Integrated **D**ata **A**nalysis **P**ipelines
for Large-scale Data Management,
HPC, and Machi**ne** Learning;
DAPHNE daughter of river god Peneus
(fountains, streams), chased by Apollo

[Louvre, Paris]

DAPHNE
https://daphne-eu.eu/

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DAPHNE: An Open and Extensible System Infrastructure for Integrated Data Analysis Pipelines

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FG DB Spring Symposium 2022; March 24/25, 2022

Motivation

➔ DAPHNE Overall Objective:
Open and extensible system infrastructure

DAPHNE

- Integrated Data Analysis Pipelines
  - Open data formats, query processing
  - Data preprocessing and cleaning
  - ML model training and scoring
  - HPC, custom codes, and simulations

- **Hardware Challenges**
  - DM+ML+HPC share compilation and runtime techniques / converging cluster hardware
  - **End of Dennard scaling:** $P = \alpha\, CFV^2$ (power density 1)
  - **End of Moore's law**
  - **Amdahl's law:** sp = 1/s

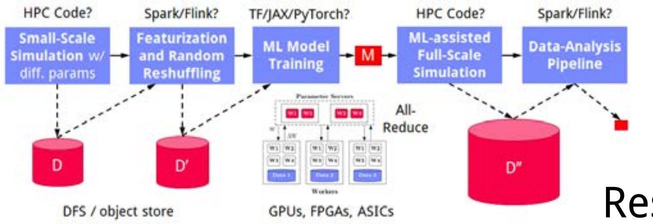
➔ Increasing Specialization

Deployment Challenges

Dev Teams

Programming Models

Different Systems/ Libraries

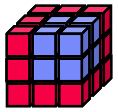


Cluster **Under-utilization**

Data/File Exchange

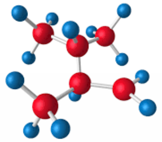
Resource Managers

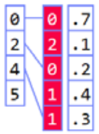
#1 Data Representations



dense

graph





sparse

compressed

Sparsity Exploitation
from Algorithms to HW

#2 Data Placement

Local vs **distributed**

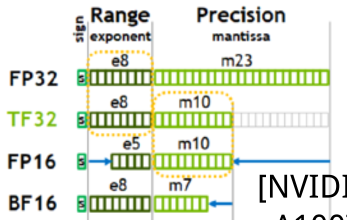
CPUs/ NUMA

GPUs

FPGAs/ ASICs

#3 Data (Value) Types

FP32, FP64, INT8, INT32, INT64, UINT8, BF16, TF32, FlexPoint



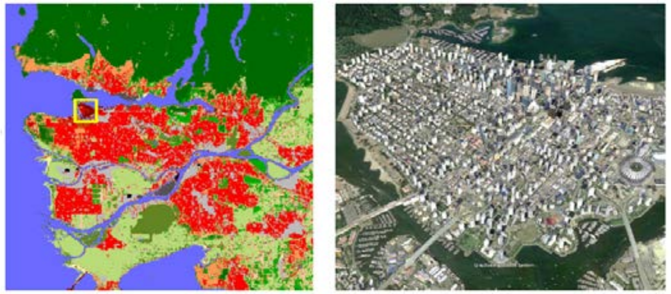
[NVIDIA A100]

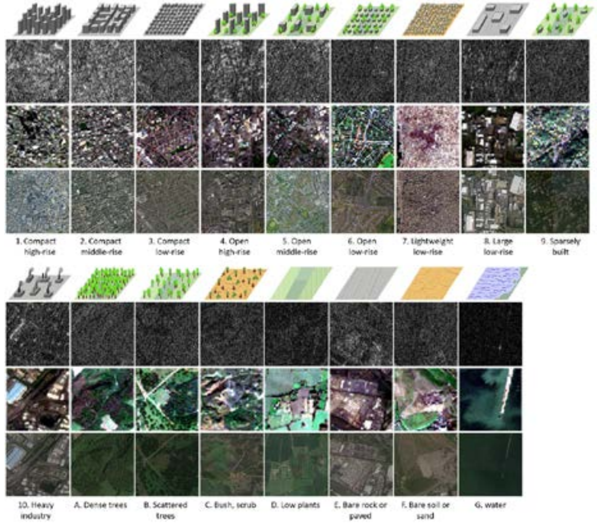
Example Use Cases

[Xiao Xiang Zhu et al: So2Sat LCZ42: A Benchmark Dataset for the Classification of Global Local Climate Zones. **GRSM 8(3) 2020**]

[So2Sat LC42: https://mediatum.ub.tum.de/1454690]

- **DLR Earth Observation**
  - **ESA Sentinel-1/2** datasets → 4PB/year
  - Training of local climate zone classifiers on **So2Sat LCZ42** (15 experts, 400K instances, 10 labels each, ~55GB HDF5)
  - **ML pipeline:** preprocessing, ResNet-20, climate models





- **IFAT Semiconductor Ion Beam Tuning**
- **KAI Semiconductor Material Degradation**
- **AVL Vehicle Development Process** (ejector geometries, KPIs)

- **ML-assisted simulations, data cleaning, augmentation**
- **Cleaning during exploratory query processing**

System Architecture

[Patrick Damme et al.: **DAPHNE:** An Open and Extensible System Infrastructure for Integrated Data Analysis Pipelines, **CIDR 2022**]

DaphneLib (API) — Python API w/ lazy evaluation

DaphneDSL (Domain-specific Language)

MLIR

MLIR-Based Compilation Chain

DaphneIR (MLIR Dialect)

Optimization Passes

New Runtime Abstractions for Data, Devices, Operations

Hierarchical Scheduling

Device Kernels (CPU, GPU, FPGA, Storage)	**Vectorized Execution Engine** (Fused Op Pipelines)	**Sync/Async I/O Buffer/Memory Management**

Local (embedded) and Distributed Environments
(standalone, HPC, data lake, cloud, DB)

Extensible Infrastructure

MLIR Dialects, Extension Catalog (new data types, kernels, scheduling algs)

Multi-level Compilation/ Runtime

Sideways Entry, DSL-level constraints (data formats & data/op placement)

Fine-grained Fusion and Parallelism

Integration w/ Resource Mgmt & Prog. Models

Language Abstractions

DAPHNE

- **Design Principles**
  - **Frame and Matrix Operations** (coarse-grained)
  - **Data Independence** (abstract data types)
  - **Extensibility** (data types, operations, HW)
- **DSL Operations**
  - **Basic built-in** operations (RA, LA)
  - **High-level built-in** operations (e.g., SQL, PS, map on frames/matrices)
  - MLIR SCF (loops, branches)
  - **Typed and untyped functions** (hierarchy of composite primitives)
  - UDFs and external libraries

Python API DaphneLib

```
dc = DaphneContext()
G = dc.from_numpy(npG)
G = (G != 0)
c = components(G, 100, True).compute()
```

Domain-specific Language DaphneDSL

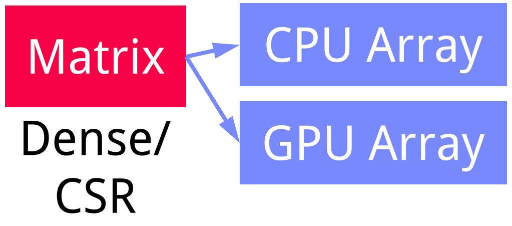
```
def components(G, maxi, verbose) {
  n = nrow(G);   // get the number of vertexes
  maxi = 100;
  c = seq(1, n); // init vertex IDs
  diff = inf;    // init diff to +Infinity
  iter = 1;
  // iterative computation of connected components
  while(diff>0 & iter<=maxi) {
    u = max(rowMaxs(G * t(c)), c); // neighbor prop
    diff = sum(u != c);    // # of changed vertexes
    c = u;                 // update assignment
    iter = iter + 1;
  }
}
```

Multiple dispatch of functions/kernels

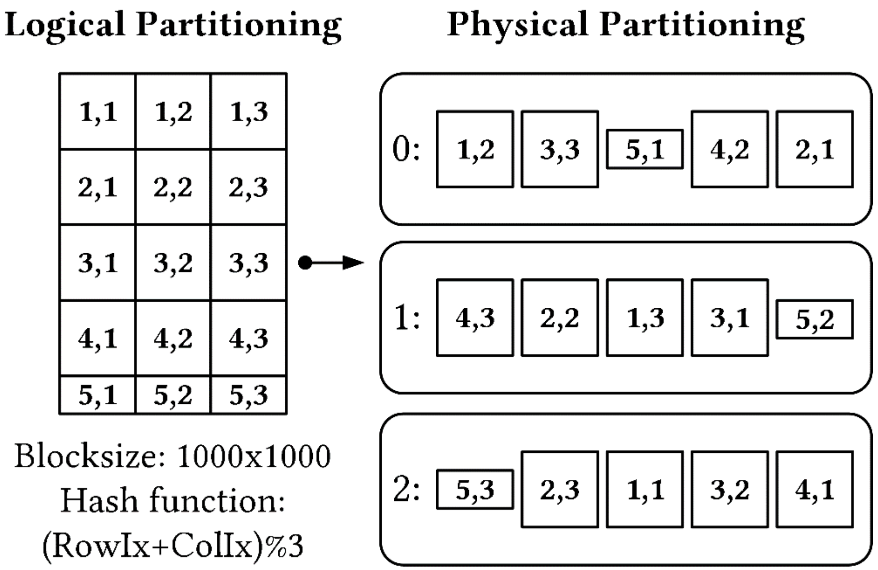
Data Representations

DAPHNE

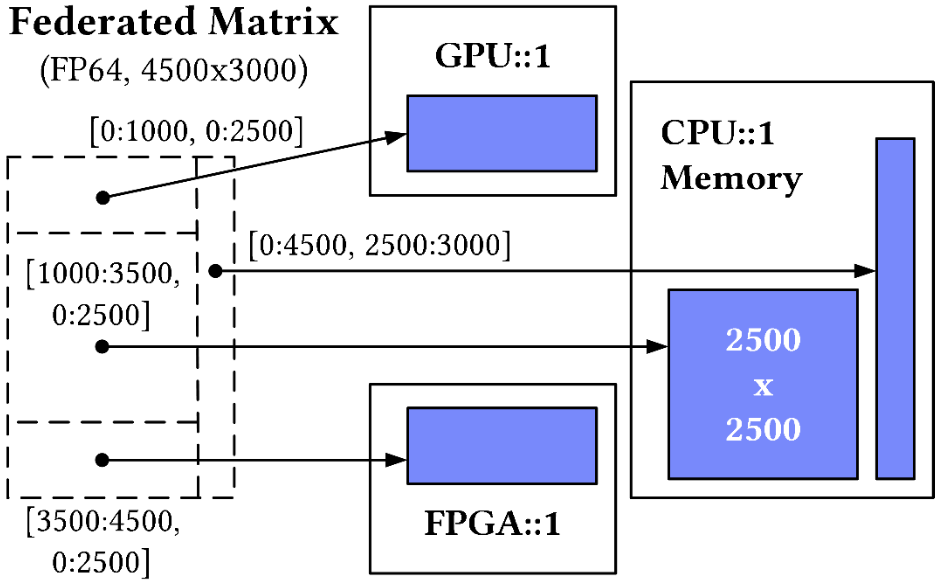
- **Data Types:** Matrix, Frame, LLVM scalars, (Tensor, List)
- **Value Types:** e.g., I8, I32, I64, UI8, UI32, UI64, FP32, FP64
- Distributed/Multi-device Data:



a) Distributed Collection of Tiles



b) Federated Matrix/Frame



Vectorized (Tiled) Execution

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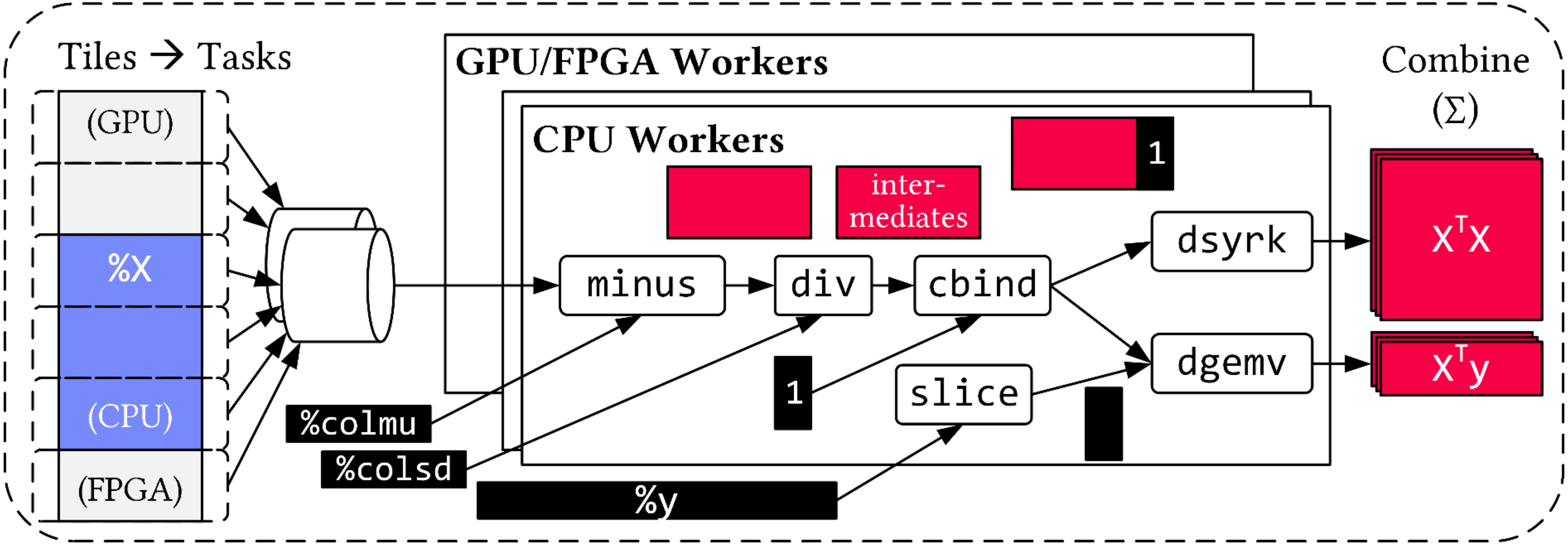
```
(%9, %10) = fusedPipeline1(%X, %y, %colmu, %colsd) {
```



Default Parallelization
Frame & Matrix Ops

Locality-aware,
Multi-device Scheduling

Fused Operator Pipelines
on Tiles/Scalars + Codegen

Vectorized (Tiled) Execution, cont.

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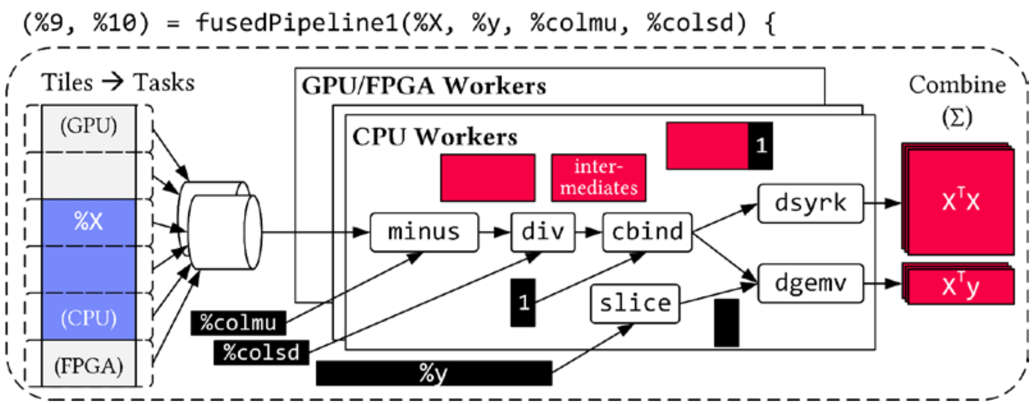
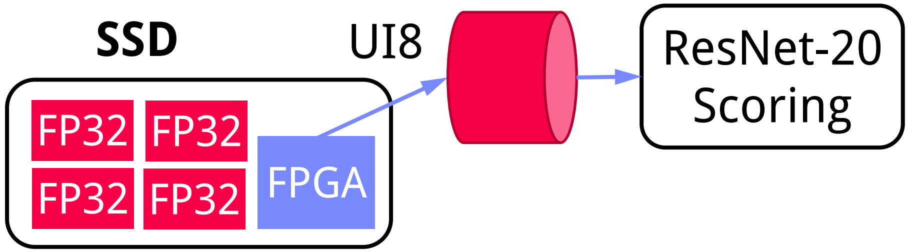
- **#1 Zero-copy Input Slicing**
  - Create view on sliced input (no-op)
  - All kernels work on views



- **#2 Sparse Intermediates**
  - Reuse dense/sparse kernels
  - Sparse pipeline intermediates for free
- **#3 Fine-grained Control**
  - Task sizes (dequeue, data access) vs data binding (cache-conscious ops)
  - Scheduling for load balance (e.g., sparse operations)
- **#4 Computational Storage**
  - Task queues connect eBPF programs, async I/O into buffers, and subsequent operator pipelines



Distributed Vectorized Execution

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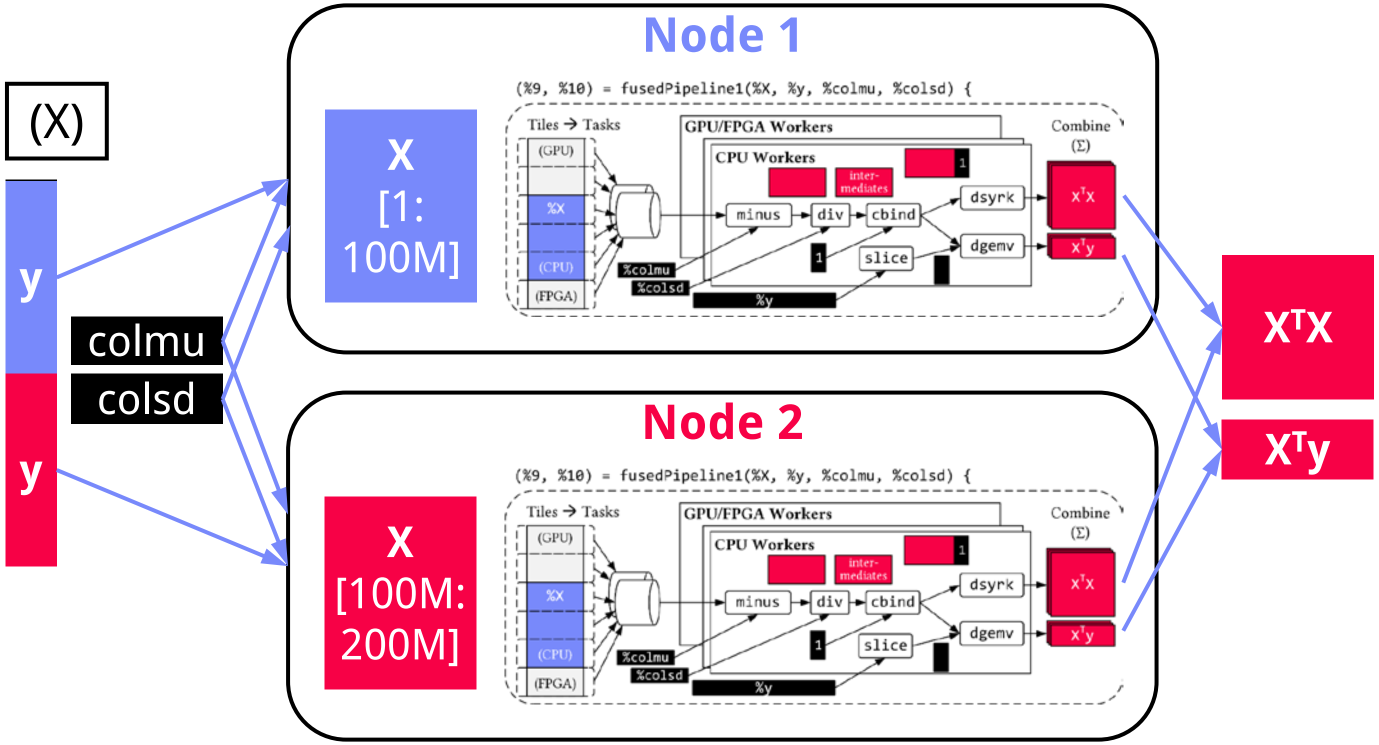
- Federated matrices/frames + distribution primitives
- Hierarchical vectorized pipelines and scheduling

- Coordinator
  (spawns distributed fused pipeline)
  - **#1 Prepare Inputs**
    (N/A, repartition, broadcasts, slices broadcasts as necessary)
  - **#2 Coarse-grained Tasks**
    (tasks run vectorized pipeline)
  - **#3 Combine Outputs**
    (N/A, all-reduce, rbind/cbind)



Experiments: Simple IDA Pipelines

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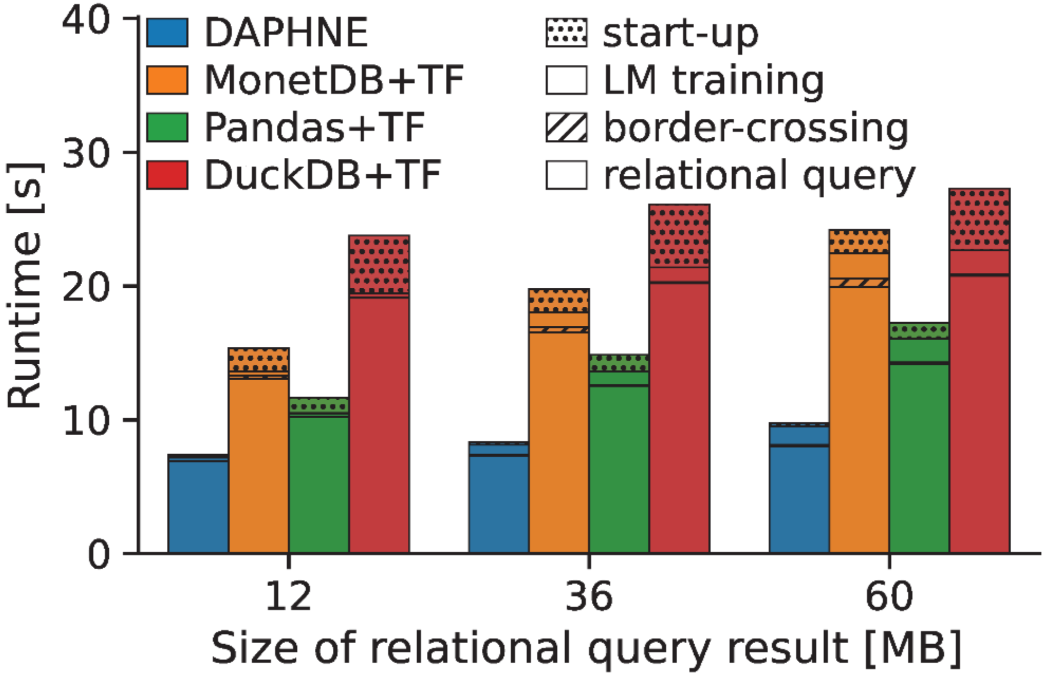
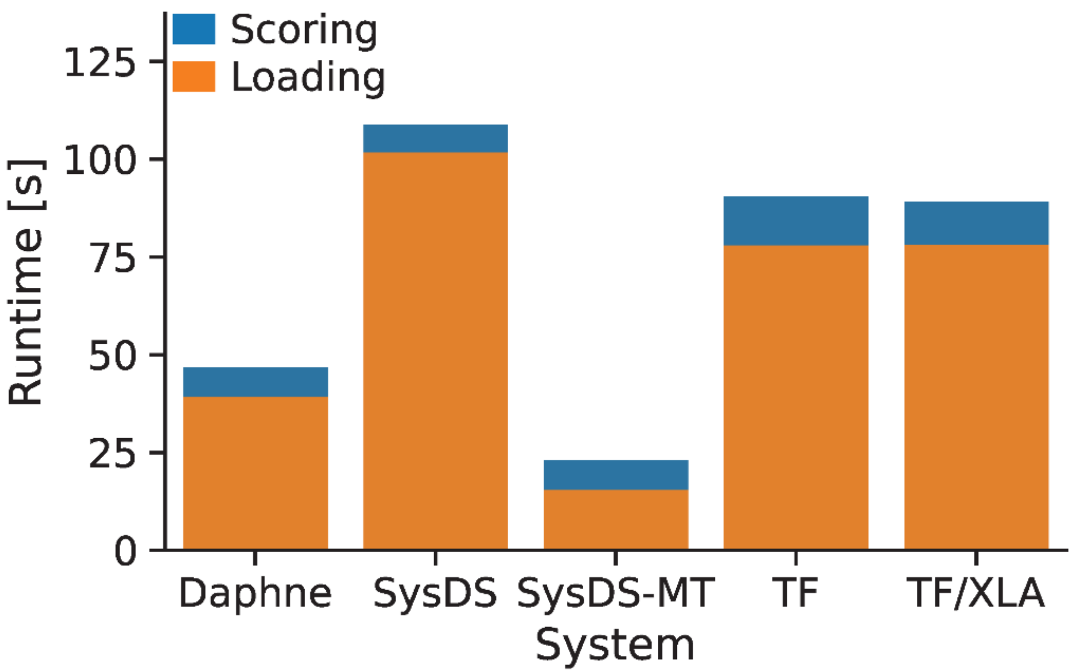
Setup: Single node w/ 2x Intel Xeon Gold 6238 (112 vcores, 7.7 TFLOP/s), 768 GB DDR4 RAM, 12x 2TB SSDs (data), NVIDIA **T4 GPU** (8.1 TFLOP/s, 16 GB), and Intel FPGA PAC D5005 (w/ Stratix **10SX FPGA**, 32 GB) since Dec 29

P1: TPC-H SF10 csv, query processing + linear regression training on CPUs



P2: So2Sat LCZ42 csv (testset), ResNet-20 scoring on GPU



Experiments: Vectorized Execution

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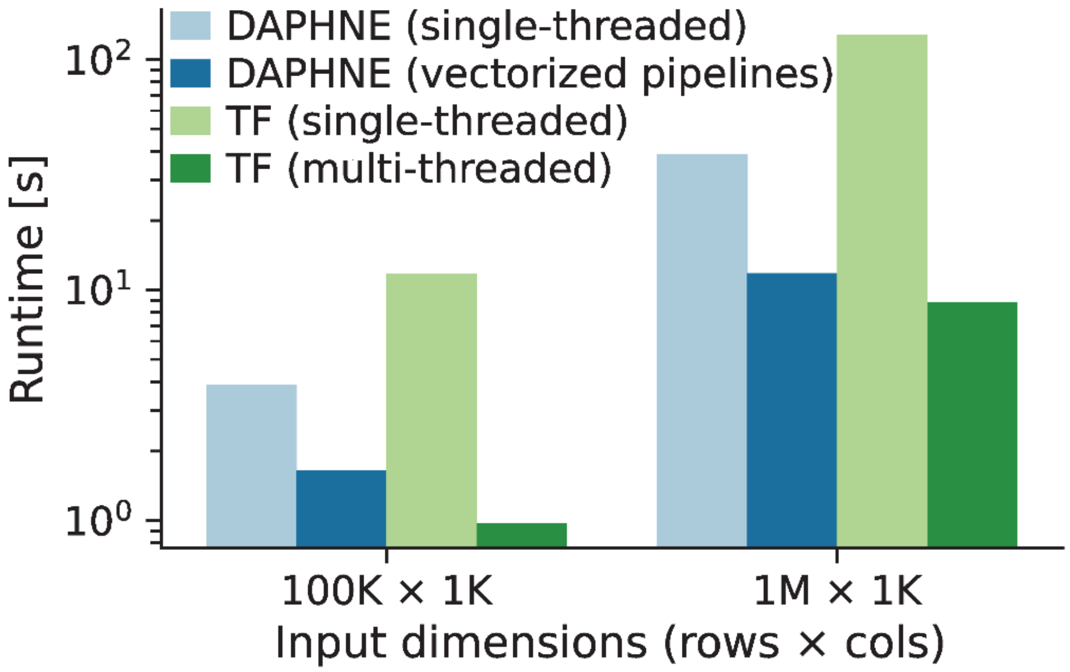
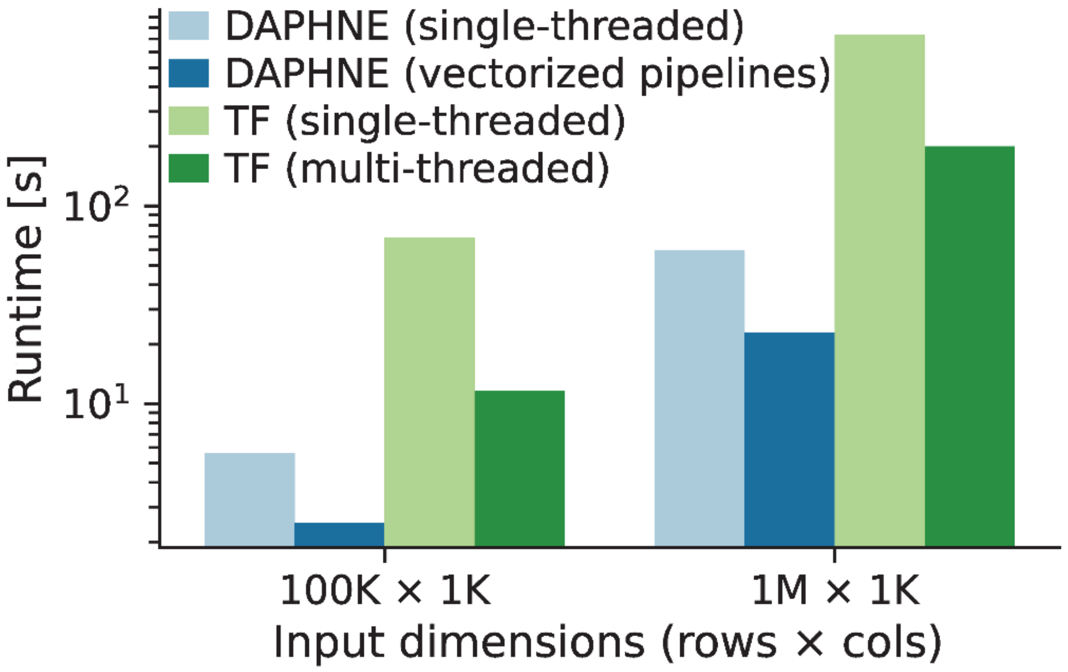
Linear Regression w/
varying Data Size and Vectorization



K-means Clustering w/
varying Data Size and Vectorization



- **Ongoing Experiments**
  - FPGA kernels on D5005, CPU+GPU vectorized pipelines
  - Distributed sparse runtime operations on Vega supercomputer
  - Sparse vectorized pipelines and scheduling algorithms

Status and Next Steps

https://daphne-eu.eu/ DAPHNE

- **Current Status**
  - System Architecture and Design
  - Initial DSL and Python API
  - MLIR-based Compiler and Runtime Prototype
  - Vectorized Execution (fused pipelines, scheduling)
  - GPU (and FPGA) Integration, BLAS/DNN Libraries
  - Standalone Distributed Runtime

➔ DAPHNE Overall Objective: Open and extensible system infrastructure

DM + HPC + ML

- **Promising Progress and Preliminary Experiments**

- **DAPHNE OSS Announcement**
  - Public **release by 03/2022**
  - **Apache v2** license
  - Towards an inclusive dev community

  ➔ Potential for collaboration in 2022-2024

Enable researchers to experiment with new prototypes and extensions