2023 IEEE International Symposium on Performance Analysis of Systems and Software

TransPimLib:

Efficient Transcendental Functions for Processing-in-Memory Systems

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https://arxiv.org/pdf/2304.01951.pdf
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Tuesday, April 25, 2023

Executive Summary

- Processing-in-Memory (PIM) promises to alleviate the *data movement bottleneck*
- However, current real-world PIM systems have very constrained hardware, which results in limited instruction sets
  - Difficulty/impossibility of computing complex operations, such as transcendental functions (e.g., trigonometric, exp, log) and other hard-to-calculate functions (e.g., square root)
  - These functions are important for modern workloads, e.g., activation functions in machine learning applications
- TransPimLib is the first library for transcendental and other hard-to-calculate functions on general-purpose PIM systems
  - CORDIC-based and LUT-based methods for trigonometric functions, hyperbolic functions, exponentiation, logarithm, square root, etc.
  - Source code: https://github.com/CMU-SAFARI/transpimlib
- We implement TransPimLib for the UPMEM PIM architecture and evaluate its methods in terms of performance, accuracy, memory requirements, and setup time
  - Three real workloads (Blackscholes, Sigmoid, Softmax)

Outline

Processing-in-memory
and transcendental functions

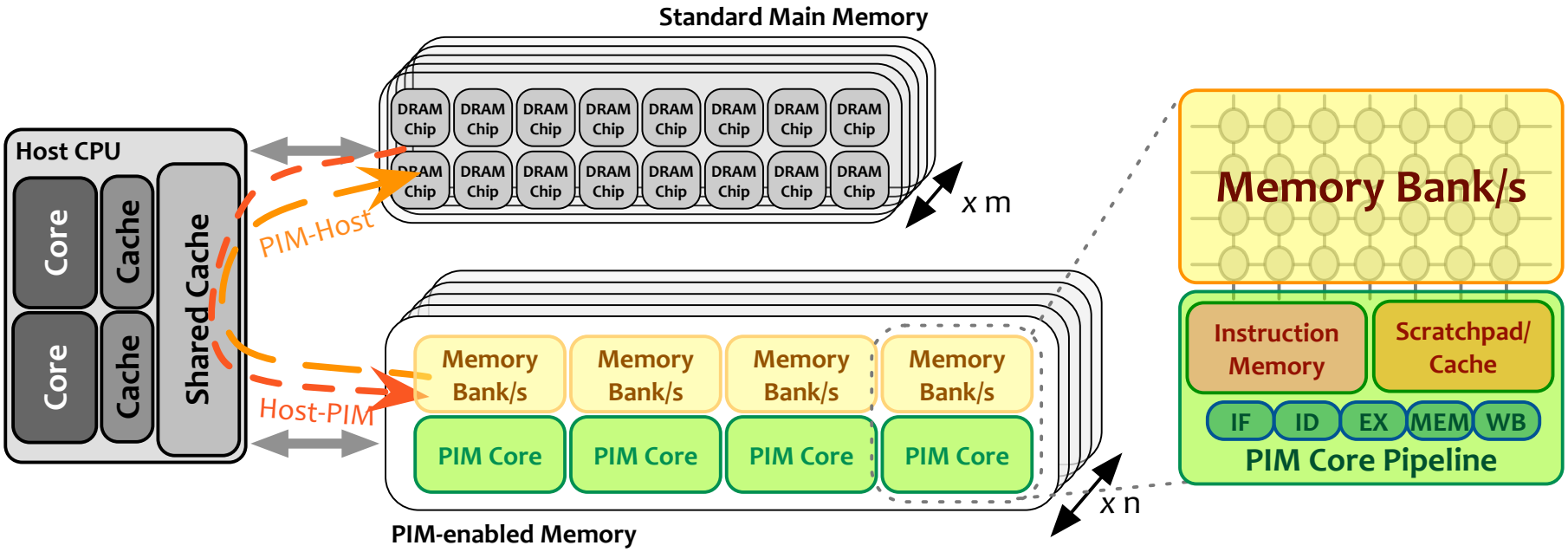
TransPimLib:
A library for transcendental
and other hard-to-calculate functions

Evaluation

Processing-in-Memory (PIM)

- PIM is a computing paradigm that advocates for memory-centric computing systems, where processing elements are placed near or inside the memory arrays
- Real-world PIM architectures are becoming a reality
  - UPMEM PIM, Samsung HBM-PIM, Samsung AxDIMM, SK Hynix AiM, Alibaba HB-PNM
- These PIM systems have some common characteristics:
  1. There is a host processor (CPU or GPU) with access to (1) standard main memory, and (2) PIM-enabled memory
  2. PIM-enabled memory contains multiple PIM processing elements (PEs) with high bandwidth and low latency memory access
  3. PIM PEs run only at a few hundred MHz and have a small number of registers and small (or no) cache/scratchpad
  4. PIM PEs may need to communicate via the host processor

A State-of-the-Art PIM System

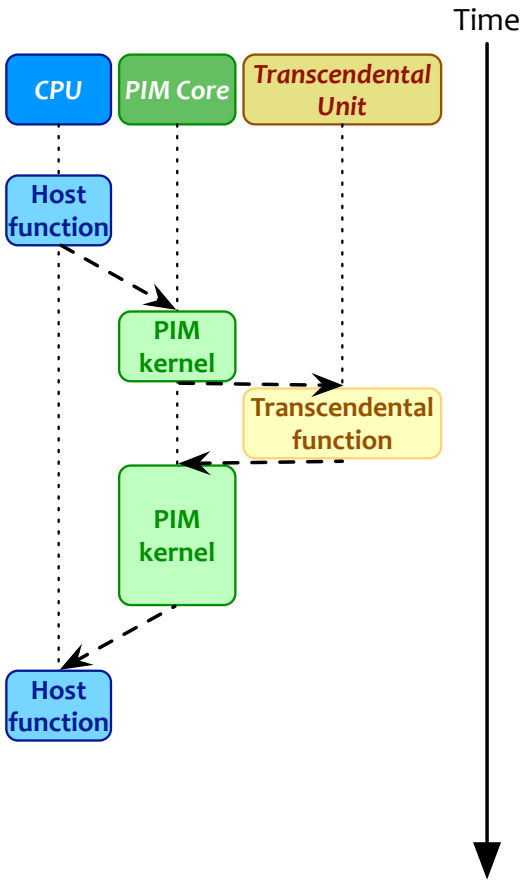


- In our work, we use the UPMEM PIM architecture
  - General-purpose processing cores called *DRAM Processing Units* (*DPUs*)
    - Up to 24 PIM threads, called *tasklets*
    - 32-bit integer arithmetic, but multiplication/division are emulated*, as well as floating-point operations
  - 64-MB DRAM bank (*MRAM*), 64-KB scratchpad (*WRAM*)

* 8-bit integer multiplication is natively supported

How to Calculate Transcendental Functions in a PIM System?

- Three possible alternatives



(a) Transcendental function executed in special PIM unit

How to Calculate Transcendental Functions in a PIM System?

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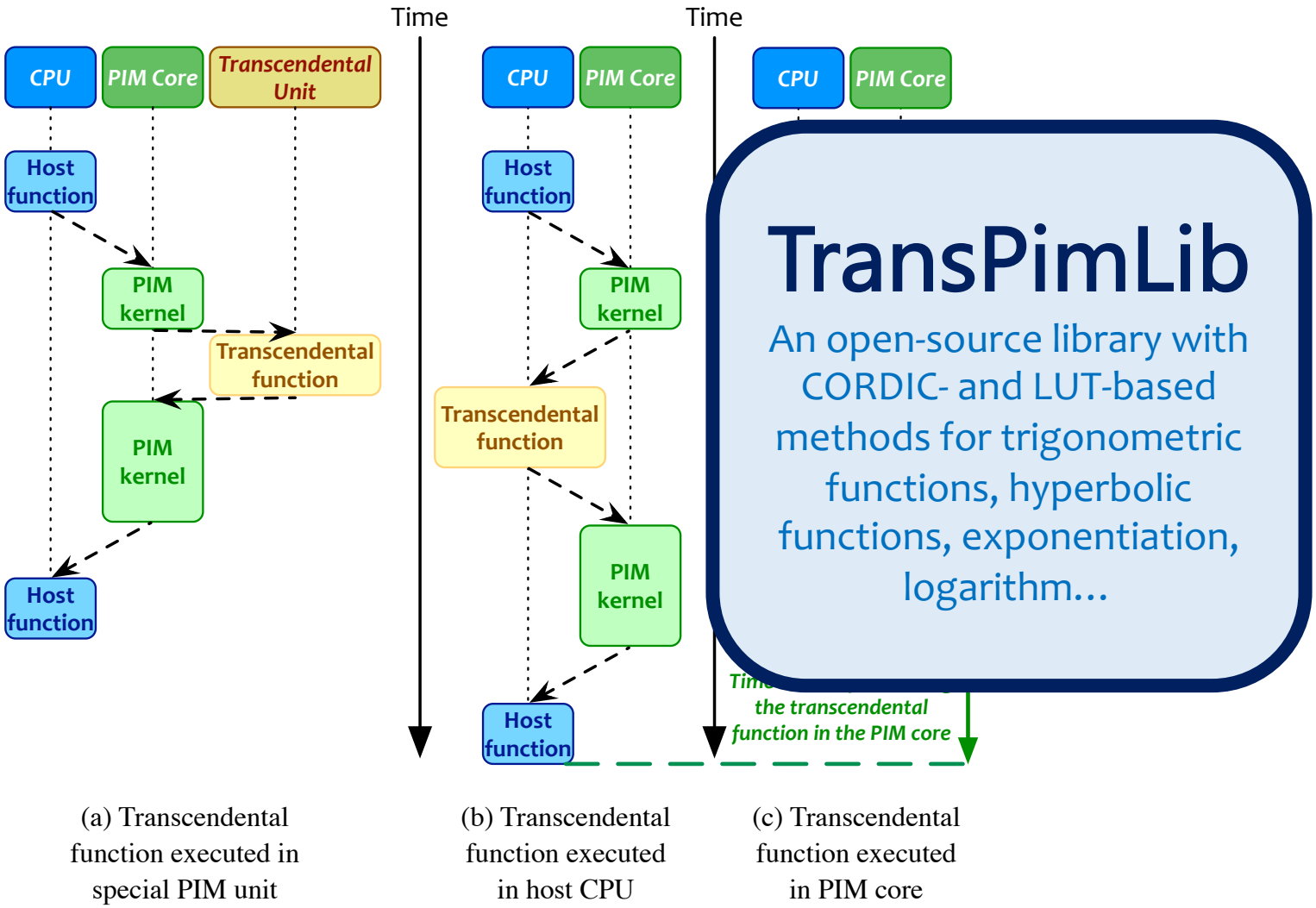

(a) Transcendental function executed in special PIM unit

(b) Transcendental function executed in host CPU

(c) Transcendental function executed in PIM core

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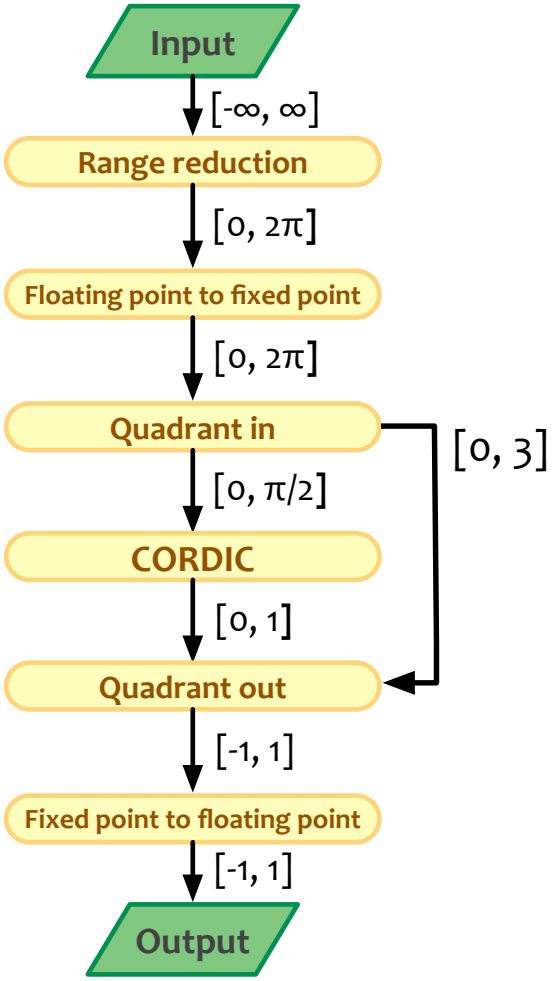
TransPimLib: Implementation

- Various methods to calculate transcendental functions:
  - Taylor approximation, minimax polynomials, CORDIC, LUTs
- CORDIC is an iterative method that uses bit-shifts, additions, and table lookups
  - In rotation mode, CORDIC computes the function value for an input θ by rotating a vector [1, 0] iteratively
  - The rotation is done by multiplying the vector and a matrix
  - The matrix represents the rotation angle, which decreases in each iteration
- Fuzzy Lookup Tables (LUTs) return an (approximate) output $f(x)$ for each input x
  - A function $a(x)$ returns an address to access the LUT
  - The table returns $LUT(a(x)) \simeq f(x)$
  - To generate the LUT, we need a helper function $a^{-1}()$, such that $x = a(a^{-1}(x))$
  - LUTs' accuracy improves with interpolation:

    $f(x) \simeq LUT(a(x)) + LUT(a(x)+1) - LUT(a(x)) \cdot \Delta$

TransPimLib: CORDIC-based Methods

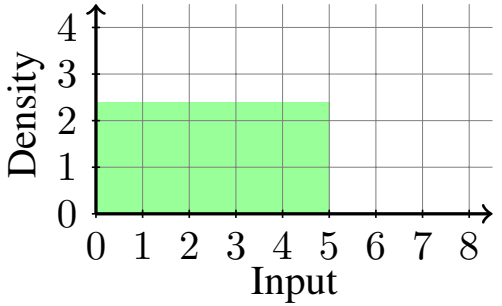
- TransPimLib contains CORDIC implementations of trigonometric (sin, cos, tan) and hyperbolic (sinh, cosh, tanh) functions, exponentiation, logarithm, and square root
- Example: Sine function

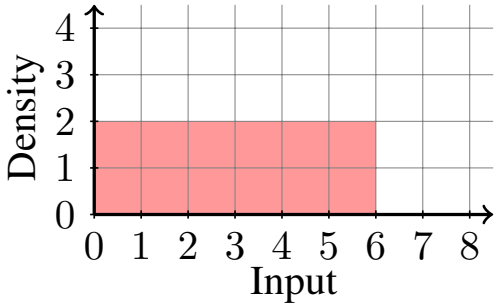


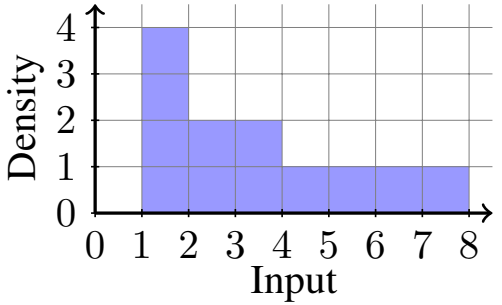
TransPimLib: LUT-based Methods

- Multiplication-based LUT (M-LUT)
  - Regular spacing between table entries
  - $a(x) = round((x - p) \cdot k)$, where k represents the LUT density
- LDEXP-based LUT (L-LUT)
  - Multiplication is cheaper if we multiply by 2^n
  - *ldexp(arg, exp)* to perform arg $\cdot\ 2^{exp}$
  - $a(x) = round((x - p) \cdot 2^n)$
    - k is a power-of-two, which results in less precision but avoids multiplication
- Direct Float Conversion-based LUT (D-LUT)
  - $a(x)$ uses the last n bits of the exponent and p bits of the mantissa
  - Piece-wise linear density: 2^n steps of 2^p addresses

Map interval [0, 5] to a 12-entry LUT

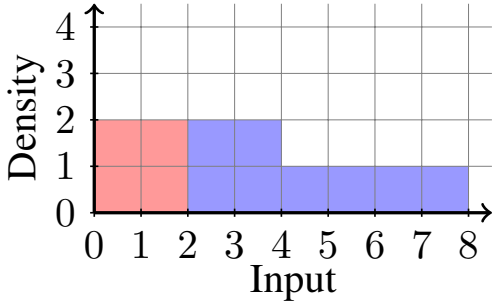


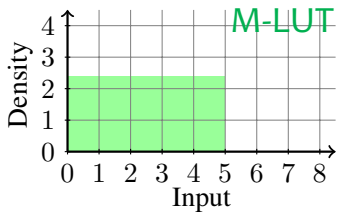


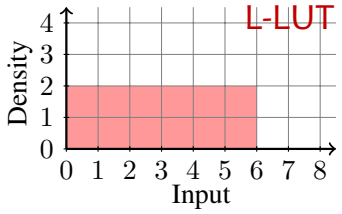


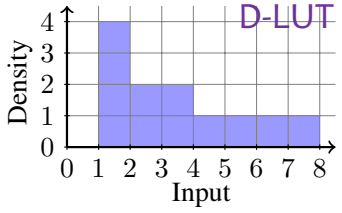
TransPimLib: Combined Methods

- Direct Float Conversion + LDEXP-based LUT (DL-LUT)
  - Uses an L-LUT between 0 and the smallest exponent and a D-LUT for larger inputs









- CORDIC+L-LUT (CORDIC+LUT)
  - Replaces the first few iterations of CORDIC with a LUT
  - Flexible tradeoff between computing cost, table size, and precision

TransPimLib: Supported Functions

Implementation Method	Supported Functions									
	sin	cos	tan	sinh	cosh	tanh	exp	log	sqrt	GELU
CORDIC	✓	✓	✓	✓	✓	✓	✓	✓	✓	
M-LUT	✓	✓	✓				✓	✓	✓	
M-LUT+Interp.	✓	✓	✓				✓	✓	✓	
L-LUT	✓	✓	✓				✓	✓	✓	
L-LUT+Interp.	✓	✓	✓				✓	✓	✓	
D-LUT+Interp.	✓					✓				✓
DL-LUT+Interp.	✓					✓				✓
CORDIC+LUT	✓	✓	✓	✓	✓	✓	✓			

Based on our preliminary analysis, we provide the most suitable methods for each of the supported functions (other than sine).

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Evaluation

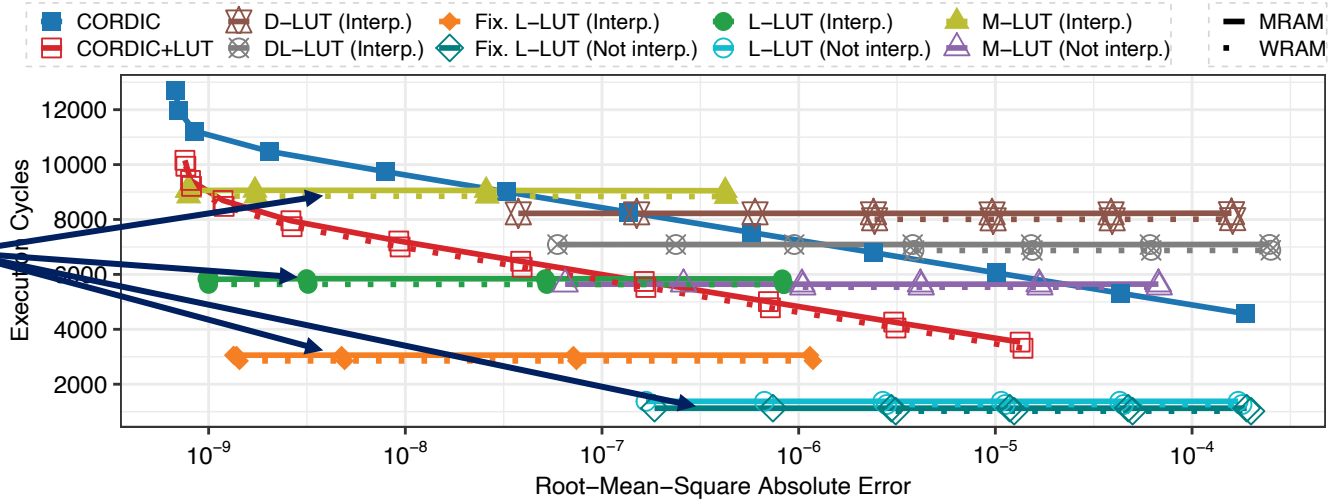
Evaluation Methodology

- Evaluated systems
  - UPMEM PIM system with 2,545 PIM cores @ 350 MHz and 159 GB of DRAM
  - 2-socket Intel Xeon CPU (32 cores)
- Microbenchmarks
  - Performance evaluation
    - We measure execution cycles
  - Accuracy evaluation
    - Root-mean-square absolute error (RMSE) with respect to the CPU with the standard math library
  - Setup time
    - Generation on the host CPU and transfers to the PIM side
  - Memory consumption
    - All tables and variables allocated in the DRAM bank of a PIM core
  - We use sine, as a representative function
- Real-world Benchmarks
  - Blackscholes: exp, log, sqrt, cumulative normal distribution (CNDF)
  - Sigmoid
  - Softmax

Microbenchmark Results: Performance (I)

- We measure the execution cycles for an accuracy range between 10^{-4} and 10^{-9}
- LUT-based versions place the LUT in either the PIM core's DRAM bank (MRAM) or the scratchpad (WRAM)

Performance of LUT-based methods is independent of the accuracy



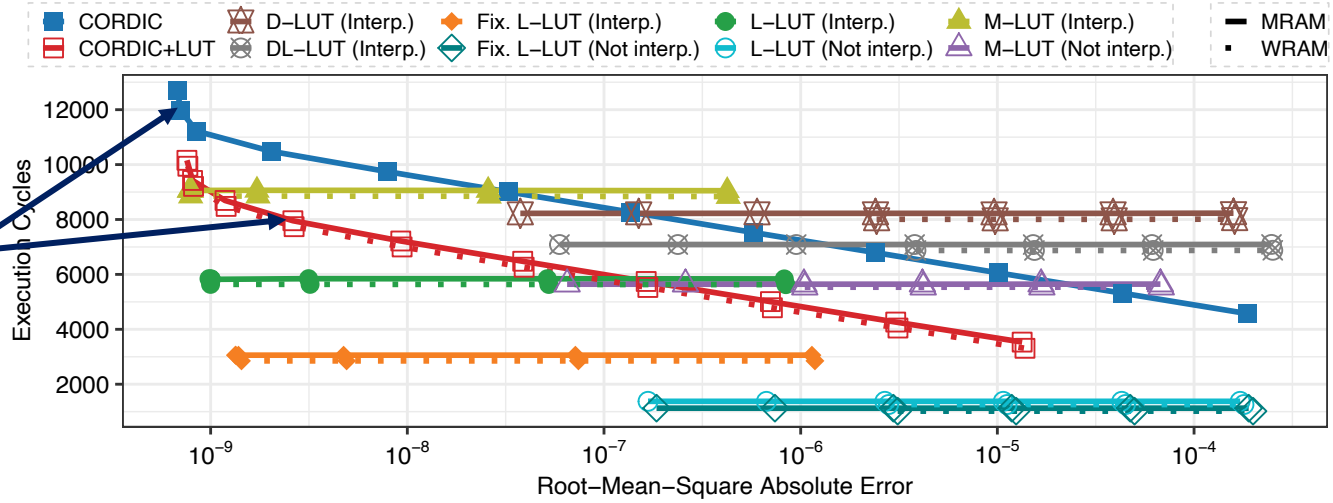
Execution cycles depend on the number of multiplications:
- Interp. M-LUT: 2 FP multiplications
- Non-interp. M-LUT and inter. L-LUT: 1 FP multiplication
- Non-interp. L-LUT: No FP multiplication

Fixed-point version of the L-LUT
- Interp. Fix. L-LUT doubles the performance of inter. L-LUT due to faster fixed-point multiplication

Microbenchmark Results: Performance (II)

- We measure the execution cycles for an accuracy range between 10^{-4} and 10^{-9}
- CORDIC-based methods take more execution cycles to provide higher accuracy

CORDIC accuracy increases with each iteration of the CORDIC algorithm



CORDIC+LUT runs faster than **CORDIC**, as it replaces the initial iterations with an L-LUT query

At some point (~10^{-9}), further increasing the LUT size or CORDIC iterations does not improve accuracy

Little benefit from placing LUTs in the scratchpad (WRAM) instead of the DRAM bank (MRAM)

Microbenchmark Results: Performance (III)

- We measure the execution cycles for an accuracy range between 10^{-4} and 10^{-9}
- CORDIC-based methods take more execution cycles to provide

Key Takeaway 1

Interpolated L-LUT methods (lookup table with LDEXP operation) offer the **best tradeoff** in terms of performance and accuracy

CORDIC+LUT runs faster than CORDIC, as it replaces the initial iterations with an L-LUT query

At some point (~10^{-9}), further increasing the LUT size or CORDIC iterations does not improve accuracy

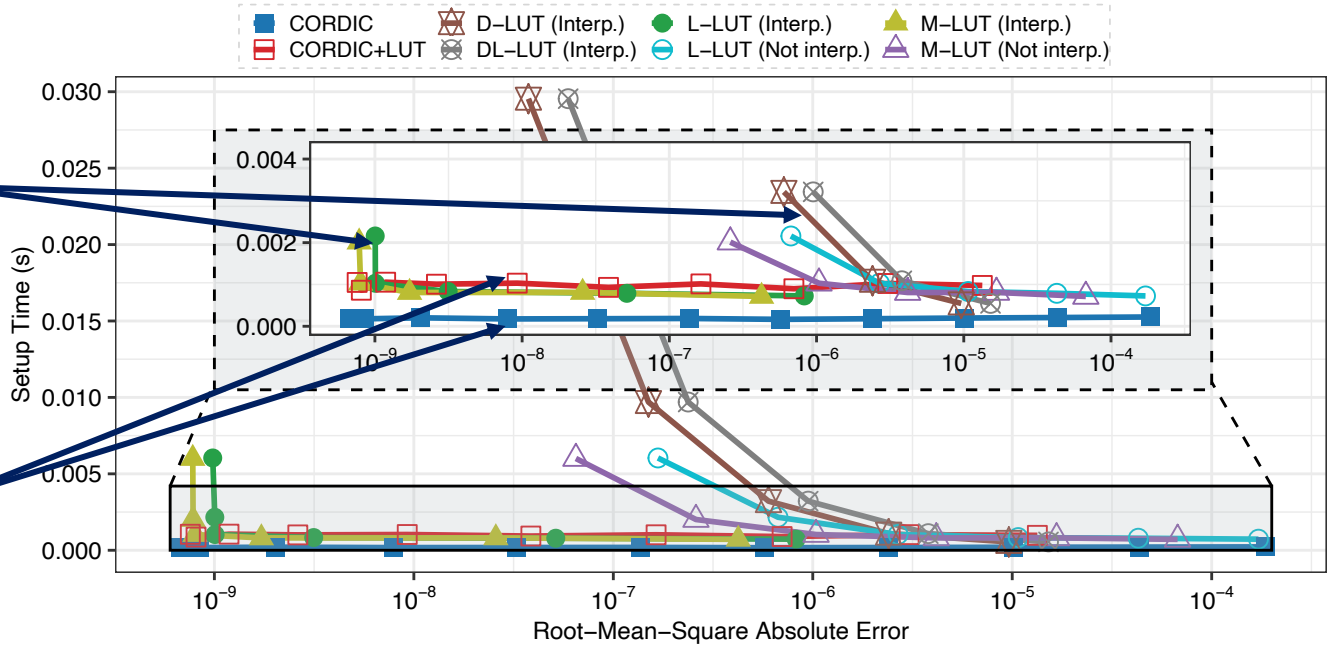
Little benefit from placing LUTs in the scratchpad (WRAM) instead of the DRAM bank (MRAM)

Microbenchmark Results: Setup Time (I)

- The setup time can also impact the decision of what method to use

For LUT-based methods, setup times increase with LUT size

CORDIC methods have flat setup times



CORDIC methods can provide higher overall performance
(i.e., setup time + PIM kernel time) than LUT-based methods
when the total number of transcendental functions in a workload is low.
For example, we estimate ~40 sine operations (see paper)

Microbenchmark Results: Setup Time (II)

- The setup time can also impact the decision of what method to use

Key Takeaway 2

CORDIC-based methods are preferable when a PIM kernel needs to execute **just a few transcendental functions** due to their low setup time in the host CPU

CORDIC methods can provide higher overall performance
(i.e., setup time + PIM kernel time) than LUT-based methods
when the total number of transcendental functions in a workload is low.
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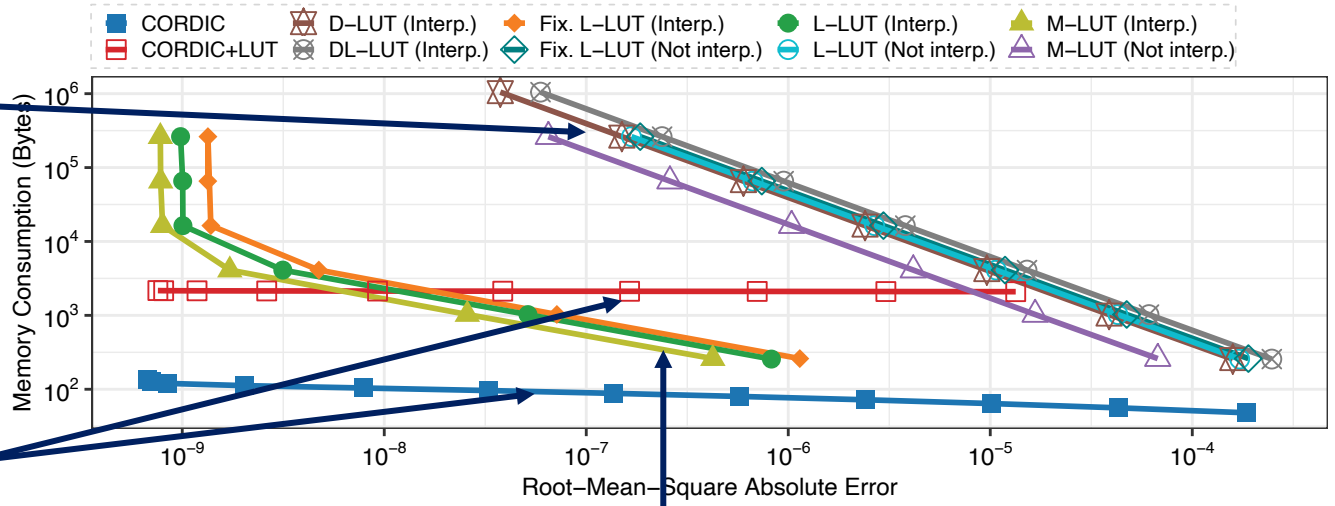
Microbenchmark Results: Memory (I)

- We also obtain the memory consumption (in bytes) in the DRAM bank of a PIM core

Accuracy of non-interp. LUT methods is limited by the available memory

Memory consumption of CORDIC methods does *not* increase exponentially



Interpolation is an effective way of increasing accuracy without increasing LUT size

Microbenchmark Results: Memory (II)

- We also obtain the memory consumption (in bytes) in

Key Takeaway 3

Interpolated L-LUT methods offer a good tradeoff in terms of accuracy, execution cycles, and memory consumption.

However, **CORDIC and CORDIC+LUT methods** are recommended for applications that require high accuracy, where the available memory is limited (e.g., needed for large datasets)

More in the Paper

- Analysis of other supported functions
- Evaluation of range reduction/extension
- Discussion and takeaway about D-LUT and DL-LUT methods

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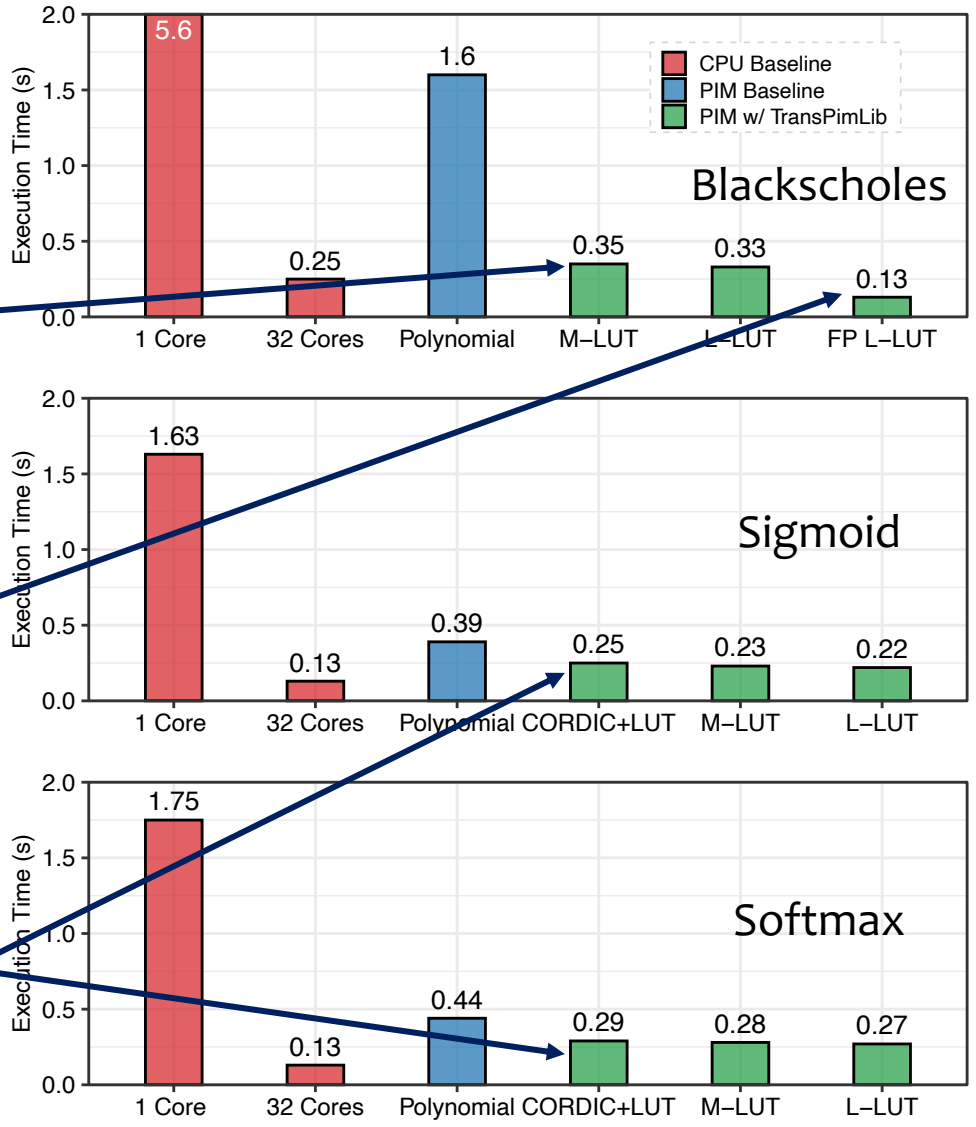
Real-world Benchmark Results (I)

- 1 & 32 CPU cores
- PIM baseline: Polynomial

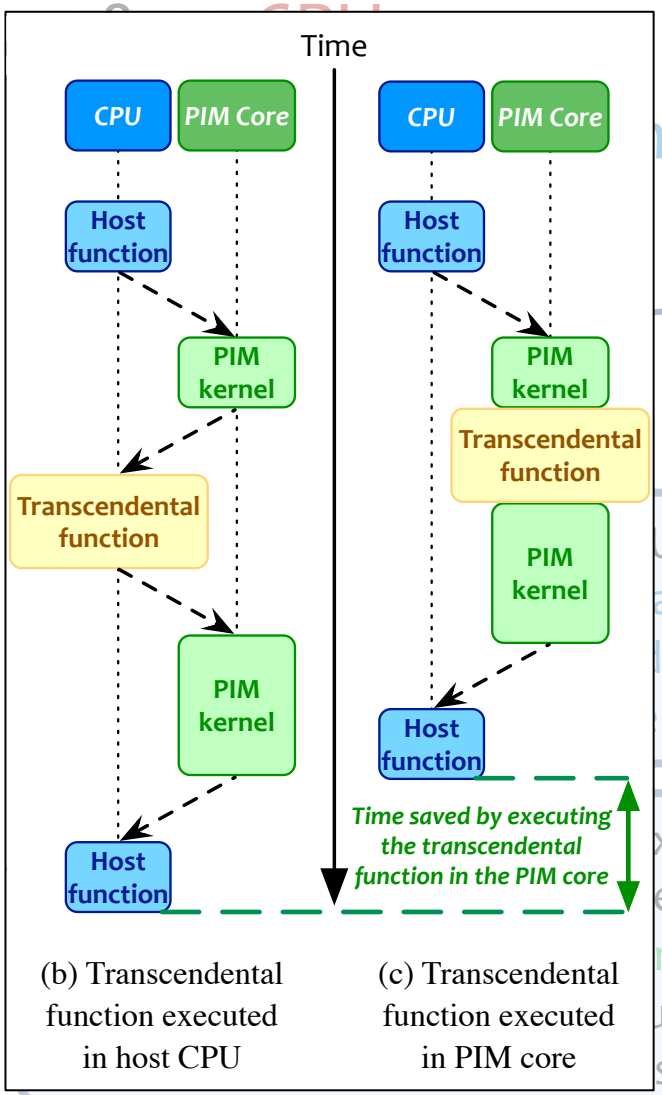
For Blackscholes, TransPimLib is 5-12x faster than the PIM baseline

Fixed-point L-LUT is 92% faster than the 32-thread CPU baseline

For Sigmoid and Softmax, TransPimLib outperforms the PIM baseline and shows that it can save data movement from executing activation functions in the host CPU



Real-world Benchmark Results (II)



Key Takeaway 4

TransPimLib can **reduce data movement from PIM cores to the CPU** (Fig. (b)) for applications running on the PIM cores.

As a result, the execution of transcendental functions in the PIM cores (Fig. (c)) could be 6–8× faster than the execution in the host CPU.

TransPimLib: arXiv Version

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Source Code

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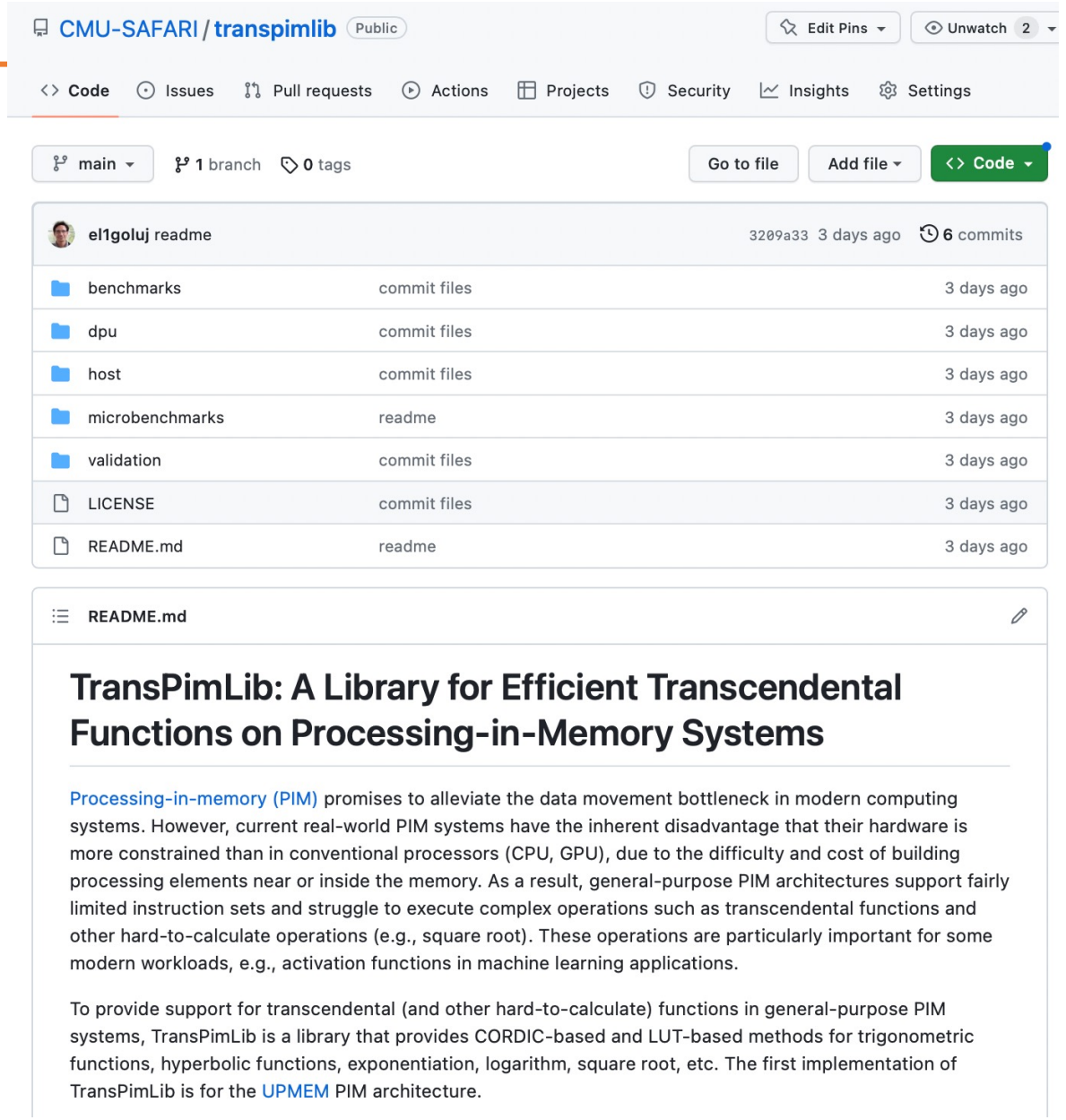

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Real PIM Tutorial (ISCA 2023)

- June 18th: Lectures + Hands-on labs + Invited lectures

ISCA 2023 Real-World PIM Tutorial

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  - Hands-on Labs (tentative)
  - Learning Materials

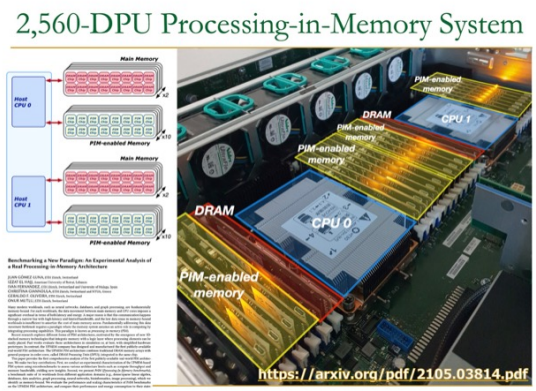
Real-world Processing-in-Memory Systems for Modern Workloads

Tutorial Description

Processing-in-Memory (PIM) is a computing paradigm that aims at overcoming the data movement bottleneck (i.e., the waste of execution cycles and energy resulting from the back-and-forth data movement between memory units and compute units) by making memory compute-capable.

Explored over several decades since the 1960s, PIM systems are becoming a reality with the advent of the first commercial products and prototypes.

A number of startups (e.g., UPMEM, Neuroblade) are already commercializing real PIM hardware, each with its own design approach and target applications. Several major vendors (e.g., Samsung, SK Hynix, Alibaba) have presented real PIM chip prototypes in the last two years. Most of these architectures have in common that they place compute units near the memory arrays. This type of PIM is called processing near memory (PNM).



PIM can provide large improvements in both performance and energy consumption for many modern applications, thereby enabling a commercially viable way of dealing with huge amounts of data that is bottlenecking our computing systems. Yet, it is critical to (1) study and understand the characteristics that make a workload suitable for a PIM architecture, (2) propose optimization strategies for PIM kernels, and (3) develop programming frameworks and tools that can lower the learning curve and ease the adoption of PIM.

This tutorial focuses on the latest advances in PIM technology, workload characterization for PIM, and programming and optimizing PIM kernels. We will (1) provide an introduction to PIM and taxonomy of PIM systems, (2) give an overview and a rigorous analysis of existing real-world PIM hardware, (3) conduct hand-on labs about important workloads (machine learning, sparse linear algebra, bioinformatics, etc.) using real PIM systems, and (4) shed light on how to improve future PIM systems for such workloads.

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