# Project Large-scale Data Engineering (LDE)
# Project Kick-off Meeting

**Dr.-Ing. Patrick Damme**
Technische Universität Berlin
Berlin Institute for the Foundations of Learning and Data
Big Data Engineering (DAMS Lab)



Last update: Oct 16, 2023

# Announcements/Org

- **Hybrid Setting with Optional Attendance**
  - In-person in TEL 811 (~20 seats)
  - Virtual via zoom
    https://tu-berlin.zoom.us/j/67376691490?pwd=NmlvWTM5VUVWRjU0UGI2bXhBVkxzQT09

# About Me

- **Since 10/2022: Postdoc at TU Berlin**, Germany
  - FG Big Data Engineering (DAMS Lab) headed by Prof. Matthias Böhm
  - Continuing work on integrated data analysis pipelines
  - Research interests in the fields of database and ML systems (especially compiler & runtime techniques, extensibility)
- **2021-2022: Postdoc at TU Graz & Know-Center GmbH**, Austria
  - Data Management group headed by Prof. Matthias Böhm
  - Started work on integrated data analysis pipelines
- **2015-2020: PhD student at TU Dresden**, Germany
  - Dresden Database Research Group headed by Prof. Wolfgang Lehner
  - PhD thesis on making complex analytical database queries more efficient through lightweight compression of intermediate results

DAPHNE

DAPHNE

MorphStore & TVL

# FG Big Data Engineering (DAMS Lab) – Teaching

**Architecture of Database Systems** (ADBS, **WiSe**)

DB system internals + prog. project

**Architecture of ML Systems** (AMLS, **SoSe**)

ML system internals, data science lifecycle + prog. project

**SE Joint ML and DM** (MLDM, **SoSe+WiSe**)

**Master**

**Bachelor**

**Data Integration and Large-Scale Analysis** (DIA, **WiSe**)

Distributed Data Management

**SE/PR Large-scale Data Engineering** (LDE, **SoSe+WiSe**)

**Intro to Scientific Methods (WiSe)**

**Data Management / Databases** (DM, **SoSe+WiSe**)

Data management from user/application perspective

**PP Prog.-Practicals Data Systems** (PPDS, **SoSe+WiSe**)

# Agenda

- **Course Organization, Outline, and Deliverables**
- **Apache SystemDS and DAPHNE**
- **List of Project Topics (Proposals)**

# Course Organization, Outline, and Deliverables

# Large-scale Data Engineering: Module Overview

20+5 places in total

bachelor + master

#41086: LDE Seminar + Project (12 ECTS) — 13 students

12 students — #41095: Seminar LDE (3) — bachelor-only

#41094: Project LDE (9 ECTS) — 6 students — bachelor-only

Mon, 14:00-16:00
TEL 811 & zoom

**Seminar LDE**

- Reading & writing scientific papers
- Giving presentations on papers
- Summary paper
- Presentation
- Lecturer & seminar mentor

Mon, 16:00-18:00
TEL 811 & zoom

**Project LDE**

- Building & evaluating prototypes
- Giving presentations on prototypes
- Prototype design/impl/tests/doc
- Presentation
- Project mentors

→ In the context of systems for data engineering, data management, machine learning

→ In combination: Ideal preparation for a bachelor/master thesis with our group

# Course Organization

- **General Contact Person**
  - Dr.-Ing. Patrick Damme (patrick.damme@tu-berlin.de)
- **Course Website**
  - https://pdamme.github.io/teaching/2023-24_winter/lde/lde_winter2023-24.html
  - One site for seminar and project
  - All material, schedule, **deadlines**
- **ISIS course**
  - https://isis.tu-berlin.de/course/view.php?id=35039
  - Announcements, discussion forum, polls
- **Language**
  - Lectures and slides: **English**
  - Communication: **English**/**German**
  - Submitted paper and presentation: **English**
  - **Informal language** (first name is fine), immediate feedback is welcome

# Semester Schedule & Deadlines

- **Kick-off Meeting Oct 16** (optional)
- **Recommended Introductory Lecture** (optional)
  - Oct 30, 14:00: Experiments, Reproducibility, and Giving Presentations
- **Self-organized Project Work**
  - Office hours for any questions (optional)
  - **Recommendation:**
    - Basic prototype working by end of Dec
    - Focus on incorporating feedback and conducting experiments afterwards
- **Final Presentations** (mandatory)
  - Feb 26, 14:00-18:00: Session #1
  - Mar 04, 14:00-18:00: Session #2
- **List of Project Topics**
  - Presented today, take your time to select afterwards
- **Topic Selection**
  - **Deadline: Oct 30, 23:59 CET** (in 2 weeks)
  - Email to Patrick Damme
    - Ranked list of **~5 topics**
    - Individual work / team work / open to both
    - Feel free to approach us as a team
  - Global topic assignment based on preferences
  - **Notification of assigned topics: Nov 06** (in 3 weeks)
- **Submission of Impl/Tests/Doc**
  - **Deadline: Feb 19, 23:59 CET** (in 18 weeks)
  - As a pull request on GitHub (exceptionally by email)
- **Submission of Presentation Slides**
  - **Deadline: The day before you present, 23:59 CET**
  - Presentation slides (PDF) to PD and project mentor

# Project Deliverables

- **Individual/Team Project Work**
  - Teams of up to 3 students **strongly encouraged**
- **Design/Implementation/Tests/Documentation**
  - Get familiar with the given task/problem
  - Develop an initial design for discussion
  - **Discuss the design during the office hours**
  - Implement your design, plus tests and docs
  - Conduct experiments and analyze/visualize results
- **Presentation**
  - Summarize the problem and your solution (design, implementation, experimental results)
  - **1 student: 10 min talk + 5 min discussion = 15 min**
  - **2 students: 13 min + 7 min = 20 min**
  - **3 students: 16 min + 9 min = 25 min**
  - Audience: engage in the discussion
- **Grading**
  - **#41086 (seminar + project)**
    - Graded portfolio exam
    - 25 pts: summary paper
    - 15 pts: presentation
    - 50 pts: design/impl/tests/doc
    - 10 pts: presentation
  - **#41094 (project-only)**
    - **Ungraded** portfolio exam
    - 85 pts: implementation/tests/documentation
    - 15 pts: presentation
- **Academic Honesty / No Plagiarism** (incl LLMs like ChatGPT)

# Portfolio Exam Registration

- **Portfolio exam registration: Nov 06 – Dec 04**
  - Binding registration in Moses/MTS
  - Including selection of project presentation date
  - Members of a team register for the same date (agree on the date within your team first)
- **Portfolio exam de-registration**
  - **Until 3 days before the first graded exam part**
    - Modules “LDE”/”Seminar LDE”: until **Jan 05**
    - Module “Project LDE”: until **Feb 16**
    - De-register yourself in Moses/MTS
  - **With sufficient reason: Until the day of the exam**
    - In case of sickness etc.
    - Modules “LDE”/”Seminar LDE”: until **Jan 08**
    - Module “Project LDE”: until **Feb 19**
- **Missing deadlines/exam without de-registration**
  - Zero points in the respective exam part
  - **Approach us early in case of problems**
- **If you don’t want to take LDE anymore**
  - Let me know asap to give students in the queue a chance to fill in

# LDE Project Characteristics

- **Unique Characteristics**
  - Each student/team gets a different topic
- **Advantages**
  - Topics are real open issues in existing systems
  - Meaningful contributions to open-source systems
  - Your work will be used by others (impact)
  - You earn 9 ECTS (~270 h of work)
  - **~6.75 weeks of full-time work**
- **Practice Open-source Processes**
  - Breakdown into subtasks
  - Code/tests/docs
  - Pull requests
  - Code review
  - Incorporate feedback to improve code
- **Remarks on Topic Descriptions**
  - Lots of open topics to work on in the two systems we develop in our group
  - Initial topic descriptions of varying level of detail
  - If there is interest in a specific topic, we will provide more detailed descriptions with some pointers (please approach project mentors directly)
  - Open to alternative topic proposals

# LDE Projects in the Context of Two Open-source Systems

- **DAPHNE EU-project**
  **https://github.com/daphne-eu/daphne**
  - Focus on integrated data analysis pipelines
  - Project implementation in C++ and Python
- **Apache SystemDS**
  **https://github.com/apache/systemds**
  - Focus on the end-to-end data science lifecycle
  - Project implementation in Java, Python, and DML

# Apache SystemDS: A Declarative ML System for the End-to-End Data Science Lifecycle

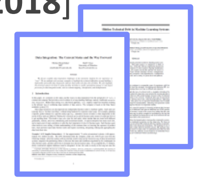
https://github.com/apache/systemds

# Landscape of ML Systems

- **Existing ML Systems**
  - **#1 Numerical computing** frameworks
  - **#2 ML Algorithm libraries** (local, large-scale)
  - **#3 Linear algebra ML systems** (large-scale)
  - **#4 Deep neural network** (DNN) frameworks
  - **#5 Model management, and deployment**
- **Exploratory Data-Science Lifecycle**
  - **Open-ended problems** w/ underspecified objectives
  - Hypotheses, data integration, run analytics
  - Unknown value → lack of system infrastructure
    → **Redundancy of manual efforts and computation**
- **Data Preparation Problem**
  - **80% Argument:** 80-90% time for finding, integrating, cleaning data
  - Diversity of tools → boundary crossing, lack of optimization

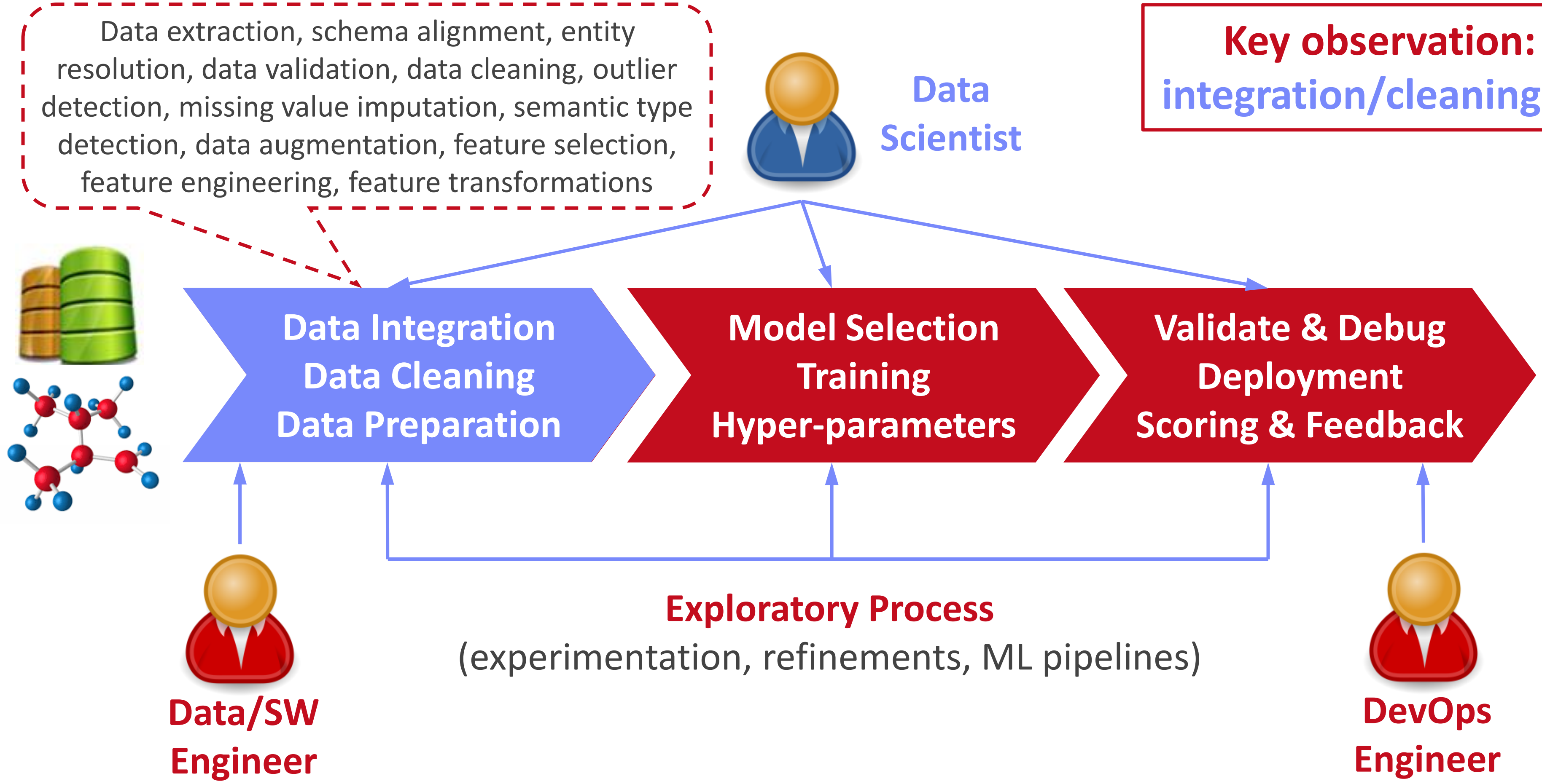
**"Take these datasets and show value or competitive advantage"**

[NIPS 2015]
[DEBull 2018]



# The Data Science Lifecycle
# (aka KDD Process, aka CRISP-DM)

**Key observation: SotA data integration/cleaning based on ML**



# Apache SystemDS [https://github.com/apache/systemds]


**APIs:** Command line, JMLC, Python
Spark MLContext, Spark ML,
(Scalable Algorithms + Primitives)

DML Scripts

**Language**

**Compiler**

**Runtime**

Write Once,
Run Anywhere

**Apache SystemML™**

**07/2020** Renamed to **Apache SystemDS**
**05/2017** Apache Top-Level Project
**11/2015** Apache Incubator Project
**08/2015** Open Source Release

**[SIGMOD'15,'17,'19,'21abc,'23abc]**
**[PVLDB'14,'16ab,'18,'22]**
**[ICDE'11,'12,'15]**
**[CIDR'17,'20]**
**[VLDBJ'18]**
**[CIKM'22]**
**[DEBull'14]**
**[PPoPP'15]**

**In-Memory Single Node**
(scale-up)

**Hadoop or Spark Cluster**
(scale-out)

**Federated**
(LA progs, PS)

**In-Progress:**

GPU

**since 2014/16**

Java

**since 2012**

hadoop

**since 2010/11**

APACHE Spark

**since 2015**

exdra

**since 2019**

# Language Abstractions and APIs

Data Independence + Impl-Agnostic Ops
➔ **"Separation of Concerns"**

- **Example:** Stepwise Linear Regression

**User Script**

```
X = read('features.csv')
Y = read('labels.csv')
[B,S] = steplm(X, Y,
  icpt=0, reg=0.001)
write(B, 'model.txt')
```

**Built-in Functions**

Feature Selection

```
m_steplm = function(...) {
  while( continue ) {
    parfor( i in 1:n ) {
      if( !fixed[1,i] ) {
        Xi = cbind(Xg, X[,i])
        B[,i] = lm(Xi, y, ...)
    } }
    # add best to Xg
    # (AIC)
} }
```

ML Algorithms

```
m_lm = function(...) {
  if( ncol(X) > 1024 )
    B = lmCG(X, y, ...)
  else
    B = lmDS(X, y, ...)
}
```

Linear Algebra Programs

```
m_lmCG = function(...) {
  while( i<maxi&nr2>tgt ) {
    q = (t(X) %*% (X %*% p))
      + lambda * p
    beta = ... }
}
```

```
m_lmDS = function(...) {
  l = matrix(reg,ncol(X),1)
  A = t(X) %*% X + diag(l)
  b = t(X) %*% y
  beta = solve(A, b) ...}
```

**Facilitates optimization across data science lifecycle tasks**

# Basic HOP and LOP DAG Compilation

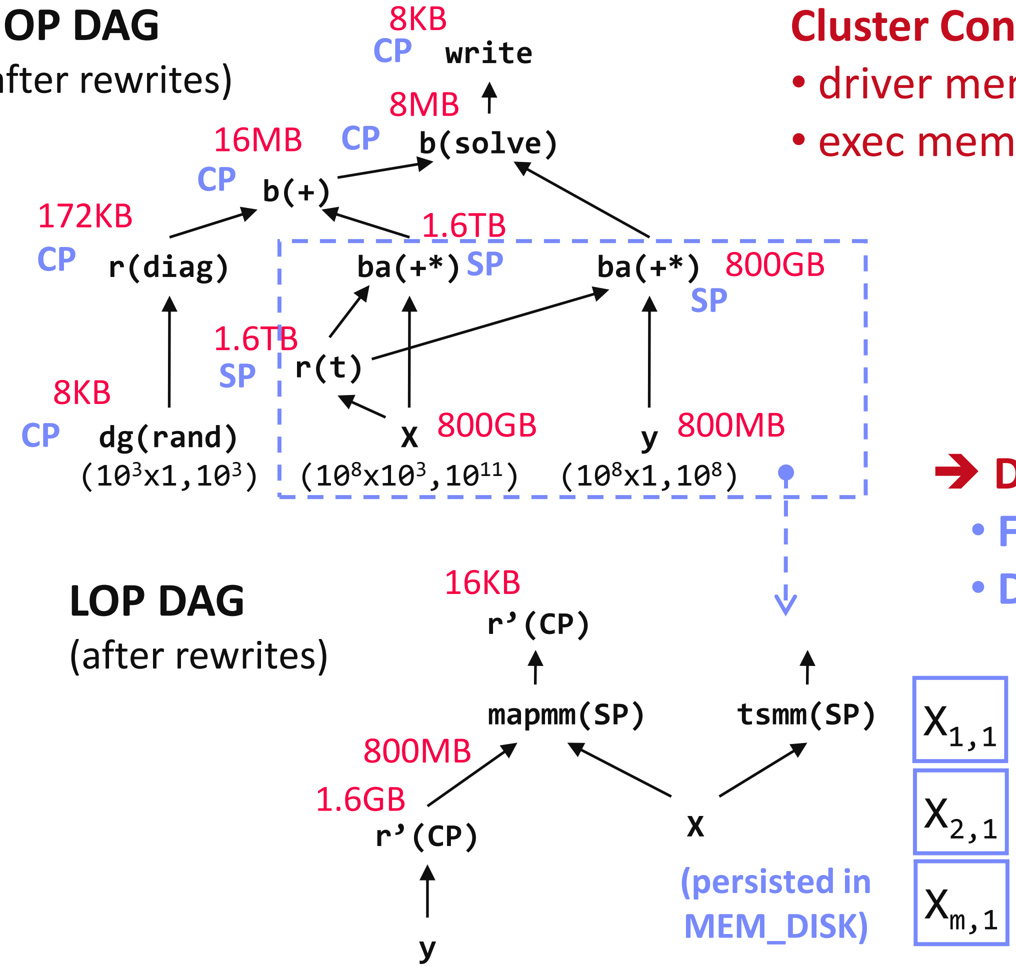
## LinregDS (Direct Solve)

```
X = read($1);
y = read($2);
intercept = $3;
lambda = 0.001;
...
if( intercept == 1 ) {
  ones = matrix(1, nrow(X), 1);
  X = append(X, ones);
}
I = matrix(1, ncol(X), 1);
A = t(X) %*% X + diag(I)*lambda;
b = t(X) %*% y;
beta = solve(A, b);
...
write(beta, $4);
```

**Scenario:**
X: $10^8$ x $10^3$, $10^{11}$
y: $10^8$ x 1, $10^8$

**HOP DAG**
(after rewrites)

**LOP DAG**
(after rewrites)




## Cluster Config:
- driver mem: 20 GB
- exec mem: 60 GB

➔ **Distributed Matrices**
- Fixed-size matrix blocks
- Data-parallel operations

➔ **Hybrid Runtime Plans:**
- Size propagation / memory estimates
- Integrated CP / Spark runtime
- Dynamic recompilation during runtime

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

https://github.com/daphne-eu/daphne

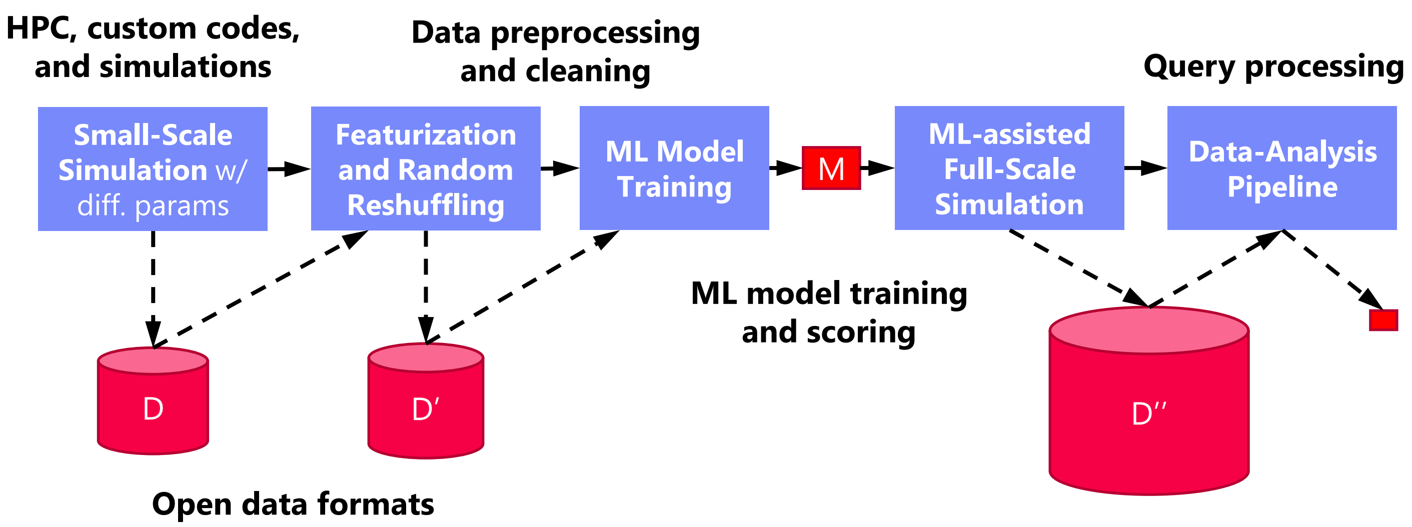
DAPHNE

# Integrated Data Analysis (IDA) Pipelines

DM + ML + HPC

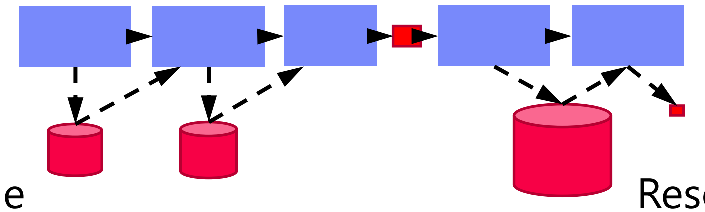
Data Management + Machine Learning + High-Perf. Computing

## Example: ML-assisted Simulation



# Challenges

## Deployment Challenges

Dev Teams
Programming Models
Different Systems/ Libraries

Cluster Under-utilization
Data/File Exchange
Resource Managers

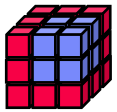
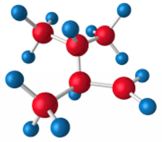
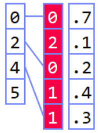
**DAPHNE: An open and extensible system infrastructure for IDA pipelines**

**Increasing Specialization**

## Hardware Challenges

- DM+ML+HPC share compilation and runtime techniques / converging cluster hardware
- **End of Dennard scaling**
- **End of Moore's law**
- **Amdahl's law**

**Data Representations**


graph



dense
sparse
compressed

**Sparsity Exploitation** from Algorithms to HW

**Data Placement**

Local vs **distributed**

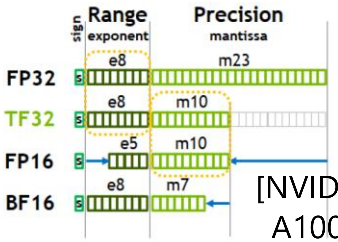
CPUs/ NUMA

GPUs


FPGAs/ ASICs

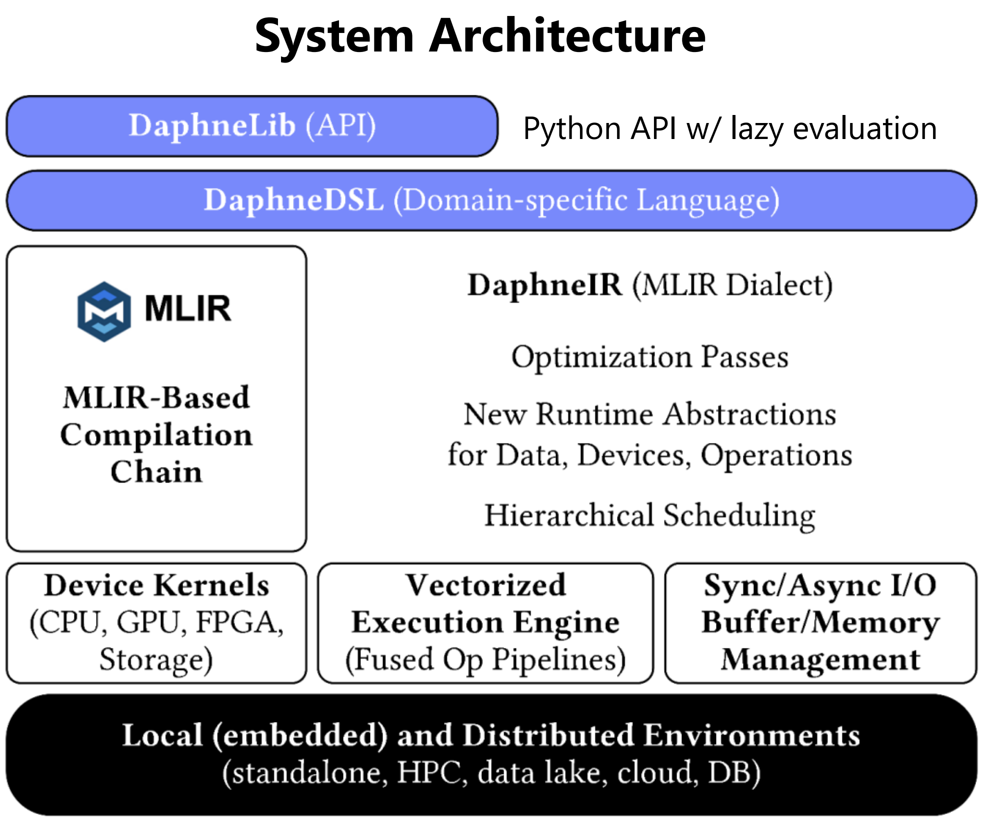
**Data (Value) Types**

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



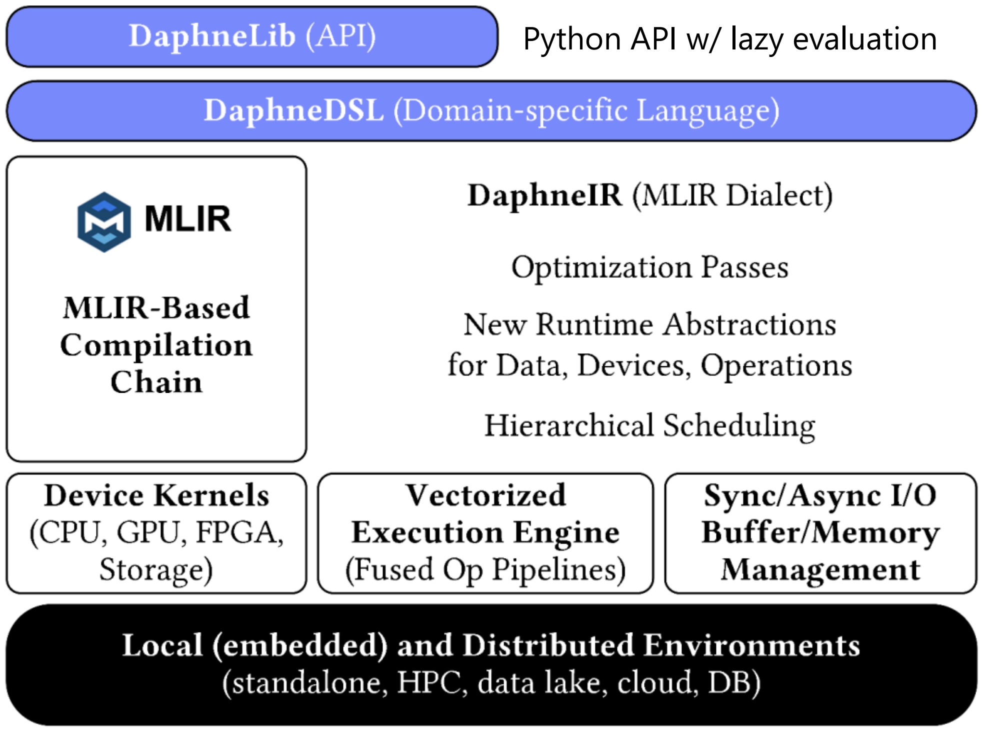
[NVIDIA A100]

# System Architecture



# Language Abstractions

## System Architecture




## DSL for linear and relational algebra

- Coarse-grained **matrix/frame operations**
- Built-in operations for **linear and relational algebra**
- **High-level operations** (e.g., SQL, parameter servers, map)
- Conditional **control flow** (branches, loops)
- Typed and untyped **user-defined functions**

- **Hierarchy of primitives** for data science tasks

- **Physical data independence**

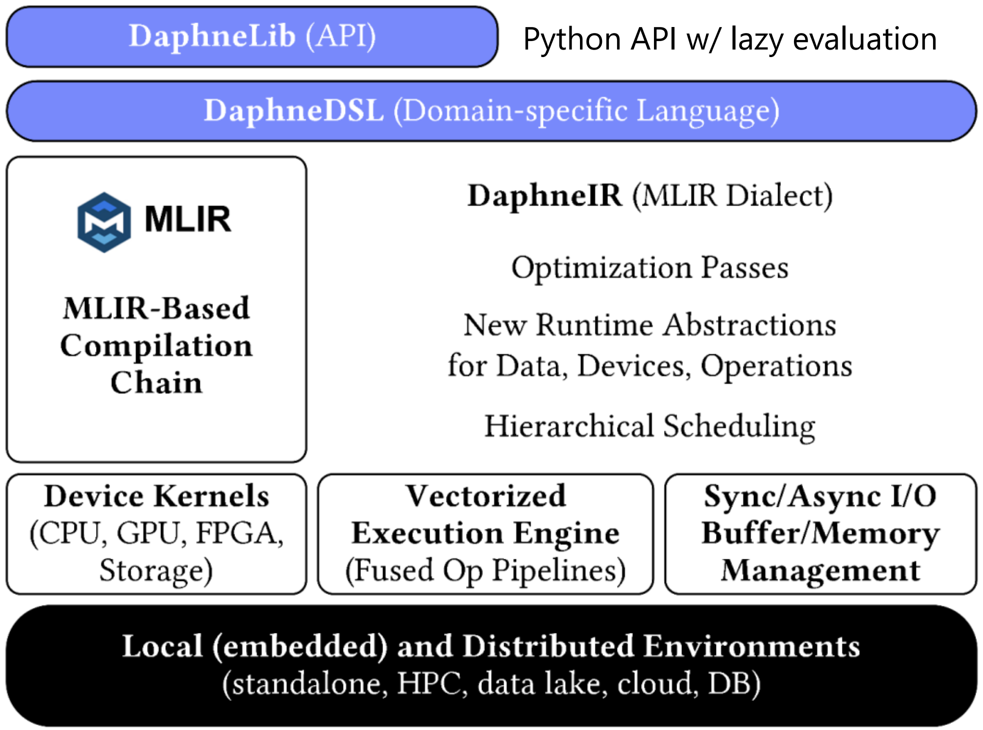
**Example: linear regression model training** (simplified)

```
def lm(X, y) { // X feature matrix, y labels
  colmu = mean(X, 1);       // column means
  colsd = stddev(X, 1);     // column stddevs
  X = (X - colmu) / colsd; // shift and scale
  X = cbind(X, 1);          // append column of ones
  A = t(X) @ X;             // t for transpose
  b = t(X) @ y;             // @ for matrix mult
  return solve(A, b);       // system of linear eq
}
```

```
my_model = lm(my_X, my_y);
```

# Optimizing Compiler

### System Architecture




## MLIR-based Optimizing Compiler

- Intermediate representation **DaphneIR (MLIR dialect)**
- **Systematic lowering** from **domain-specific operations** to calls to pre-compiled **kernels for heterogeneous hardware**

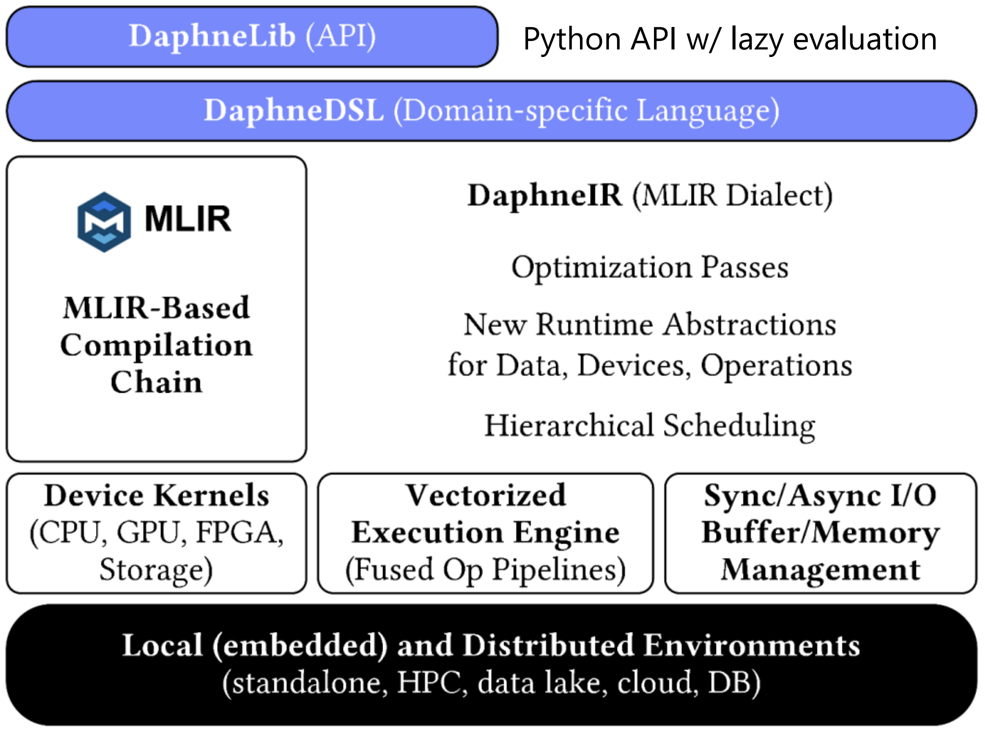
- Traditional **programming language rewrites**
- Type & property **inference**, inter-procedural analysis
- **Domain-specific rewrites** from linear and relational algebra
- Memory management & garbage collection
- **Device placement** & **physical operator selection**

**Example: linear regression model training** (simplified)

```
%10:2 = "daphne.vectorizedPipeline"(%5, %colmu, %colsd, %7, %6) ({
^bb0(%arg0: ..., %arg1: ..., %arg2: ..., %arg3: ..., %arg4: ...):
  %12 = "daphne.ewSub"(%arg0, %arg1) : ...
  %13 = "daphne.ewDiv"(%12, %arg2) : ...
  %14 = "daphne.colBind"(%13, %arg3) : ...
  %15 = "daphne.gemv"(%14, %arg4) : ... // rewritten from matmul/@
  %16 = "daphne.syrk"(%14) : ...         // rewritten from matmul/@
  "daphne.return"(%15, %16) : ...
}, ...
```

# Runtime

## System Architecture




## Distributed and Local Vectorized Execution

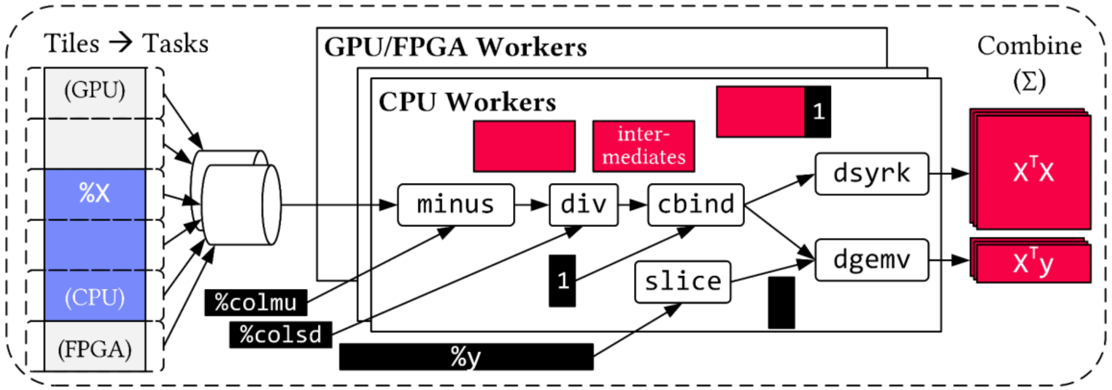
- **Fused operator pipelines** on tiles/vectors of data
- Coarse-grained tasks and cache-conscious data binding

- Device **kernels for heterogeneous hardware**
- Integration of **computational storage** (e.g., eBPF programs)

- **Scheduling for load balancing** (e.g., for ops on sparse data)
- Different **distributed backends** (e.g., gRPC, OpenMPI)

**Example: linear regression model training** (simplified)

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



# Which System to Choose for Your LDE Project: SystemDS or DAPHNE?

- **Lot's of Similarities**
  - Open-source systems, with major influence of our research group
  - Declarative DSL for linear (and relational) algebra
  - Domain-specific compiler
  - Runtime with local and distributed execution, hardware accelerators
  - Focus on efficient and effective execution of machine learning and data science tasks
  - …
- **Some Differences**
  - SystemDS
    - More mature system (since 2010, including history from SystemML)
    - Mainly written in Java and Python
    - Tasks in system internals and DSL scripts
  - DAPHNE
    - Younger system (since 2021)
    - Mainly written in C++ and Python
    - Tasks in system internals
    - Based on MLIR (compiler framework)

# How to Get Started

- **Suggested Initial Steps**
  - Navigate to the GitHub repo of the respective system
  - Browse the documentation
  - Set up your development environment and try to build and run the system
  - Browse the source code, identify the points related to your task
  - Read the contribution guidelines
  - Start early to identify blocking issues

# List of Project Topics (Proposals)

See list at https://pdamme.github.io/teaching/2023-24_winter/lde/ProjectTopics.pdf

# Summary and Q&A

- Course Organization, Outline, and Deliverables
- Apache SystemDS and DAPHNE
- List of Project Topics (Proposals)

- Remaining Questions?

- See you during the office hours ☺