SimplePIM:

A Software Framework for Productive and Efficient Processing-in-Memory

Jinfan Chen, Juan Gómez Luna, Izzat El Hajj, Yuxin Guo, Onur Mutlu

https://arxiv.org/pdf/2310.01893.pdf

https://github.com/CMU-SAFARI/SimplePIM

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Executive Summary

- Processing-in-Memory (PIM) promises to alleviate the *data movement bottleneck*
- Real PIM hardware is now available, e.g., UPMEM PIM
- However, programming real PIM hardware is challenging, e.g.:
  - Distribute data across PIM memory banks,
  - Manage data transfers between host cores and PIM cores, and between PIM cores,
  - Launch PIM kernels on the PIM cores, etc.
- SimplePIM is a high-level programming framework for real PIM hardware
  - Iterators such as `map`, `reduce`, and `zip`
  - Collective communication with `broadcast`, `scatter`, and `gather`
- Implementation on UPMEM and evaluation with six different workloads
  - Reduction, vector add, histogram, linear/logistic regression, K-means
  - 4.4x fewer lines of code compared to hand-optimized code
  - Between 15% and 43% faster than hand-optimized code for three workloads
- Source code: https://github.com/CMU-SAFARI/SimplePIM

Outline

Processing-in-memory
and PIM programming

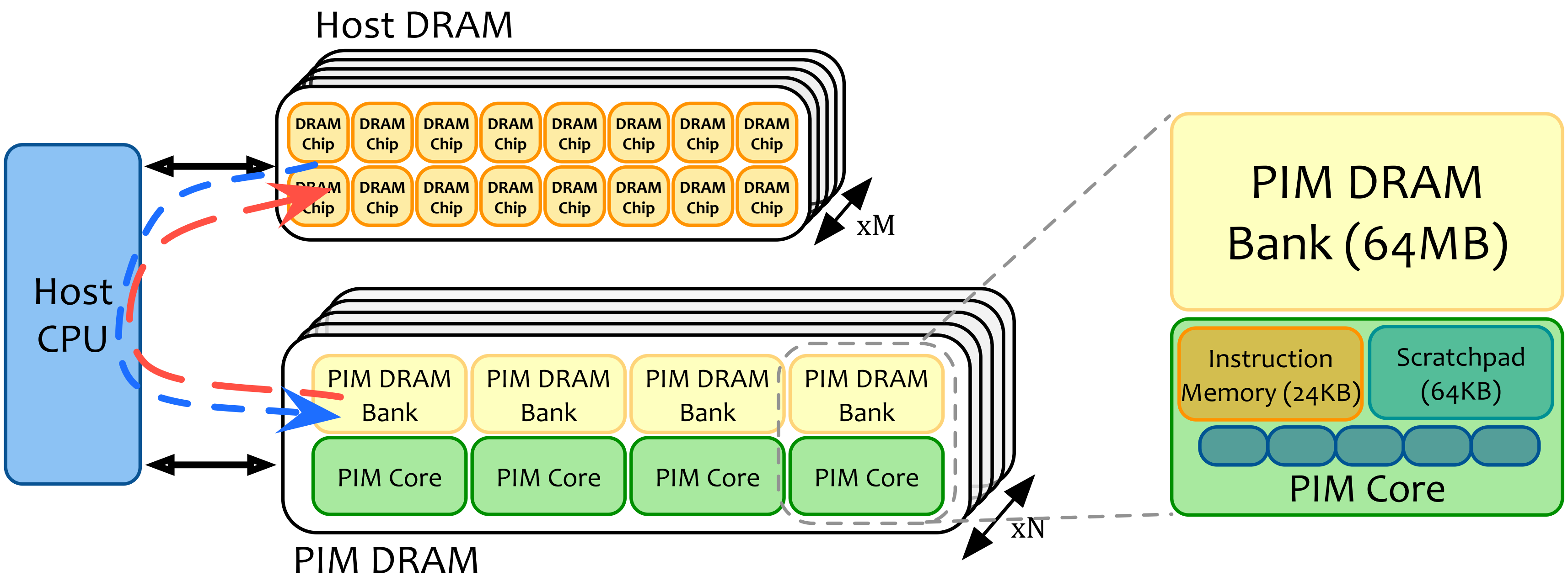
SimplePIM:
A high-level programming framework for
processing-in-memory

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

Programming a PIM System (I)

- Example: Hand-optimized histogram with UPMEM SDK

```
... // Initialize global variables and functions for histogram
int main_kernel() {
  if (tasklet_id == 0)
    mem_reset(); // Reset the heap
  ... // Initialize variables and the histogram
  T *input_buff_A = (T*)mem_alloc(2048); // Allocate buffer in scratchpad memory

  for (unsigned int byte_index = base_tasklet; byte_index < input_size; byte_index += stride) {
    // Boundary checking
    uint32_t l_size_bytes = (byte_index + 2048 >= input_size) ? (input_size - byte_index) : 2048;
    // Load scratchpad with a DRAM block
    mram_read((const __mram_ptr void*)(mram_base_addr_A + byte_index), input_buff_A, l_size_bytes);
    // Histogram calculation
    histogram(hist, bins, input_buff_A, l_size_bytes/sizeof(uint32_t));
  }
  ...
  barrier_wait(&my_barrier); // Barrier to synchronize PIM threads
  ... // Merging histograms from different tasklets into one histo_dpu
  // Write result from scratchpad to DRAM
  if (tasklet_id == 0)
    if (bins * sizeof(uint32_t) <= 2048)
      mram_write(histo_dpu, (__mram_ptr void*)mram_base_addr_histo, bins * sizeof(uint32_t));
    else
      for (unsigned int offset = 0; offset < ((bins * sizeof(uint32_t)) >> 11); offset++) {
        mram_write(histo_dpu + (offset << 9), (__mram_ptr void*)(mram_base_addr_histo +
                   (offset << 11)), 2048);
      }
  return 0;
}
```

Programming a PIM System (II)

- PIM programming is challenging
  - Manage data movement between host DRAM and PIM DRAM
    - Parallel, serial, broadcast, and gather/scatter transfers
  - Manage data movement between PIM DRAM bank and scratchpad
    - 8-byte aligned and maximum of 2,048 bytes
  - Multithreaded programming model
  - Inter-thread synchronization
    - Barriers, handshakes, mutexes, and semaphores

Our Goal

Design a high-level programming framework that abstracts these hardware-specific complexities and provides a clean yet powerful interface for ease of use and high program performance

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The SimplePIM Programming Framework

- SimplePIM provides standard abstractions to build and deploy applications on PIM systems
  - Management interface
    - Metadata for PIM-resident arrays
  - Communication interface
    - Abstractions for host-PIM and PIM-PIM communication
  - Processing interface
    - Iterators (`map`, `reduce`, `zip`) to implement workloads

Management Interface

- Metadata for PIM-resident arrays
  - `array_meta_data_t` describes a PIM-resident array
  - `simple_pim_management_t` for managing PIM-resident arrays

- `lookup`: Retrieves all relevant information of an array

```
array_meta_data_t* simple_pim_array_lookup(const char* id,
simple_pim_management_t* management);
```

- `register`: Registers the metadata of an array

```
void simple_pim_array_register(array_meta_data_t* meta_data,
simple_pim_management_t* management);
```

- `free`: Removes the metadata of an array

```
void simple_pim_array_free(const char* id, simple_pim_management_t* management);
```

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Host-to-PIM Communication: Broadcast

- SimplePIM Broadcast
  - Transfers a host array to all PIM cores in the system

```
void simple_pim_array_broadcast(char* const id, void* arr, uint64_t len,
uint32_t type_size, simple_pim_management_t* management);
```

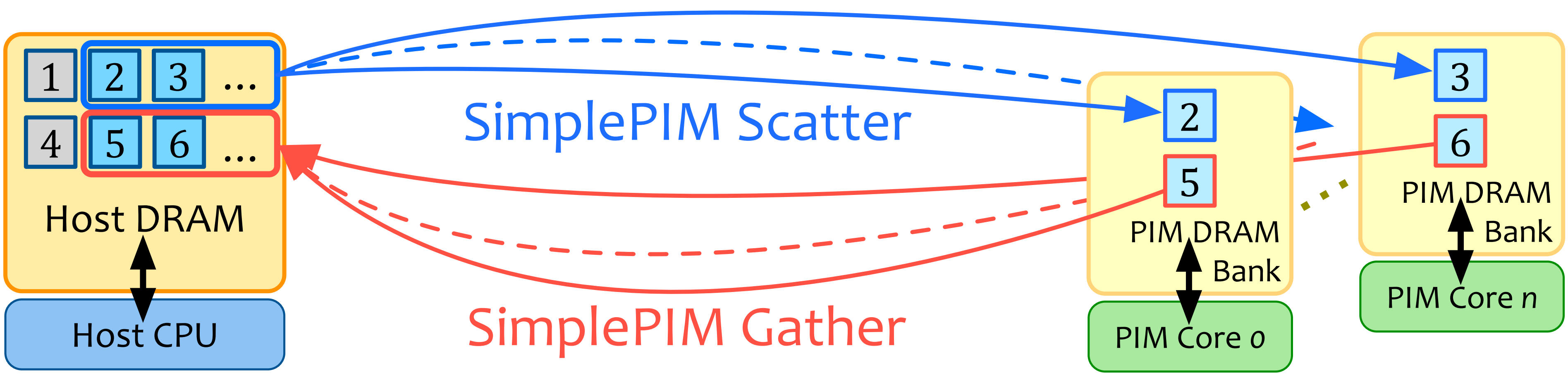
Host-to-PIM Communication: Scatter/Gather

- SimplePIM Scatter
  - Distributes an array to PIM DRAM banks

```
void simple_pim_array_scatter(char* const id, void* arr, uint64_t len,
uint32_t type_size, simple_pim_management_t* management);
```

- SimplePIM Gather
  - Collects portions of an array from PIM DRAM banks

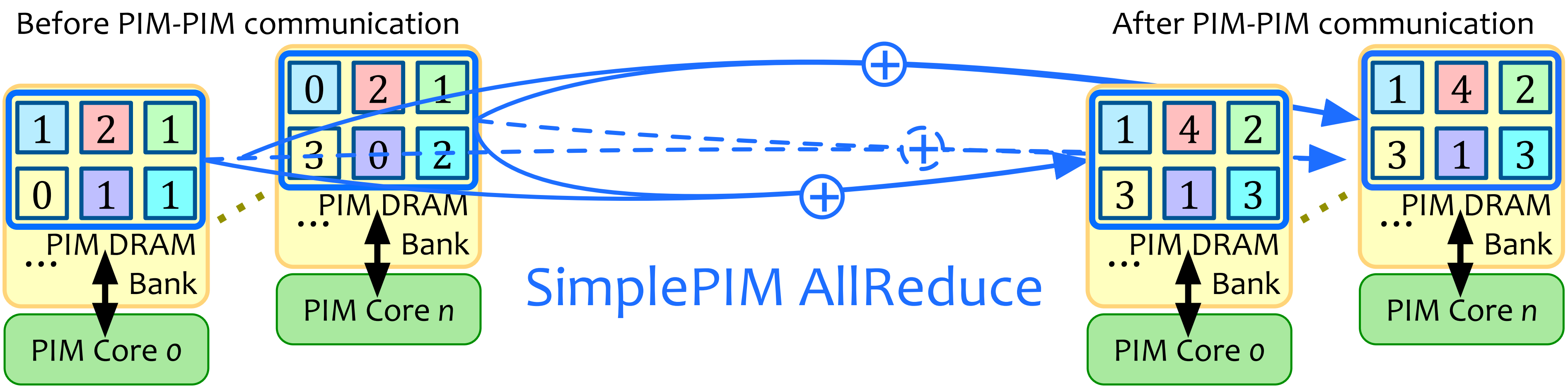
```
void* simple_pim_array_gather(char* const id, simple_pim_management_t*
management);
```



PIM-PIM Communication: AllReduce

- SimplePIM AllReduce
  - Used for algorithm synchronization
  - The programmer specifies an accumulative function

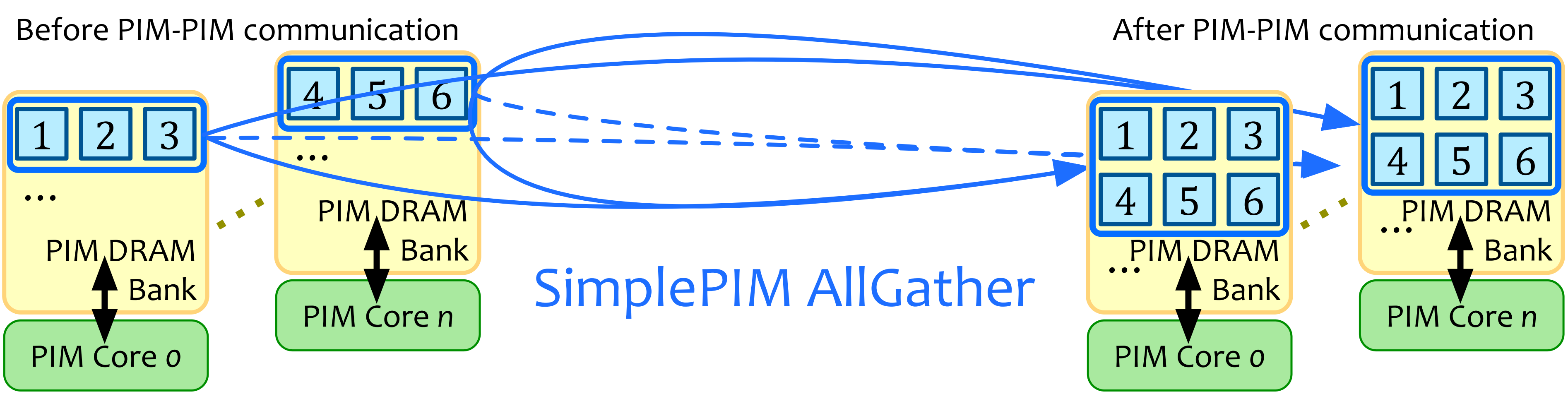
```
void simple_pim_array_allreduce(char* const id, handle_t* handle,
simple_pim_management_t* management);
```



PIM-PIM Communication: AllGather

- SimplePIM AllGather
  - Combines array pieces and distributes the complete array to all PIM cores

```
void simple_pim_array_allgather(char* const id, char* new_id,
simple_pim_management_t* management);
```



The SimplePIM Programming Framework

- SimplePIM provides standard abstractions to build and deploy applications on PIM systems
  - Management interface
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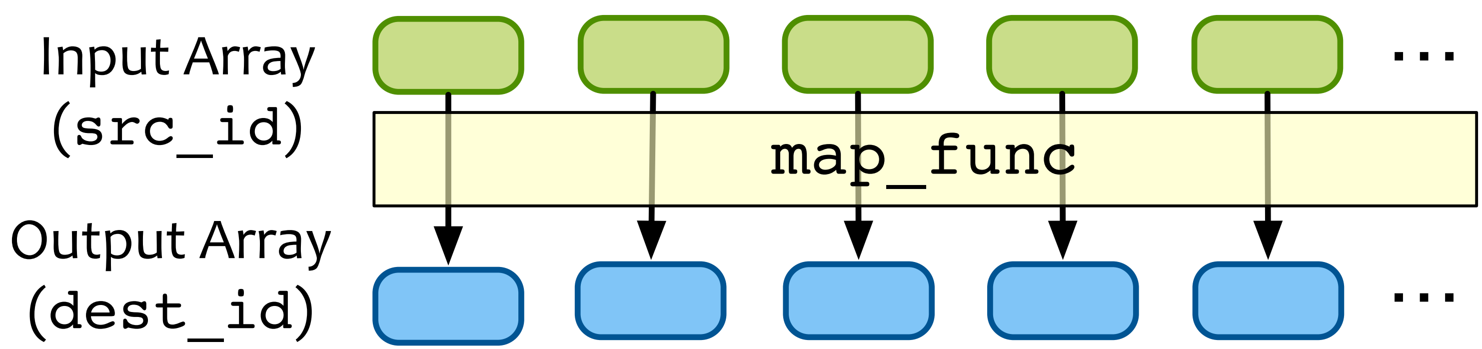
Processing Interface: Map

- Array Map
  - Applies `map_func` to every element of the data array

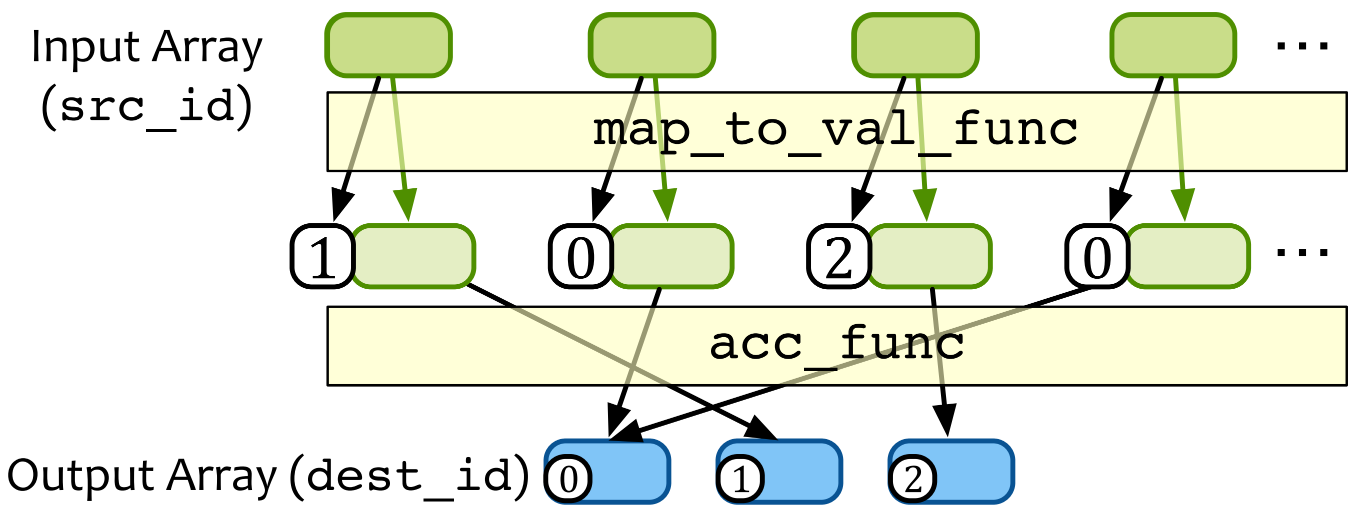
```
void simple_pim_array_map(const char* src_id, const char* dest_id,
uint32_t output_type, handle_t* handle, simple_pim_management_t* management);
```



Processing Interface: Reduction

- Array Reduction
  - The `map_to_val_func` function transforms an input element to an output value and an output index
  - The `acc_func` function accumulates the output values onto the output array

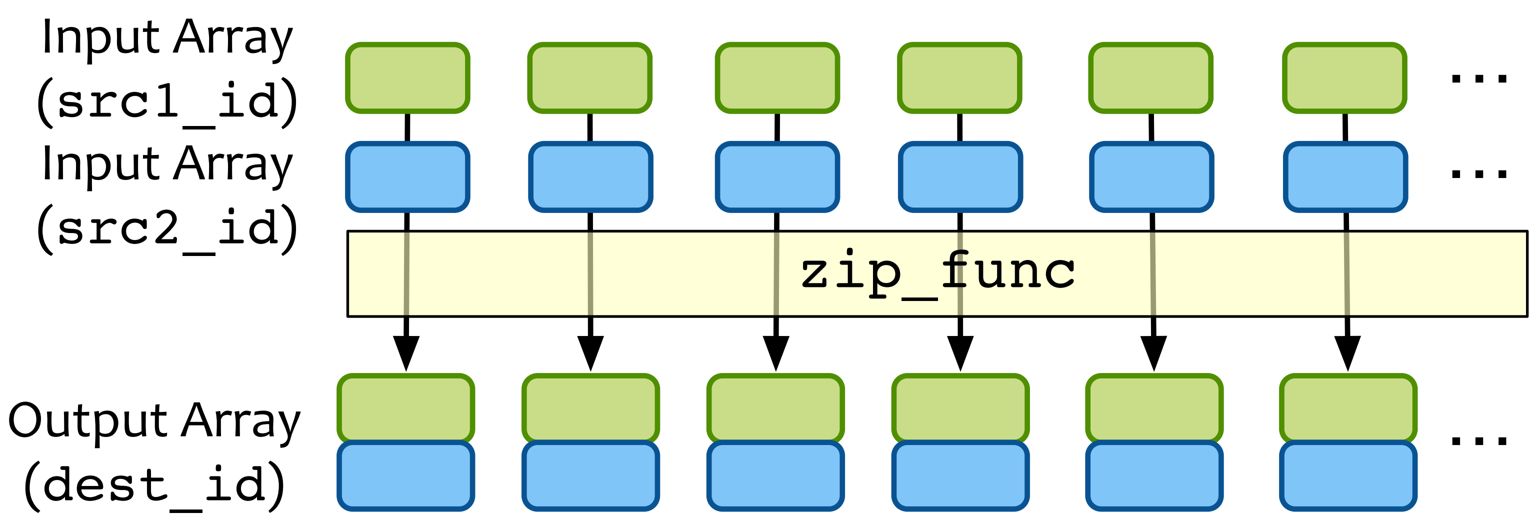
```
void simple_pim_array_red(const char* src_id, const char* dest_id,
uint32_t output_type, uint32_t output_len, handle_t* handle,
simple_pim_management_t* management);
```



Processing Interface: Zip

- Array Zip
  - Takes two input arrays and combines their elements into an output array

```
void simple_pim_array_zip(const char* src1_id, const char* src2_id,
const char* dest_id, simple_pim_management_t* management);
```



SimplePIM's UPMEM Implementation

- Communication interface
  - SimplePIM automatically handles alignment requirements and inserts padding as needed
- Processing interface
  - Array map
    - Invokes PIM cores and PIM threads, and handles PIM DRAM-scratchpad transfers
  - Array reduction
    - Shared accumulator reduction
    - Thread-private accumulator reduction
  - Array zip
    - Lazy approach to minimize data copying

General Code Optimizations

- Strength reduction
- Loop unrolling
- Avoiding boundary checks
- Function inlining
- Adjustment of data transfer sizes

More in the Paper

- Strength reduction
- Loop unrolling

SimplePIM: A Software Framework for Productive and Efficient Processing-in-Memory

Jinfan Chen[1] Juan Gómez-Luna[1] Izzat El Hajj[2] Yuxin Guo[1] Onur Mutlu[1]
[1]ETH Zürich [2]American University of Beirut

- Function inlining
- Adju

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Evaluation Methodology

- Evaluated system
  - UPMEM PIM system with 2,432 PIM cores with 159 GB of PIM DRAM
- Real-world Benchmarks
  - Vector addition
  - Reduction
  - Histogram
  - K-Means
  - Linear regression
  - Logistic regression
- Comparison to hand-optimized codes in terms of programming productivity and performance

Productivity Improvement (I)

- Example: Hand-optimized histogram with UPMEM SDK

```c
... // Initialize global variables and functions for histogram
int main_kernel() {
  if (tasklet_id == 0)
    mem_reset(); // Reset the heap
  ... // Initialize variables and the histogram
  T *input_buff_A = (T*)mem_alloc(2048); // Allocate buffer in scratchpad memory

  for (unsigned int byte_index = base_tasklet; byte_index < input_size; byte_index += stride) {
    // Boundary checking
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    // Load scratchpad with a DRAM block
    mram_read((const __mram_ptr void*)(mram_base_addr_A + byte_index), input_buff_A, l_size_bytes);
    // Histogram calculation
    histogram(hist, bins, input_buff_A, l_size_bytes/sizeof(uint32_t));
  }
  ...
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  ... // Merging histograms from different tasklets into one histo_dpu
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                   (offset << 11)), 2048);
      }
  return 0;
}
```

Productivity Improvement (II)

- Example: SimplePIM histogram

```
// Programmer-defined functions in the file "histo_filepath"
void init_func (uint32_t size, void* ptr) {
  char* casted_value_ptr = (char*) ptr;
  for (int i = 0; i < size; i++)
    casted_value_ptr[i] = 0;
}

void acc_func (void* dest, void* src) {
  *(uint32_t*)dest += *(uint32_t*)src;
}

void map_to_val_func (void* input, void* output, uint32_t* key) {
  uint32_t d = *((uint32_t*)input);
  *(uint32_t*)output = 1;
  *key = d * bins >> 12;
}

// Host side handle creation and iterator call
handle_t* handle = simple_pim_create_handle("histo_filepath", REDUCE, NULL, 0);

// Transfer (scatter) data to PIM, register as "t1"
simple_pim_array_scatter("t1", src, bins, sizeof(T), management);

// Run histogram on "t1" and produce "t2"
simple_pim_array_red("t1", "t2", sizeof(T), bins, handle, management);
```

Productivity Improvement (III)

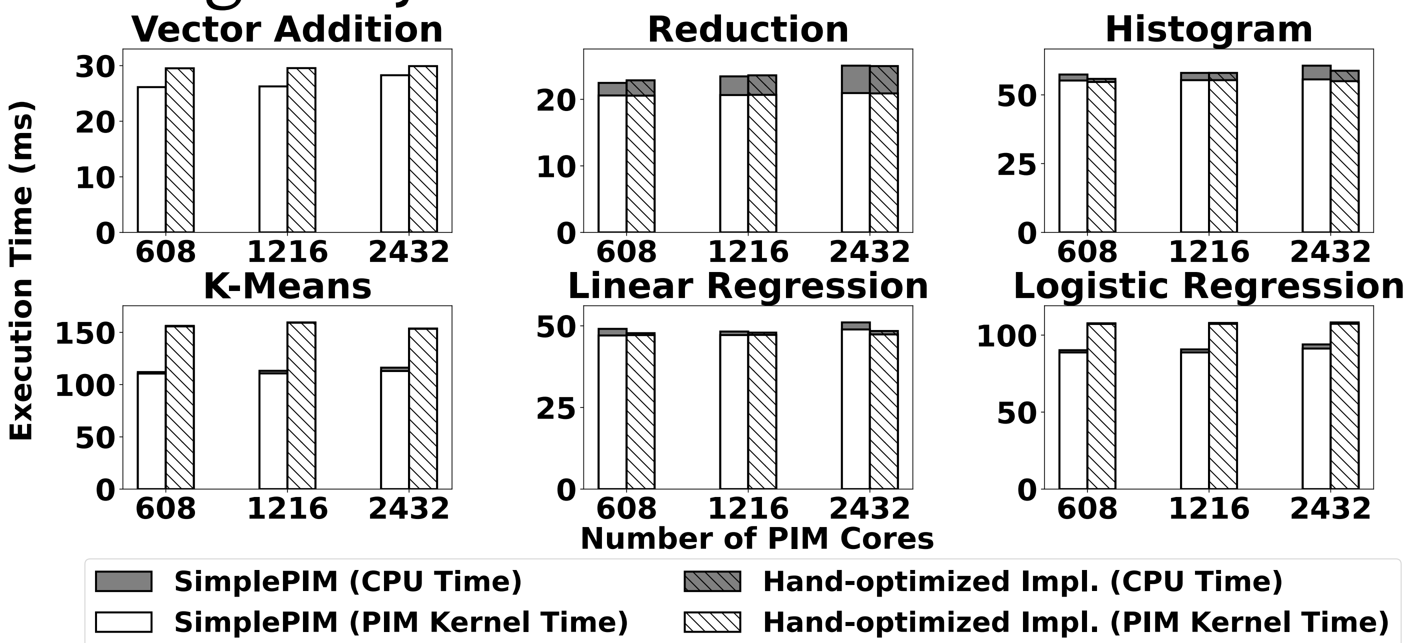
- Lines of code (LoC) reduction

	SimplePIM	Hand-optimized	LoC Reduction
Reduction	14	83	5.93×
Vector Addition	14	82	5.86×
Histogram	21	114	5.43×
Linear Regression	48	157	3.27×
Logistic Regression	59	176	2.98×
K-Means	68	206	3.03×

SimplePIM reduces the number of lines of effective code by a factor of 2.98× to 5.93×

Performance Evaluation (I)

- Weak scaling analysis

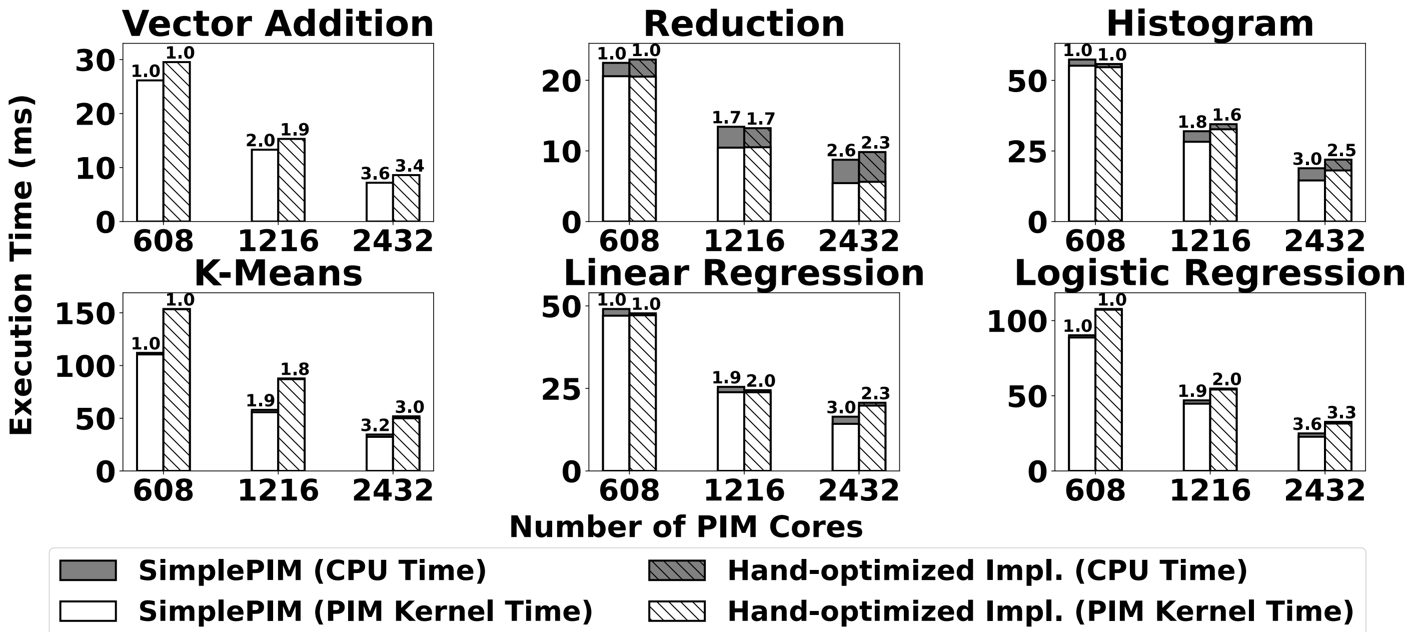


SimplePIM achieves comparable performance for `reduction`, `histogram`, and `linear regression`

SimplePIM outperforms hand-optimized implementations for `vector addition`, `logistic regression`, and `k-means` by 10%-37%

Performance Evaluation (II)

- Strong scaling analysis

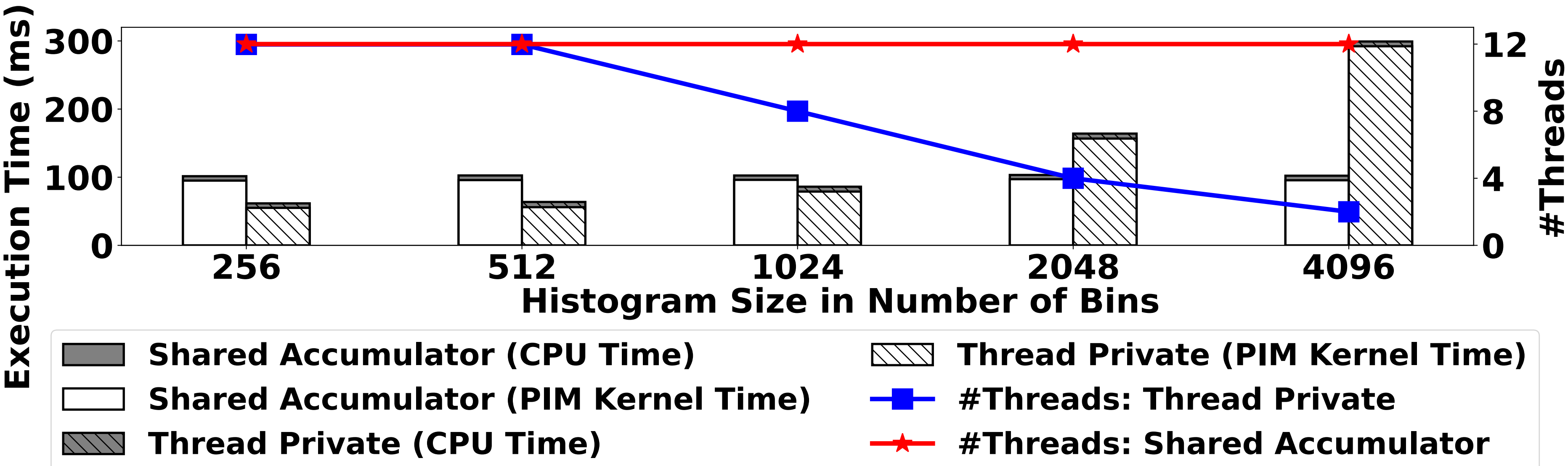


SimplePIM scales better than hand-optimized implementations for `reduction`, `histogram`, and `linear regression`

SimplePIM outperforms hand-optimized implementations for `vector addition`, `logistic regression`, and `k-means` by 15%-43%

Variants of Array Reduction

- Shared accumulator version versus thread-private version for `histogram`



The thread-private version is up to 70% faster than the shared accumulator version for histograms of 256-1024 bins

The number of active PIM threads of the thread-private version reduces after 1024 bins due to limited scratchpad size

Discussion

- SimplePIM is devised for PIM architectures with
  - A host processor with access to standard main memory and PIM-enabled memory
  - PIM processing elements (PEs) that communicate via the host processor
  - The number of PIM PEs scales with memory capacity
- SimplePIM emulates the communication between PIM cores via the host processor
- Other parallel patterns can be incorporated in future work
  - Prefix sum and filter can be easily added
  - Stencil and convolution would require fine-grained scatter-gather for halo cells
  - Random access patterns would be hard to support

SimplePIM: arXiv Version

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Source Code

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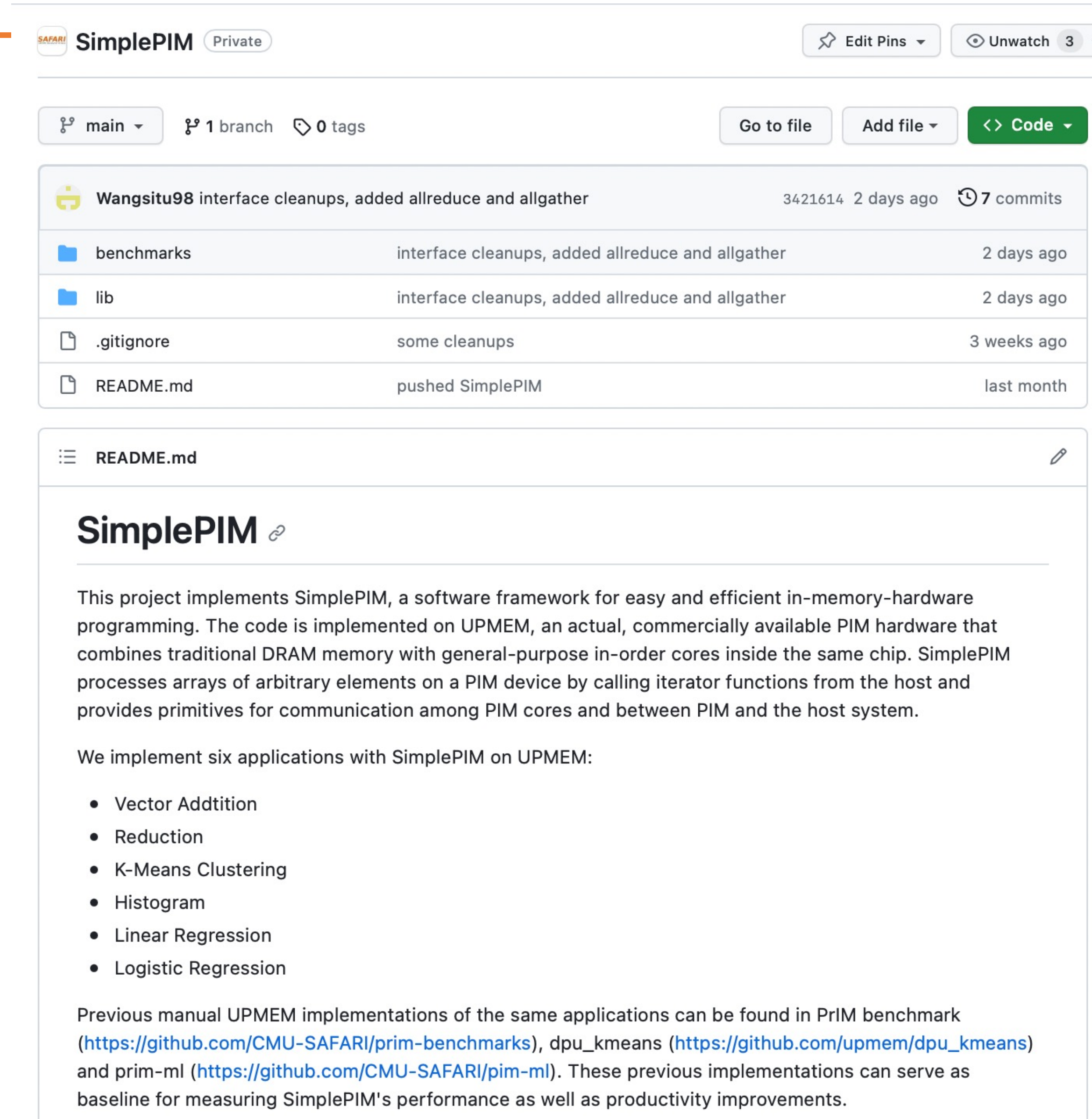

Conclusion

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  - Reduction, vector add, histogram, linear/logistic regression, K-means
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PIM Review and Open Problems

A Modern Primer on Processing in Memory

Onur Mutlu[a,b], Saugata Ghose[b,c], Juan Gómez-Luna[a], Rachata Ausavarungnirun[d]

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[d] *King Mongkut's University of Technology North Bangkok*

Onur Mutlu, Saugata Ghose, Juan Gomez-Luna, and Rachata Ausavarungnirun,
"A Modern Primer on Processing in Memory"
Invited Book Chapter in ***Emerging Computing: From Devices to Systems - Looking Beyond Moore and Von Neumann***, Springer, 2023

https://arxiv.org/pdf/1903.03988.pdf

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