded mode	`cp.async.{commit_group, wait_group}`	

ASYNCHRONOUS PROGRAMMING MODEL

```
#include <cuda/barrier> // ISO C++20 conforming extension
using barrier = cuda::barrier<cuda::thread_scope_block>;
```

```
__device__ void exhibit_A3()
{
  __shared__ barrier b1, b2;
  // ^^initialization omitted
   cuda::memcpy_async(/* ... */, b1);
     cuda::memcpy_async(/* ... */, b2);
  b1.arrive_and_wait();
  compute();
    b2.arrive_and_wait();
    compute();
}
```

Data

```
__device__ void exhibit_B3()
{
  __shared__ barrier b1, b2;
  // ^^initialization omitted
  compute_head();
  auto t1 = b1.arrive();
    compute_head();
    auto t2 = b2.arrive();
  b1.wait(t1);
  compute_tail();
    b2.wait(t2);
    compute_t
}
```

Compute

MULTI-BUFFERING PIPELINES IN C++

```
#include <cuda/barrier> // ISO C++20 conforming extension
using barrier = cuda::barrier<cuda::thread_scope_block>;

__global__ void exhibit_C(/* ... */) {
  __shared__ barrier b[2];
  // ^^initialization omitted
  barrier::arrival_token t[2];
  cuda::memcpy_async(/* ... */, b[0]);
  t[0] = b[0].arrive();
  for(int step = 0, next = 1; step < steps; ++step, ++next) {
    if(next < steps) {
      b[next & 1].wait(t[next & 1]);
      cuda::memcpy_async(/* ... */, b[next & 1]);
      t[next & 1] = b[next & 1].arrive();
    }
    b[step & 1].wait(t[step & 1]);
    compute();
    t[step & 1] = b[step & 1].arrive();
  }
}
```

Data

Compute

MULTI-BUFFERING PIPELINES IN C++

```
#include <cuda/barrier> // ISO C++20 conforming extension
using barrier = cuda::barrier<cuda::thread_scope_block>;

__global__ void exhibit_C(/* ... */) {
  __shared__ barrier b[2];
  // ^^initialization omitted
  barrier::arrival_token t[2];
  cuda::memcpy_async(/* ... */, b[0]);
  t[0] = b[0].arrive();
  for(int step = 0, next = 1; step < steps; ++step, ++next) {
    if(next < steps) {
      b[next & 1].wait(t[next & 1]);
      cuda::memcpy_async(/* ... */, b[next & 1]);
      t[next & 1] = b[next & 1].arrive();
    }
    b[step & 1].wait(t[step & 1]);
    compute();
    t[step & 1] = b[step & 1].arrive();
  }
}
```

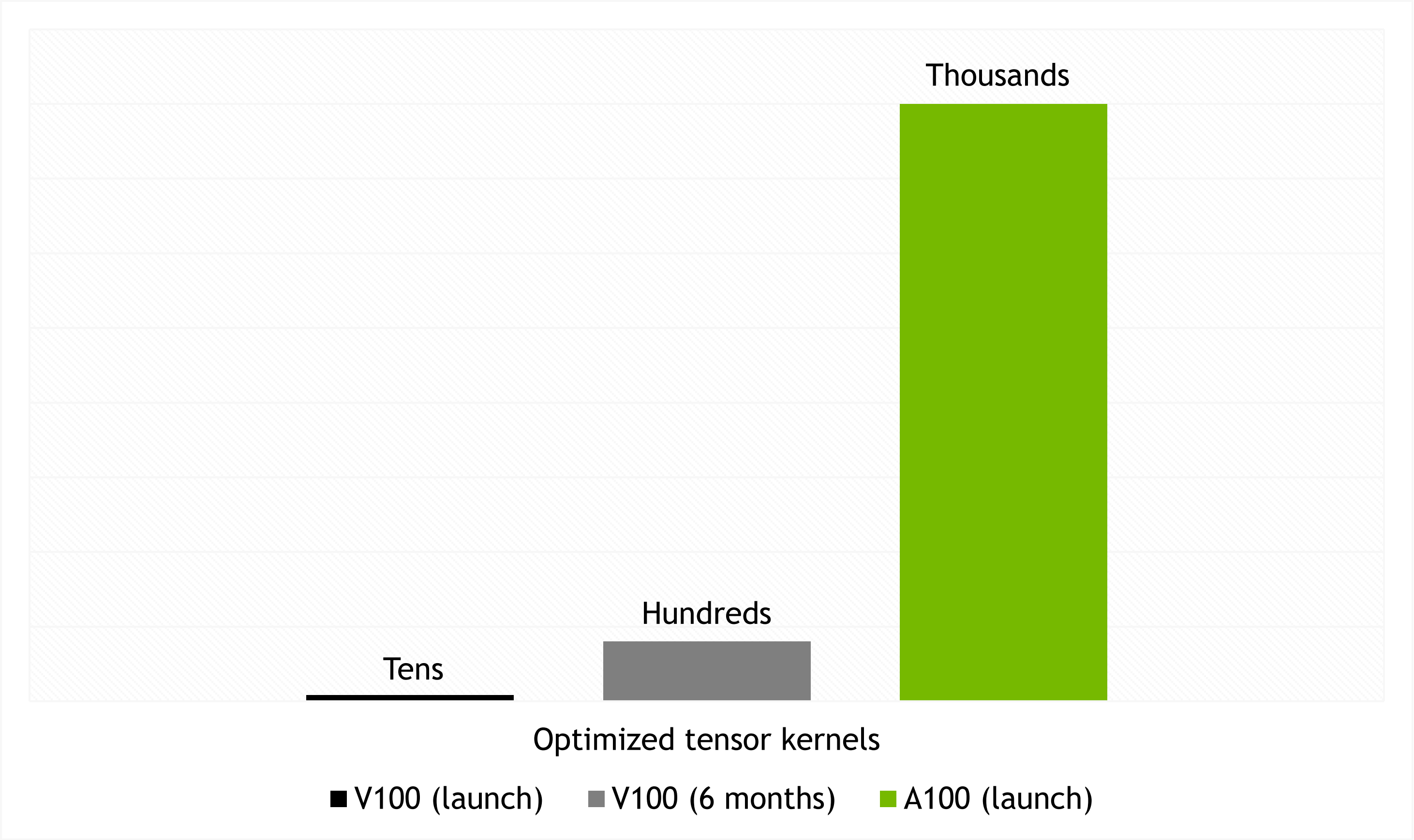
Data

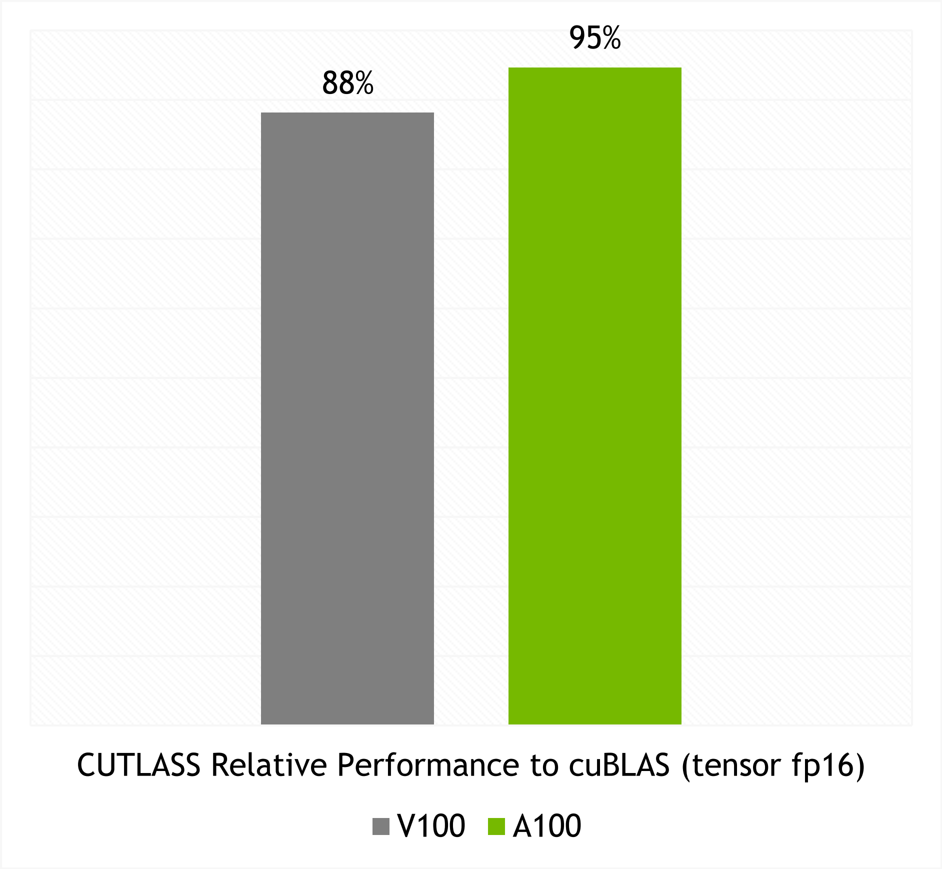
\+

Compute

→S21760: CUDA New Features And Beyond, 5/19 10:15am PDT

OUR PRODUCTIVITY GAINS FROM A100

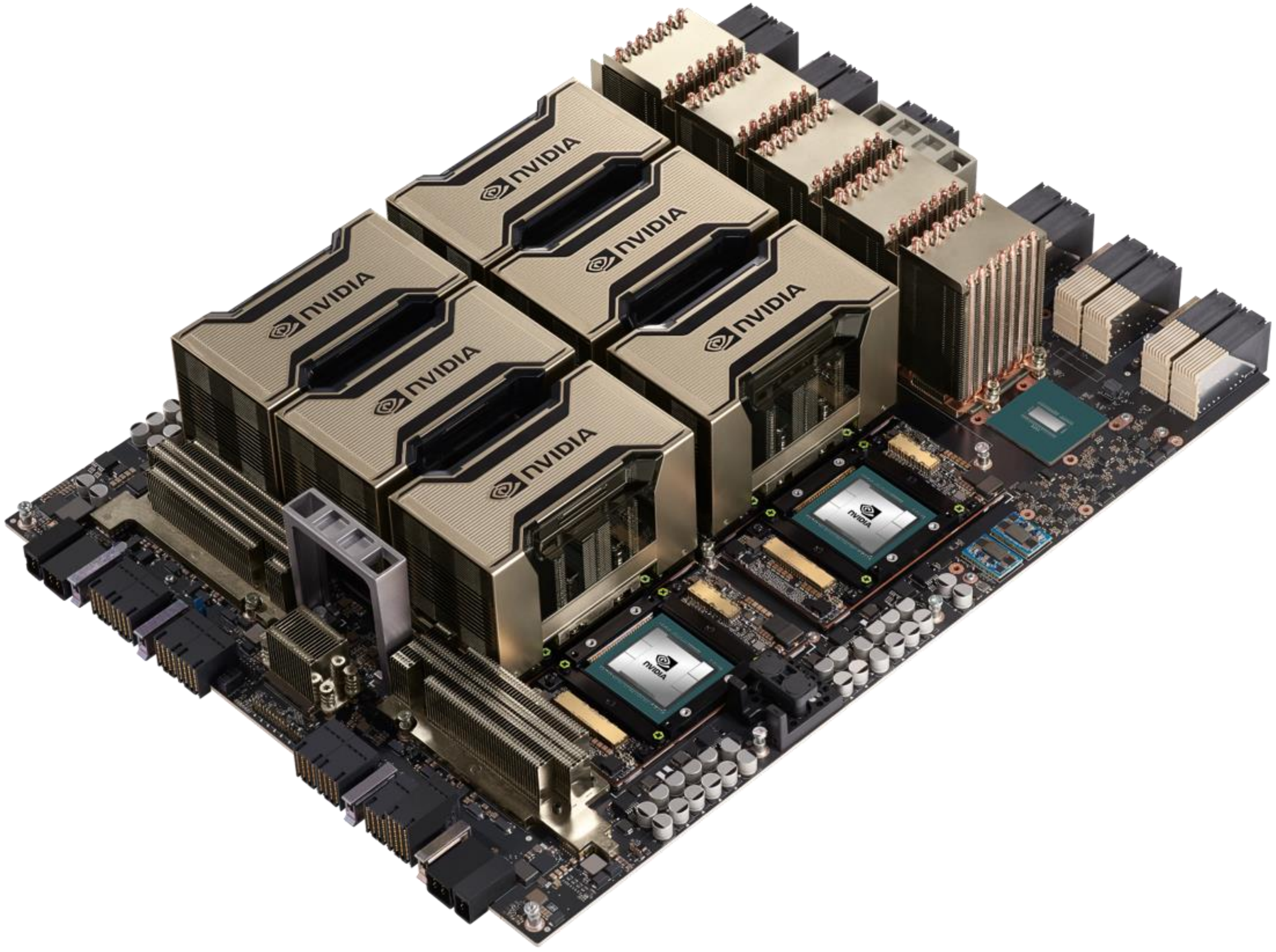


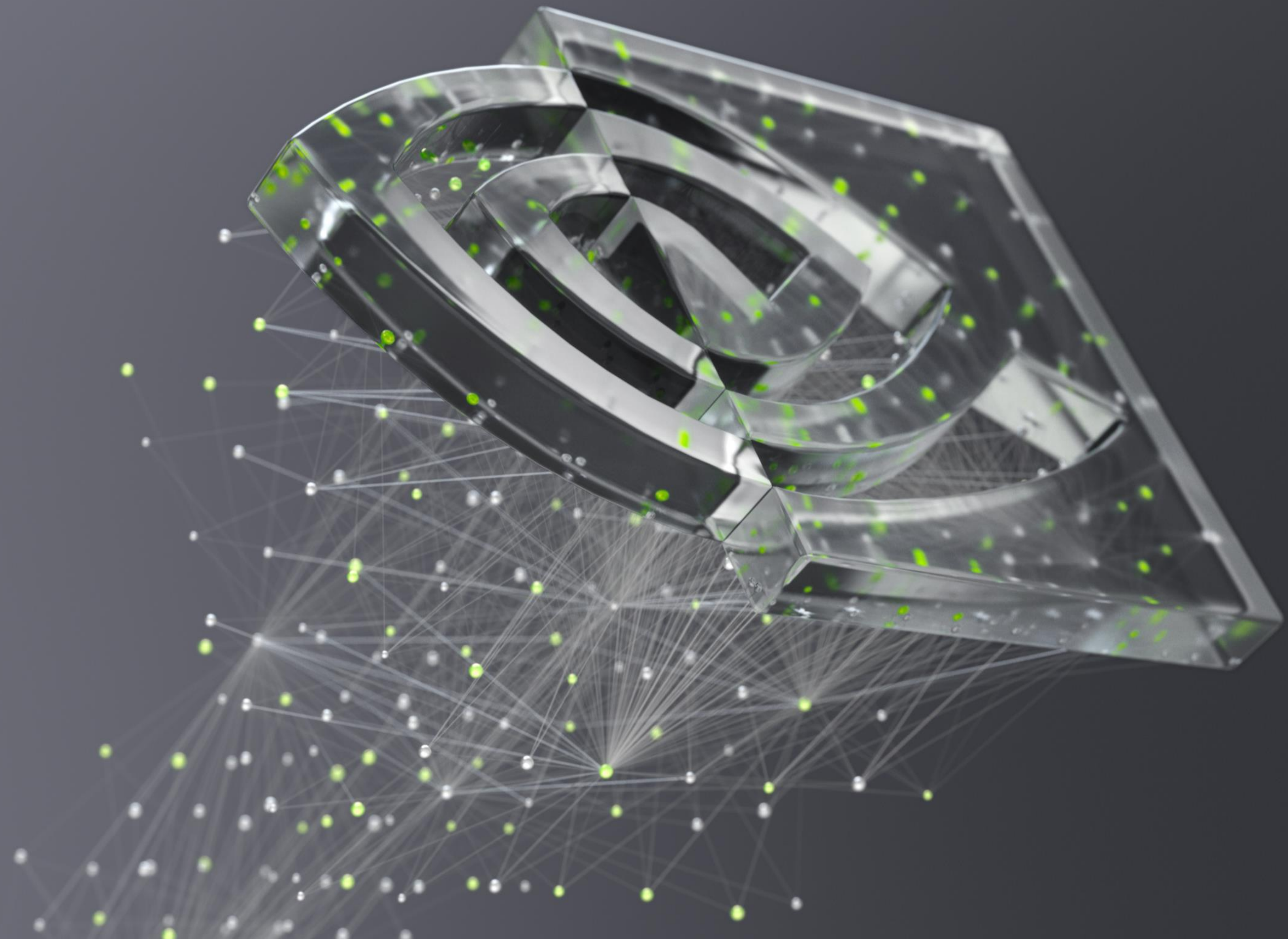


→S21745: Developing CUDA kernels to push Tensor Cores to the Absolute Limit on NVIDIA A100, 5/21 11:30AM PST

CLOSING

UNPRECEDENTED ACCELERATION AT EVERY SCALE





Whitepaper: NVIDIA A100 Tensor Core GPU Architecture

www.nvidia.com/nvidia-ampere-architecture-whitepaper