SCIENCE
PASSION
TECHNOLOGY

Architecture of ML Systems
07 Hardware Accelerators

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Last update: Apr 29, 2021

Announcements/Org

- **#1 Video Recording**
  - Link in **TeachCenter** & **TUbe** (lectures will be public)
  - Streaming: https://tugraz.webex.com/meet/m.boehm
  - Corona traffic light **RED** until end of April

- **#2 Programming Projects / Exercises** (36/57)
  - **Apache SystemDS:** 24 projects / 37 students
  - **DAPHNE:** 2 projects / 2 students
  - **Exercises:** 10 projects / 18 students → TeachCenter
  - Kickoff meetings completed
  - **Deadline:** **June 30** (soft)

DAPHNE Projects

Apache SystemDS Projects

Overview Project Types

Programming Projects

Refinement until March 26
(bring you own if you want)
Project Selection by April 02

Categories of Execution Strategies

Batch **SIMD/SPMD**	Batch/Mini-batch, Independent Tasks **MIMD**	Mini-batch
05_a Data-Parallel Execution [Apr 16]	**05_b Task-Parallel Execution** [Apr 16]	**06 Parameter Servers** (data, model) [Apr 23]

07 Hybrid Execution and HW Accelerators [Apr 30]

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08 Caching, Partitioning, Indexing, and Compression [May 07]

Agenda

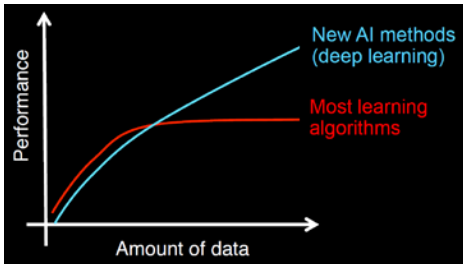
- **Motivation and Terminology**
- **GPUs in ML Systems**
- **FPGAs in ML Systems**
- **ASICs and other HW Accelerators**

Motivation and Terminology

Recap: Driving Factors for ML

- **Improved Algorithms and Models**
  - Success across data and application domains (e.g., health care, finance, transport, production)
  - More complex models which leverage large data

[**Credit:** Andrew Ng'14]



- **Availability of Large Data Collections**
  - Increasing automation and monitoring ➔ data (simplified by cloud computing & services)
  - Feedback loops, **data programming/augmentation**

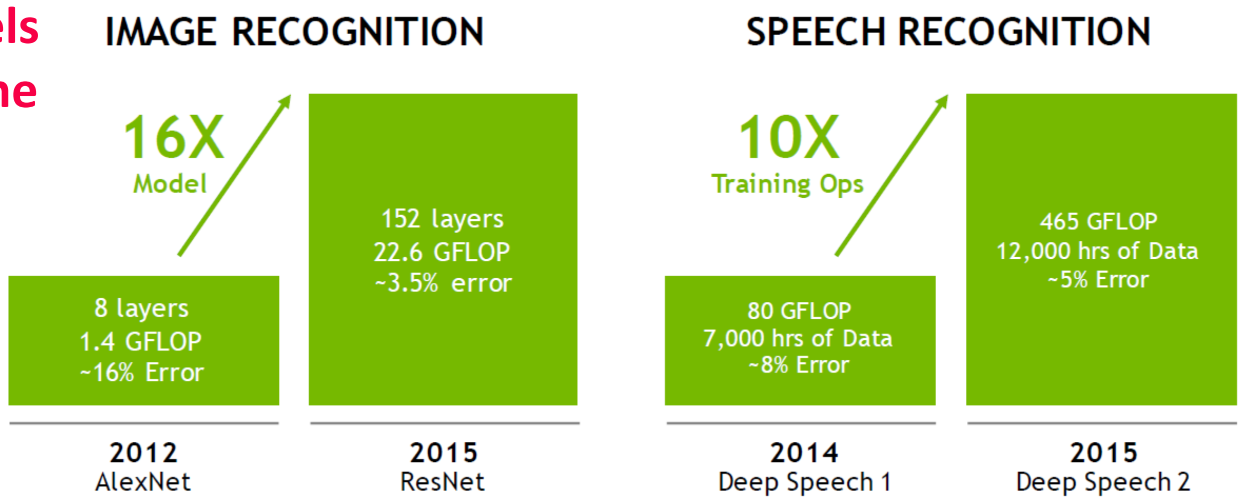
Feedback Loop

$$\begin{tikzcd}
 & \text{Data} \arrow[dr] & \\
\text{Usage} \arrow[ur] & & \text{Model} \arrow[ll]
\end{tikzcd}$$

- **HW & SW Advancements**
  - Higher performance of hardware and infrastructure (cloud)
  - Open-source large-scale computation frameworks, ML systems, and vendor-provides libraries

DNN Challenges

- **#1 Larger Models and Scoring Time**



- **#2 Training Time**
  - ResNet18: 10.76% error, 2.5 days training
  - ResNet50: 7.02% error, 5 days training
  - ResNet101: 6.21% error, 1 week training
  - ResNet152: 6.16% error, **1.5 weeks training**

Efficient Methods and Hardware for Deep Learning

Song Han

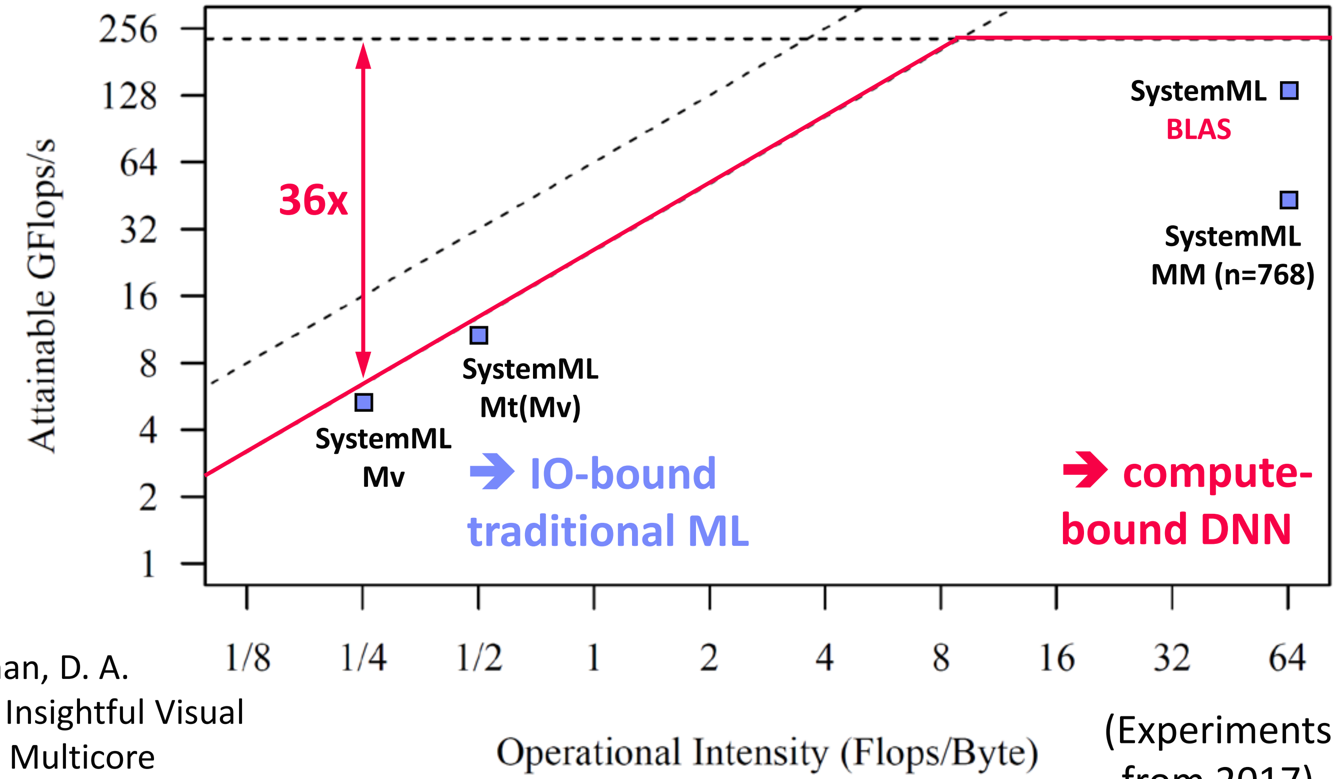
Stanford University

[Song Han: Efficient Methods and Hardware for Deep Learning, Stanford cs231n, 2017]

- **#3 Energy Efficiency**

Excursus: Roofline Analysis

- **Setup:** 2x6 E5-2440 @2.4GHz–2.9GHz, DDR3 RAM @1.3GHz (ECC)
  - Max mem bandwidth (local): 2 sock x 3 chan x 8B x 1.3G trans/s → **2 x 32GB/s**
  - Max mem bandwidth (QPI, full duplex) → **2 x 12.8GB/s**
  - Max floating point ops: 12 cores x 2*4dFP-units x 2.4GHz → **2 x 115.2GFlops/s**
- **Roofline Analysis**
  - Off-chip memory traffic
  - Peak compute



(Experiments from 2017)

[S. Williams, A. Waterman, D. A. Patterson: Roofline: An Insightful Visual Performance Model for Multicore Architectures. **Commun. ACM 2009**]

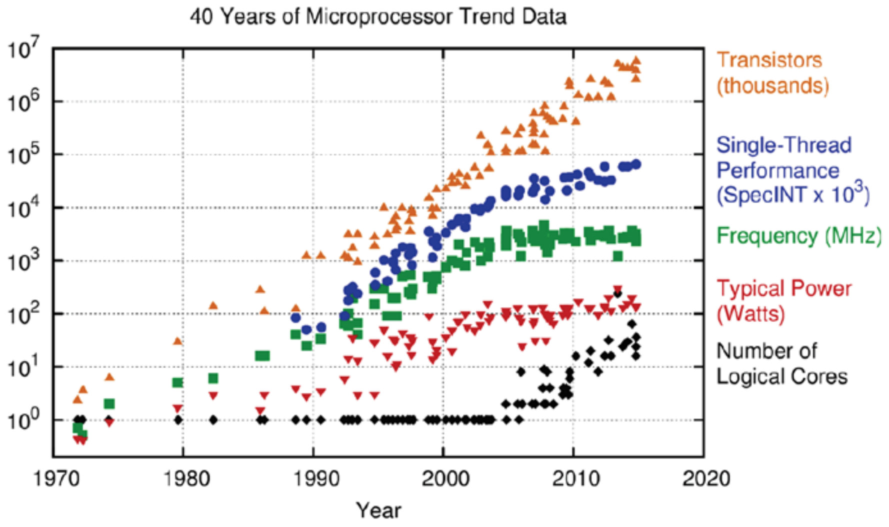
HW Challenges

[S. Markidis, E. Laure, N. Jansson, S. Rivas-Gomez and S. W. D. Chien: Moore's Law and Dennard Scaling]

- **#1 End of Dennard Scaling** (~2005)
  - **Law:** power stays proportional to the area of the transistor
  - Ignored leakage current / threshold voltage → **increasing power density S^2** (power wall, heat) → stagnating frequency

$P = \alpha CFV^2$ (**power density 1**)
(P .. Power, C .. Capacitance, F .. Frequency, V .. Voltage)

- **#2 End of Moore's Law** (~2010-20)
  - **Law:** #transistors/performance/ CPU frequency doubles every 18/24 months
  - Original: # transistors per chip doubles every two years **at constant costs**
  - Now increasing costs (10/7/5nm)

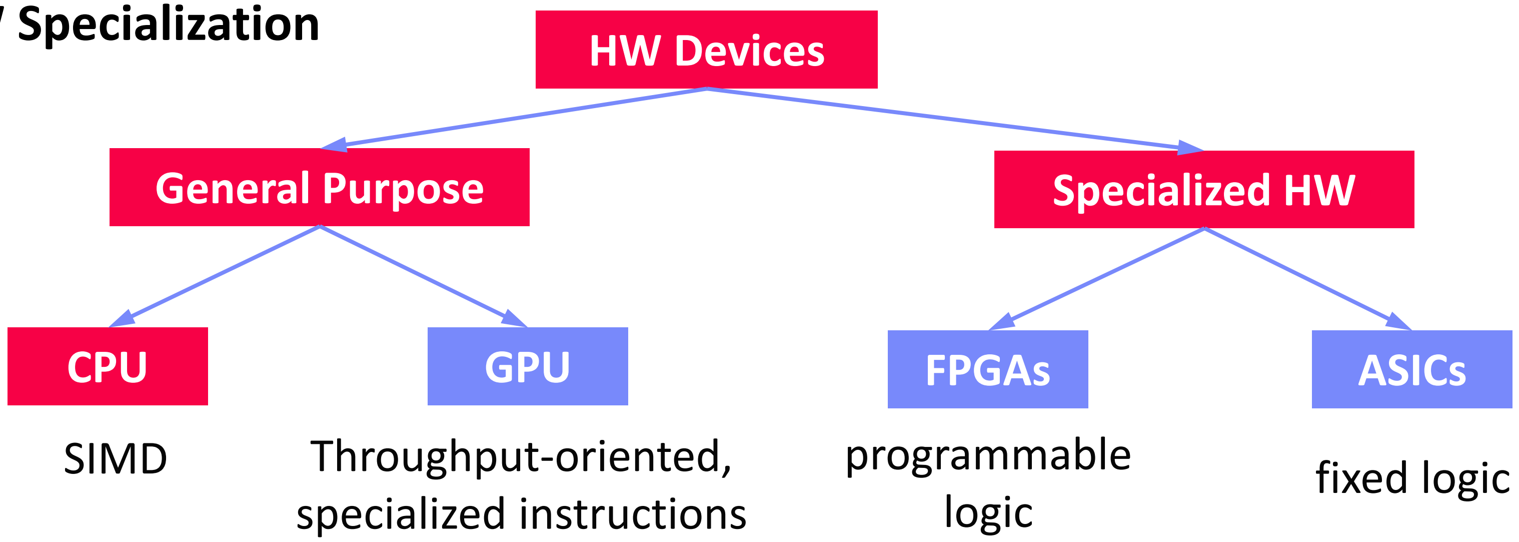


Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2015 by K. Rupp

→ Consequences: Dark Silicon and Specialization

Towards Specialized Hardware

- **HW Specialization**



- **Additional Specialization**
  - **Data Transfer & Types:** e.g., low-precision, quantization
  - **Sparsity Exploitation:** e.g., sparsification, exploit across ops, defer weight decompression just before instruction execution
  - **Near-Data Processing:** e.g., operations in main memory, storage class memory (SCM), secondary storage (e.g., SSDs), and tertiary storage (e.g., tapes)

08 Caching, Indexing and Compression

Graphics Processing Units (GPUs) in ML Systems

NVIDIA Volta V100 – Specifications

- **Tesla V100 NVLink**
  - FP64: **7.8 TFLOPs**, FP32: **15.7 TFLOPs**
  - DL FP16: **125 TFLOPs**
  - NVLink: 300GB/s
  - Device HBM: 32 GB (**900 GB/s**)
  - Power: 300 W

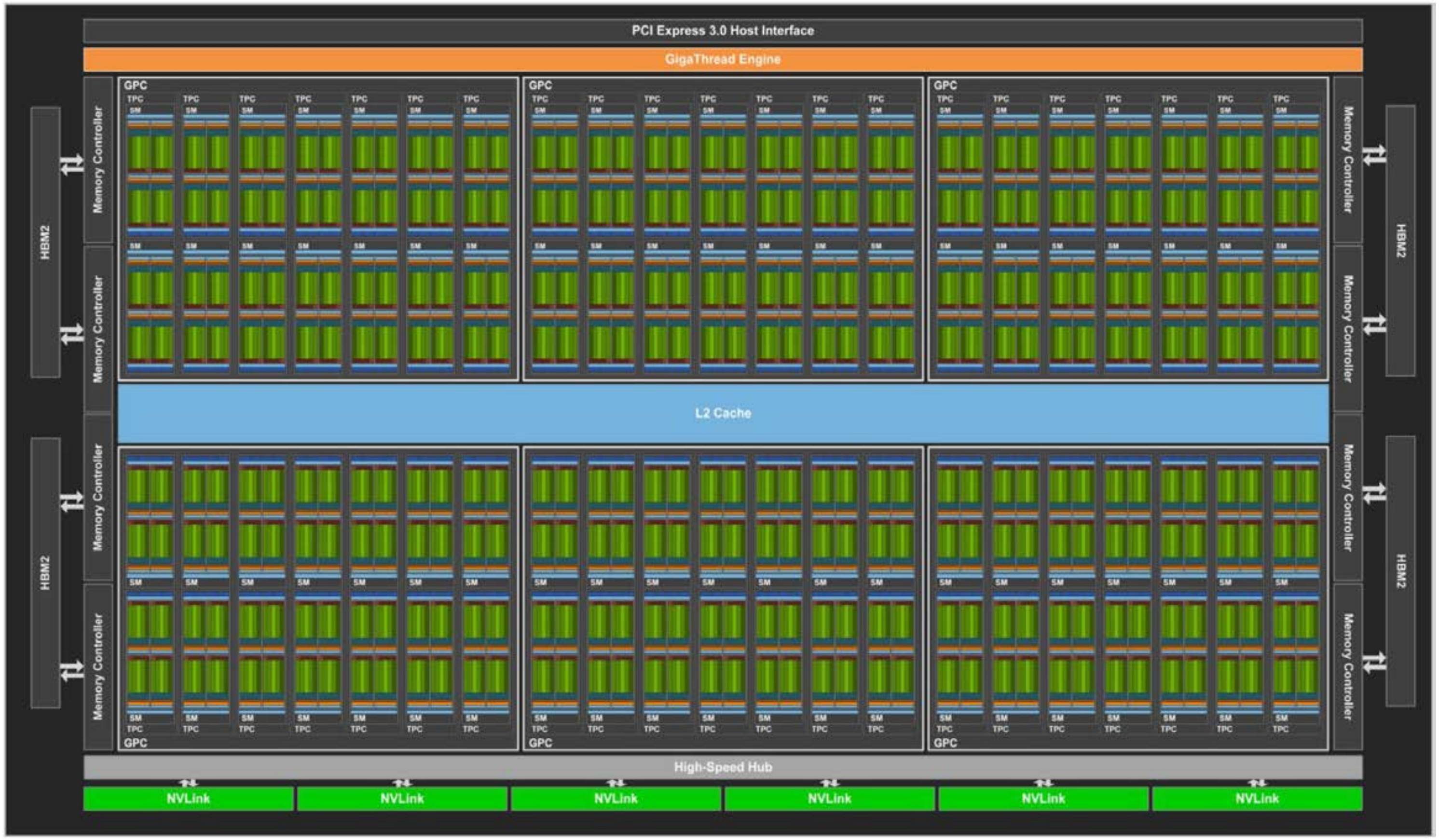
- **Tesla V100 PCIe**
  - FP64: 7 TFLOPs, FP32: 14 TFLOPs
  - DL FP16: 112 TFLOPs
  - PCIe: 32 GB/s
  - Device HBM: 16 GB (900 GB/s)
  - Power: **250 W**

[Credit: https://nvidia.com/de-de/data-center/tesla-v100/]

NVIDIA Volta V100 – Architecture

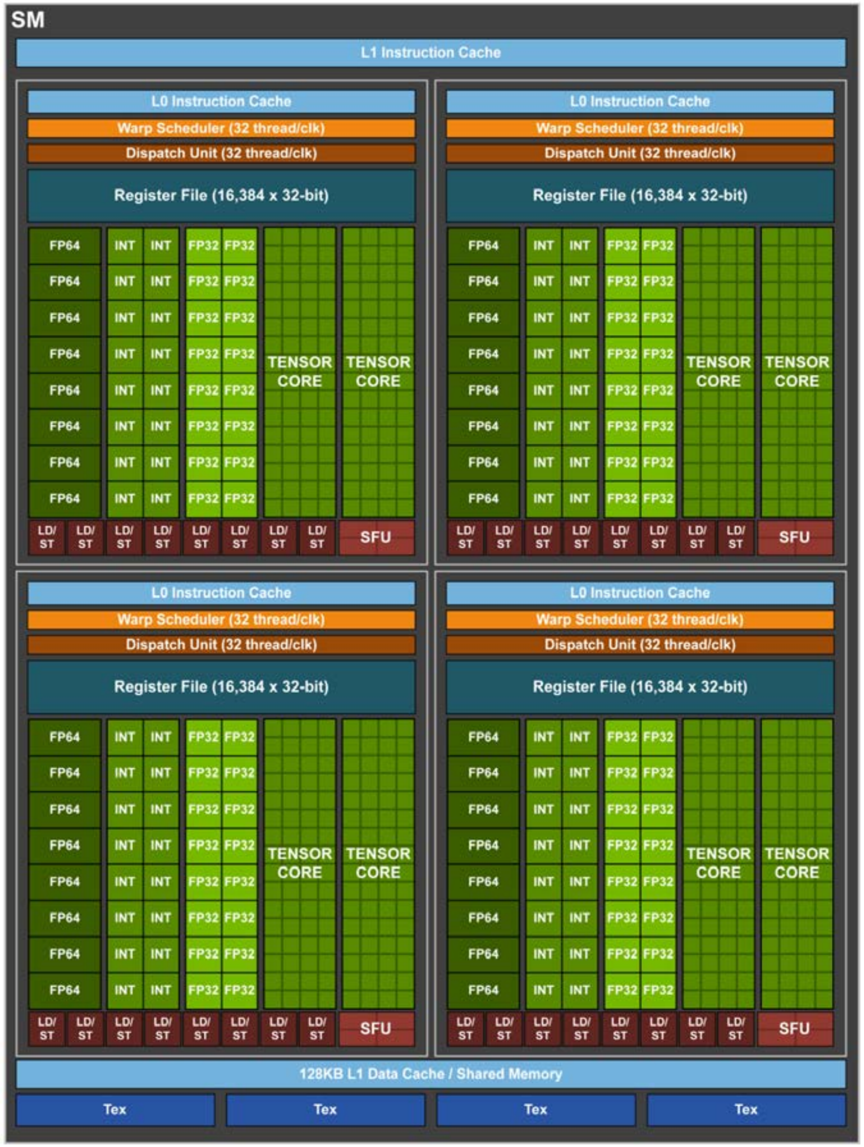
- **6 GPU Processing Clusters (GPCs)**
  - 7 Texture Processing Clusters (TPC)
  - 14 Streaming Multiprocessors (SM)

[NVIDIA Tesla V100 GPU Architecture, Whitepaper, **Aug 2017**]



NVIDIA Volta V100 – SM Architecture

- **FP64 cores: 32**
- **FP32 cores: 64**
- **INT32 cores: 64**
- **“Tensor cores”: 8**
- **Max warps /SM: 64**
- **Threads/warp: 32**


SM
L1 Instruction Cache
L0 Instruction Cache
Warp Scheduler (32 thread/clk)
Dispatch Unit (32 thread/clk)
Register File (16,384 x 32-bit)
FP64
INT
FP32
TENSOR CORE
LD/ST
SFU
128KB L1 Data Cache / Shared Memory
Tex

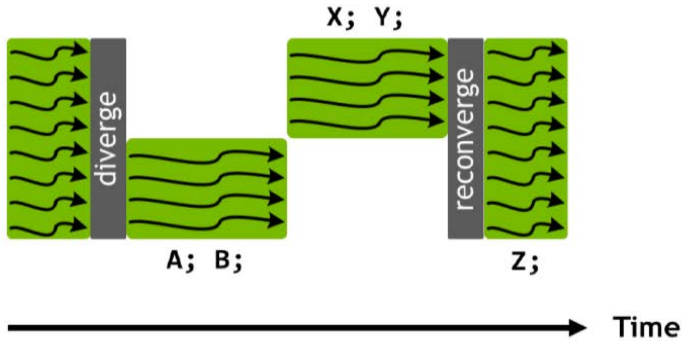
Single Instruction Multiple Threads (SIMT)

- **32 Threads grouped to warps and execute in SIMT model**

- **Pascal P100 Execution Model**
  - Warps use a single program counter + active mask

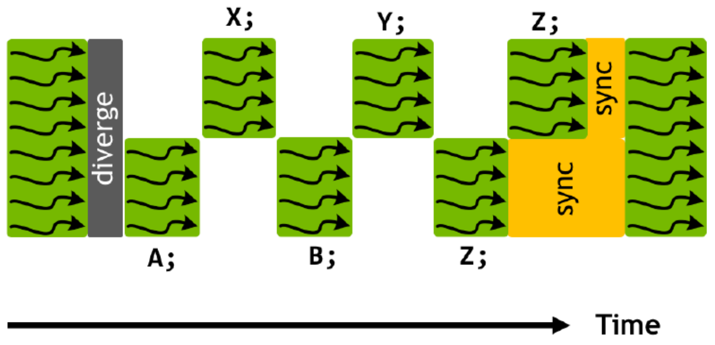
```
if (threadIdx.x < 4) {
    A;
    B;
} else {
    X;
    Y;
}
Z;
```

Thread Divergence



- **Volta V100 Execution Model**
  - Independent thread scheduling
  - Per-thread program counters and call stacks

```
if (threadIdx.x < 4) {
    A;
    B;
} else {
    X;
    Y;
}
Z;
__syncwarp()
```



  - New **__syncwarp()** primitive (if needed) + **convergence optimizer**

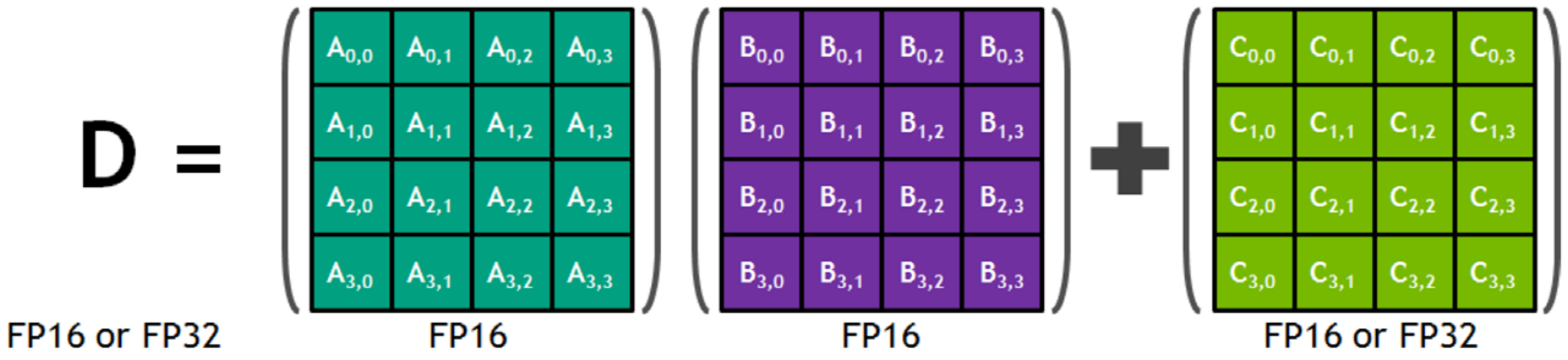
NVIDIA Volta V100 – Tensor Cores

- "Tensor Core"
  - Specialized instruction for **4x4 by 4x4 fused matrix multiply**
  - Two FP16 inputs and FP32 accumulator
  - Exposed as warp-level matrix operations w/ special load, mm, acc, and store

[Bill Dally: Hardware for Deep Learning. **SysML 2018**]

D = A %*% B + C

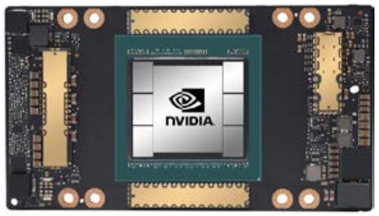
64 FMA operations



$$D = \begin{pmatrix} A_{0,0} & A_{0,1} & A_{0,2} & A_{0,3} \\ A_{1,0} & A_{1,1} & A_{1,2} & A_{1,3} \\ A_{2,0} & A_{2,1} & A_{2,2} & A_{2,3} \\ A_{3,0} & A_{3,1} & A_{3,2} & A_{3,3} \end{pmatrix} \begin{pmatrix} B_{0,0} & B_{0,1} & B_{0,2} & B_{0,3} \\ B_{1,0} & B_{1,1} & B_{1,2} & B_{1,3} \\ B_{2,0} & B_{2,1} & B_{2,2} & B_{2,3} \\ B_{3,0} & B_{3,1} & B_{3,2} & B_{3,3} \end{pmatrix} + \begin{pmatrix} C_{0,0} & C_{0,1} & C_{0,2} & C_{0,3} \\ C_{1,0} & C_{1,1} & C_{1,2} & C_{1,3} \\ C_{2,0} & C_{2,1} & C_{2,2} & C_{2,3} \\ C_{3,0} & C_{3,1} & C_{3,2} & C_{3,3} \end{pmatrix}$$

NVIDIA Ampere A100

[NVIDIA A100 Tensor Core GPU Architecture - UNPRECEDENTED ACCELERATION AT EVERY SCALE, Whitepaper, **Aug 2020**]



- **Specification**
  - 7nm, 8 GPC x 8 TPC * 2 SM = 128 SMs, 40GB HBM
  - FP64: 9.7 TFLOPs / FP64 TensorCore: 19.5 TFLOPs
  - FP32 19.5 TFLOPs, FP16: 78 TFLOPs, BF16: 39 TFLOPs
  - TF32 TensorCore 156 TFLOPs / 312 TFLOPs (sparse)
  - FP16 TensorCore 312 TFLOPs / 624 TFLOPs (sparse), INT8, INT4

- **New Features**
  - New generation of “TensorCores” (FP64, **new data types:** TF32, BF16)
  - Fine-grained **sparsity exploitation**
  - Multi-instance **GPU (MIG) virtualization**: up to 7 virtual GPU instances
  - Link technologies: **NVLink 3** (25GB/s bidirectional) x 12 links = 600GB/s
  - **Submission of task graphs** (launch a workflow of kernels)

Excursus: Amdahl's Law

- **Amdahl's law**
  - Given a fixed problem size, **Amdahl's law gives the maximum speedup**
  - T is the execution time, **s is the serial fraction**, and p the number of processors

Execution Time $$T_p = \frac{(1-s)T}{p} + sT$$

Speedup $$S_p = \frac{T}{T_p}$$

Upper-Bound Speedup $$\overline{S_p} = \lim_{p \to \infty} S_p = \frac{1}{s}$$

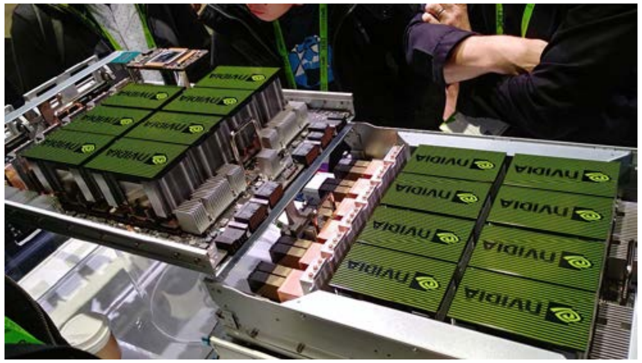
- **Examples**
  - Serial fraction s = 0.01 → max S_p = 100
  - Serial fraction s = **0.05** → max S_p = **20**
  - Serial fraction s = **0.1** → max S_p = **10**
  - Serial fraction s = 0.5 → max S_p = 2

GPUs for DNN Training

- **GPUs for DNN Training** (2009)
  - Deep belief networks
  - Sparse coding

[Rajat Raina, Anand Madhavan, Andrew Y. Ng: Large-scale deep unsupervised learning using graphics processors. **ICML 2009**]

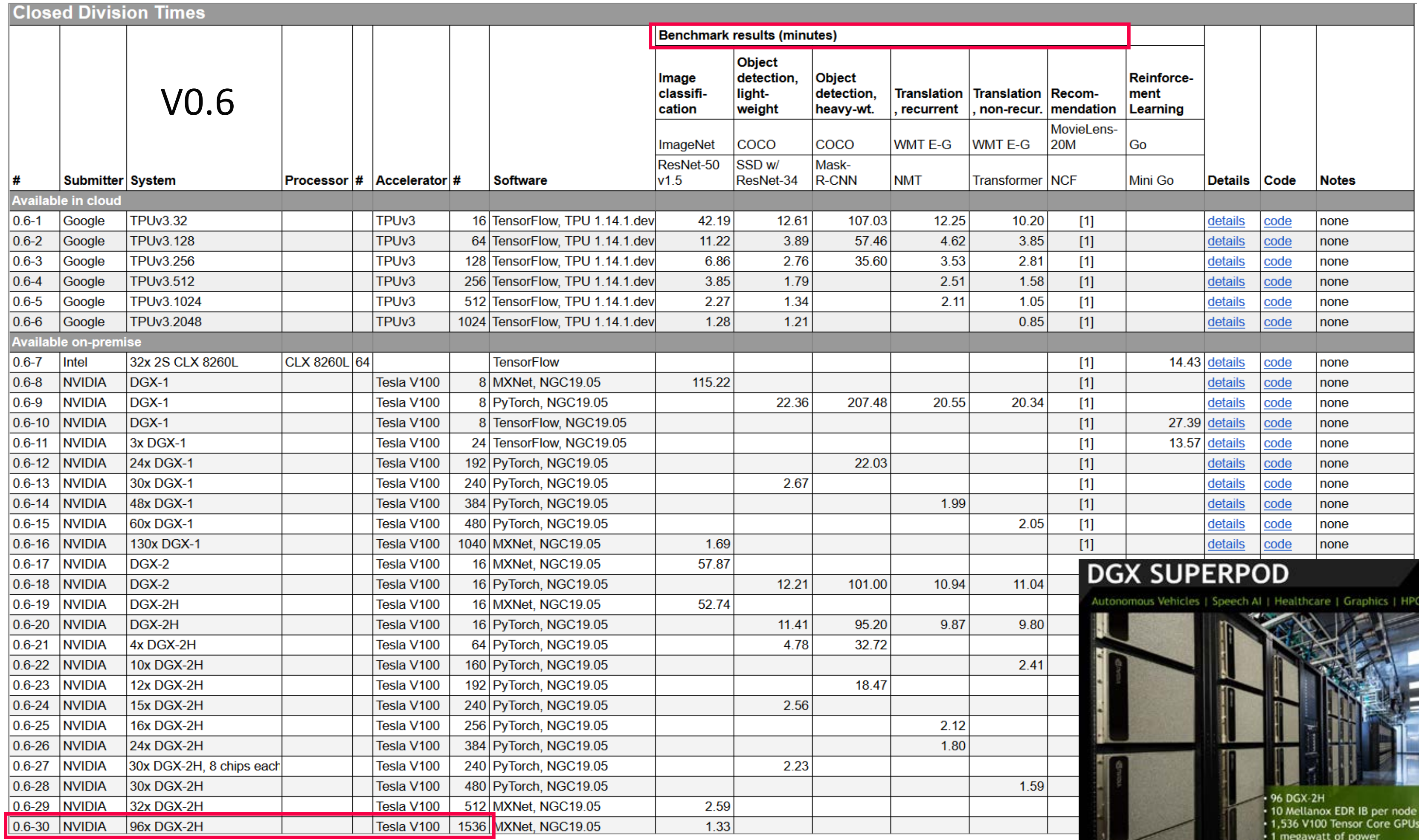
- **Multi-GPU Learning** (Now)
  - Exploit multiple GPUs with a mix of **data- and model-parallel parameter servers**
  - Dedicated ML systems for multi-GPU learning
  - Dedicated HW: e.g., NVIDIA DGX-1 (8xP100), **NVIDIA DGX-2 (16xV100, NVSwitch)**, NVIDIA DGX A100 (8x A100, NVSwitch, Mellanox)



- **DNN Framework support**
  - All specialized DNN frameworks have very good support for GPU training
  - Most of them also support multi-GPU training

Recap: DNN Benchmarks

[**MLPerf** v0.6: https://mlperf.org/training-results-0-6/,
MLPerf v0.7: https://mlperf.org/training-results-0-7]



Closed Division Times

V0.6

#	Submitter	System	Processor	#	Accelerator	#	Software	Benchmark results (minutes) Image classification ImageNet ResNet-50 v1.5	Object detection, light-weight COCO SSD w/ ResNet-34	Object detection, heavy-wt. COCO Mask-R-CNN	Translation, recurrent WMT E-G NMT	Translation, non-recur. WMT E-G Transformer	Recom-mendation MovieLens-20M NCF	Reinforce-ment Learning Go Mini Go	Details	Code	Notes
Available in cloud																	
0.6-1	Google	TPUv3.32			TPUv3	16	TensorFlow, TPU 1.14.1.dev	42.19	12.61	107.03	12.25	10.20	[1]		details	code	none
0.6-2	Google	TPUv3.128			TPUv3	64	TensorFlow, TPU 1.14.1.dev	11.22	3.89	57.46	4.62	3.85	[1]		details	code	none
0.6-3	Google	TPUv3.256			TPUv3	128	TensorFlow, TPU 1.14.1.dev	6.86	2.76	35.60	3.53	2.81	[1]		details	code	none
0.6-4	Google	TPUv3.512			TPUv3	256	TensorFlow, TPU 1.14.1.dev	3.85	1.79		2.51	1.58	[1]		details	code	none
0.6-5	Google	TPUv3.1024			TPUv3	512	TensorFlow, TPU 1.14.1.dev	2.27	1.34		2.11	1.05	[1]		details	code	none
0.6-6	Google	TPUv3.2048			TPUv3	1024	TensorFlow, TPU 1.14.1.dev	1.28	1.21			0.85	[1]		details	code	none
Available on-premise																	
0.6-7	Intel	32x 2S CLX 8260L	CLX 8260L	64			TensorFlow						[1]	14.43	details	code	none
0.6-8	NVIDIA	DGX-1			Tesla V100	8	MXNet, NGC19.05	115.22					[1]		details	code	none
0.6-9	NVIDIA	DGX-1			Tesla V100	8	PyTorch, NGC19.05		22.36	207.48	20.55	20.34	[1]		details	code	none
0.6-10	NVIDIA	DGX-1			Tesla V100	8	TensorFlow, NGC19.05						[1]	27.39	details	code	none
0.6-11	NVIDIA	3x DGX-1			Tesla V100	24	TensorFlow, NGC19.05						[1]	13.57	details	code	none
0.6-12	NVIDIA	24x DGX-1			Tesla V100	192	PyTorch, NGC19.05			22.03			[1]		details	code	none
0.6-13	NVIDIA	30x DGX-1			Tesla V100	240	PyTorch, NGC19.05		2.67				[1]		details	code	none
0.6-14	NVIDIA	48x DGX-1			Tesla V100	384	PyTorch, NGC19.05				1.99		[1]		details	code	none
0.6-15	NVIDIA	60x DGX-1			Tesla V100	480	PyTorch, NGC19.05					2.05	[1]		details	code	none
0.6-16	NVIDIA	130x DGX-1			Tesla V100	1040	MXNet, NGC19.05	1.69					[1]		details	code	none
0.6-17	NVIDIA	DGX-2			Tesla V100	16	MXNet, NGC19.05	57.87									
0.6-18	NVIDIA	DGX-2			Tesla V100	16	PyTorch, NGC19.05		12.21	101.00	10.94	11.04					
0.6-19	NVIDIA	DGX-2H			Tesla V100	16	MXNet, NGC19.05	52.74									
0.6-20	NVIDIA	DGX-2H			Tesla V100	16	PyTorch, NGC19.05		11.41	95.20	9.87	9.80					
0.6-21	NVIDIA	4x DGX-2H			Tesla V100	64	PyTorch, NGC19.05		4.78	32.72							
0.6-22	NVIDIA	10x DGX-2H			Tesla V100	160	PyTorch, NGC19.05					2.41					
0.6-23	NVIDIA	12x DGX-2H			Tesla V100	192	PyTorch, NGC19.05			18.47							
0.6-24	NVIDIA	15x DGX-2H			Tesla V100	240	PyTorch, NGC19.05		2.56								
0.6-25	NVIDIA	16x DGX-2H			Tesla V100	256	PyTorch, NGC19.05				2.12						
0.6-26	NVIDIA	24x DGX-2H			Tesla V100	384	PyTorch, NGC19.05				1.80						
0.6-27	NVIDIA	30x DGX-2H, 8 chips each			Tesla V100	240	PyTorch, NGC19.05		2.23								
0.6-28	NVIDIA	30x DGX-2H			Tesla V100	480	PyTorch, NGC19.05					1.59					
0.6-29	NVIDIA	32x DGX-2H			Tesla V100	512	MXNet, NGC19.05	2.59									
0.6-30	NVIDIA	96x DGX-2H			Tesla V100	1536	MXNet, NGC19.05	1.33									

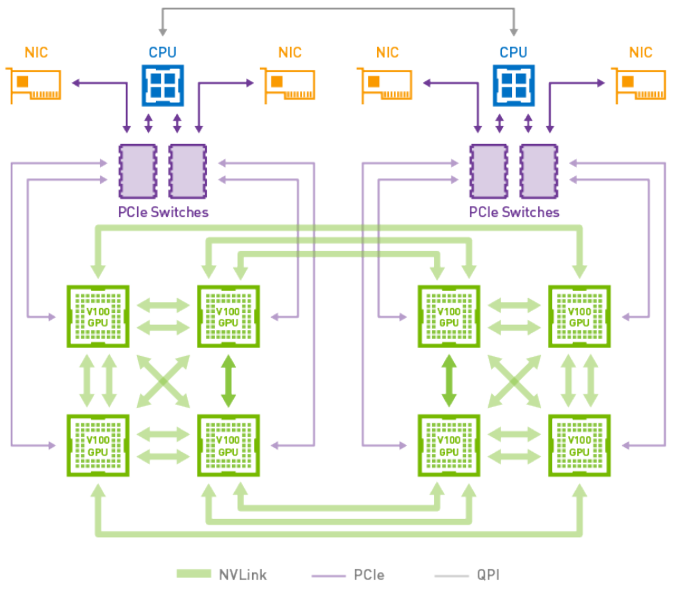
DGX SUPERPOD
Autonomous Vehicles | Speech AI | Healthcare | Graphics | HPC
• 96 DGX-2H
• 10 Mellanox EDR IB per node
• 1,536 V100 Tensor Core GPUs
• 1 megawatt of power

96 x DGX-2H = 96 * 16 = 1536 V100 GPUs
➔ ~ 96 * $400K = **$35M – $40M**

[https://www.forbes.com/sites/tiriasresearch/2019/06/19/nvidia-offers-a-turnkey-supercomputer-the-dgx-superpod/#693400f43ee5]

GPU Link Technologies

- **Classic PCI Express**
  - Peripheral Component Interconnect Express (default)
  - **v3 x16 lanes: 16GB/s**, v4 (2017) x16 lanes: 32GB/s, v5 (2019) x16 lanes: 64GB/s
- **#1 NVLink**
  - Proprietary technology
  - Requires NVLink-enabled CPU (e.g., IBM Power 8/9)
  - Connect GPU-GPU and GPU-CPU
  - NVLink 1: 80+80 GB/s
  - NVLink 2: 150+150 GB/s



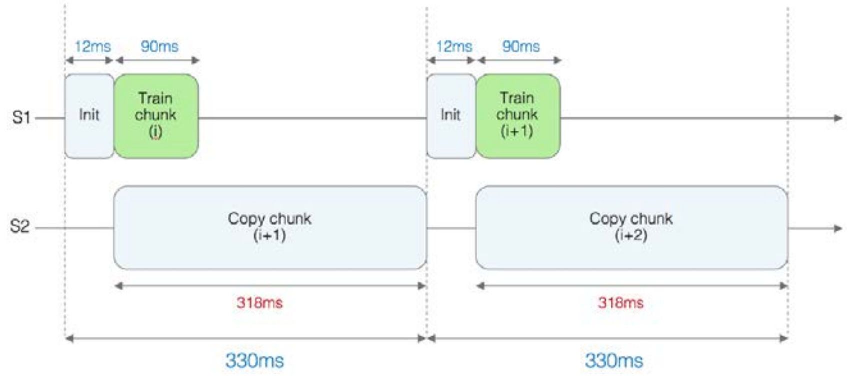
- **#1 NVSwitch**
  - Fully connected GPUs, each communicating at 300GB/s

GPU Link Technologies, cont.

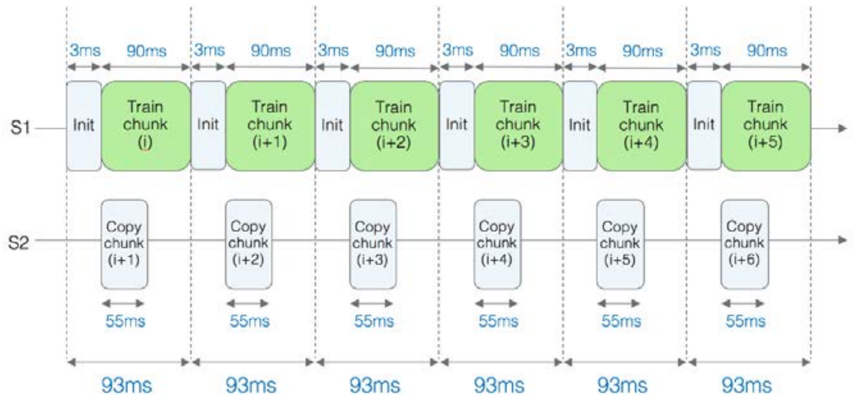
[Celestine Dünner et al.: Snap ML: A Hierarchical Framework for Machine Learning. **NeurIPS 2018**]

- **Recap: Amdahl's Law**
- **Experimental Setup**
  - SnapML, 4 IBM Power x 4 V100 GPUs, NVLink 2.0
  - 200 million training examples of the Criteo dataset (> GPU mem)
  - Train a logistic regression model

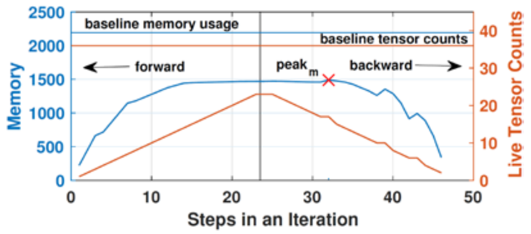
PCIe v3 Interconnect



NVLink Interconnect



Handling Memory Constraints



[Linnan Wang et al: Superneurons: dynamic GPU memory management for training deep neural networks. **PPOPP 2018**]

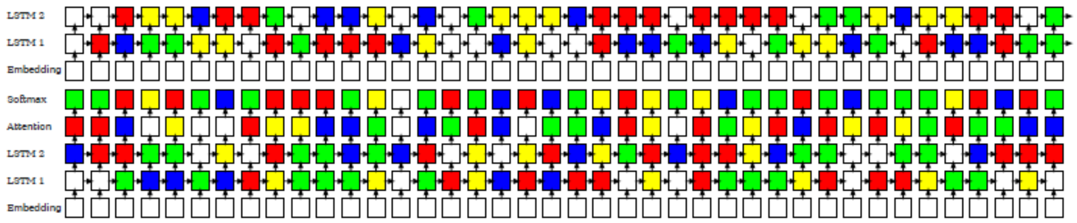
- **Problem: Limited Device Memory**
  - Large models and activations during training
- **#1 Live Variable Analysis**
  - Remove intermediates that are no longer needed
  - **Examples:** SystemML, TensorFlow, MXNet, Superneurons
- **#2 GPU-CPU Eviction**
  - Evict variables from GPU to CPU memory under memory pressure
  - **Examples:** SystemML, Superneurons, GeePS, (TensorFlow)
- **#3 Recomputation**
  - Recompute inexpensive operations (e.g., activations of forward pass)
  - **Examples:** MXNet, Superneurons
- **#4 Reuse Allocations**
  - Reuse allocated matrices and tensors via free lists, but **fragmentation**
  - **Examples:** SystemML, Superneurons

Hybrid CPU/GPU Execution

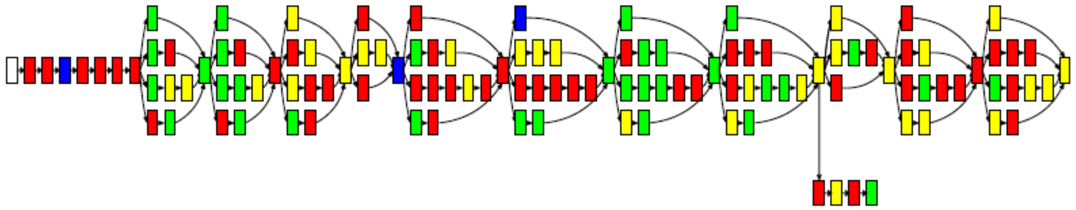
- **Manual Placement**
  - Most DNN frameworks allow manual placement of variables and operations on individual CPU/GPU devices
  - **Heuristics and intuition of human experts**
- **Automatic Placement**
  - Sequence-to-sequence model to predict which operations should run on which device
  - Examples:

[Azalia Mirhoseini et al: Device Placement Optimization with Reinforcement Learning. **ICML 2017**]

Neural MT graph



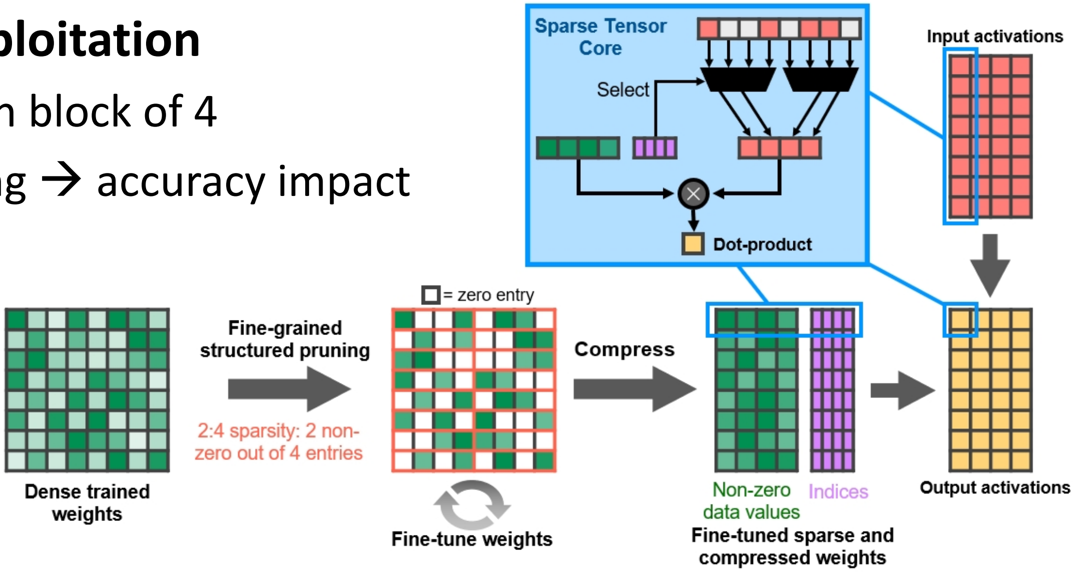
Inception V3



Sparsity in DNN

- **State-of-the-art**
  - Very limited support of sparse tensors in TensorFlow, PyTorch, etc
  - GPU operations for linear algebra (cuSparse), early support in ASICs
  - Problem: Irregular structures of sparse matrices/tensors
- **Common Techniques**
  - #1: Blocking/clustering of rows/columns by number of non-zeros
  - #2: Padding rows/columns to common number of non-zeros
- **Example A100 Sparsity Exploitation**
  - Constraint: 2 non-zeros in block of 4
  - Structured valued pruning → accuracy impact
  - Regular access pattern

[NVIDIA A100 Tensor Core GPU Architecture, Whitepaper, **Aug 2020**]

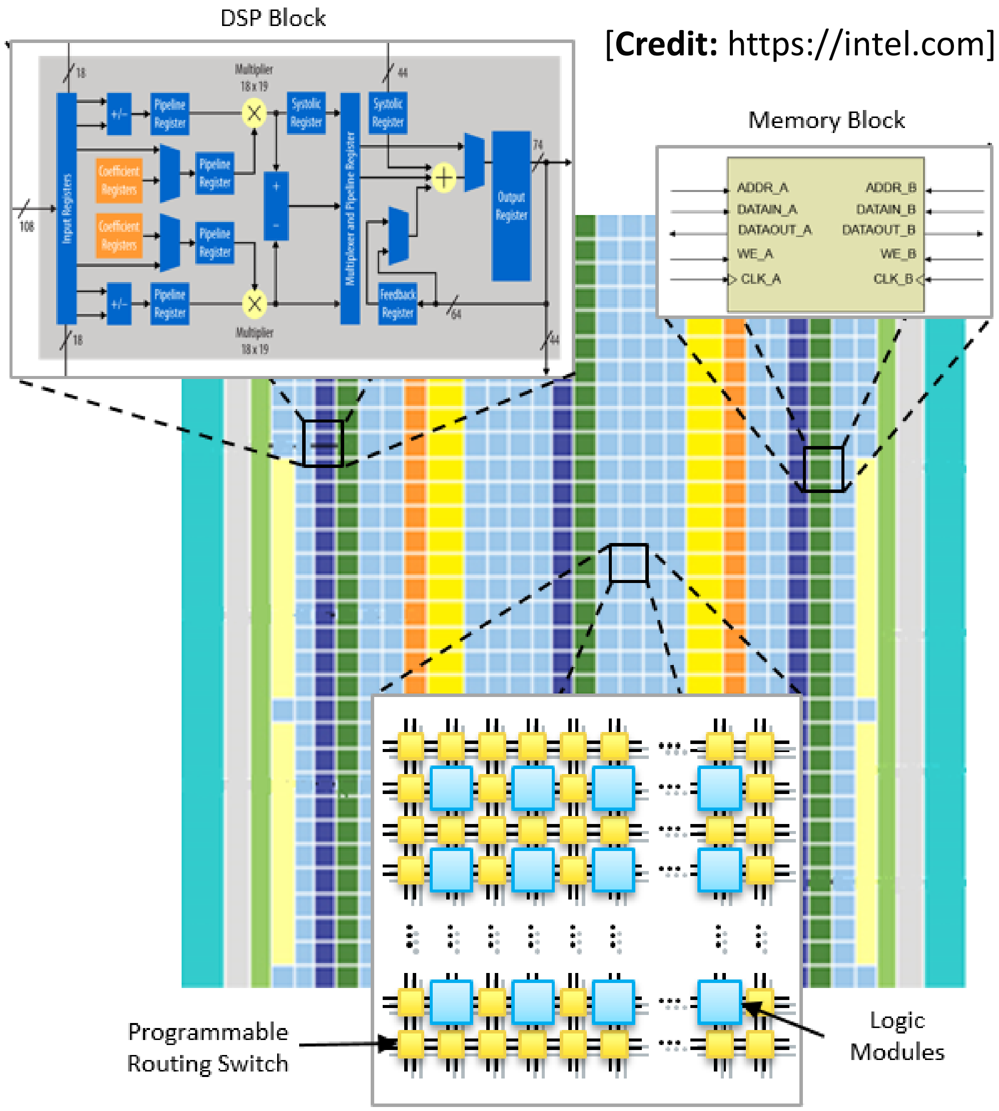


Field-Programmable Gate Arrays (FPGAs) in ML Systems

FPGA Overview

[**Credit:** https://intel.com]

- **FPGA Definition**
  - Integrated circuit that allows **configuring custom hardware designs**
  - Reconfiguration in <1s
  - HW description language: e.g.., VHDL, Verilog
- **FPGA Components**
  - **#1 lookup table** (LUT) as logic gates
  - **#2 flip-flops** (registers)
  - **#3 interconnect network**
  - Additional memory and DSP blocks



Example FPGA Characteristics

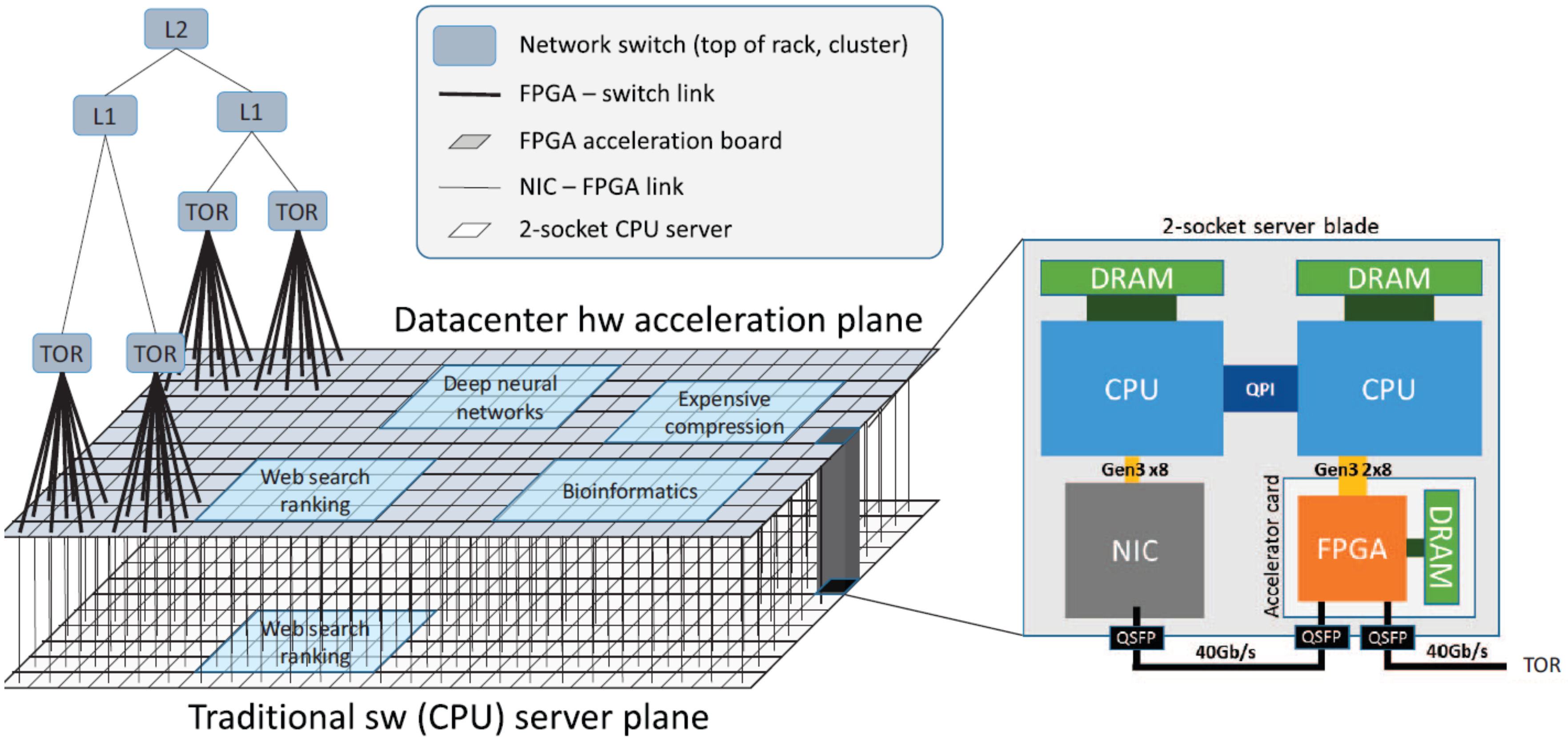
- **Intel (Altera) Stratix 10 SoC FPGA**
  - 64bit quad-core ARM
  - 10 TFLOPs FP32
  - 80GFLOPs/W
  - Other configurations w/ HBM2

- **Xilinx Virtex UltraSCALE+**
  - DSP: 21.2 TMACs
  - 64MB on-chip memory
  - 8GB HBM2 w/ 460GB/s

FPGAs in Microsoft's Data Centers

- **Microsoft Catapult**
  - Dual-socket Xeon w/ PCIe-attached FPGA
  - Pre-filtering neural networks, compression, and other workloads

[Adrian M. Caulfield et al.: A cloud-scale acceleration architecture. **MICRO 2016**]

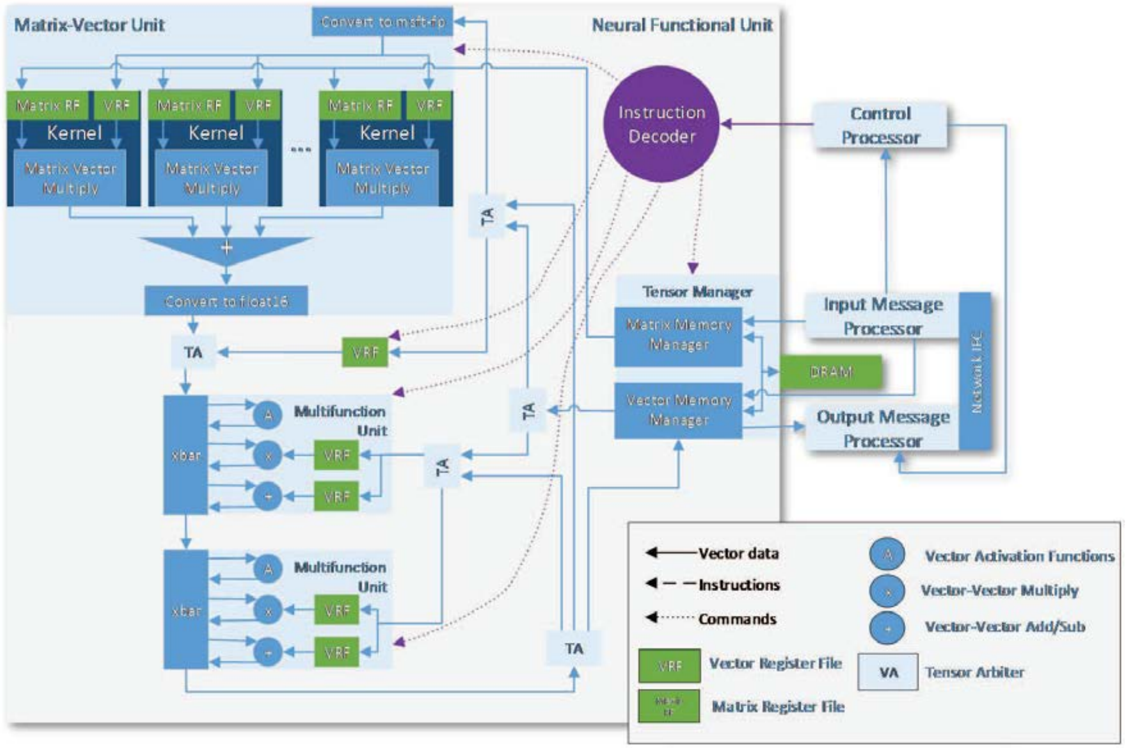


FPGAs in Microsoft's Data Centers, cont.

- **Microsoft Brainwave**
  - ML serving w/ low latency (e.g., Bing)
  - Intel Stratix 10 FPGA
  - Distributed **model parallelism**, precision-adaptable
  - Peak 39.5 TFLOPs

[Eric S. Chung et al: Serving DNNs in Real Time at Datacenter Scale with Project Brainwave. **IEEE Micro 2018**]

- **Brainwave NPU**
  - Neural processing unit
  - Dense matrix-vector multiplication



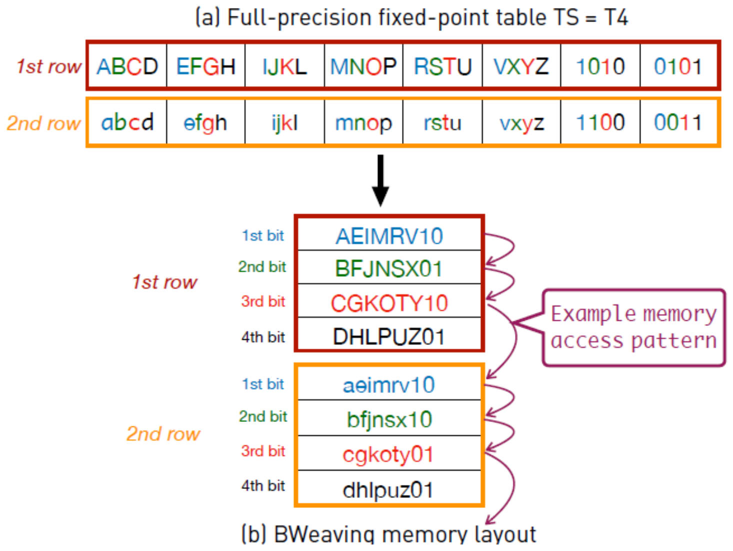
FPGAs in other ML Systems

- **In-DB Acceleration of Advanced Analytics (DAnA)**
  - Compilation of python DSL into micro instructions for multi-threaded FPGA-execution engine
  - Striders to directly **interact with the buffer pool**

[Divya Mahajan et al: In-RDBMS Hardware Acceleration of Advanced Analytics. **PVLDB 2018**]

- **MLWeaving**
  - Adapted **BitWeaving** to numeric matrices
  - Data layout basis for **Any-Precision Learning**
  - Related FPGA implementation of SGD, matrix-vector multiplication for GLM
  - **Manual Selection** + Heuristics

[Zeke Wang et al: Accelerating Generalized Linear Models with MLWeaving. **PVLDB 2019**]



- **Efficient FPGA implementations of specific operations and algorithms**
- **Specialized neural network topologies**

Application-Specific Integrated Circuit (ASICs) and other HW Accelerators

Overview ASICs

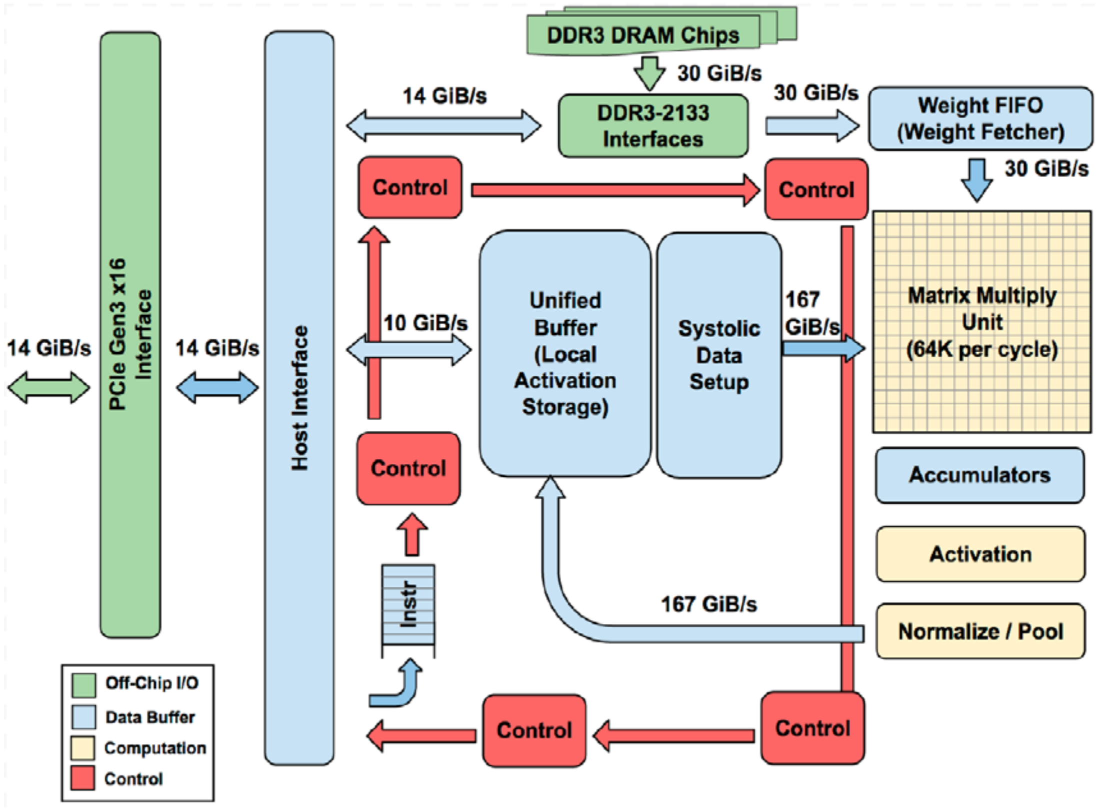
- **Motivation**
  - Additional improvements of performance, power/energy
  - → **Additional specialization via custom hardware**
- **#1 General ASIC DL Accelerators**
  - HW support for matrix multiply, convolution and activation functions
  - Examples: **Google TPU**, **NVIDIA DLA** (in NVIDIA Xavier SoC), **Intel Nervana NNP**
- **#2 Specialized ASIC Accelerators**
  - Custom instructions for specific domains such as computer vision
  - Example: (Cadence) **Tensilica Vision processor** (image processing)
- **#3 Other Accelerators/Technologies** (some skepticism)
  - a) **Neuromorphic computing / spiking neural networks**
    (e.g., SyNAPSE → IBM TrueNorth, HP memristor for computation storage)
  - b) **Analog computing** (especially for ultra-low precision/quantization)

Tensor Processing Unit (TPU v1)

- **Motivation**
  - Cost-effective ML scoring (no training)
  - Latency- and throughput-oriented
  - **Improve cost-performance over GPUs by 10x**

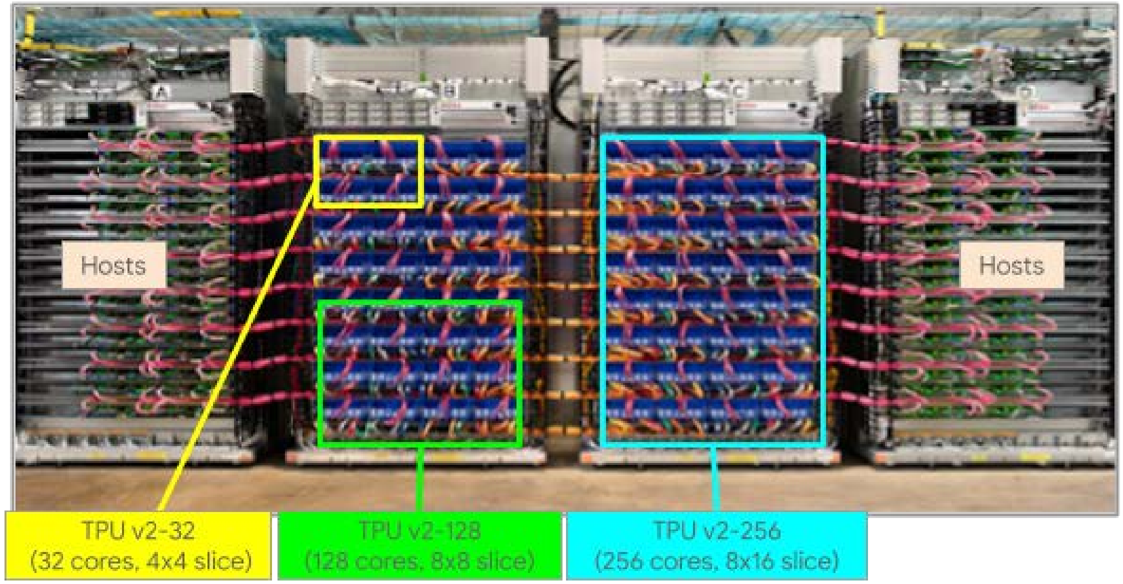
[Norman P. Jouppi et al: In-Datacenter Performance Analysis of a Tensor Processing Unit. **ISCA 2017**]

- **Architecture**
  - 256x256 8bit matrix multiply unit (systolic array → **pipelining**)
  - 64K MAC per cycle (92 TOPs at 8 bit)
  - 50% if one input 16bit
  - 25% if all inputs 16 bit



Tensor Processing Unit (TPU v2)

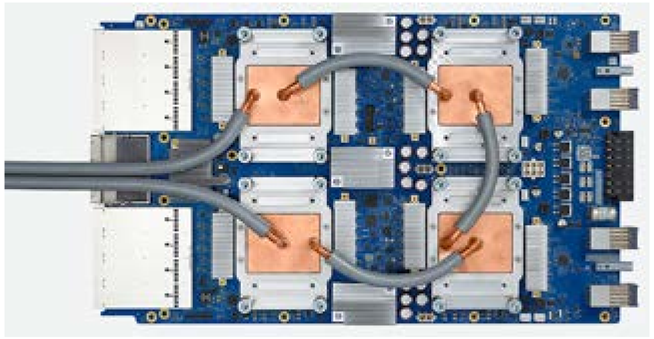
- **Motivation**
  - **Cost effective ML training** (**not scoring**) because edge device w/ custom inference but training in data centers
  - Unveiled at **Google I/O 2017**
  - Board w/ **4 TPU chips**
  - Pod w/ **64 boards** and custom high-speed network
  - Shelf w/ 2 boards or 1 processor
- **Cloud Offering (beta)**
  - Min 32 cores
  - Max 512 cores



Tensor Processing Unit (TPU v3)

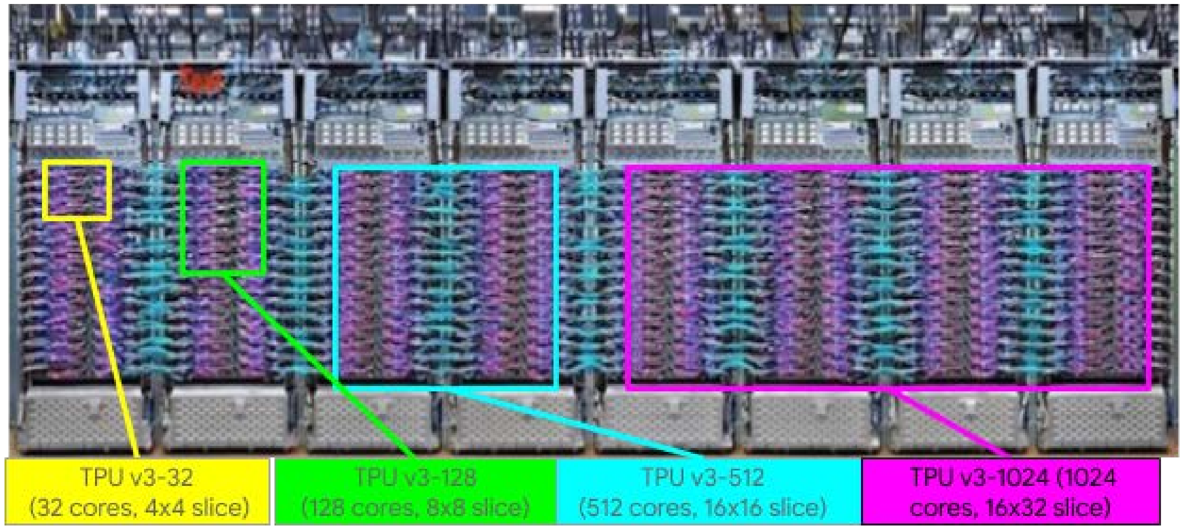
- **Motivation**
  - Competitive cost-performance compared to state-of-the-art GPUs
  - Unveiled at **Google I/O 2018**
  - Added **liquid cooling**
  - Twice as many racks per pod, twice as many TPUs per rack

  ➔ TPUv3 promoted as **8x higher performance** than TPUv2



- **Cloud Offering (beta)**
  - Min 32 cores
  - Max 2048 cores (~100PFLOPs)

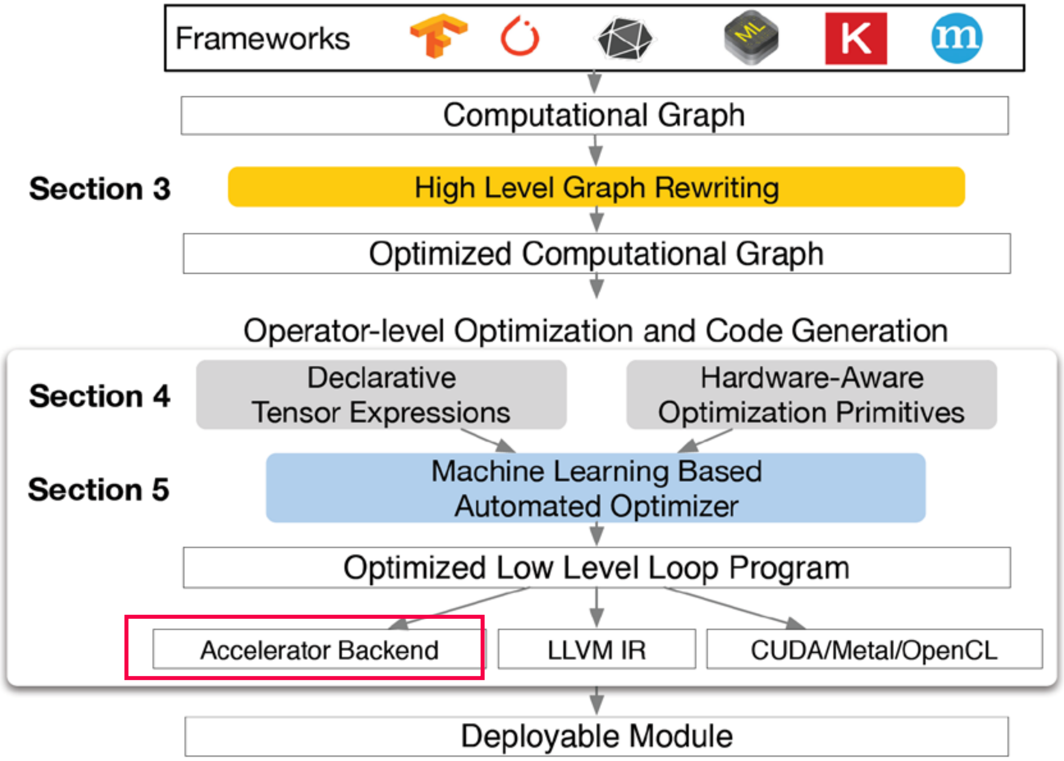
[TOP 500 Supercomputers:
Summit @ Oak Ridge NL ('18):
200.7 PFLOP/s (2.4M cores)]


TPU v3-32 (32 cores, 4x4 slice)
TPU v3-128 (128 cores, 8x8 slice)
TPU v3-512 (512 cores, 16x16 slice)
TPU v3-1024 (1024 cores, 16x32 slice)

Recap: Operator Fusion and Code Generation

- **TVM: Code Generation for HW Accelerators**
  - Graph- /operator-level optimizations for **embedded and HW accelerators**
  - **Lack of low-level instruction set!**
  - Schedule Primitives
    - Loop Transform
    - Thread Binding
    - Compute Locality
    - Tensorization
    - Latency Hiding

[Tianqi Chen et al: TVM: An Automated End-to-End Optimizing Compiler for Deep Learning. **OSDI 2018**]


Frameworks
Computational Graph
Section 3
High Level Graph Rewriting
Optimized Computational Graph
Operator-level Optimization and Code Generation
Section 4
Declarative Tensor Expressions
Hardware-Aware Optimization Primitives
Section 5
Machine Learning Based Automated Optimizer
Optimized Low Level Loop Program
Accelerator Backend
LLVM IR
CUDA/Metal/OpenCL
Deployable Module

➔ **Apache** tvm

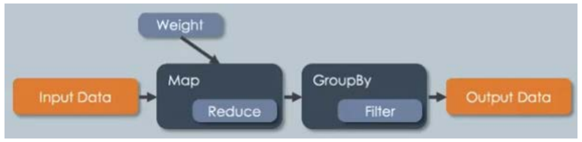
SambaNova

[Kunle Olukotun: Let the Data Flow!, **CIDR 2021**, https://www.youtube.com/watch?v=iHhHHBuk3W4, **SDSC 2020**, https://www.youtube.com/watch?v=E7se0KEa4BY]

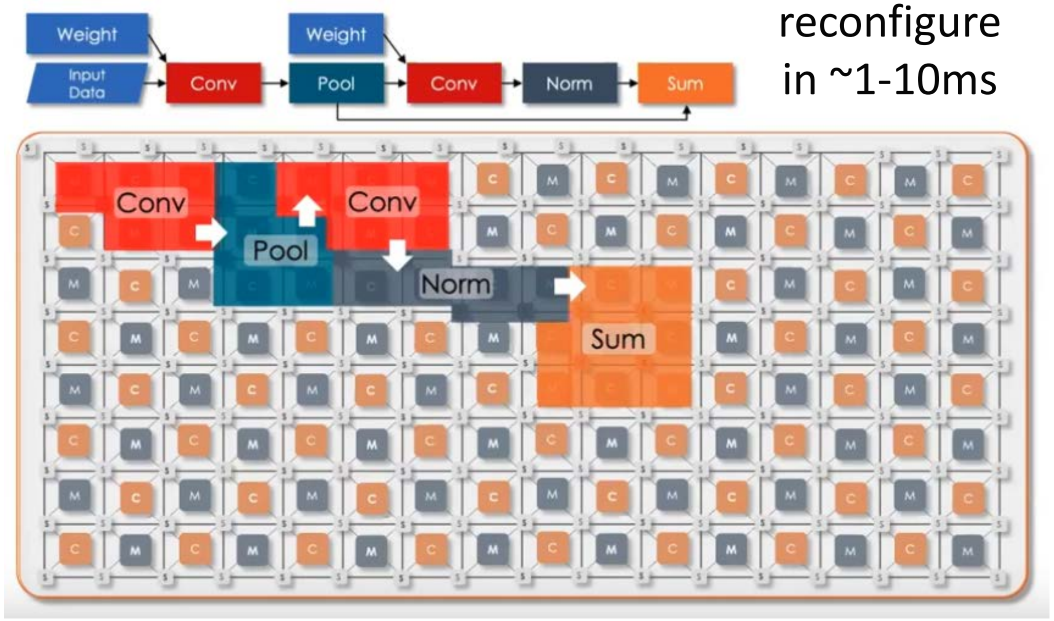
- **Overview**
  - Reconfigurable data flow architecture
  - Based on **hierarchical parallel patterns** (map, zip, reduce, flatMap, groupBy)
  - Reconfigurable Dataflow Unit (**RDU**), 100s of TFLOPs, 100s MB on chip

DataScale SN10-8R Quarter Rack (includes 1 x SN10-8, 12TB)
DataScale SN10-8R Half Rack (includes 2 x SN10-8, 24TB)
DataScale SN10-8R Full Rack (includes 4 x SN10-8, 48TB)

- **Mapping of Dataflow Computation**
  - DNN / ML
  - Graph processing
  - SQL query processing

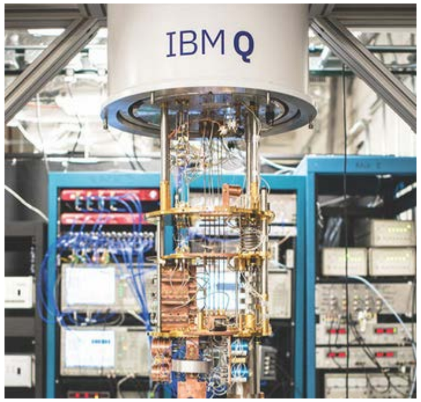


reconfigure in ~1-10ms



Excursus: Quantum Machine Learning

- **Background** (Schrödinger's cat)
  - Concepts: superposition, entanglement, de-coherence / uncertainty
- **IBM Q**
  - Hardware and software stack for quantum computing
  - **Qiskit:** OSS Python framework [https://qiskit.org/]
  - Experiment w/ quantum computers up to 20 qubit
  - **Gates:** Hadamard, NOT, Phases, Pauli, barriers transposed conjugate, if, measurement



- **Early ML (Systems) Work**
  - **Training quantum neural networks** (relied on quantum search in O(√N)
  - **SVM classification** w/ large feature space
  - **TensorFlow Quantum** (TFQ), on OSS **Cirq** for hybrid models [https://www.tensorflow.org/quantum]

[Bob Ricks, Dan Ventura: Training a Quantum Neural Network. **NIPS 2003**]

[Vojtěch Havlíček et al: Supervised learning with quantum-enhanced feature spaces. **Nature 2019**]

ML Hardware Fallacies and Pitfalls

- **Recommended Reading**
  - [Jeff Dean, David A. Patterson, Cliff Young: A New Golden Age in Computer Architecture: Empowering the Machine-Learning Revolution. **IEEE Micro 2018**]

- **#1 Fallacy: Throughput over Latency**
  - Given the large size of the ML problems, the HW focus should be op/s (throughput) rather than time to solution (latency)
- **#2 Fallacy: Runtime over Accuracy**
  - Given large speedup, ML researchers would be willing to sacrifice accuracy
- **#3 Pitfall: Designing HW using last year's models**
- **#4 Pitfall: Designing ML HW assuming the ML system is untouchable**

- -

- **Trend: Chip Placement**
  - Chip placement as part of chip design process
  - SRAM, logic → optimize power, performance, area

[Azalia Mirhoseini, Anna Goldie, et al: Chip Placement with Deep Reinforcement Learning. **CoRR 2020**]

Summary and Conclusions

- **Different Levels of Hardware Specialization**
  - General-purpose CPUs and GPUs
  - FPGAs, DNN ASICs, and other technologies

Increasing importance of specialization:
End of Moore's Law
End of Dennard Scaling

- **Next Lectures**
  - **08 Caching, Partitioning, Indexing and Compression** [May 07]
  - **May 14:** Ascension Day (Christi Himmelfahrt) + "Rektorstag"

(Part A: Overview and ML System Internals)

  - **09 Data Acquisition, Cleaning, and Preparation** [May 21]
  - **10 Model Selection and Management** [May 28]
  - **11 Model Debugging, Fairness, Explainability** [Jun 04]
  - **12 Model Serving Systems and Techniques** [Jun 11]

(Part B: ML Lifecycle Systems)