Pathways: Asynchronous Distributed Dataflow for ML

by Barham et al., 2022

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[Paper link]

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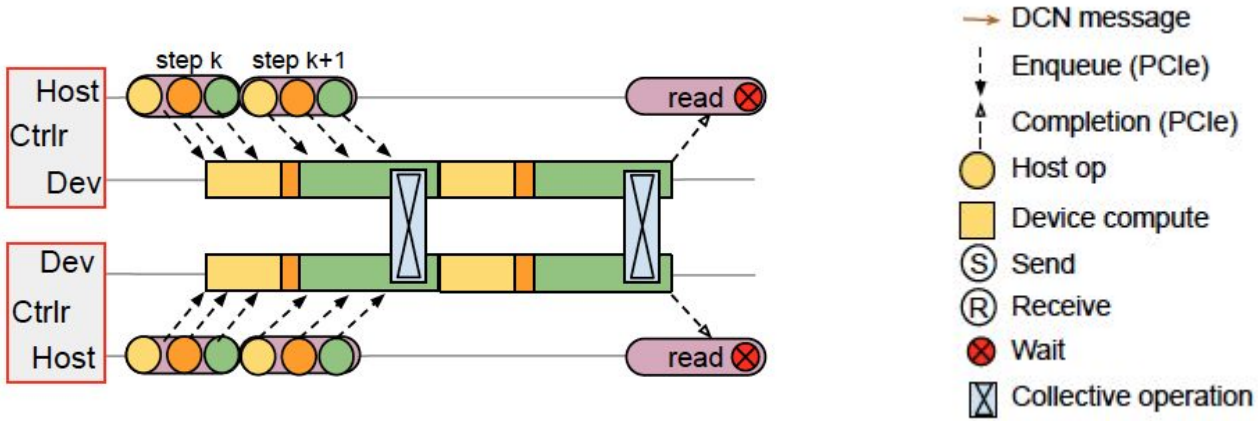
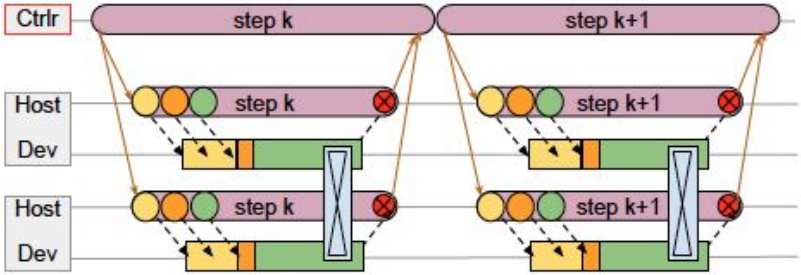
Yesterday…

- Single Program Multiple Data paradigm (SPMD)
  - All accelerators run the same computation and communicate collectively!

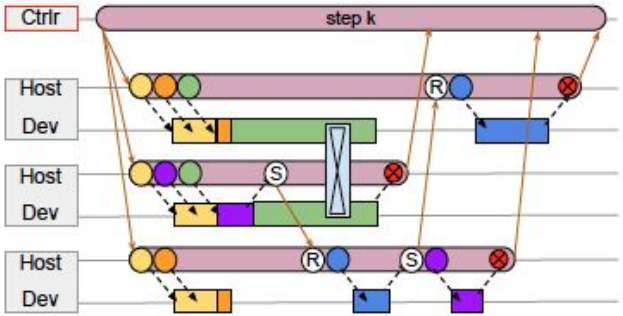


(a) JAX/PyTorch SPMD

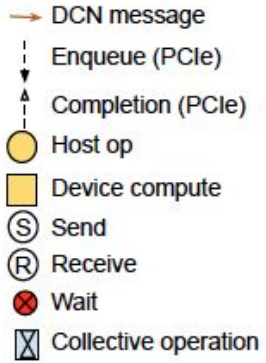
Yesterday…



(b) TF1 SPMD



(c) TF1 non-SPMD



Yesterday… and Today!

- Single Program Multiple Data paradigm (SPMD)
  - All accelerators run the same computation and communicate collectively!

- Large models struggle to scale using SPMD. Instead:
  - Pipelining
  - Use of sparsity (e.g. MoE)
  - …
- Heterogeneous clusters
  - Multiple Program Multiple Data (MPMD)
- Foundation models and model sharing

SPMD models and multi-controller (PyTorch, Tensorflow, JAX)

- Low latency (dispatch over fast PCIe) 🔥
- Implementation fairly straightforward (ctrl+c, ctrl+v) 🔥
- but…
- Poor flexibility! 😖

So, maybe single-controller systems?

- General distributed dataflow model (MPMD) 🔥
- Virtualisation of resources 🔥
- but…
- Dispatch over slower Data Center Network (DCN) 😖
- Still important to have SPMD ability -> Gang-scheduling 😖

The Challenge

Low latency + workload flexibility

Solution!

Sharded dataflow graph + Asynchronous operations

Pathways Programming Model

- XLA computations -- “compiled functions”
  - Resources known beforehand (input/output shapes, types, etc.)
  - Each compiled function maps to a single (sharded) node in the dataflow graph
- Functions can be placed on specific virtual devices with desired network topology and other constraints
- Pathways automatically handles data movement and resharding

Pathways System Architecture

- Resource Manager
- Client
- Coordination
- Gang-scheduled dynamic dispatch
- Parallel async dispatch
- Data management

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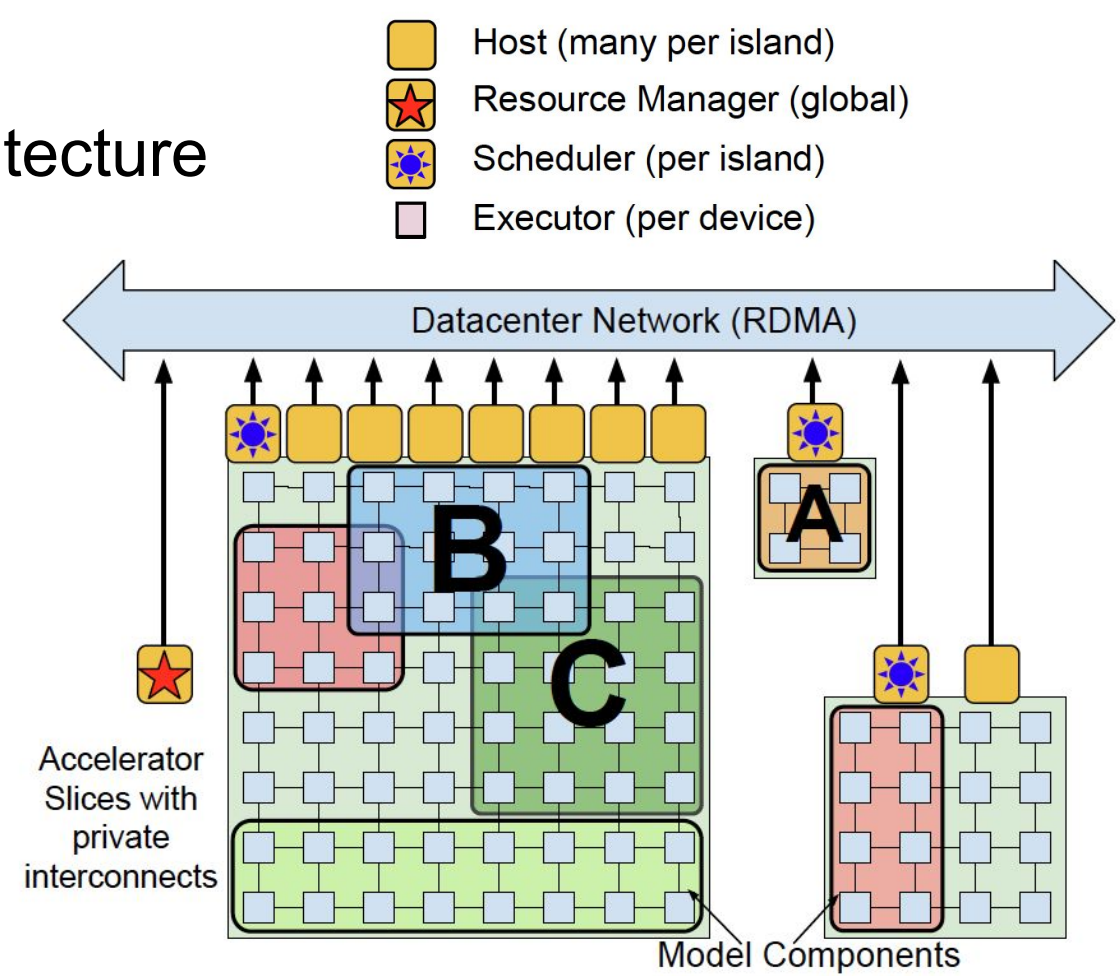
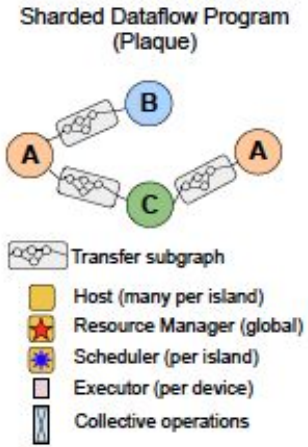
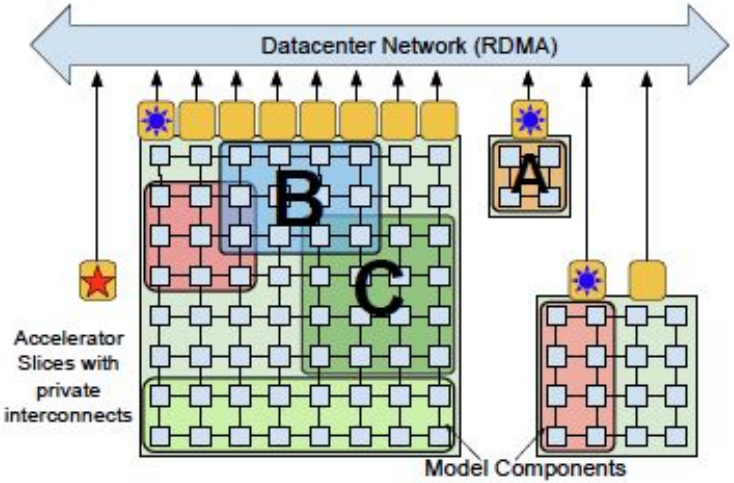
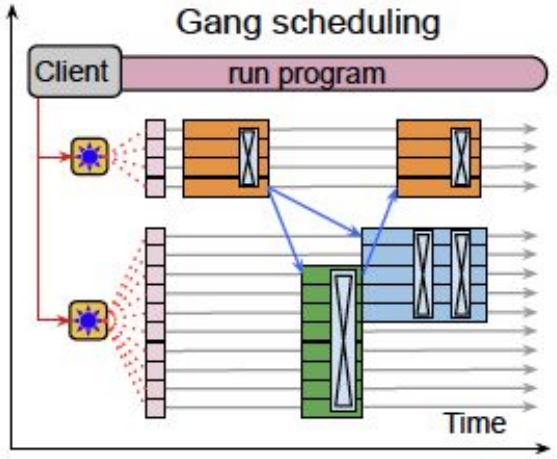


Pathways System Architecture

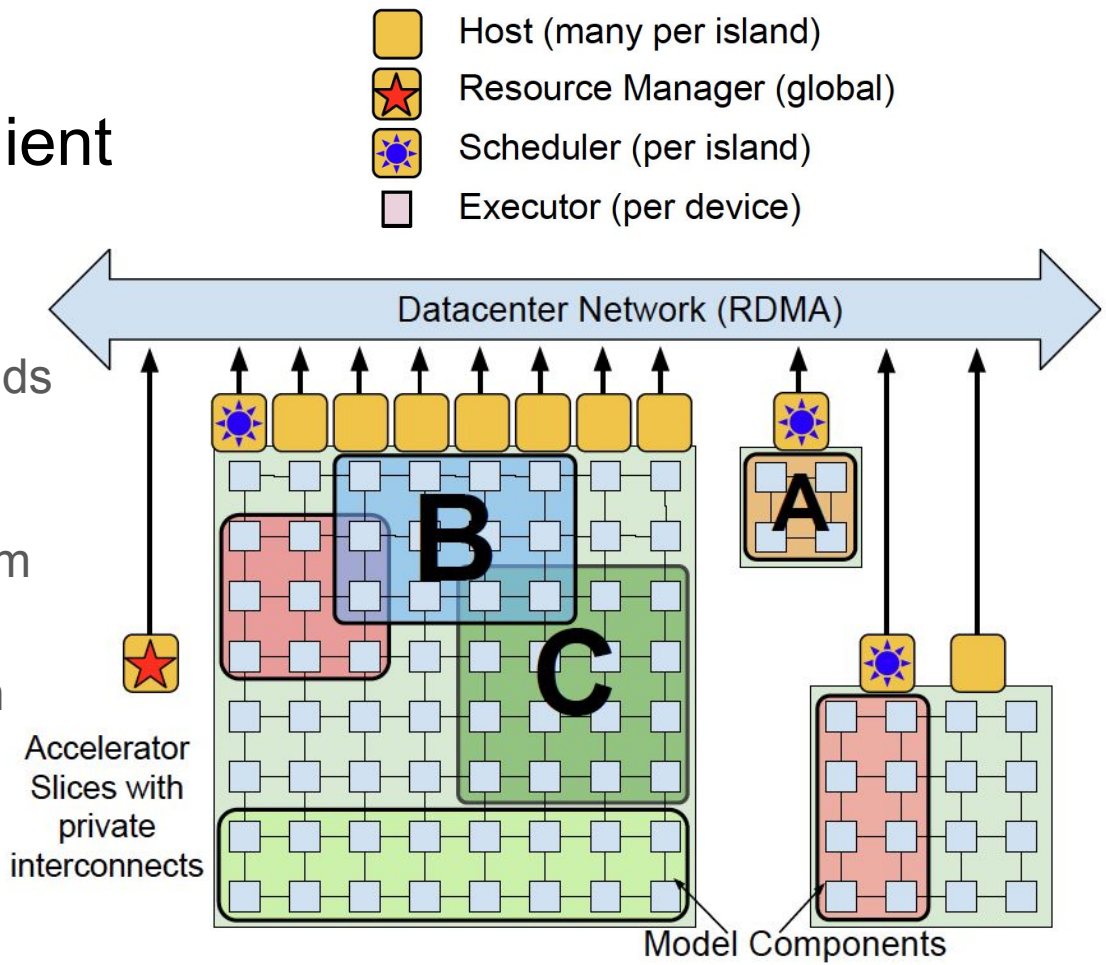






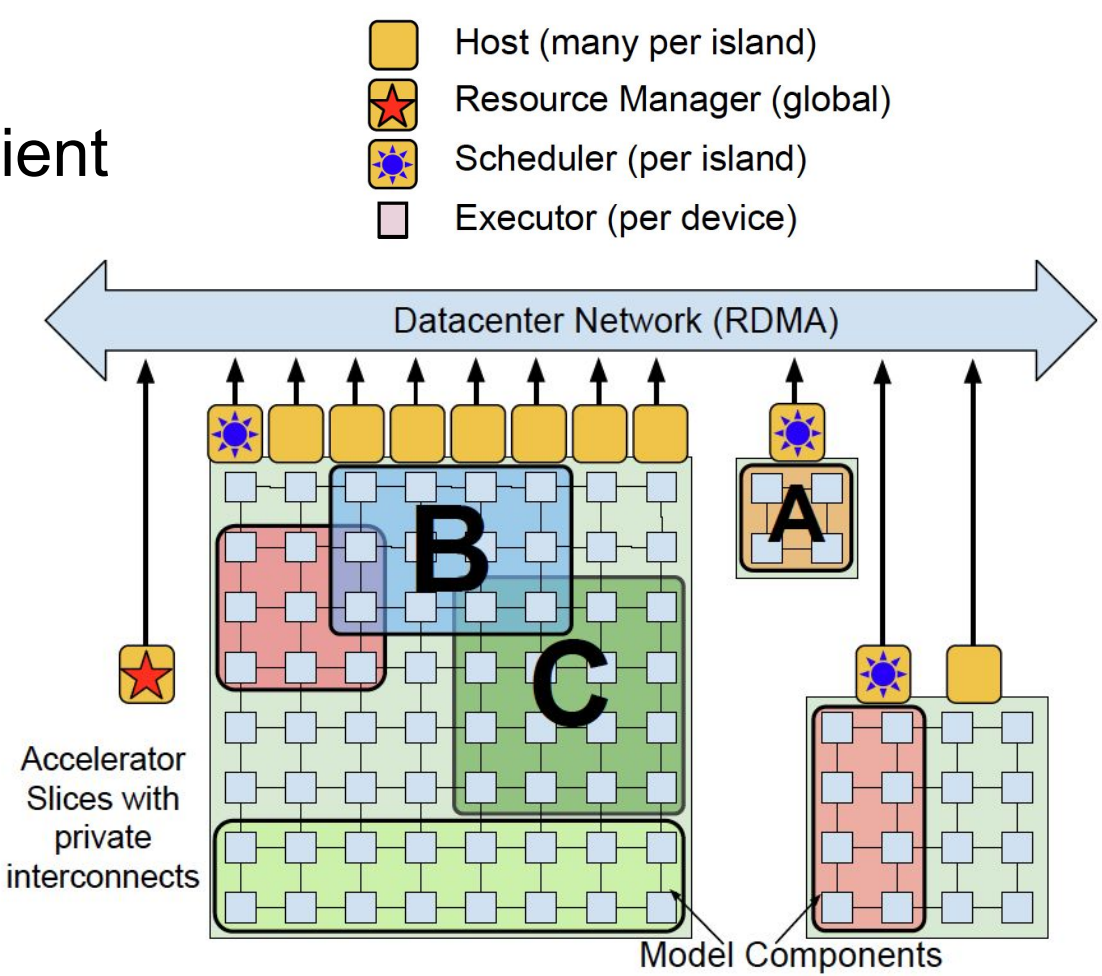
Resource Manager & Client

- Accelerators grouped in islands
- Virtualisation of resources
  - one-to-one virtual to physical
- Dynamic scaling of the system
- Single-controller allows pause/resume and migration



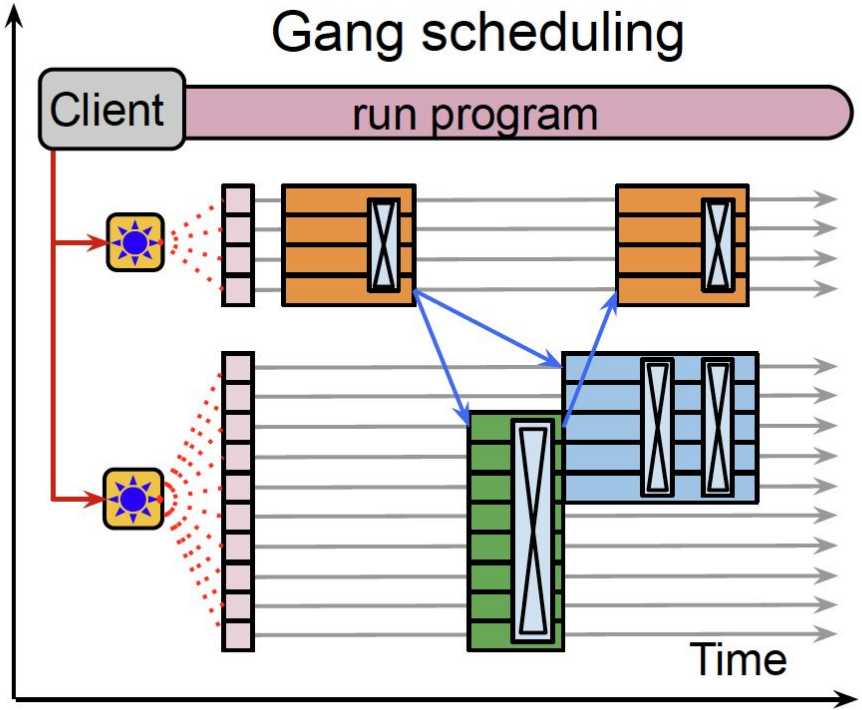
Resource Manager & Client

- Client registers computations and get them compiled
- Creates device-agnostic IR
- Sharded buffer for instruction and data buffers

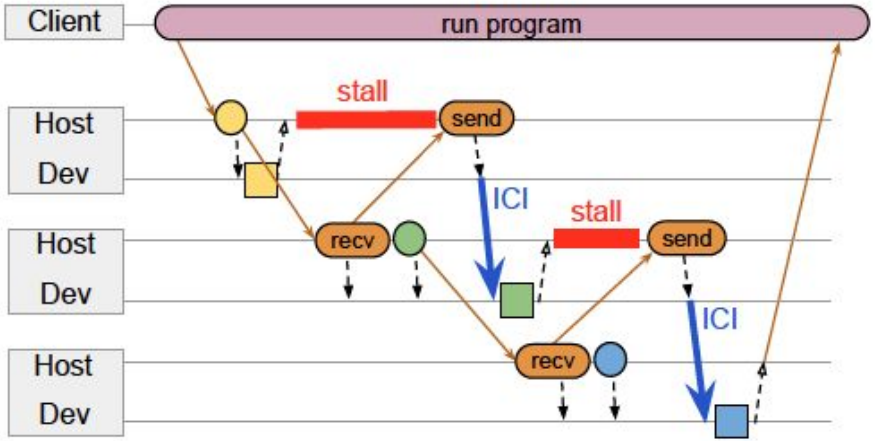


Coordination and Gang-Scheduling

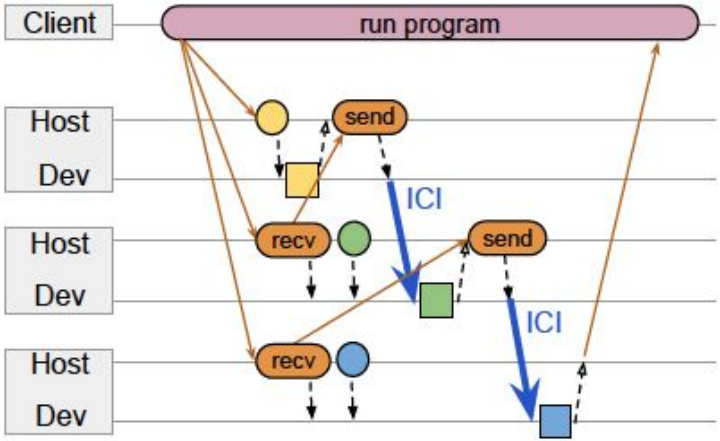
- Cross-host coordination using *Plaque* -- closed-source (😡) sharded dataflow system
  - Sparse, low-latency communication
- Plaque
  - Async enquing the execution of computation and network sends
  - Communication with scheduler for consistent ordering of fn execution
- Centralised scheduler per island managing all computation
  - Simple FIFO allocation



Parallel Asynchronous Dispatch



(a) Sequential dispatch



(b) Parallel dispatch

Evaluation

- Single-controller dispatch overheads
  - set of mini-benchmarks
- Multi-tenancy
- Large scale model performance (real machine learning workloads)
  - text-to-text transformer
  - large language model

Single-Controller Dispatch Overheads

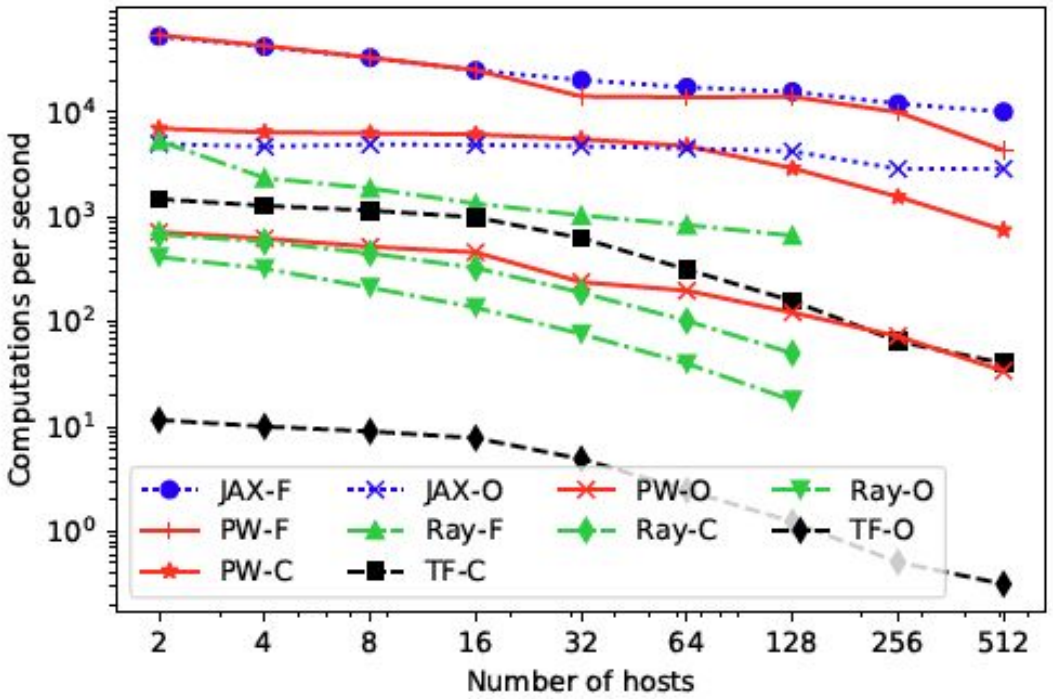
Trivial gang-scheduled computation containing a single AllReduce.

Measuring throughput

-O - Separate call for each instruction

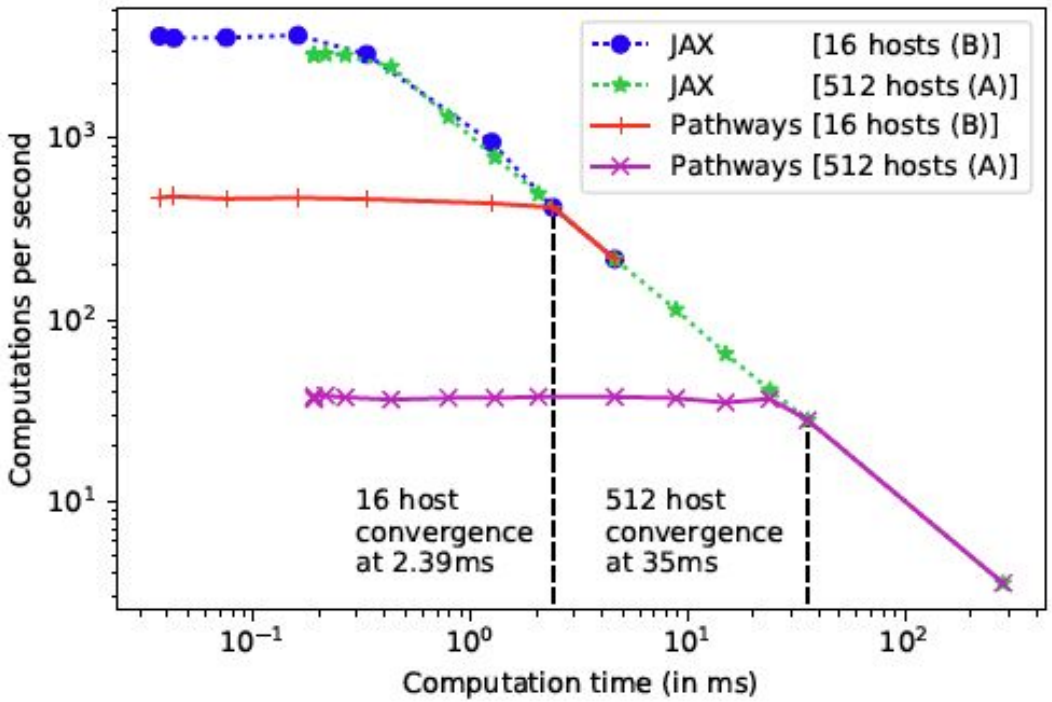
-C - Chained, 128 nodes,
single client call

-F - Fused, single node
single client call



Single-Controller Dispatch Overheads

Smallest computation to match throughput between Pathways and JAX, masking the single-controller overhead.



Multi-Tenancy

Aggregated throughput when multiple clients concurrently submit different Pathways programs

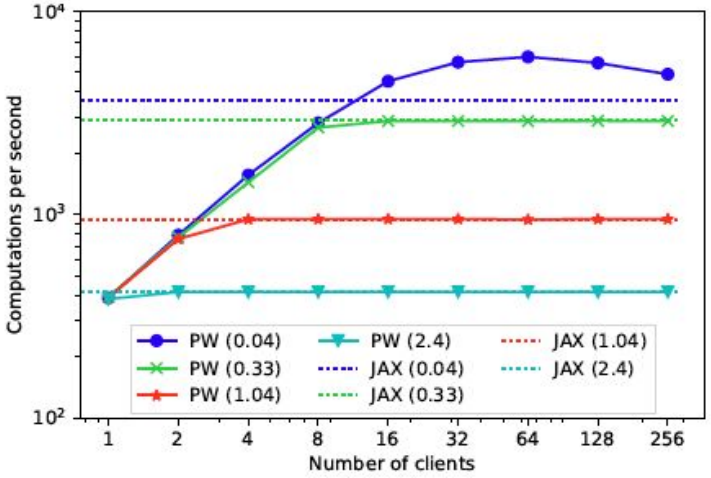


Figure 8. Aggregate throughput of concurrent programs (compute times in ms). PATHWAYS time-multiplexes accelerators between programs efficiently incurring no overhead to context switch.

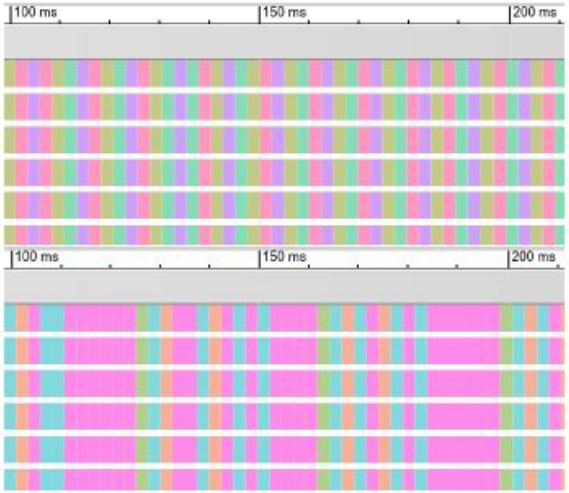


Figure 9. Traces of a sample of cores on PATHWAYS showing interleaving of gang-scheduled concurrent programs with proportional-share ratios of 1:1:1:1 (Upper) and 1:2:4:8 (Lower) between 4 clients.

Large Scale Model Performance

Text-to-text Transformer

Identical performance because realistic computations are large enough to mask single-controller overheads!

Table 1. Training throughput (tokens/s) of Text-to-text Transformer model configurations from (Raffel et al., 2019) on JAX multi-controller and PATHWAYS.

Model	Params	TPU cores	JAX	PATHWAYS
T5-Base	270M	32	618k	618k
T5-Large	770M	32	90.4k	90.4k
T5-3B	3B	512	282.8k	282.8k
T5-11B	11B	512	84.8k	84.8k

Large Scale Model Performance

3B Transformer-based language model (decoder-only)

Table 2. Training throughput (tokens/s) of 3B Transformer language model, using SPMD or multiple pipeline stages, with C TPU cores in PATHWAYS. For pipeline-parallel models, there are S stages and each batch is split into M μ-batches.

Model configuration	TPU cores	PATHWAYS
Model-parallel (SPMD)	128	125.7k
Pipelining, S=4, M=16	128	133.7k
Pipelining, S=8, M=32	128	132.7k
Pipelining, S=16, M=64	128	131.4k
Pipelining, S=16, M=64	512	507.8k

Large Scale Model Performance

3B Transformer-based language model (decoder-only)

Here pipeline has competitive performance to SPMD.

Collective communication within the SPMD computation incurs higher overhead than pipeline bubble overhead.

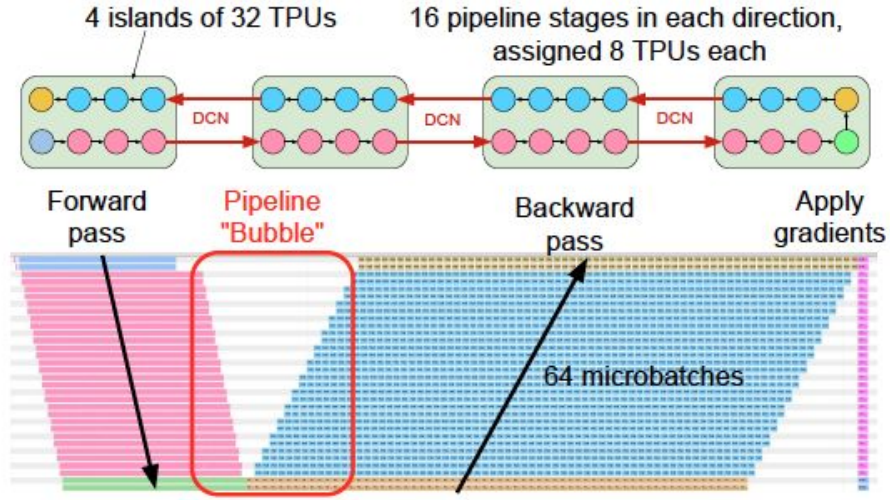


Figure 10. 3B Transformer model pipelined over 128 TPUs: PATHWAYS can efficiently train models over islands of TPUs connected via DCN achieving the same throughput (131.4k tokens/sec) on 4 islands of 32 cores each on configuration (C) as using a single island of 128 cores on configuration (B).

Final Thoughts and Further Research

- Design impacted by the use of TPUs over GPUs -- fusing many computations into a TPU kernel.
- No software released and use of closed-source systems 😖

- Room for further improvements in dynamic resource management
- Fine-grained control flow -- selective parameter updates
  - Useful for MoE architectures with routing
  - Data-dependent data exchanges between nodes

Good news!

- Single-controller model allows simple access to much richer computation patterns
- Low-latency achieved with minimal overheads in real machine learning scenarios

Thank you!