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

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Berlin Institute for the Foundations of Learning and Data
Big Data Engineering (DAMS Lab)

Last update: Apr 14, 2024

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

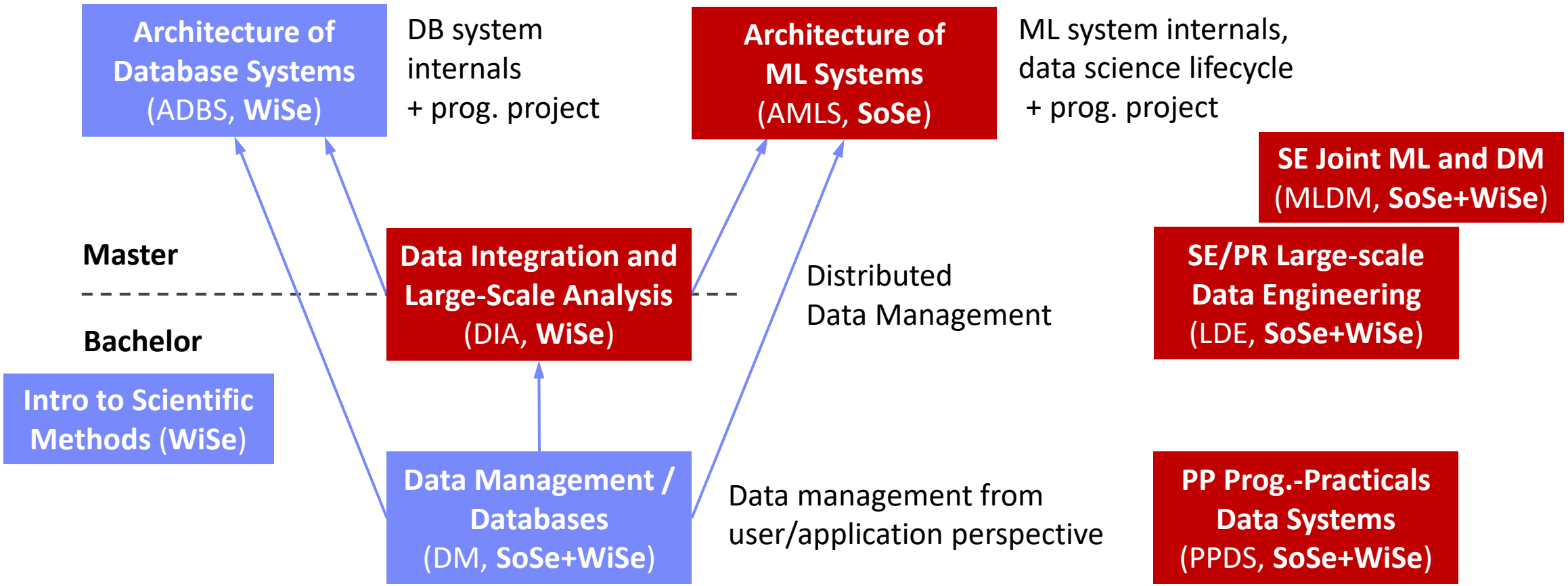
About Me

- **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

FG Big Data Engineering (DAMS Lab) – Teaching



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 places in total

bachelor + master

#41086: LDE Seminar + Project (12 ECTS) — 10 students

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

#41183: Project LDE (9 ECTS) — 8 students — bachelor-only

Seminar LDE

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

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

Project LDE

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

- 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/2024_summer/lde/lde_summer2024.html
  - One site for seminar and project
  - All material, schedule, **deadlines**
- **ISIS course**
  - https://isis.tu-berlin.de/course/view.php?id=37443
  - Announcements, discussion forum, polls for topic selection
- **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 Apr 15** (optional)
- **Recommended Introductory Lecture** (optional)
  - May 06, 14:00: Experiments, Reproducibility, and Giving Presentations
- **Self-organized Project Work**
  - Office hours for any questions (optional)
  - **Recommendation:**
    - Basic prototype working by end of June
    - Focus on incorporating feedback and conducting experiments afterwards
- **Final Presentations** (mandatory)
  - Aug 05, 14:00-18:00: All teams and individuals

- **List of Project Topics**
  - Presented today, take your time to select afterwards
- **Topic Selection**
  - **Deadline: Apr 29, 23:59 CET** (in 2 weeks)
  - Ranked list of **5 topics** via poll on the ISIS course, plus preferences on individual/team work, plus optionally concrete team members
  - Global topic assignment based on preferences
  - **Notification of assigned topics: May 06** (in 3 weeks)
- **Submission of Impl/Tests/Doc**
  - **Deadline: Jul 29, 23:59 CET** (in 15 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
  - **#41183 (project-only)**
    - Graded portfolio exam
    - 85 pts: implementation/tests/documentation
    - 15 pts: presentation
- **Academic Honesty / No Plagiarism** (incl LLMs like ChatGPT)

Portfolio Exam Registration

- **Portfolio exam registration: May 06 – Jun 03**
  - Binding registration in Moses/MTS
  - Including selection of seminar presentation date (first-come-first-serve)
- **Portfolio exam de-registration**
  - **Until 3 days before the first graded exam part**
    - Modules “LDE”/”Seminar LDE”: until **Jun 21**
    - Module “Project LDE”: until **Jul 26**
    - 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 **Jun 24**
    - Module “Project LDE”: until **Jul 29**
- **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 team/individual 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

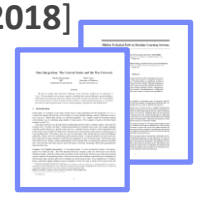
Landscape of ML Systems

- **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**

"Take these datasets and show value or competitive advantage"

[NIPS 2015]
[DEBull 2018]

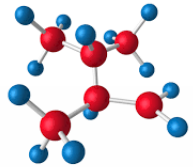


- **Data Preparation Problem**
  - **80% Argument:** 80-90% time for finding, integrating, cleaning data
  - Diversity of tools → boundary crossing, lack of optimization

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

Data extraction, schema alignment, entity resolution, data validation, data cleaning, outlier detection, missing value imputation, semantic type detection, data augmentation, feature selection, feature engineering, feature transformations

Key observation: SotA data integration/cleaning based on ML



Data Scientist

Data Integration
Data Cleaning
Data Preparation

Model Selection
Training
Hyper-parameters

Validate & Debug
Deployment
Scoring & Feedback

Data/SW Engineer

Exploratory Process
(experimentation, refinements, ML pipelines)

DevOps Engineer

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

[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]

Apache SystemML™

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

In-Memory Single Node
(scale-up)

In-Progress:

GPU

since 2014/16

Java

since 2012

Hadoop or Spark Cluster
(scale-out)

since 2010/11

since 2015

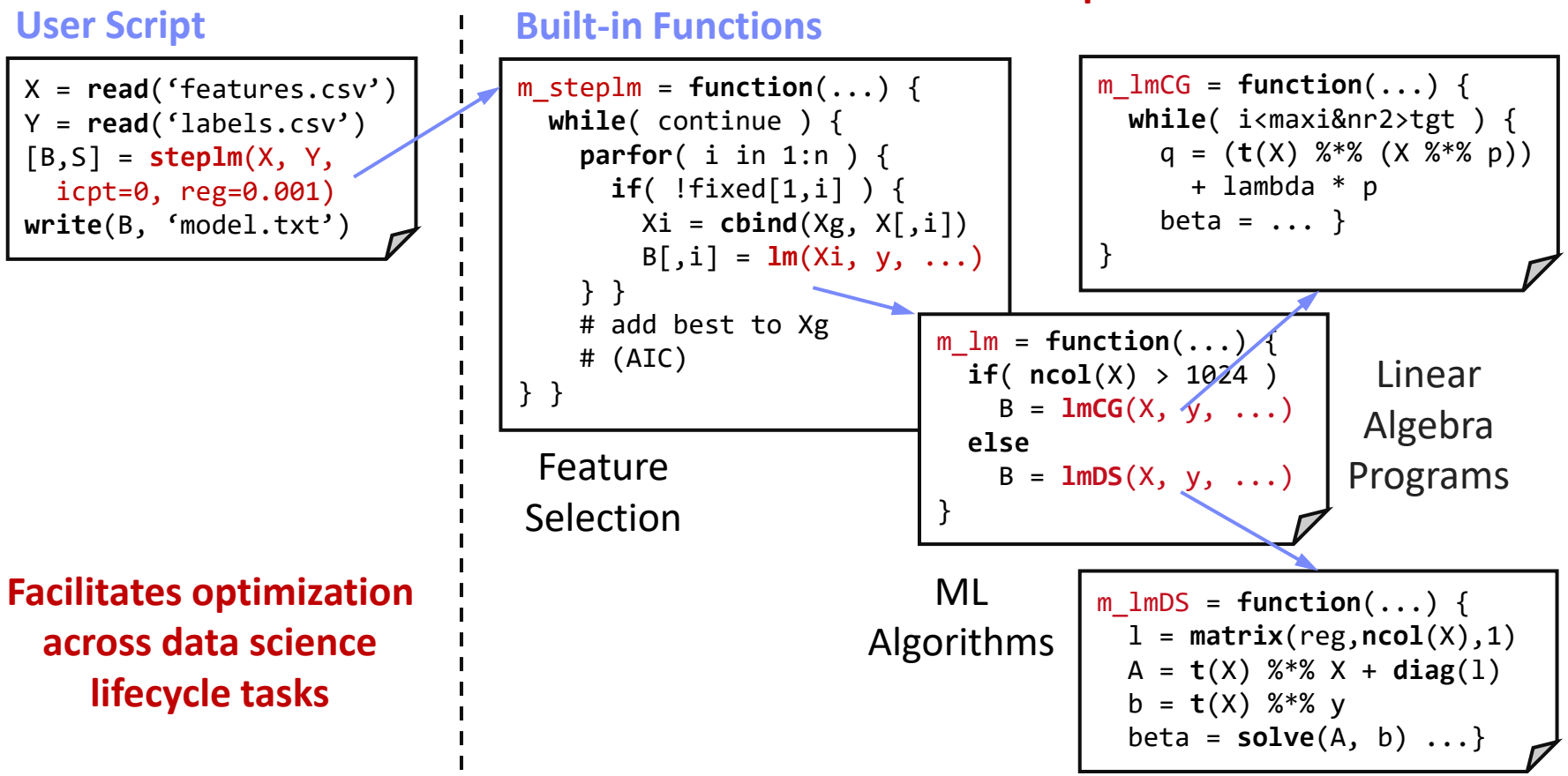
Federated
(LA progs, PS)

since 2019

Language Abstractions and APIs

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

- **Example:** Stepwise Linear Regression



Facilitates optimization across data science lifecycle tasks

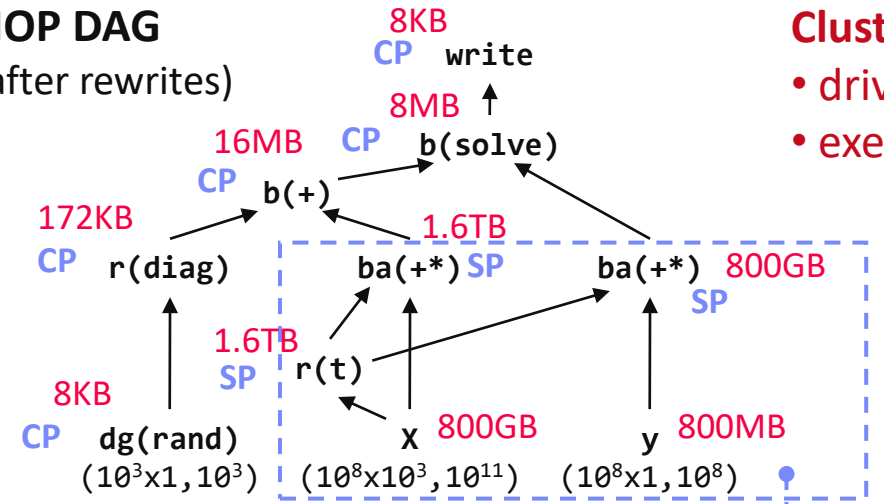
Basic HOP and LOP DAG Compilation

LinregDS (Direct Solve)

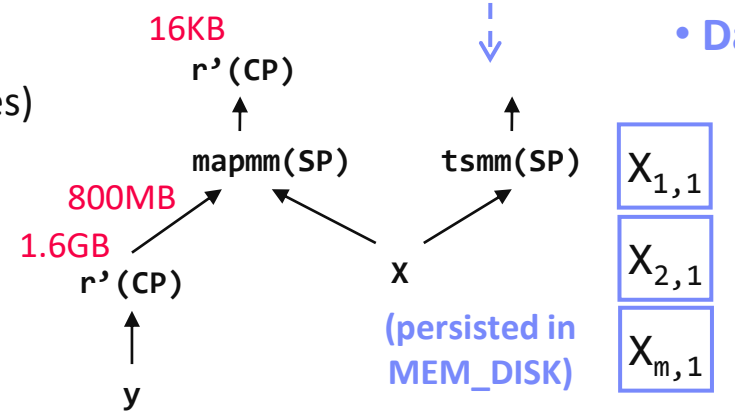
```
X = read($1);
y = read($2);
intercept = $3;
lambda = 0.001;
...
if( intercept == 1 ) {
  ones = matrix(1, nrow(X), 1);
  X = append(X, ones);
}
I = matrix(1, ncol(X), 1);
A = t(X) %*% X + diag(I)*lambda;
b = t(X) %*% y;
beta = solve(A, b);
...
write(beta, $4);
```

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

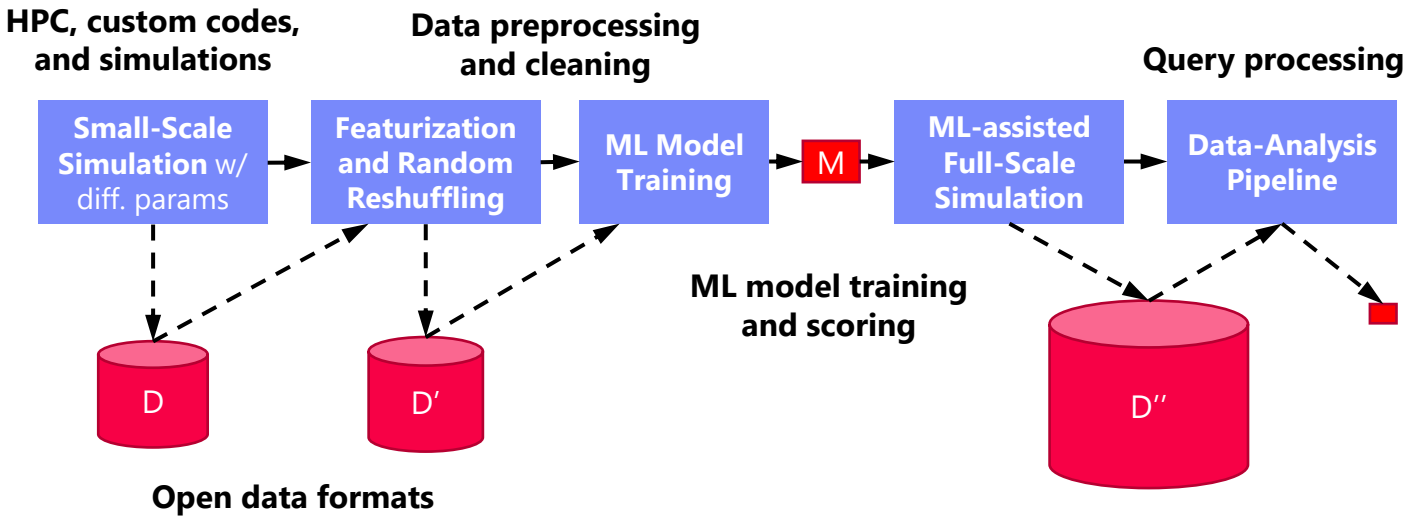
BIFOLD

Integrated Data Analysis (IDA) Pipelines

DM + ML + HPC

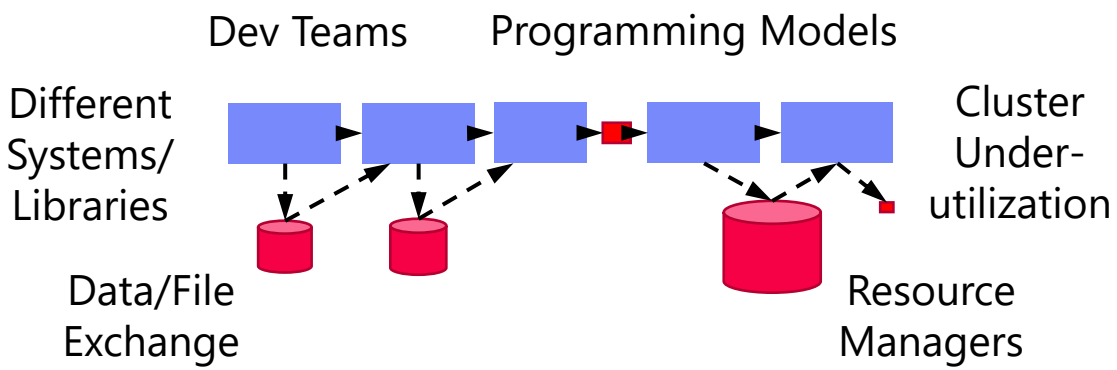
Data Management + Machine Learning + High-Perf. Computing

Example: ML-assisted Simulation



Challenges

Deployment Challenges



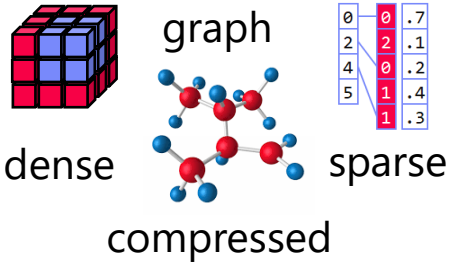
DAPHNE: An open and extensible system infrastructure for IDA pipelines

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**

Increasing Specialization

Data Representations



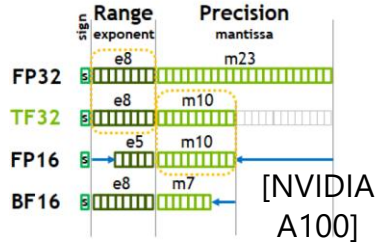
Sparsity Exploitation from Algorithms to HW

Data Placement

Local vs **distributed**

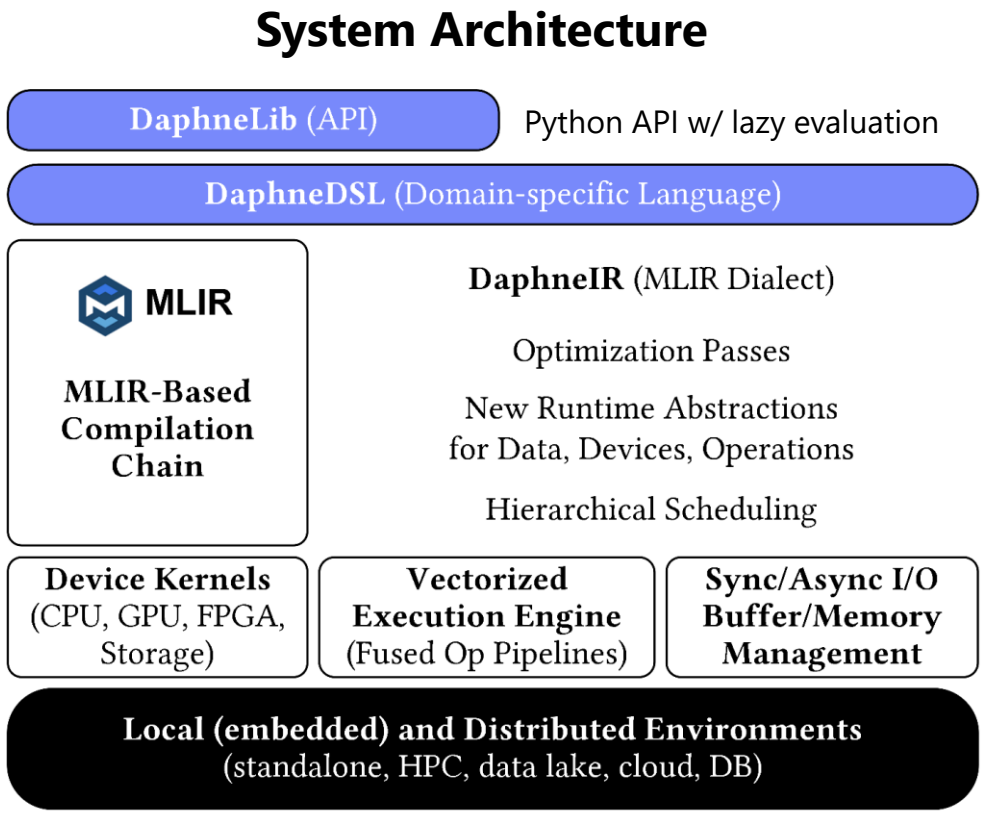
Data (Value) Types

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



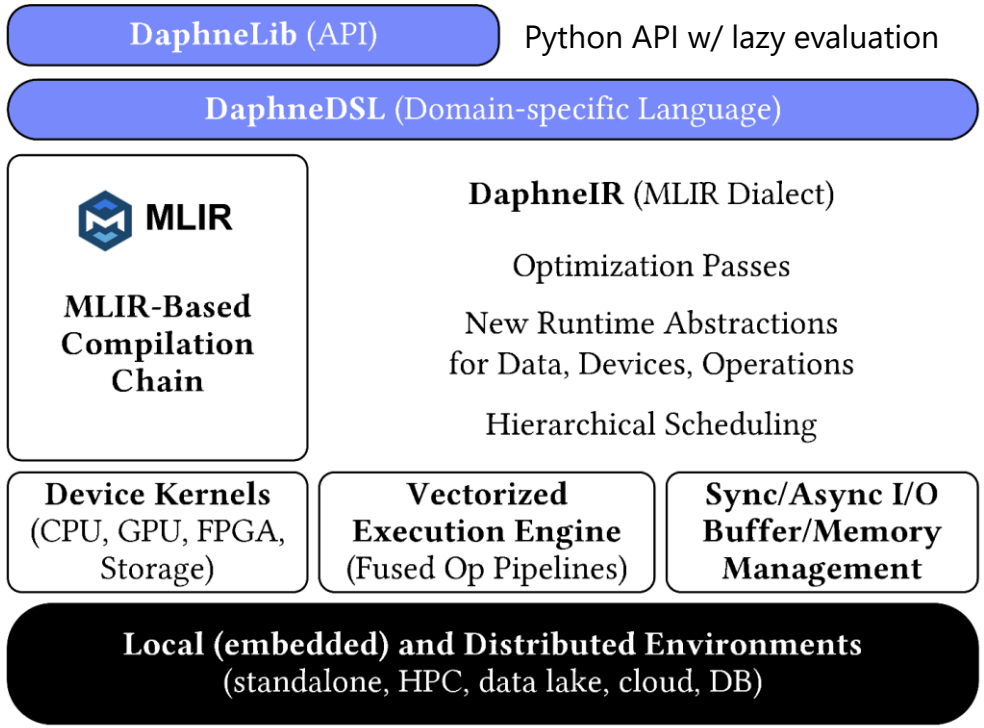
[NVIDIA A100]

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)

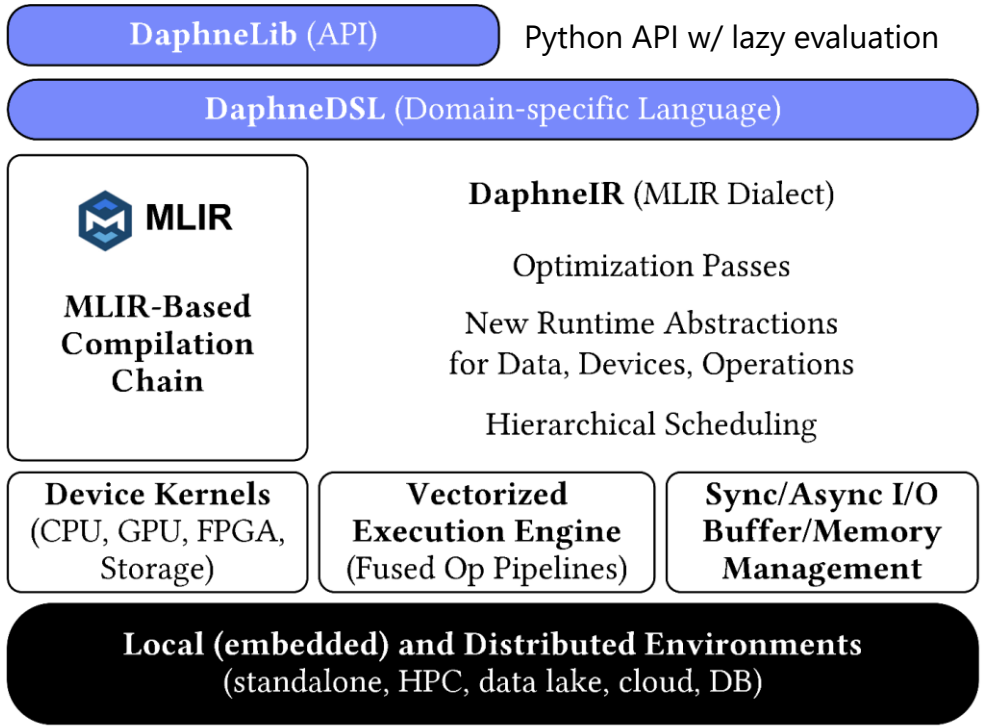
```
def lm(X, y) { // X feature matrix, y labels
  colmu = mean(X, 1);       // column means
  colsd = stddev(X, 1);     // column stddevs
  X = (X - colmu) / colsd; // shift and scale
  X = cbind(X, 1);          // append column of ones
  A = t(X) @ X;             // t for transpose
  b = t(X) @ y;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

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


BIFOLD

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**

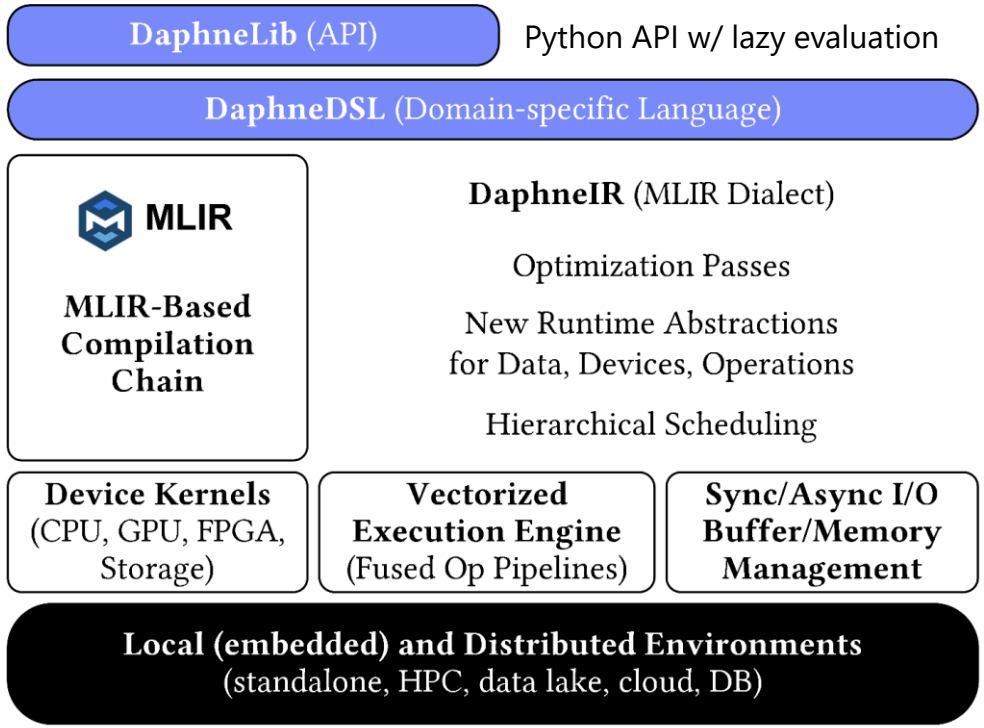
- Traditional **programming language rewrites**
- Type & property **inference**, inter-procedural analysis
- **Domain-specific rewrites** from linear and relational algebra
- Memory management & garbage collection
- **Device placement** & **physical operator selection**

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

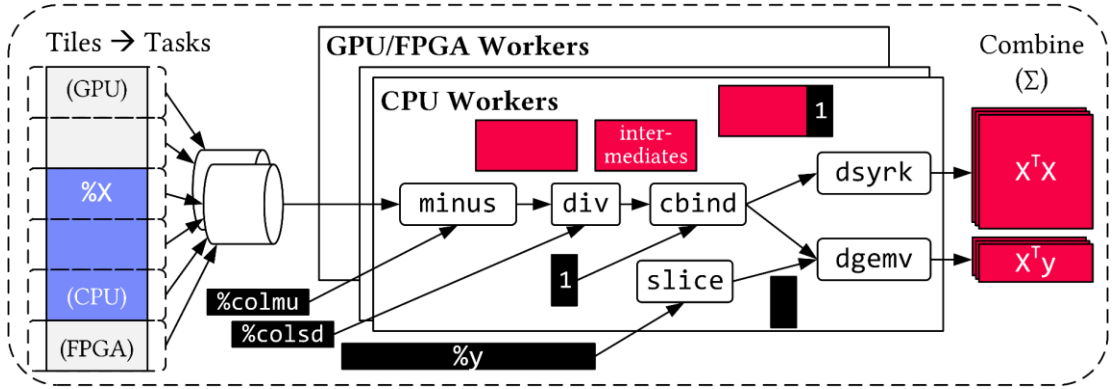
- **Fused operator pipelines** on tiles/vectors of data
- Coarse-grained tasks and cache-conscious data binding

- 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) {
```



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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/2024_summer/lde/ProjectTopics.pdf

Summary and Q&A

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

- **Remaining Questions?**

- **Reminder: Seminar Introductory Lecture Recommended for the Project**
  - 03 Experiments, Reproducibility, and Giving Presentations [May 06, 14:00]

- **See you during the office hours ☺**