ACPdl: Data-Structure and Global Memory Allocator Library over a Thin PGAS-Layer

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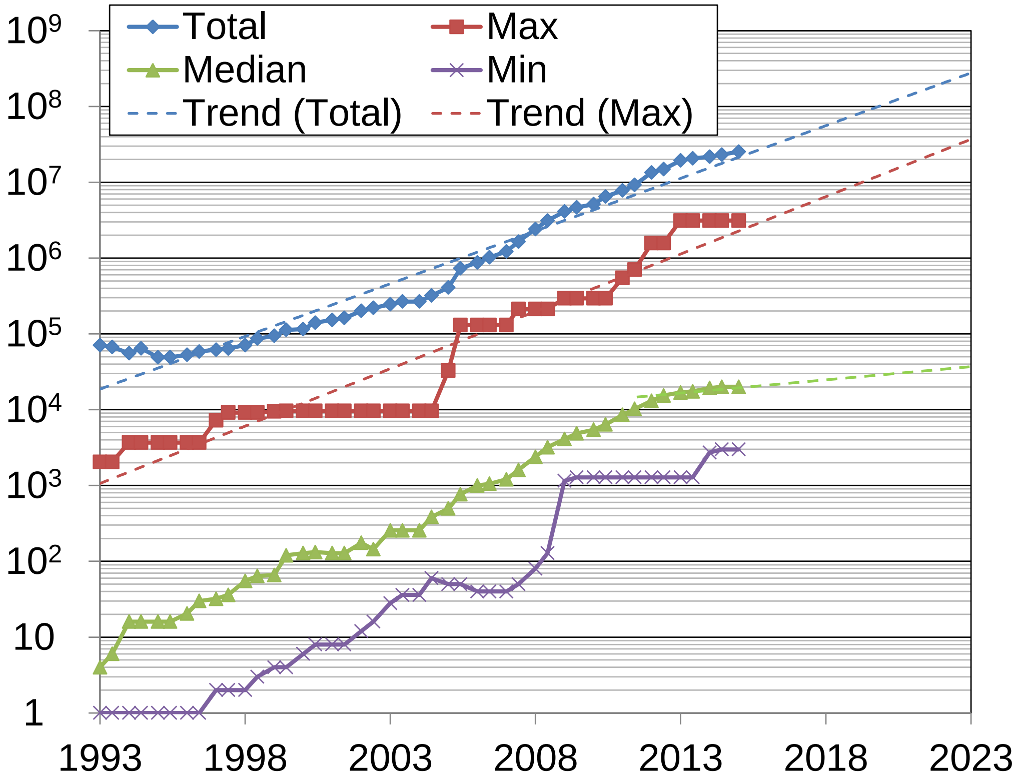
Increasing Core Count per System

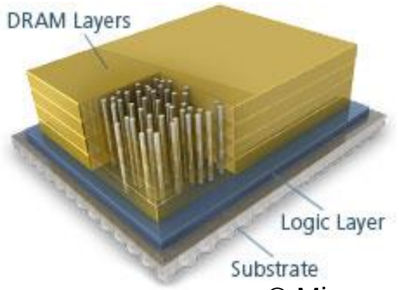
- The maximum core count per system will exceed 10 million by around 2020
  - Many-core and heterogeneous processors will extend the trend
- The growth rate of median core count is slowing down
  - Commodity clusters will keep using multi-core processors

Statistics of core counts in the TOP500 lists



Memory Technology Trends

- The diverging trends of memory technologies
  - High-throughput 3D stacked memories for “Exaflops” systems
    e.g. HMC, HBM
  - Large-capacity vertical 3D memories for “Exabyte” systems
    e.g. 3D NAND, 3D Xpoint
  - All-in-one machines will have a deeper memory hierarchy
- A memory issue with “Exaflops” systems
  - Each core will have a small memory capacity
  - Peer-to-peer communication contexts will consume large amount of memory



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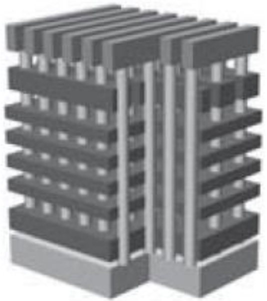
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RDMA Protocol

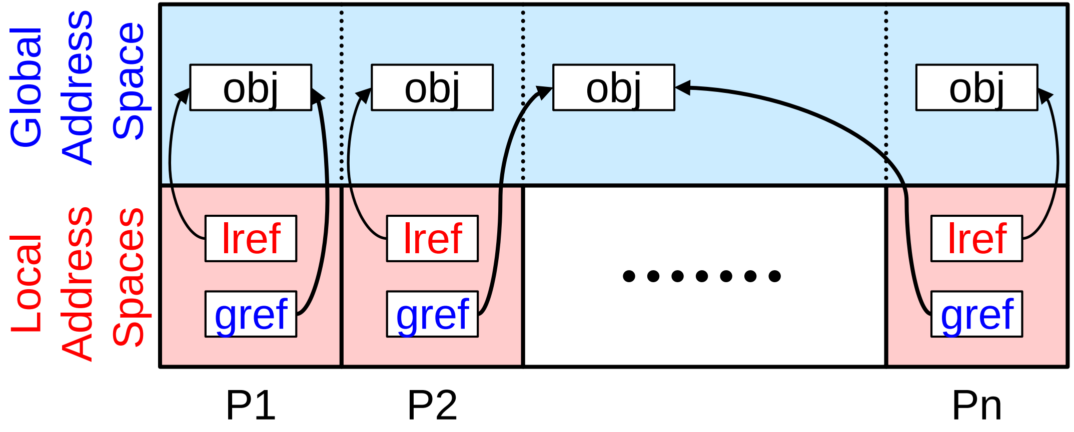
- Remote Direct Memory Access (RDMA) is a type of protocol
  - Accesses data directly by specifying its memory address

    Get protocol transfers data from remote memory to local memory

    Put protocol transfers data from local memory to remote memory
- Pros
  - Connection-less, as far as the reliable delivery is guaranteed
  - Supported by almost all modern HPC interconnect devices
- Cons
  - Too primitive interfaces and the lack of device standards

PGAS Programming Model

- **P**artitioned: a local reference refers a local object
- **G**lobal **A**ddress **S**pace: a global reference refers a remote object
  - Referring a global reference implicitly designates an RDMA transfer
  - PGAS languages are easy to write communication



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Advanced Communication Primitives (ACP)

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- ACP is a new communication library to build PGAS middleware
  - Such as domain-specific languages and parallel computation frameworks
  - ACP is a library for developers, not for ordinary application programmers
- ACP does not include parallelism and parallel execution models
  - The upper-layer software may provide them
- Interfaces are designed for the memory-efficient programming
  - Each primitive consumes memory explicitly
  - Programmers can maintain the amount of memory consumption

Software Structure of ACP

- ACP basic layer (ACPbl)
  - A thin PGAS layer to abstract features of interconnect devices
- ACP data library (ACPdl)
  - Data structure library for processing irregular data
- ACP communication library (ACPcl)
  - Message passing library for processing regular data
  - Not included in this presentation

ACP Basic Layer

- Key features
  - 64-bit global address
  - Starter memory
  - Remote-to-remote data transfer

- Design philosophy
  - Features should be implementable in hardwired logic without micro-controllers
  - An implementation over existing devices may create a communication thread to emulate the features

ACPbl: 64-bit Global Address

- A 64-bit global address (GA) is assigned to registered memory
  - 64-bit value is easy to be handled by overlying software

- Memory registration and address translation interface
  - **acp_register_memory**() returns a translation key
  - **acp_query_ga**() translates a local address to a GA using a translation key
  - **acp_query_address**() translates a GA to a local address

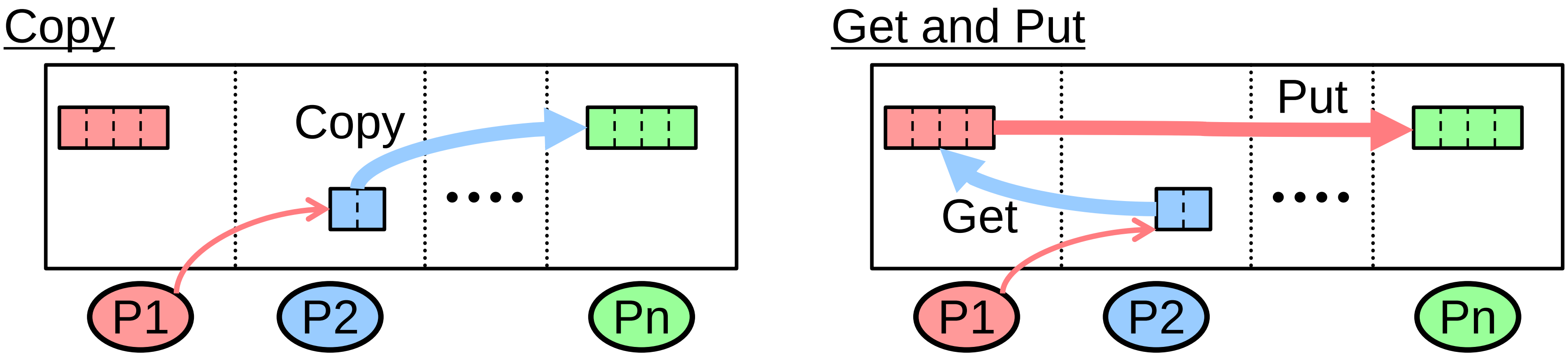
ACPbl: Starter Memory

- A pre-registered memory region for each process
  - The size is specified by environment variables or command line options
- A ready-to-use shared resource
  - Allocated and zero-cleared in **acp_init**()
  - **acp_query_starter_ga**() returns GA of starter memory of an arbitrary process
- The intended usage is to place shared static variables
  - cf. data and bss segments in program memory

ACPbl: Remote-to-Remote Data Transfer

- **acp_copy**() performs a remote-to-remote data transfer
  - Copy protocol is a superset of Get and Put protocols

    Equivalent Get and Put sequence may be redundant
  - Non-blocking function with a memory fence designation



ACPbl: Four Implementations

- ACPbl/UDP
  - A reference implementation with software-implemented reliable delivery
- ACPbl/InfiniBand (ACPbl/IB)
  - Using RDMA over reliable connection
  - Implemented distributed address translation tables and translation cache
- ACPbl/Tofu and ACPbl/Tofu2
  - Using connection-less RDMA with remote-side memory fence

- All implementations are thread safe

ACP Data Library

- ACPbl is too low level, even for developers
- ACPdl provides data structure interfaces for irregular data
- ACPdl includes the global memory allocator
  - To create and delete remote data asynchronously
- Interfaces are derived from familiar libraries
  - Memory allocator from C standard library: **acp_malloc**(), **acp_free**()
  - Data structure types from C++ STL: **vector**, **list**, **map**, etc.
- Algorithms have been revised from the ground up

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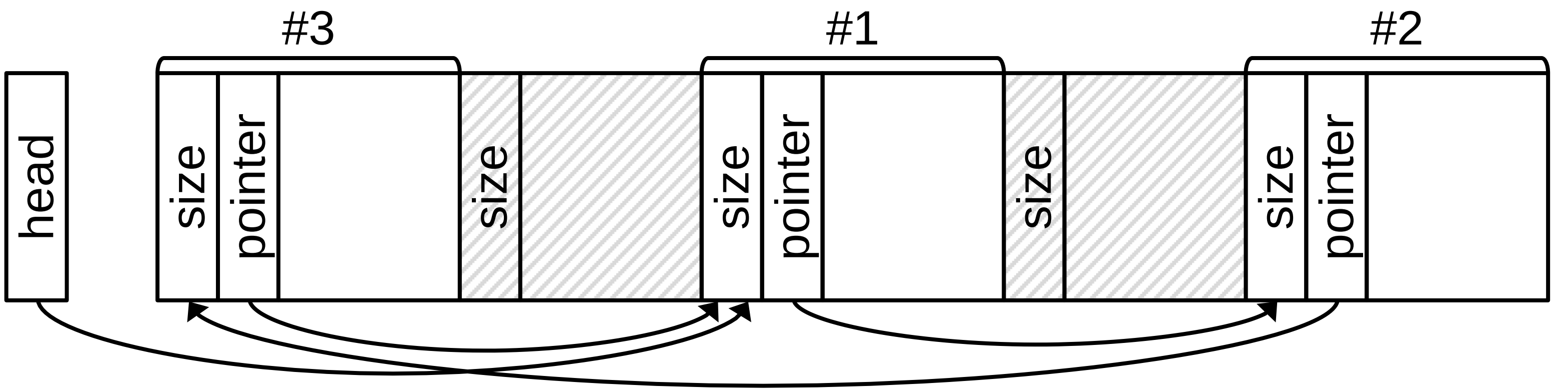
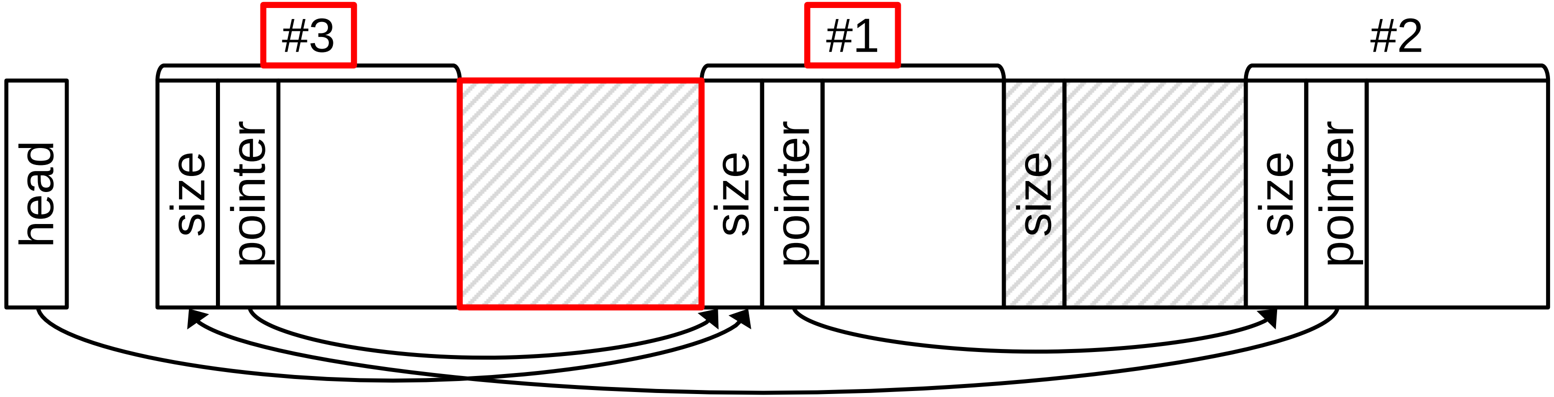
Initial Memory Management Algorithm

- This algorithm is similar to that in the Kernighan and Ritchie's book
- Free blocks are linked and sorted by address
- The allocation algorithm has O(1) computational complexity of typical cases



O(n) Complexity of the Deallocation

- To avoid fragmentation, adjacent free blocks should be merged
- Nearest free blocks for a block can be found from the free list
- Searching a list has O(n) computational complexity
  - This may be an issue for memory efficient programing



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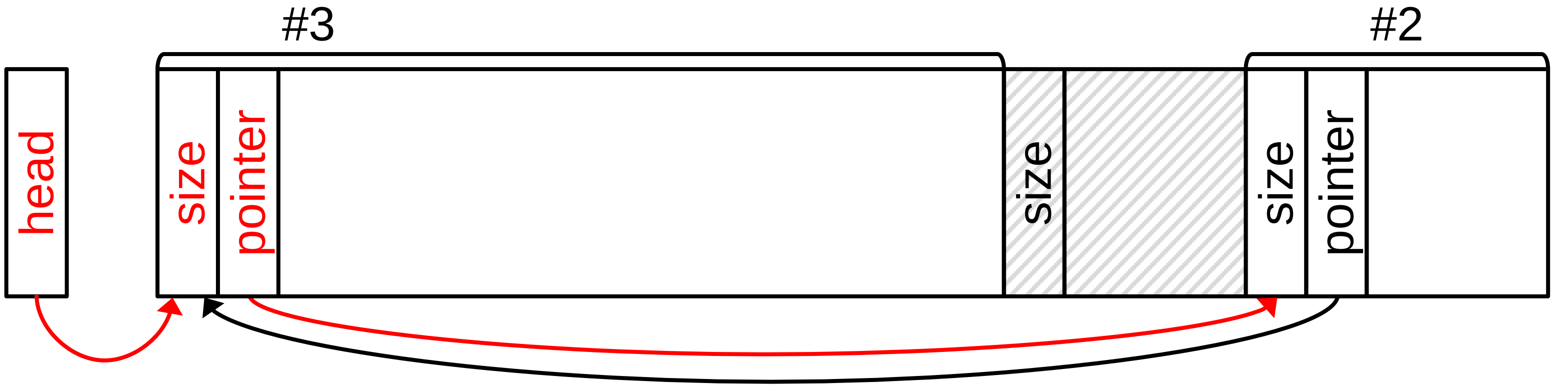
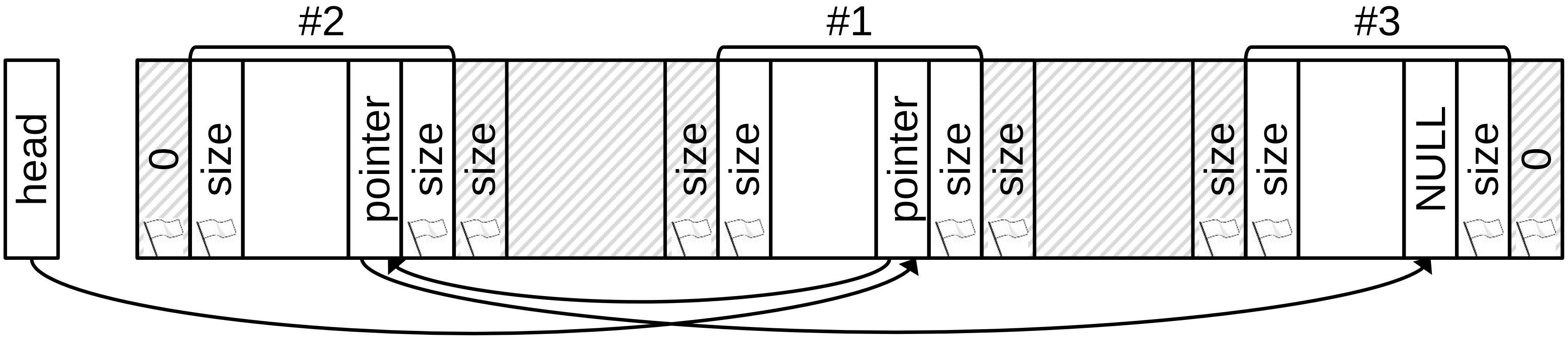


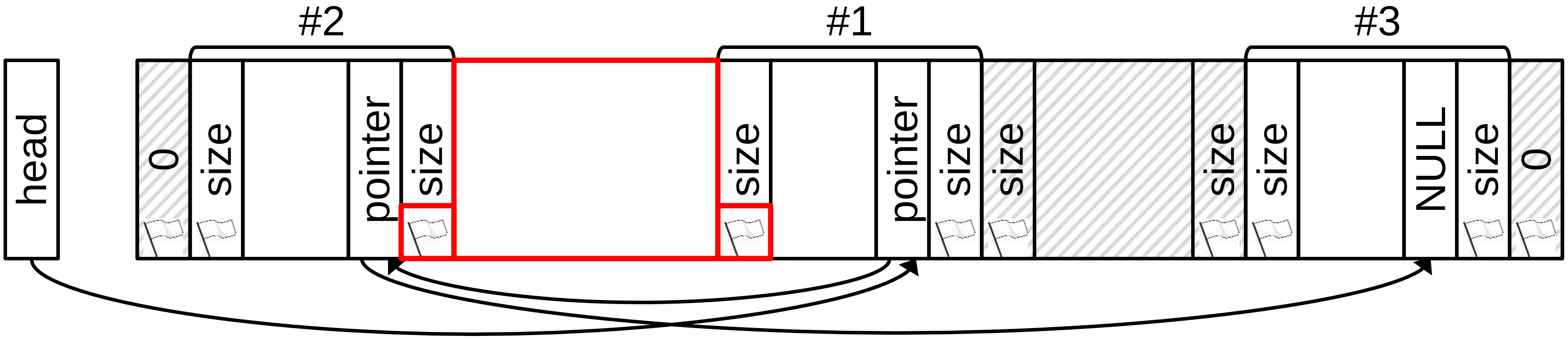
Improved Memory Management Algorithm

- **acp_free**() and **acp_malloc**() cooperatively merge free blocks
- Merge in **acp_free**() is done without searching the free list
  - Each block indicates a linked-free/unlinked-free/allocated flag for merging
- The deallocation algorithm has been improved to O(1) complexity



Merging Free Blocks in **acp_free**()

- The freed block will be …
  - Merged if the next block is not allocated or the previous block is unlinked-free
  - Unlinked-free if the previous block is linked-free and the next block is allocated
- Otherwise, the freed block is linked into the head of the free list



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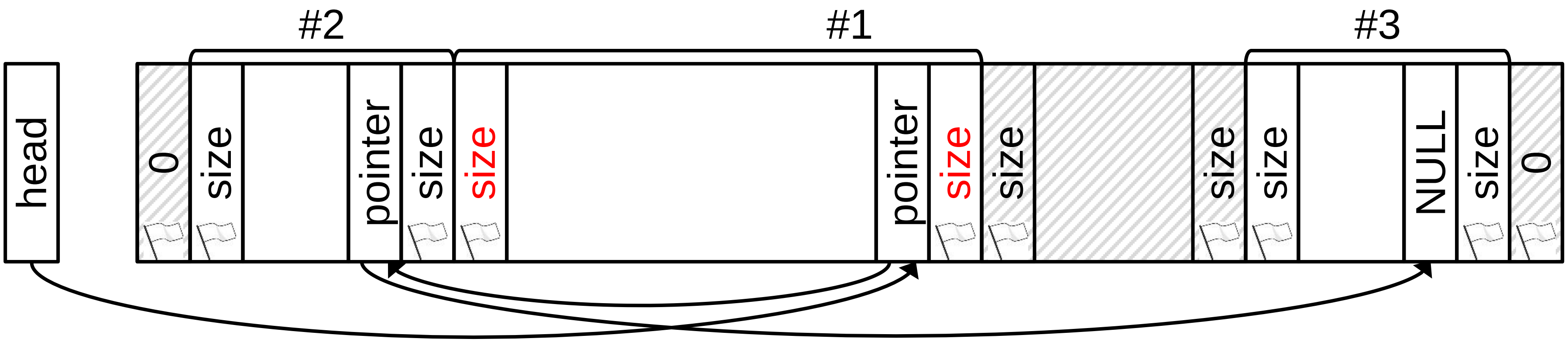
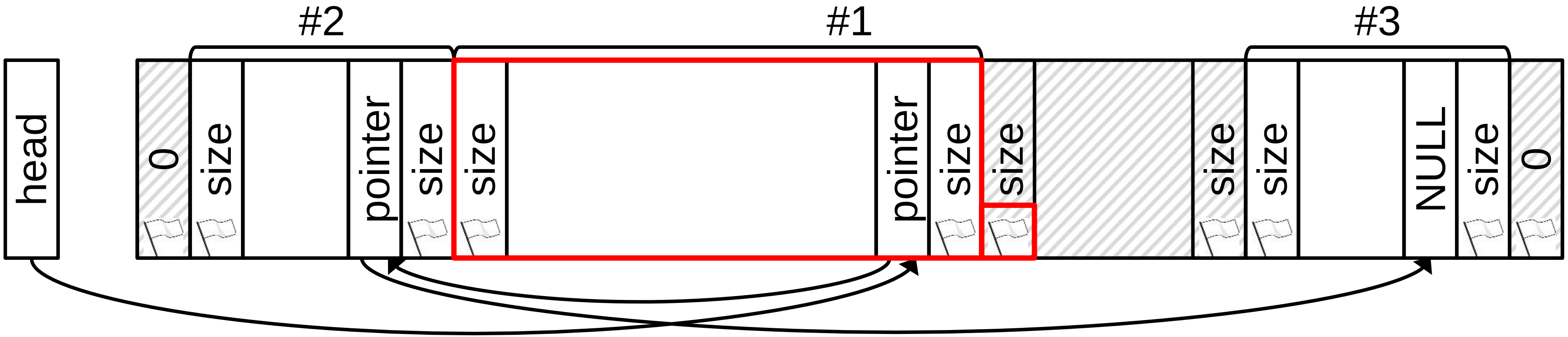


Merging Free Blocks in **acp_malloc()**

- When a free block is tested for allocation, the next block is checked
  - If the next block is unlinked-free, the next block will be merged into the block
  - If the next block is linked-free,

    the block is removed from the list and merged into the next block,

    then the search for allocation is restarted from the head



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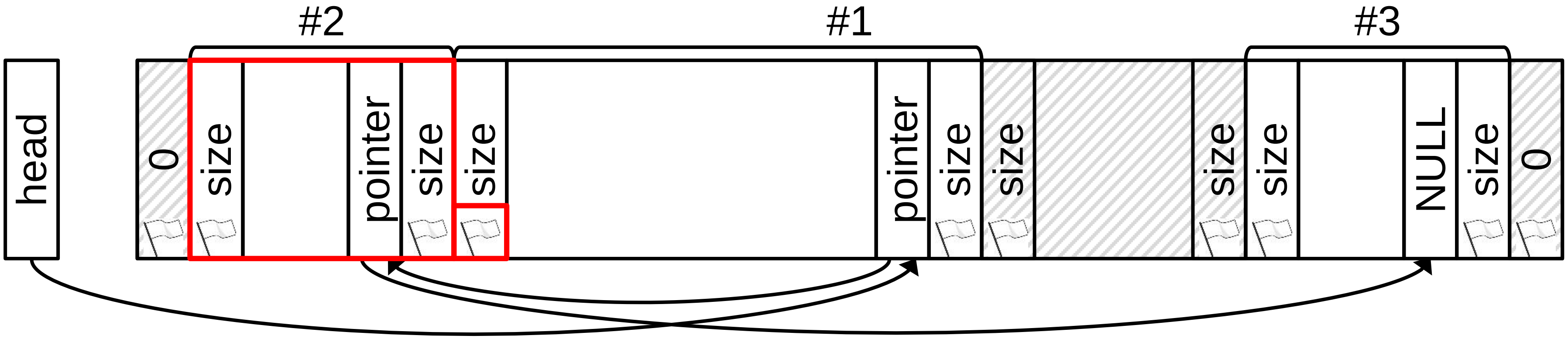

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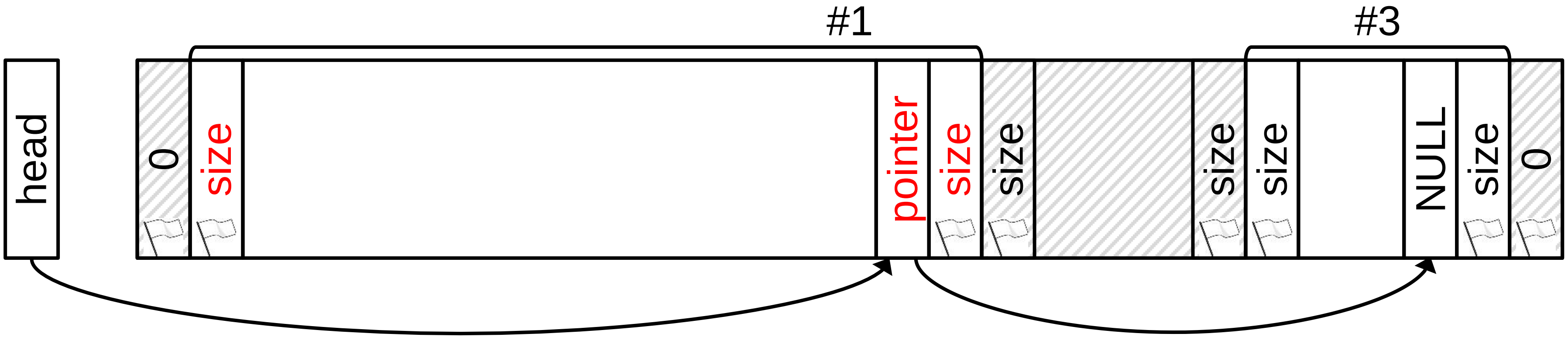
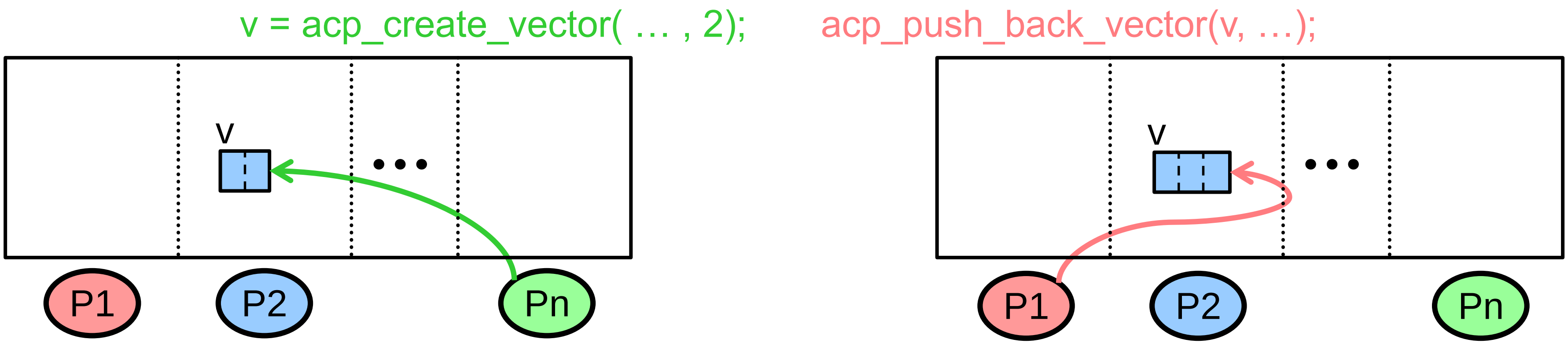


Vector Data Structure

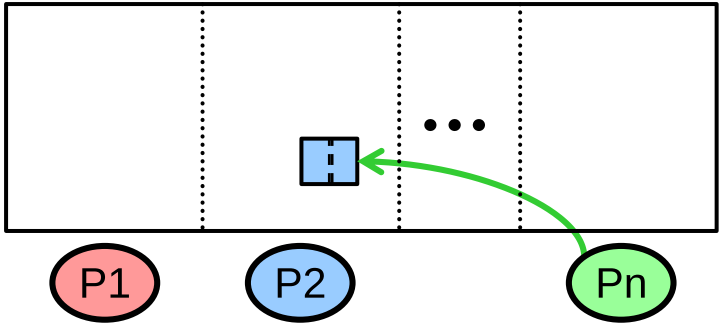
- A resizable contiguous memory
- **acp_create_vector** () creates a vector on the specified process
- **acp_push_back_vector**() appends data to a vector



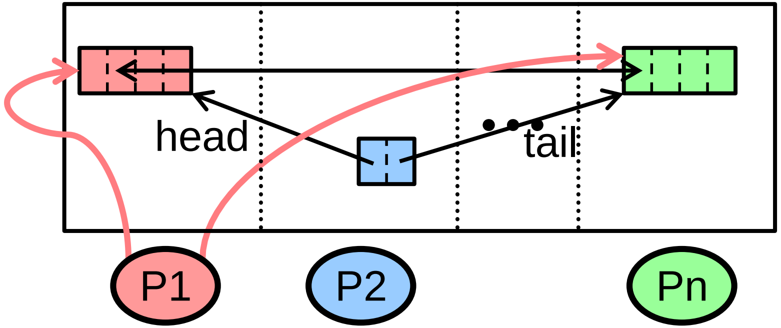
List Data Structure

- A bi-directional linked list
- **acp_create_list**() creates an empty list on the specified process
- **acp_push_back_vector**() appends an element on the specified process to a list

l = acp_create_list(2);



acp_push_back_list(l, … , 1);
acp_push_back_list(l, … , n);



Map Data Structure

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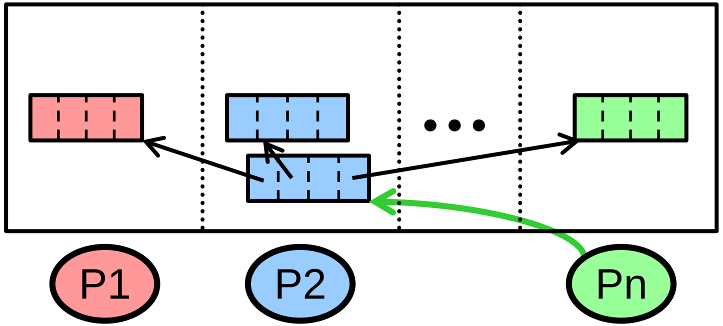
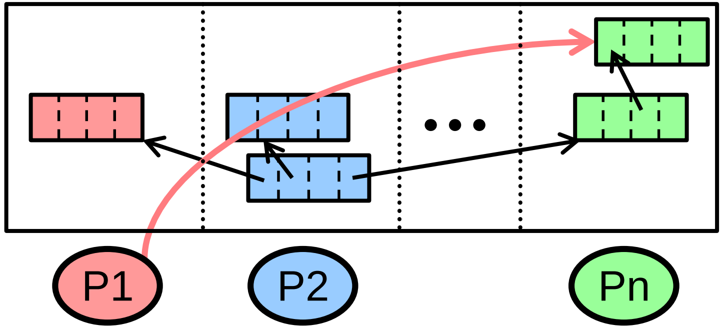
- A distributed associative array on the specified group of processes
- **acp_create_map**() creates a map on the specified process
- **acp_insert_map**() puts a key-value pair to a map
- **acp_find_map**() gets the value of a key

m = acp_create_map(n, &ranks, … , 2);



acp_insert_map(m, …);



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Evaluation

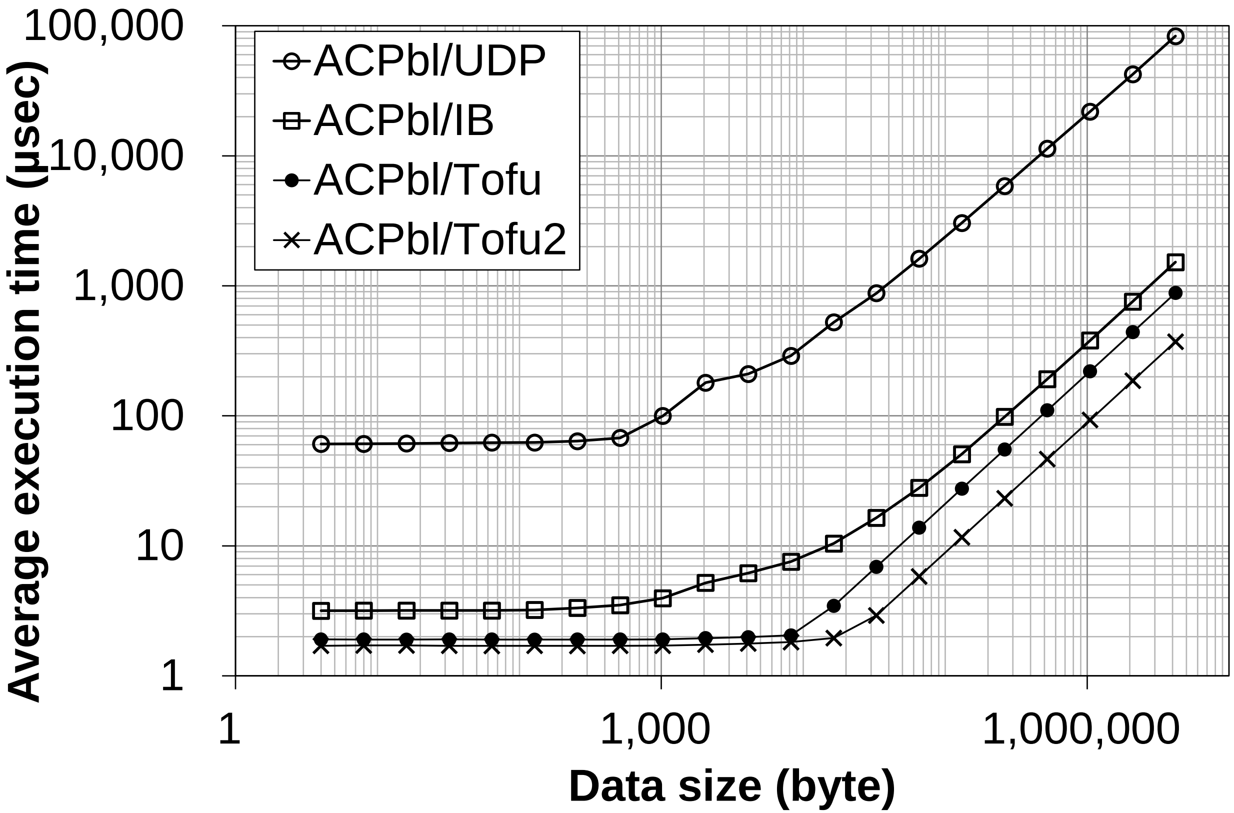
- **acp_copy**()
  - Remote-to-local, local-to-remote and remote-to-remote data transfer latencies
- **acp_malloc**() and **acp_free**()
  - Consecutive allocations of random, maximum 32KB, size of memory
  - And then consecutive out-of-order deallocations
- **acp_insert_map**() and **acp_find_map**()
  - Consecutive insertions of key-value pairs
  - And then consecutive searches of random key, 50% chance to hit

Evaluation Environment

	ACPbl/UDP	ACPbl/IB	ACPbl/Tofu	ACPbl/Tofu2
Node	Fujitsu PRIMERGY RX200 S5	Fujitsu PRIMERGY RX200 S7	Fujitsu PRIMEHPC FX10	Fujitsu PRIMEHPC FX100
CPU	Xeon E5520 4 cores 2.27 GHz 2 sockets/node	Xeon E5-2609 4 cores 2.4 GHz 2 sockets/node	SPARC64^{TM} IXfx 16 cores 1.848 GHz 1 socket/node	SPARC64^{TM} XIfx 32+2 cores 1.975 GHz 1 socket/node
Memory / node	DDR3 SDRAM 48GB 51.2 GB/s	DDR3L SDRAM 8GB 25.6 GB/s	DDR3 SDRAM 64GB 85 GB/s	HMC 32GB 480 GB/s
Network / link	Gigabit Ethernet 0.125 GB/s	InfiniBand QDR 4.0 GB/s	Tofu interconnect 5.0 GB/s	Tofu interconnect 2 12.5 GB/s

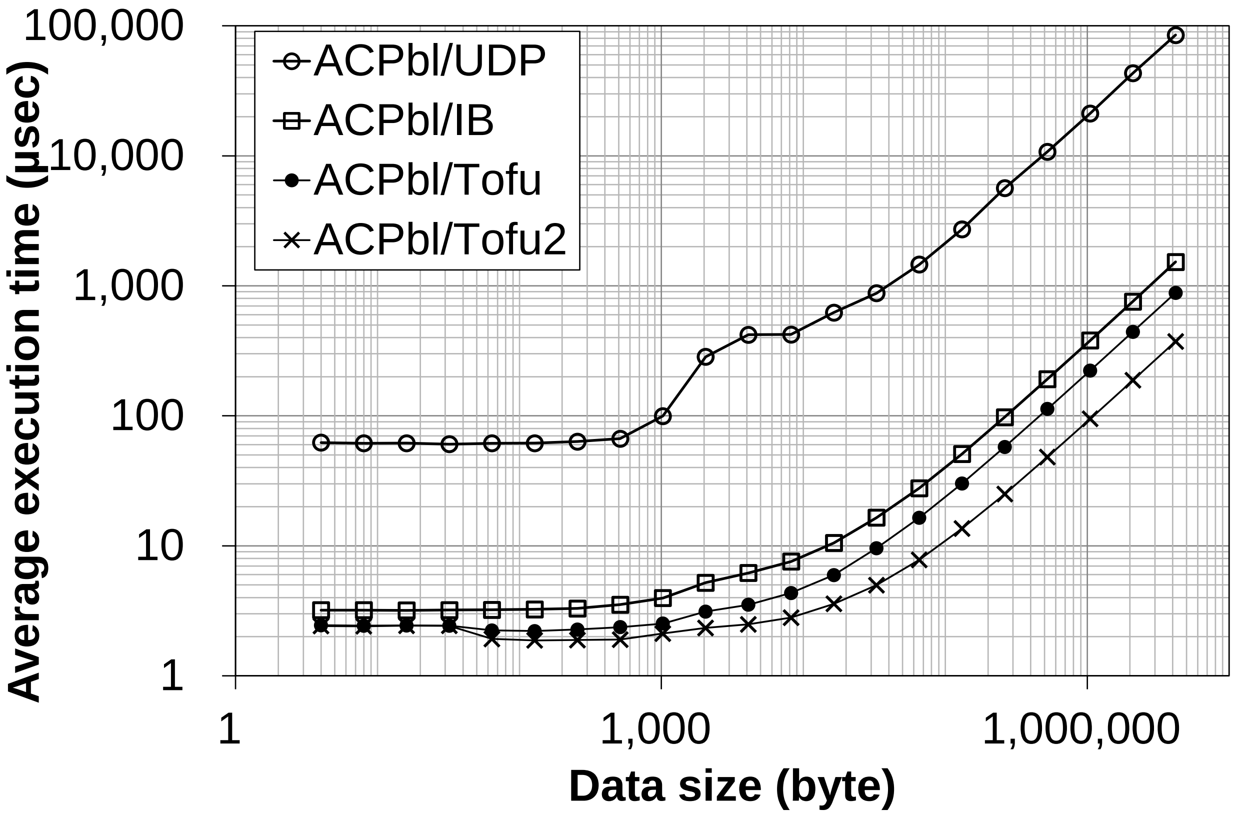
Results: **acp_copy**() remote-to-local

- IB, Tofu and Tofu2 are two orders of magnitude faster than UDP



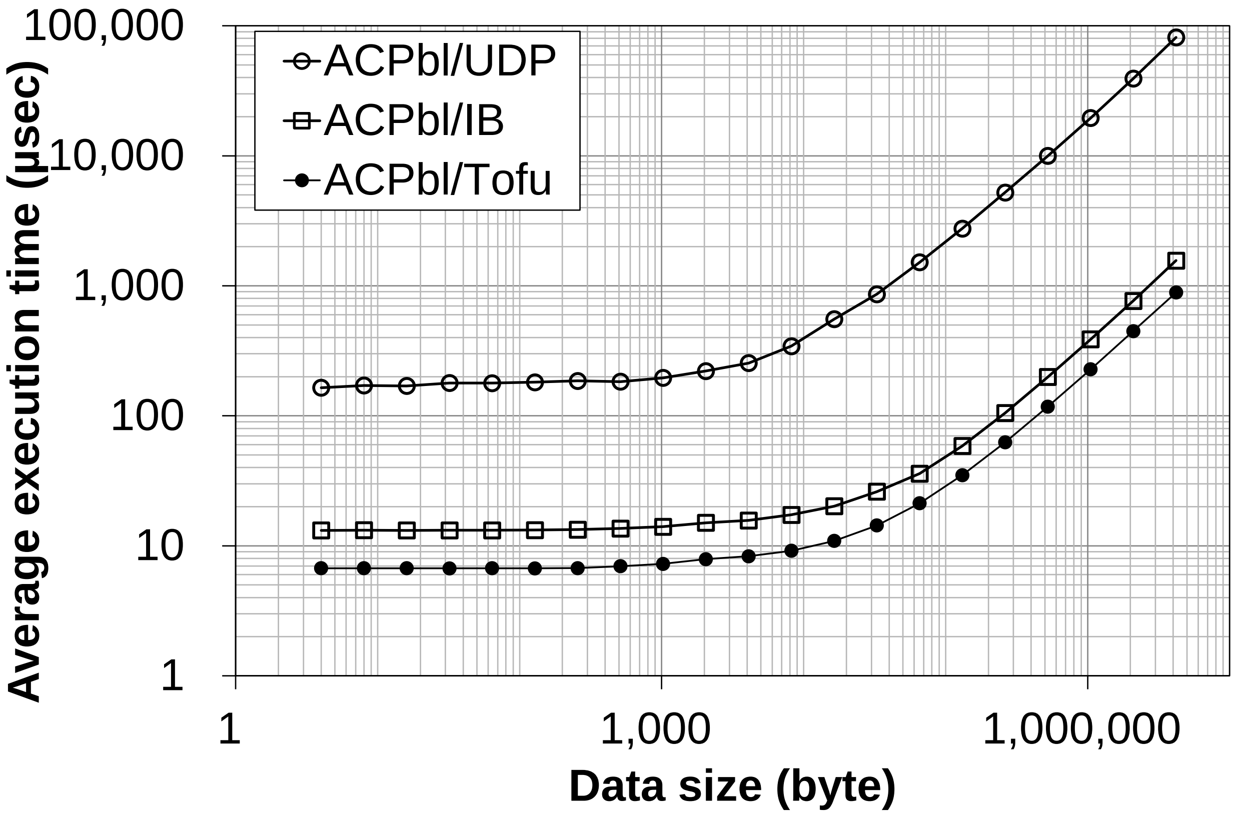
Results: **acp_copy**() local-to-remote

- Results show the nearly same performance as remote-to-local data transfer



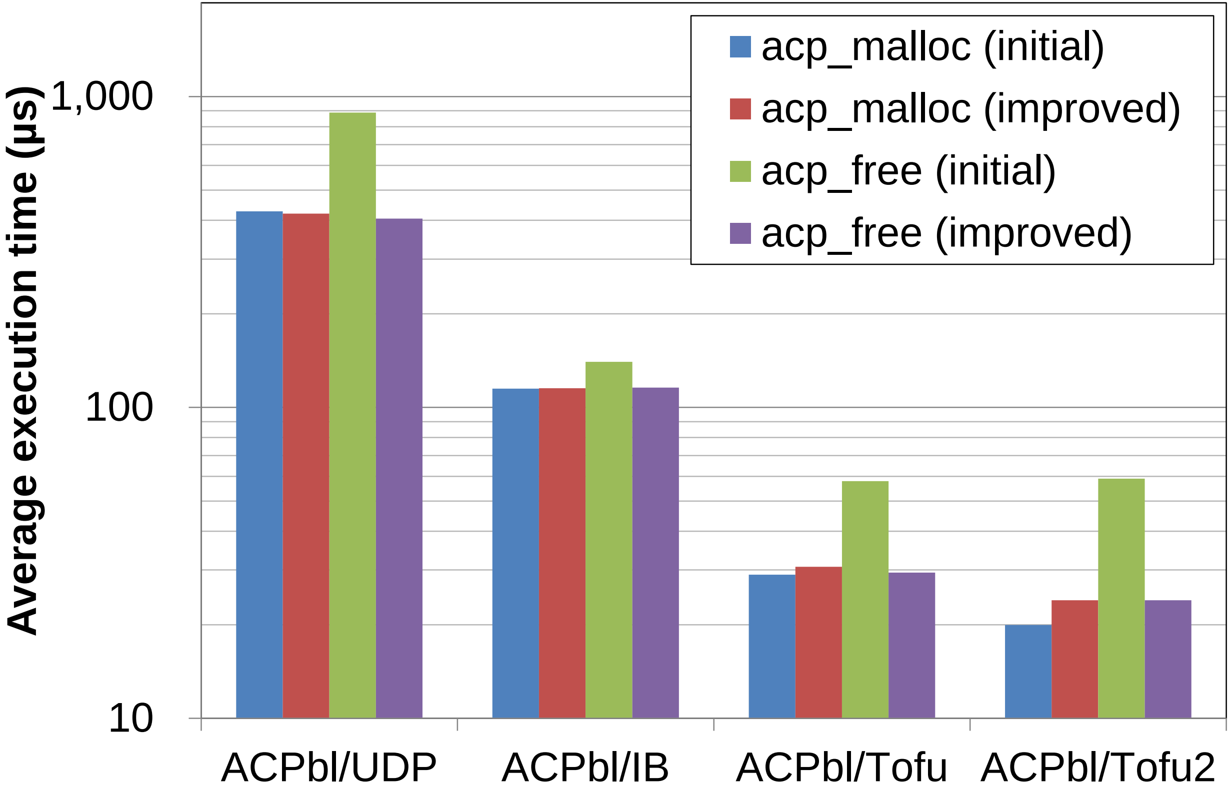
Results: **acp_copy**() remote-to-remote

- Results show the almost same throughput as remote-to-local and local-to-remote
- Latencies for small data deteriorated due to control communication



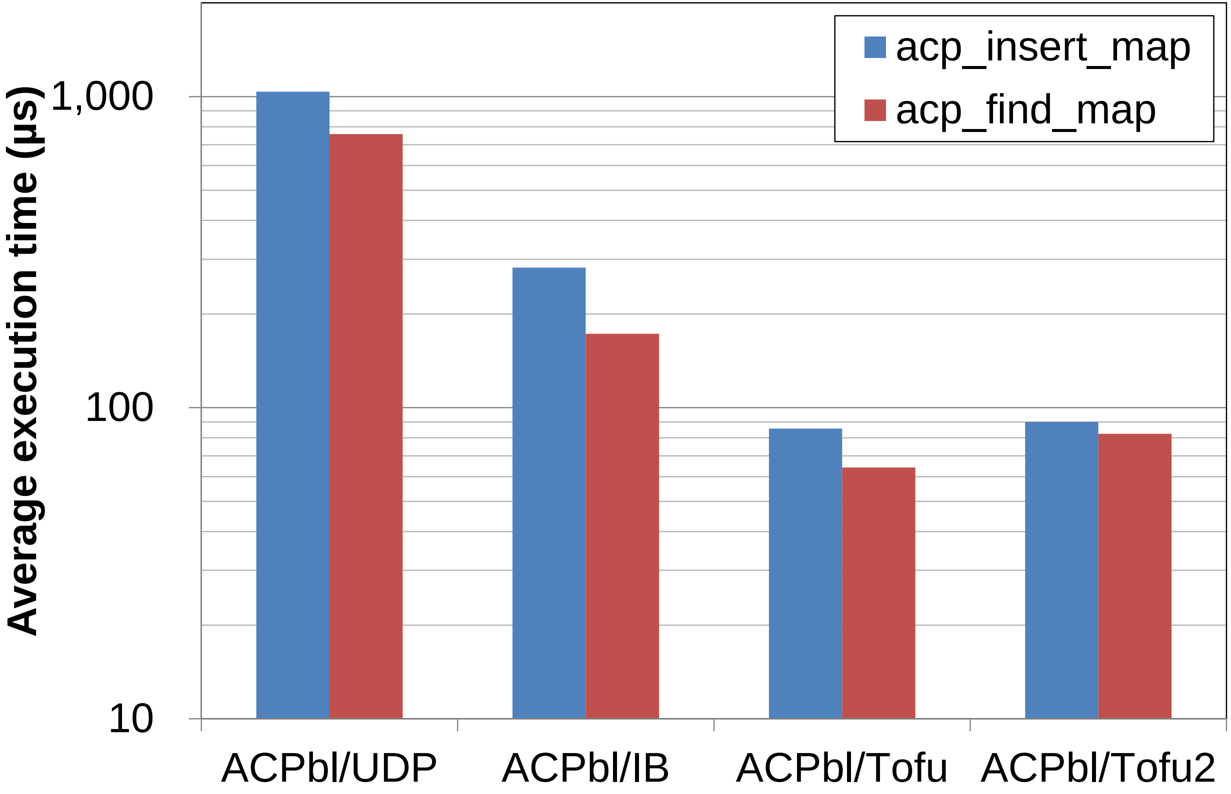
Results: **acp_malloc**() and **acp_free**()

- The improved algorithm reduced the latency of **acp_free**()
- Tofu and Tofu2 are only one order of magnitude faster than UDP
- IB is much worse



Results: **acp_insert_map(), acp_find_map()**

- Similar but two or three times longer results than **acp_malloc**



Discussion

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- It seems that the dependency control affected the results
  - For **acp_copy**, UDP was two orders of magnitude slower than the others
    - Dependencies are controlled in the communication thread
  - For the ACPdl functions, UDP was only one order of magnitude slower
    - Dependencies are controlled in the main thread
    - Overhead between main and communication threads may deteriorate message rate
- It seems that translation cache misses affected ACPbl/IB’s results
  - Evaluations of the ACPdl functions accessed remote memory randomly
- These issues will be further investigated in our future work

Summary

- ACP is a new communication library to build PGAS middleware
  - Interfaces are designed for the memory-efficient programming
- ACP basic layer is a thin PGAS layer
  - 64-bit global address, Starter memory, Remote-to-remote data transfer
- ACP data library provides data structure interfaces
  - An improved algorithm for global memory allocator is implemented
- Four versions of the basic layer and data library are evaluated
  - It seems that communication thread overhead and translation cache miss deteriorate the performance of the data library

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ACP download: http://ace-project.kyushu-u.ac.jp/index.html