CSCE 435 Group project

0. Group number: 5

1. Group members:

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- Communication via Slack

2. Project topic (e.g., parallel sorting algorithms)

2a. Brief project description (what algorithms will you be comparing and on what architectures)

- Bitonic Sort: SPMD (CPU)
- Sample Sort: SPMD (CPU)
- Merge Sort: SPMD (CPU)
- Radix Sort: SPMD (CPU)

2b. Pseudocode for each parallel algorithm

- For MPI programs, include MPI calls you will use to coordinate between processes

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Bitonic Sort

```
def parallel_bitonic_sort(arr):
    MPI_Init()
    rank = MPI_Comm_rank()   # Get the rank of the current process
    n_procs = MPI_Comm_size()   # Get the total number of processes

    # Divide array for parallel sorting
    local_arr = []
    if rank == 0:
        # Divide & dispatch subarrays in host process
        sub_arr_size = len(arr) // n_procs
        local_arr = arr[:sub_arr_size]
        for i in range(1, n_procs):
            worker_arr = arr[i * sub_arr_size : (i + 1) * sub_arr_size]
            MPI_Send(worker_arr, dest=i)
    else:
        # Receive local subarray from host process in worker process
        local_arr = MPI_Recv(source=0)

    # Sort local subarrays into bitonically alternating pairs (ascending-descending-ascending-etc.)
    if rank % 2 == 0:
        local_bitonic_sort(local_arr, 0, len(local_arr), ascending=True)
    else:
        local_bitonic_sort(local_arr, 0, len(local_arr), ascending=False)

    # Iteratively & parallelly merge bitonic pairs of locally sorted subarrays
    step = 1
    while step < n_procs:
        if rank % (step * 2) == 0:
            # Receive data from partner process and bitonic merge sort into local array
            recv_arr = MPI_Recv(source=rank + step)
            local_arr.extend(recv_arr)
            local_bitonic_merge(local_arr, 0, len(local_arr), True)
        else:
            # Send local array to process waiting to merge and exit
            MPI_Send(local_arr, dest=rank - step)
            break
        step = step * 2 # Double step for next iteration

    # Host process now contains fully-sorted array
    if rank == 0:
        print(local_arr)

    MPI_Finalize()

def local_bitonic_sort(arr, low, count, ascending):
    if count > 1:
        k = count // 2
```

```
        local_bitonic_sort(arr, low, k, True)        # Sort first half in ascending order
        local_bitonic_sort(arr, low + k, k, False)    # Sort second half in descending order
        local_bitonic_merge(arr, low, count, ascending) # Bitonic merge sorted halves

def local_bitonic_merge(arr, low, count, ascending):
    if count <= 1:
        return  # Break recursion on base case
    k = count // 2
    # Iteratively swap such that all elements in the first half are:
    #   - less than all elements in the second half if ascending
    #   - greater than all elements in the second half if descending
    for i in range(low, low + k):
        if arr[i] > arr[k + i] == ascending:
            swap(arr[i], arr[k + i])
    # Recursively merge each half to sort
    local_bitonic_merge(arr, low, k, ascending)
    local_bitonic_merge(arr, low + k, k, ascending)
```

Sample Sort

```
// Note, generating data separately in each process could be more efficient, but due to the nature of sample sort and how the master process distributes the data to worker processes, I'm not sure whether this is possible
// This function uses sample sort to sort the n element array A using s samples
function sample_sort(A, n, s):
    MPI_Init()
    rank = MPI_Comm_rank()
    // The number of worker processes is also the number of buckets
    num_processes = MPI_Comm_size()
    // For now, assume that n % num_processes = 0
    bucket_size = n/num_processes

    if rank == 0:
        // First, the master process needs to send data to the worker processes
        for i from 0 to num_processes - 1:
            MPI_Send(A[i:i*bucket_size], dest = i)

    else:
        // Worker process receives work from master process
        current_bucket = MPI_Recv(source=0)
        quicksort(current_bucket, current_bucket.size)
        local_samples = []
        // Choose s random values from current_bucket and add to local_samples
        for i from 1 to s:
            r = random(1, bucket_size)
            local_samples.add(current_bucket[r])
        MPI_Send(samples, dest = 0)

    if rank == 0:
        master_samples = []
        // Gather all local samples from each of the worker processes and combine into master_samples
        MPI_Gather(master_samples, MPI_Comm_World)
        quicksort(master_samples, master_samples.size)

        splitters = []
        // Choose num_processes - 1 values from master_samples randomly to be the splitters
        for i from 1 to num_processes - 1:
            splitter = master_samples[random(1, bucket_size)]
            local_samples.add(splitter)

        quicksort(splitters, splitters.size)
        // Split elements by bucket

        buckets = [][]
        for i from 0 to n:
            for j from 1 to num_processes - 1
                if A[i] > splitters[j-1] && A[i] <= splitters[j]
                # Put into the jth bucket
                buckets[j].add(A[i])
        for i from 1 to num_processes:
            quicksort(buckets[i], buckets[i].size)

        # combine all buckets[i] into result
        return result

// Sorts A recursively using quicksort
```

```
function quicksort(A, n):
    // Choose the rightmost element as the pivot
    pivot = A[n-1]

    // elements in left will be less than or equal to A[pivot], elements in the right will be greater than or equal to A[pivot]
    left_size = 0
    left = []
    right_size = 0
    right = []
    for i from left to right, i not equal to pivot:
        if A[i] <= A[pivot]:
            left.add(A[i])
            left_size++
        else:
            right.add(A[i])
            right_size++
    sorted_left = quicksort(left, left_size)
    sorted_right = quicksort(right, right_size)
    // Combine sorted_left with A[pivot] and sorted_right to create the final array result
    return result
```

Merge Sort

```
def parallel_merge_sort(A, N):
  MPI_Init()
  rank = MPI_Comm_rank()  # Get the rank of the current process
  size = MPI_Comm_size()   # Get the total number of processes

  # Divide the array among processes
  if rank == 0:
      sub_array_size = N // size  # Calculate the size of each sub-array
      # Send portions of the array to each process
      for i in range(1, size):
          # Sending sub-arrays to other processes
          MPI_Send(A[i * sub_array_size:(i + 1) * sub_array_size], dest=i)
      local_array = A[0:sub_array_size]  # Root keeps its portion of the array
  else:
      # Receive the assigned sub-array for non-root processes
      local_array = MPI_Recv(source=0)

  # Custom merge sort on the sub-array
  merge_sort(local_array)  # Each process sorts its own sub-array

  # Merging step using iterative merging (recursive doubling)
  step = 1  # Start with a step size of 1 for merging
  while step < size:  # Continue until the step size is greater than the number of processes
      if rank % (2 * step) == 0:  # Check if the process is an even-ranked process for merging
          if rank + step < size:  # Ensure there is a process to receive the data
              # Receive the sorted sub-array from the partner process
              received_array = MPI_Recv(source=rank + step)
              # Merge the local sorted array with the received array
              local_array = merge(local_array, received_array)
      else:
          # Send the local sorted array to the partner process
          MPI_Send(local_array, dest=rank - step)
          break  # Exit the loop after sending the data
      step *= 2  # Double the step size for the next iteration

  # Finalize MPI
  MPI_Finalize()  # Clean up the MPI environment before exiting

def merge_sort(arr):
   # Custom merge sort implementation
   if len(arr) > 1:
      #define pointers
      mid = len(arr) // 2   # Find the midpoint of the array
      left = arr[:mid]      # Split the array into two halves
      right = arr[mid:]

      # Recursively sort the left and right halves
      merge_sort(left)
      merge_sort(right)

      # Merging the sorted halves back together
```

```
        i = j = k = 0  # Initialize indices for left, right, and merged arrays
        while i < len(left) and j < len(right):
            if left[i] < right[j]:  # Compare elements from both halves
                arr[k] = left[i]     # Add the smaller element to the merged array
                i += 1
            else:
                arr[k] = right[j]    # Add the smaller element to the merged array
                j += 1
            k += 1  # Move to the next position in the merged array

        # Add any remaining elements from the left half
        while i < len(left):
            arr[k] = left[i]
            i += 1
            k += 1

        # Add any remaining elements from the right half
        while j < len(right):
            arr[k] = right[j]
            j += 1
            k += 1

    return arr
```

Radix Sort

```
def parallel_radix_sort(arr):
    comm = MPI.COMM_WORLD
    rank = comm.Get_rank()
    size = comm.Get_size()

    # chunk size and local chunk for each process
    chunk_size = len(arr) // size
    local_chunk = arr[rank * chunk_size: (rank + 1) * chunk_size]

    # step 1: count for local chunk -> Histogram
    max_value = comm.allreduce(np.max(local_chunk), op=MPI.MAX)
    num_buckets = int(np.log2(max_value)) + 1
    local_histogram = np.zeros((num_buckets, 256), dtype=int)

    for num in local_chunk:
        for byte_index in range(num_buckets):
            bucket = (num >> (byte_index * 8)) & 0xFF
            local_histogram[byte_index][bucket] += 1

    # step 2: partial sums
    global_histogram = np.zeros_like(local_histogram)
    comm.Reduce(local_histogram, global_histogram, op=MPI.SUM, root=0)

    if rank == 0:
        for i in range(num_buckets):
            np.cumsum(global_histogram[i], out=global_histogram[i])

    comm.Bcast(global_histogram, root=0)

    # step 3: reorder
    sorted_arr = np.zeros_like(arr)
    for byte_index in range(num_buckets):
        offsets = np.zeros(256, dtype=int)
        comm.Exscan(local_histogram[byte_index], offsets, op=MPI.SUM)

        for i, num in enumerate(local_chunk):
            bucket = (num >> (byte_index * 8)) & 0xFF
            index = offsets[bucket] + global_histogram[byte_index][bucket] - \
                    np.sum(local_histogram[byte_index][bucket+1:])
            sorted_arr[index] = num
            offsets[bucket] += 1

        comm.Allgather(local_chunk, arr)
        local_chunk = arr[rank * chunk_size: (rank + 1) * chunk_size]

    return sorted_arr
```

2c. Evaluation plan - what and how will you measure and compare

- Input sizes {2^16, 2^18, 2^20, 2^22, 2^24, 2^26, 2^28}
- Input types {Sorted, Random, Reverse sorted, 1%perturbed}
- Number of Processes {2, 4, 8, 16, 32, 64, 128, 256, 512, 1024}
- Strong scaling (same problem size, increase number of processors/nodes)
- Weak scaling (increase problem size, increase number of processors)

3a. Caliper instrumentation

Please use the caliper build `/scratch/group/csce435-f24/Caliper/caliper/share/cmake/caliper` (same as lab2 build.sh) to collect caliper files for each experiment you run.

Your Caliper annotations should result in the following calltree (use `Thicket.tree()` to see the calltree):

```
main
|_ data_init_X      # X = runtime OR io
|_ comm
|    |_ comm_small
|    |_ comm_large
|_ comp
|    |_ comp_small
|    |_ comp_large
|_ correctness_check
```

Required region annotations:

- `main` - top-level main function.
  - `data_init_X` - the function where input data is generated or read in from file. Use *data_init_runtime* if you are generating the data during the program, and *data_init_io* if you are reading the data from a file.
  - `correctness_check` - function for checking the correctness of the algorithm output (e.g., checking if the resulting data is sorted).
  - `comm` - All communication-related functions in your algorithm should be nested under the `comm` region.
    - Inside the `comm` region, you should create regions to indicate how much data you are communicating (i.e., `comm_small` if you are sending or broadcasting a few values, `comm_large` if you are sending all of your local values).
    - Notice that auxillary functions like MPI_init are not under here.
  - `comp` - All computation functions within your algorithm should be nested under the `comp` region.
    - Inside the `comp` region, you should create regions to indicate how much data you are computing on (i.e., `comp_small` if you are sorting a few values like the splitters, `comp_large` if you are sorting values in the array).
    - Notice that auxillary functions like data_init are not under here.
  - `MPI_X` - You will also see MPI regions in the calltree if using the appropriate MPI profiling configuration (see **Builds/**). Examples shown below.

All functions will be called from `main` and most will be grouped under either `comm` or `comp` regions, representing communication and computation, respectively. You should be timing as many significant functions in your code as possible. **Do not** time print statements or other insignificant operations that may skew the performance measurements.

Nesting Code Regions Example - all computation code regions should be nested in the "comp" parent code region as following:

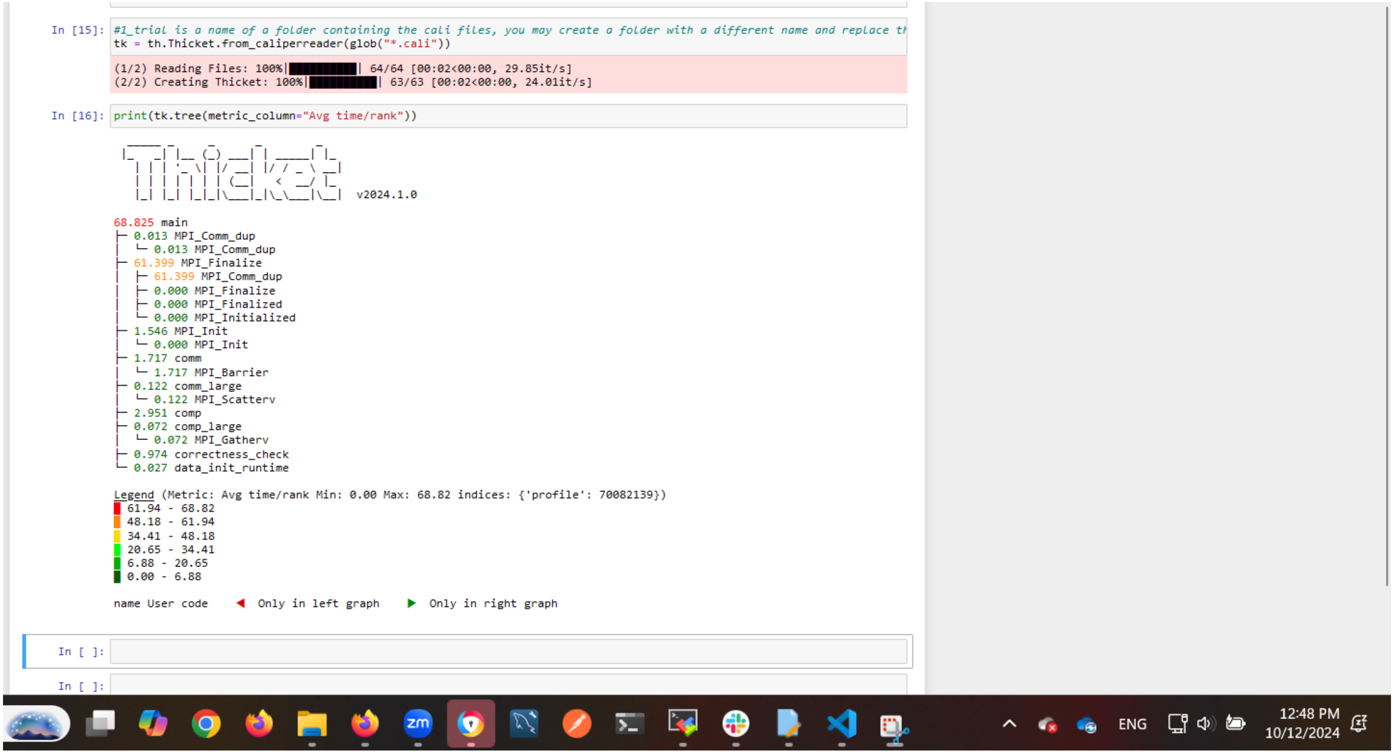
```
CALI_MARK_BEGIN("comp");
CALI_MARK_BEGIN("comp_small");
sort_pivots(pivot_arr);
CALI_MARK_END("comp_small");
CALI_MARK_END("comp");

# Other non-computation code
...

CALI_MARK_BEGIN("comp");
CALI_MARK_BEGIN("comp_large");
sort_values(arr);
CALI_MARK_END("comp_large");
CALI_MARK_END("comp");
```

Calltree Example:

```
# MPI Mergesort
4.695 main
├─ 0.001 MPI_Comm_dup
├─ 0.000 MPI_Finalize
├─ 0.000 MPI_Finalized
├─ 0.000 MPI_Init
├─ 0.000 MPI_Initialized
├─ 2.599 comm
│  ├─ 2.572 MPI_Barrier
│  └─ 0.027 comm_large
```

```
│     ├─ 0.011 MPI_Gather
│     └─ 0.016 MPI_Scatter
├─ 0.910 comp
│  └─ 0.909 comp_large
├─ 0.201 data_init_runtime
└─ 0.440 correctness_check
```

Calltree for Merge Sort:



Calltree for Bitonic Sort:

```
243.487 main
├─ 229.875 MPI_Comm_dup
├─ 0.000 MPI_Finalize
├─ 0.000 MPI_Finalized
├─ 0.000 MPI_Init
├─ 0.000 MPI_Initialized
├─ 7.126 comm
│  ├─ 6.933 MPI_Barrier
│  └─ 0.194 comm_large
│     ├─ 0.092 MPI_Gather
│     └─ 0.102 MPI_Scatter
├─ 4.807 comp
│  └─ 4.807 comp_large
├─ 1.947 correctness_check
└─ 0.061 data_init_runtime

Legend (Metric: Avg time/rank Min: 0.00 Max: 243.49 indices: {'profile': np.int64(188812254)})
219.14 - 243.49
170.44 - 219.14
...
0.00 - 24.35

name User code ◀ Only in left graph ▶ Only in right graph
```

Calltree for Radx Sort:

```
  _____ _     _      _        _
 |_   _| |__ (_) ___| | _____| |_
   | | | '_ \| |/ __| |/ / _ \ __|
   | | | | | | | (__|   <  __/ |_
   |_| |_| |_|_|\___|_|\_\___|\__|  v2024.1.0

23.795 main
├─ 0.000 MPI_Init
├─ 7.128 MPI_Comm_dup
├─ 0.101 data_init_runtime
├─ 14.588 comm
│  ├─ 12.884 comm_small
│  │  └─ 12.883 MPI_Barrier
│  └─ 1.704 comm_large
│     ├─ 0.843 MPI_Bcast
│     └─ 0.013 MPI_Reduce
├─ 0.062 comp
│  ├─ 0.021 comp_large
│  └─ 5.231 comp_small
├─ 0.000 MPI_Finalize
├─ 1.917 correctness_check
├─ 0.000 MPI_Initialized
└─ 0.000 MPI_Finalized

Legend (Metric: Avg time/rank Min: 0.00 Max: 23.79 indices: {'profile': 3298551018})
█ 21.42 - 23.79
█ 16.66 - 21.42
█ 11.90 - 16.66
█ 7.14 - 11.90
█ 2.38 - 7.14
█ 0.00 - 2.38
```

Calltree for Sample Sort:

```
  _____ _     _      _        _
 |_   _| |__ (_) ___| | _____| |_
   | | | '_ \| |/ __| |/ / _ \ __|
   | | | | | | | (__|   <  __/ |_
   |_| |_| |_|_|\___|_|\_\___|\__|  v2024.1.0

7.123 main
├─ 0.000 MPI_Init
├─ 0.027 comm
│  └─ 0.027 comm_small
│     ├─ 0.007 MPI_Gather
│     ├─ 0.020 MPI_Recv
│     └─ 0.003 MPI_Send
├─ 0.089 comp
│  ├─ 0.086 comp_large
│  │  ├─ 0.074 MPI_Gatherv
│  │  └─ 0.007 comp_large
│  │     └─ 0.007 comp
│  │        ├─ 0.003 MPI_Comm_dup
│  │        ├─ 0.000 MPI_Finalize
│  │        ├─ 0.000 MPI_Finalized
│  │        ├─ 0.000 MPI_Initialized
│  │        ├─ 0.003 comm
│  │        │  ├─ 0.003 comm_large
│  │        │  │  └─ 0.003 MPI_Gatherv
│  │        │  └─ 0.001 comm_small
│  │        │     └─ 0.001 MPI_Gather
│  │        ├─ 0.000 comp
│  │        │  └─ 0.000 comp_small
│  │        └─ 0.001 correctness_check
│  └─ 0.003 comp_small
│     └─ 0.002 MPI_Reduce
└─ 0.000 data_init_runtime

Legend (Metric: Avg time/rank Min: 0.00 Max: 7.12 indices: {'profile': 295277911})
█ 6.41 - 7.12
█ 4.99 - 6.41
█ 3.56 - 4.99
█ 2.14 - 3.56
█ 0.71 - 2.14
█ 0.00 - 0.71

name User code    ◀  Only in left graph    ▶  Only in right graph
```

3b. Collect Metadata

Have the following code in your programs to collect metadata:

```
adiak::init(NULL);
adiak::launchdate();    // launch date of the job
adiak::libraries();     // Libraries used
adiak::cmdline();       // Command line used to launch the job
adiak::clustername();   // Name of the cluster
adiak::value("algorithm", algorithm); // The name of the algorithm you are using (e.g., "merge", "bitonic")
adiak::value("programming_model", programming_model); // e.g. "mpi"
adiak::value("data_type", data_type); // The datatype of input elements (e.g., double, int, float)
adiak::value("size_of_data_type", size_of_data_type); // sizeof(datatype) of input elements in bytes (e.g., 1, 2, 4)
adiak::value("input_size", input_size); // The number of elements in input dataset (1000)
adiak::value("input_type", input_type); // For sorting, this would be choices: ("Sorted", "ReverseSorted", "Random",
"1_perc_perturbed")
adiak::value("num_procs", num_procs); // The number of processors (MPI ranks)
adiak::value("scalability", scalability); // The scalability of your algorithm. choices: ("strong", "weak")
adiak::value("group_num", group_number); // The number of your group (integer, e.g., 1, 10)
adiak::value("implementation_source", implementation_source); // Where you got the source code of your algorithm. choices:
("online", "ai", "handwritten").
```

They will show up in the `Thicket.metadata` if the caliper file is read into Thicket.

Metadata for Merge Sort:

algorithm	programming_model	data_type	size_of_data_type	input_size	input_type	num_procs	scalability	group_num	implementation_sou
merge	mpi	int	4	65536	Random	2	strong	5	handwritten
merge	mpi	int	4	65536	Random	4	strong	5	handwritten
merge	mpi	int	4	65536	Random	8	strong	5	handwritten
merge	mpi	int	4	65536	Random	16	strong	5	handwritten
merge	mpi	int	4	65536	Random	32	strong	5	handwritten
merge	mpi	int	4	65536	Random	64	strong	5	handwritten
merge	mpi	int	4	65536	Random	128	strong	5	handwritten
merge	mpi	int	4	65536	Random	256	strong	5	handwritten
merge	mpi	int	4	65536	Random	512	strong	5	handwritten
merge	mpi	int	4	65536	Random	1024	strong	5	handwritten
merge	mpi	int	4	262144	Random	2	strong	5	handwritten
merge	mpi	int	4	262144	Random	4	strong	5	handwritten
merge	mpi	int	4	262144	Random	8	strong	5	handwritten
merge	mpi	int	4	262144	Random	16	strong	5	handwritten
merge	mpi	int	4	262144	Random	32	strong	5	handwritten
merge	mpi	int	4	262144	Random	64	strong	5	handwritten
merge	mpi	int	4	262144	Random	128	strong	5	handwritten
merge	mpi	int	4	262144	Random	256	strong	5	handwritten
merge	mpi	int	4	262144	Random	512	strong	5	handwritten
merge	mpi	int	4	262144	Random	1024	strong	5	handwritten
merge	mpi	int	4	1048576	Random	2	strong	5	handwritten
merge	mpi	int	4	1048576	Random	4	strong	5	handwritten
merge	mpi	int	4	1048576	Random	8	strong	5	handwritten
merge	mpi	int	4	1048576	Random	16	strong	5	handwritten
merge	mpi	int	4	1048576	Random	32	strong	5	handwritten
merge	mpi	int	4	1048576	Random	64	strong	5	handwritten
merge	mpi	int	4	1048576	Random	128	strong	5	handwritten
merge	mpi	int	4	1048576	Random	256	strong	5	handwritten
merge	mpi	int	4	1048576	Random	512	strong	5	handwritten
merge	mpi	int	4	1048576	Random	1024	strong	5	handwritten
merge	mpi	int	4	4194304	Random	2	strong	5	handwritten
merge	mpi	int	4	4194304	Random	4	strong	5	handwritten
merge	mpi	int	4	4194304	Random	8	strong	5	handwritten
merge	mpi	int	4	4194304	Random	16	strong	5	handwritten
merge	mpi	int	4	4194304	Random	32	strong	5	handwritten
merge	mpi	int	4	4194304	Random	64	strong	5	handwritten
merge	mpi	int	4	4194304	Random	128	strong	5	handwritten
merge	mpi	int	4	4194304	Random	256	strong	5	handwritten
merge	mpi	int	4	4194304	Random	512	strong	5	handwritten
merge	mpi	int	4	4194304	Random	1024	strong	5	handwritten
merge	mpi	int	4	16777216	Random	2	strong	5	handwritten
merge	mpi	int	4	16777216	Random	4	strong	5	handwritten
merge	mpi	int	4	16777216	Random	8	strong	5	handwritten
merge	mpi	int	4	16777216	Random	16	strong	5	handwritten

algorithm	programming_model	data_type	size_of_data_type	input_size	input_type	num_procs	scalability	group_num	implementation_sou
merge	mpi	int	4	16777216	Random	32	strong	5	handwritten
merge	mpi	int	4	16777216	Random	64	strong	5	handwritten
merge	mpi	int	4	16777216	Random	128	strong	5	handwritten
merge	mpi	int	4	16777216	Random	256	strong	5	handwritten
merge	mpi	int	4	16777216	Random	512	strong	5	handwritten
merge	mpi	int	4	16777216	Random	1024	strong	5	handwritten
merge	mpi	int	4	67108864	Random	2	strong	5	handwritten
merge	mpi	int	4	67108864	Random	4	strong	5	handwritten
merge	mpi	int	4	67108864	Random	8	strong	5	handwritten
merge	mpi	int	4	67108864	Random	16	strong	5	handwritten
merge	mpi	int	4	67108864	Random	32	strong	5	handwritten
merge	mpi	int	4	67108864	Random	64	strong	5	handwritten
merge	mpi	int	4	67108864	Random	128	strong	5	handwritten
merge	mpi	int	4	67108864	Random	256	strong	5	handwritten
merge	mpi	int	4	67108864	Random	512	strong	5	handwritten
merge	mpi	int	4	67108864	Random	1024	strong	5	handwritten
merge	mpi	int	4	268435456	Random	2	strong	5	handwritten
merge	mpi	int	4	268435456	Random	4	strong	5	handwritten
merge	mpi	int	4	268435456	Random	8	strong	5	handwritten
merge	mpi	int	4	268435456	Random	16	strong	5	handwritten
merge	mpi	int	4	268435456	Random	32	strong	5	handwritten
merge	mpi	int	4	268435456	Random	64	strong	5	handwritten
merge	mpi	int	4	268435456	Random	128	strong	5	handwritten
merge	mpi	int	4	268435456	Random	256	strong	5	handwritten
merge	mpi	int	4	268435456	Random	512	strong	5	handwritten

Metadata for Bitonic Sort:

algorithm	programming_model	data_type	size_of_data_type	input_size	input_type	num_procs	scalability	group_num	implementation_sou
bitonic	mpi	int	4	268435456	Random	128	strong	5	handwritten
bitonic	mpi	int	4	4194304	Random	256	strong	5	handwritten
bitonic	mpi	int	4	1048576	Random	16	strong	5	handwritten
bitonic	mpi	int	4	65536	Random	4	strong	5	handwritten
bitonic	mpi	int	4	16777216	Random	256	strong	5	handwritten
bitonic	mpi	int	4	1048576	Random	32	strong	5	handwritten
bitonic	mpi	int	4	262144	Random	256	strong	5	handwritten
bitonic	mpi	int	4	1048576	Random	64	strong	5	handwritten
bitonic	mpi	int	4	4194304	Random	1024	strong	5	handwritten
bitonic	mpi	int	4	16777216	Random	2	strong	5	handwritten
bitonic	mpi	int	4	16777216	Random	1024	strong	5	handwritten
bitonic	mpi	int	4	268435456	Random	1024	strong	5	handwritten
bitonic	mpi	int	4	262144	Random	128	strong	5	handwritten
bitonic	mpi	int	4	16777216	Random	8	strong	5	handwritten
bitonic	mpi	int	4	268435456	Random	512	strong	5	handwritten
bitonic	mpi	int	4	1048576	Random	256	strong	5	handwritten
bitonic	mpi	int	4	4194304	Random	128	strong	5	handwritten
bitonic	mpi	int	4	65536	Random	64	strong	5	handwritten

algorithm	programming_model	data_type	size_of_data_type	input_size	input_type	num_procs	scalability	group_num	implementation_sou
bitonic	mpi	int	4	65536	Random	1024	strong	5	handwritten
bitonic	mpi	int	4	268435456	Random	256	strong	5	handwritten
bitonic	mpi	int	4	67108864	Random	256	strong	5	handwritten
bitonic	mpi	int	4	268435456	Random	8	strong	5	handwritten
bitonic	mpi	int	4	67108864	Random	512	strong	5	handwritten
bitonic	mpi	int	4	262144	Random	8	strong	5	handwritten
bitonic	mpi	int	4	67108864	Random	1024	strong	5	handwritten
bitonic	mpi	int	4	16777216	Random	4	strong	5	handwritten
bitonic	mpi	int	4	67108864	Random	2	strong	5	handwritten
bitonic	mpi	int	4	262144	Random	4	strong	5	handwritten
bitonic	mpi	int	4	262144	Random	64	strong	5	handwritten
bitonic	mpi	int	4	1048576	Random	2	strong	5	handwritten
bitonic	mpi	int	4	262144	Random	16	strong	5	handwritten
bitonic	mpi	int	4	4194304	Random	2	strong	5	handwritten
bitonic	mpi	int	4	67108864	Random	64	strong	5	handwritten
bitonic	mpi	int	4	268435456	Random	16	strong	5	handwritten
bitonic	mpi	int	4	67108864	Random	8	strong	5	handwritten
bitonic	mpi	int	4	262144	Random	512	strong	5	handwritten
bitonic	mpi	int	4	4194304	Random	64	strong	5	handwritten
bitonic	mpi	int	4	268435456	Random	4	strong	5	handwritten
bitonic	mpi	int	4	67108864	Random	32	strong	5	handwritten
bitonic	mpi	int	4	65536	Random	256	strong	5	handwritten
bitonic	mpi	int	4	1048576	Random	1024	strong	5	handwritten
bitonic	mpi	int	4	65536	Random	8	strong	5	handwritten
bitonic	mpi	int	4	16777216	Random	16	strong	5	handwritten
bitonic	mpi	int	4	65536	Random	16	strong	5	handwritten
bitonic	mpi	int	4	16777216	Random	512	strong	5	handwritten
bitonic	mpi	int	4	1048576	Random	8	strong	5	handwritten
bitonic	mpi	int	4	4194304	Random	4	strong	5	handwritten
bitonic	mpi	int	4	268435456	Random	64	strong	5	handwritten
bitonic	mpi	int	4	16777216	Random	32	strong	5	handwritten
bitonic	mpi	int	4	16777216	Random	64	strong	5	handwritten
bitonic	mpi	int	4	67108864	Random	4	strong	5	handwritten
bitonic	mpi	int	4	1048576	Random	128	strong	5	handwritten
bitonic	mpi	int	4	4194304	Random	32	strong	5	handwritten
bitonic	mpi	int	4	262144	Random	32	strong	5	handwritten
bitonic	mpi	int	4	65536	Random	2	strong	5	handwritten
bitonic	mpi	int	4	67108864	Random	128	strong	5	handwritten
bitonic	mpi	int	4	67108864	Random	16	strong	5	handwritten
bitonic	mpi	int	4	65536	Random	128	strong	5	handwritten
bitonic	mpi	int	4	268435456	Random	2	strong	5	handwritten
bitonic	mpi	int	4	65536	Random	32	strong	5	handwritten
bitonic	mpi	int	4	262144	Random	1024	strong	5	handwritten
bitonic	mpi	int	4	1048576	Random	4	strong	5	handwritten
bitonic	mpi	int	4	268435456	Random	32	strong	5	handwritten

algorithm	programming_model	data_type	size_of_data_type	input_size	input_type	num_procs	scalability	group_num	implementation_sou
bitonic	mpi	int	4	16777216	Random	128	strong	5	handwritten
bitonic	mpi	int	4	1048576	Random	512	strong	5	handwritten
bitonic	mpi	int	4	262144	Random	2	strong	5	handwritten
bitonic	mpi	int	4	65536	Random	512	strong	5	handwritten
bitonic	mpi	int	4	4194304	Random	8	strong	5	handwritten
bitonic	mpi	int	4	4194304	Random	16	strong	5	handwritten
bitonic	mpi	int	4	4194304	Random	512	strong	5	handwritten

Metadata for Radix Sort:

algorithm	programming_model	data_type	size_of_data_type	input_size	input_type	num_procs	scalability	group_num	implementation_sou
radix	mpi	int	4	65536	Random	1024	strong	5	handwritten
radix	mpi	int	4	65536	Random	512	strong	5	handwritten
radix	mpi	int	4	65536	Random	256	strong	5	handwritten
radix	mpi	int	4	65536	Random	128	strong	5	handwritten
radix	mpi	int	4	65536	Random	64	strong	5	handwritten
radix	mpi	int	4	65536	Random	32	strong	5	handwritten
radix	mpi	int	4	65536	Random	16	strong	5	handwritten
radix	mpi	int	4	65536	Random	8	strong	5	handwritten
radix	mpi	int	4	65536	Random	4	strong	5	handwritten
radix	mpi	int	4	65536	Random	2	strong	5	handwritten
radix	mpi	int	4	262144	Random	1024	strong	5	handwritten
radix	mpi	int	4	262144	Random	512	strong	5	handwritten
radix	mpi	int	4	262144	Random	256	strong	5	handwritten
radix	mpi	int	4	262144	Random	128	strong	5	handwritten
radix	mpi	int	4	262144	Random	64	strong	5	handwritten
radix	mpi	int	4	262144	Random	32	strong	5	handwritten
radix	mpi	int	4	262144	Random	16	strong	5	handwritten
radix	mpi	int	4	262144	Random	8	strong	5	handwritten
radix	mpi	int	4	262144	Random	4	strong	5	handwritten
radix	mpi	int	4	262144	Random	2	strong	5	handwritten
radix	mpi	int	4	1048576	Random	1024	strong	5	handwritten
radix	mpi	int	4	1048576	Random	512	strong	5	handwritten
radix	mpi	int	4	1048576	Random	256	strong	5	handwritten
radix	mpi	int	4	1048576	Random	128	strong	5	handwritten
radix	mpi	int	4	1048576	Random	64	strong	5	handwritten
radix	mpi	int	4	1048576	Random	32	strong	5	handwritten
radix	mpi	int	4	1048576	Random	16	strong	5	handwritten
radix	mpi	int	4	1048576	Random	8	strong	5	handwritten
radix	mpi	int	4	1048576	Random	4	strong	5	handwritten
radix	mpi	int	4	1048576	Random	2	strong	5	handwritten
radix	mpi	int	4	4194304	Random	1024	strong	5	handwritten
radix	mpi	int	4	4194304	Random	512	strong	5	handwritten
radix	mpi	int	4	4194304	Random	256	strong	5	handwritten
radix	mpi	int	4	4194304	Random	128	strong	5	handwritten
radix	mpi	int	4	4194304	Random	64	strong	5	handwritten
radix	mpi	int	4	4194304	Random	32	strong	5	handwritten

algorithm	programming_model	data_type	size_of_data_type	input_size	input_type	num_procs	scalability	group_num	implementation_sou
radix	mpi	int	4	4194304	Random	16	strong	5	handwritten
radix	mpi	int	4	4194304	Random	8	strong	5	handwritten
radix	mpi	int	4	4194304	Random	4	strong	5	handwritten
radix	mpi	int	4	4194304	Random	2	strong	5	handwritten
radix	mpi	int	4	16777216	Random	1024	strong	5	handwritten
radix	mpi	int	4	16777216	Random	512	strong	5	handwritten
radix	mpi	int	4	16777216	Random	256	strong	5	handwritten
radix	mpi	int	4	16777216	Random	128	strong	5	handwritten
radix	mpi	int	4	16777216	Random	64	strong	5	handwritten
radix	mpi	int	4	16777216	Random	32	strong	5	handwritten
radix	mpi	int	4	16777216	Random	16	strong	5	handwritten
radix	mpi	int	4	16777216	Random	8	strong	5	handwritten
radix	mpi	int	4	16777216	Random	4	strong	5	handwritten
radix	mpi	int	4	16777216	Random	2	strong	5	handwritten
radix	mpi	int	4	67108864	Random	1024	strong	5	handwritten
radix	mpi	int	4	67108864	Random	512	strong	5	handwritten
radix	mpi	int	4	67108864	Random	256	strong	5	handwritten
radix	mpi	int	4	67108864	Random	128	strong	5	handwritten
radix	mpi	int	4	67108864	Random	64	strong	5	handwritten
radix	mpi	int	4	67108864	Random	32	strong	5	handwritten
radix	mpi	int	4	67108864	Random	16	strong	5	handwritten
radix	mpi	int	4	67108864	Random	8	strong	5	handwritten
radix	mpi	int	4	67108864	Random	4	strong	5	handwritten
radix	mpi	int	4	67108864	Random	2	strong	5	handwritten
radix	mpi	int	4	268435456	Random	1024	strong	5	handwritten
radix	mpi	int	4	268435456	Random	512	strong	5	handwritten
radix	mpi	int	4	268435456	Random	256	strong	5	handwritten
radix	mpi	int	4	268435456	Random	128	strong	5	handwritten
radix	mpi	int	4	268435456	Random	64	strong	5	handwritten
radix	mpi	int	4	268435456	Random	32	strong	5	handwritten
radix	mpi	int	4	268435456	Random	16	strong	5	handwritten
radix	mpi	int	4	268435456	Random	8	strong	5	handwritten
radix	mpi	int	4	268435456	Random	4	strong	5	handwritten
radix	mpi	int	4	268435456	Random	2	strong	5	handwritten

Metadata for sample sort:

algorithm	programming_model	data_type	size_of_data_type	input_size	input_type	num_procs	scalability	group_num	implementation_sou
sample	mpi	int	4	65536	Random	64	strong	5	handwritten
sample	mpi	int	4	65536	Random	2	strong	5	handwritten
sample	mpi	int	4	65536	Random	8	strong	5	handwritten
sample	mpi	int	4	65536	Random	16	strong	5	handwritten
sample	mpi	int	4	65536	Random	4	strong	5	handwritten
sample	mpi	int	4	65536	Random	32	strong	5	handwritten
sample	mpi	int	4	65536	Random	128	strong	5	handwritten

See the `Builds/` directory to find the correct Caliper configurations to get the performance metrics. They will show up in the `Thicket.dataframe` when the Caliper file is read into Thicket.

4. Performance evaluation

Include detailed analysis of computation performance, communication performance. Include figures and explanation of your analysis.

4a. Vary the following parameters

For input_size's:

- 2^16, 2^18, 2^20, 2^22, 2^24, 2^26, 2^28

For input_type's:

- Sorted, Random, Reverse sorted, 1%perturbed

MPI: num_procs:

- 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024

This should result in 4x7x10=280 Caliper files for your MPI experiments.

4b. Hints for performance analysis

To automate running a set of experiments, parameterize your program.

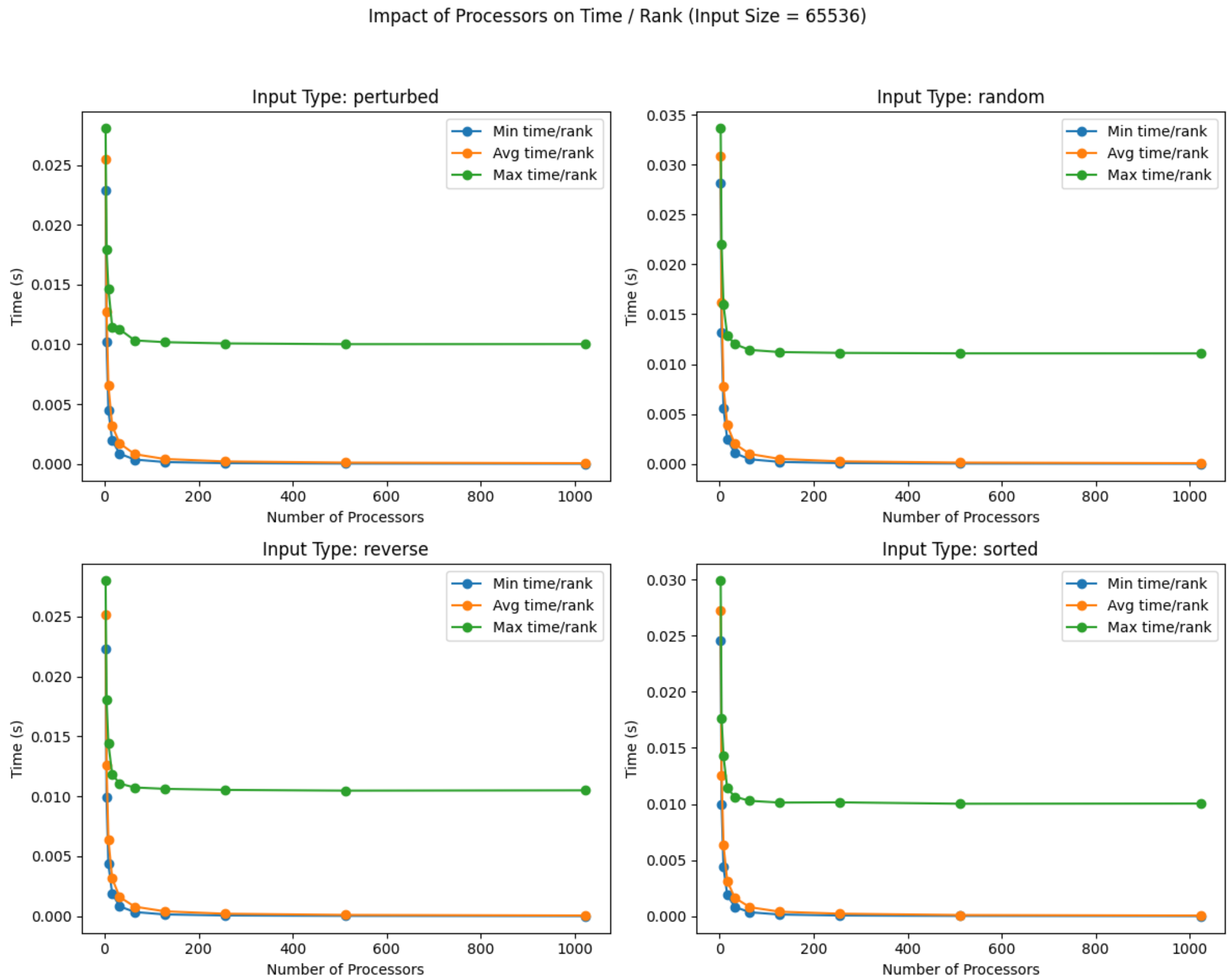
- input_type: "Sorted" could generate a sorted input to pass into your algorithms
- algorithm: You can have a switch statement that calls the different algorithms and sets the Adiak variables accordingly
- num_procs: How many MPI ranks you are using

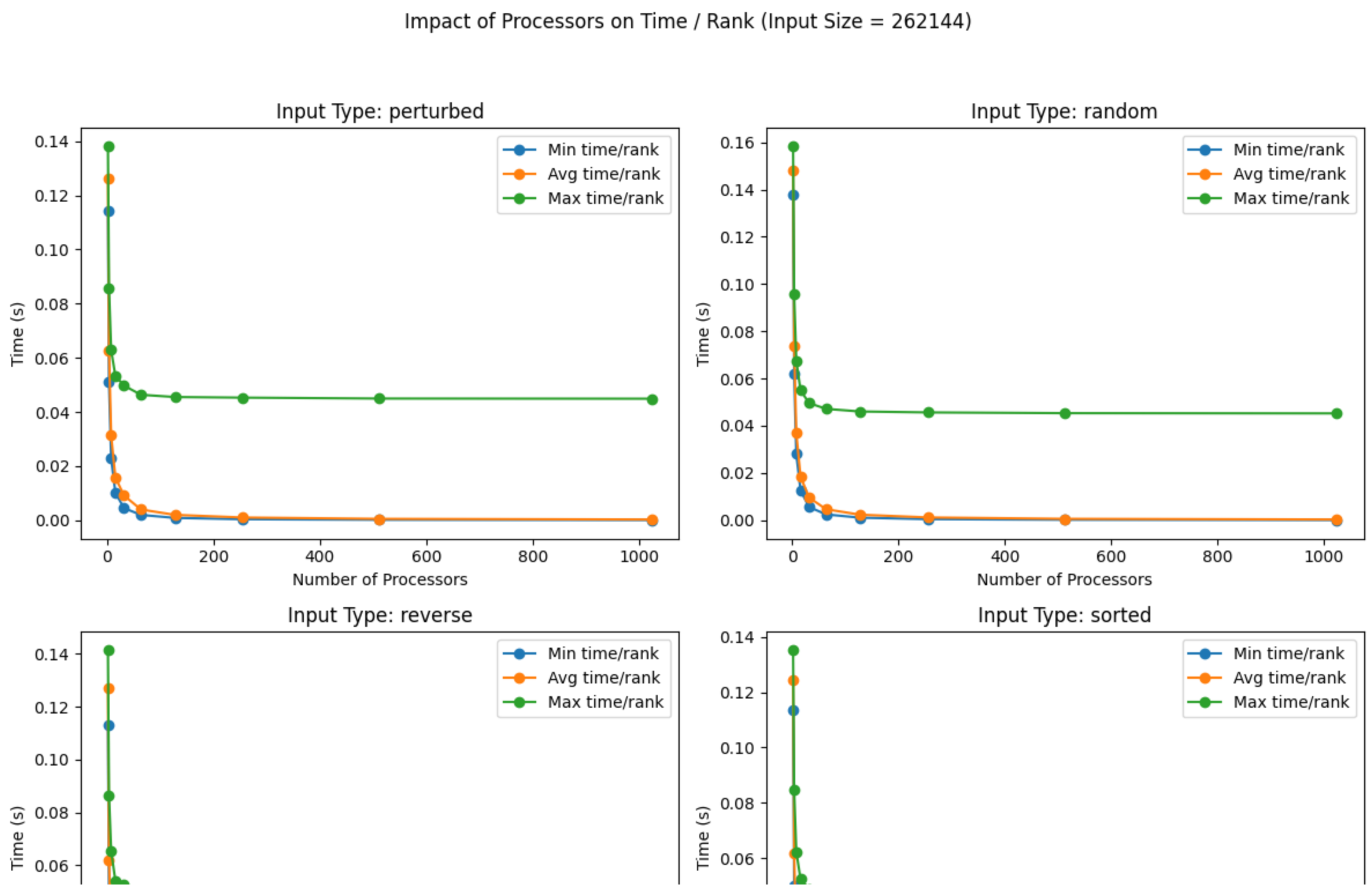
When your program works with these parameters, you can write a shell script that will run a for loop over the parameters above (e.g., on 64 processors, perform runs that invoke algorithm2 for Sorted, ReverseSorted, and Random data).

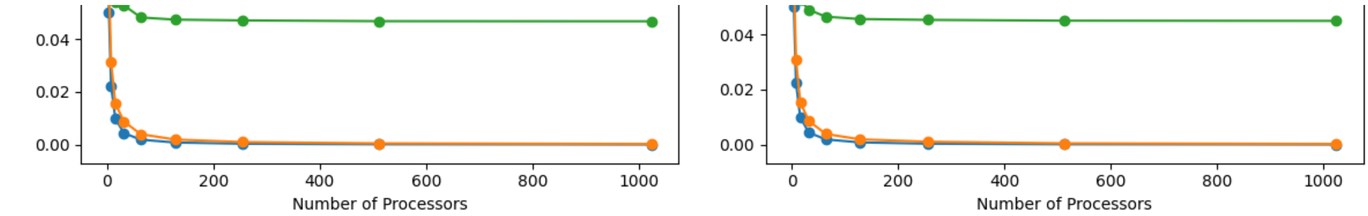
4c. You should measure the following performance metrics

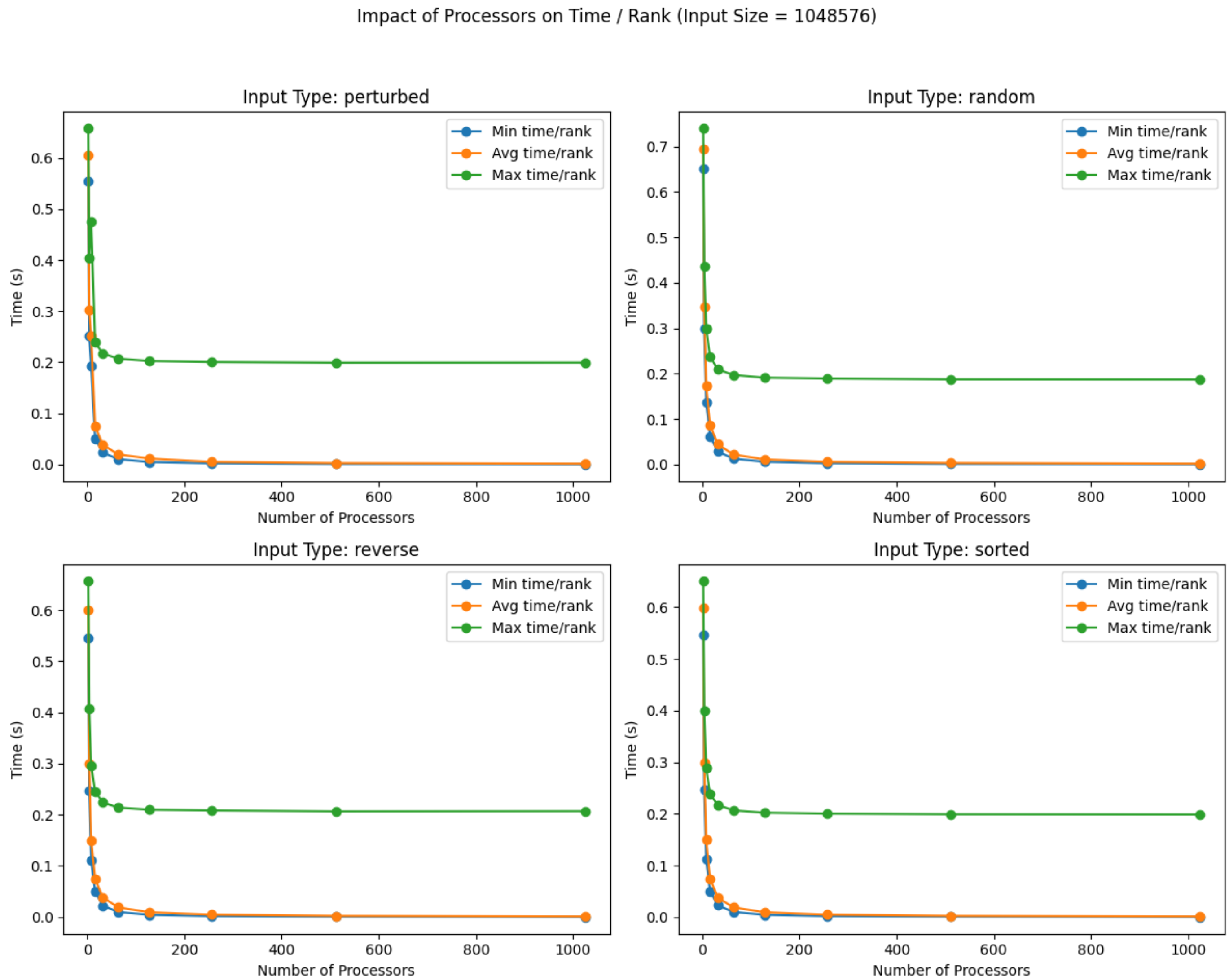
- `Time`
  - Min time/rank
  - Max time/rank
  - Avg time/rank
  - Total time
  - Variance time/rank

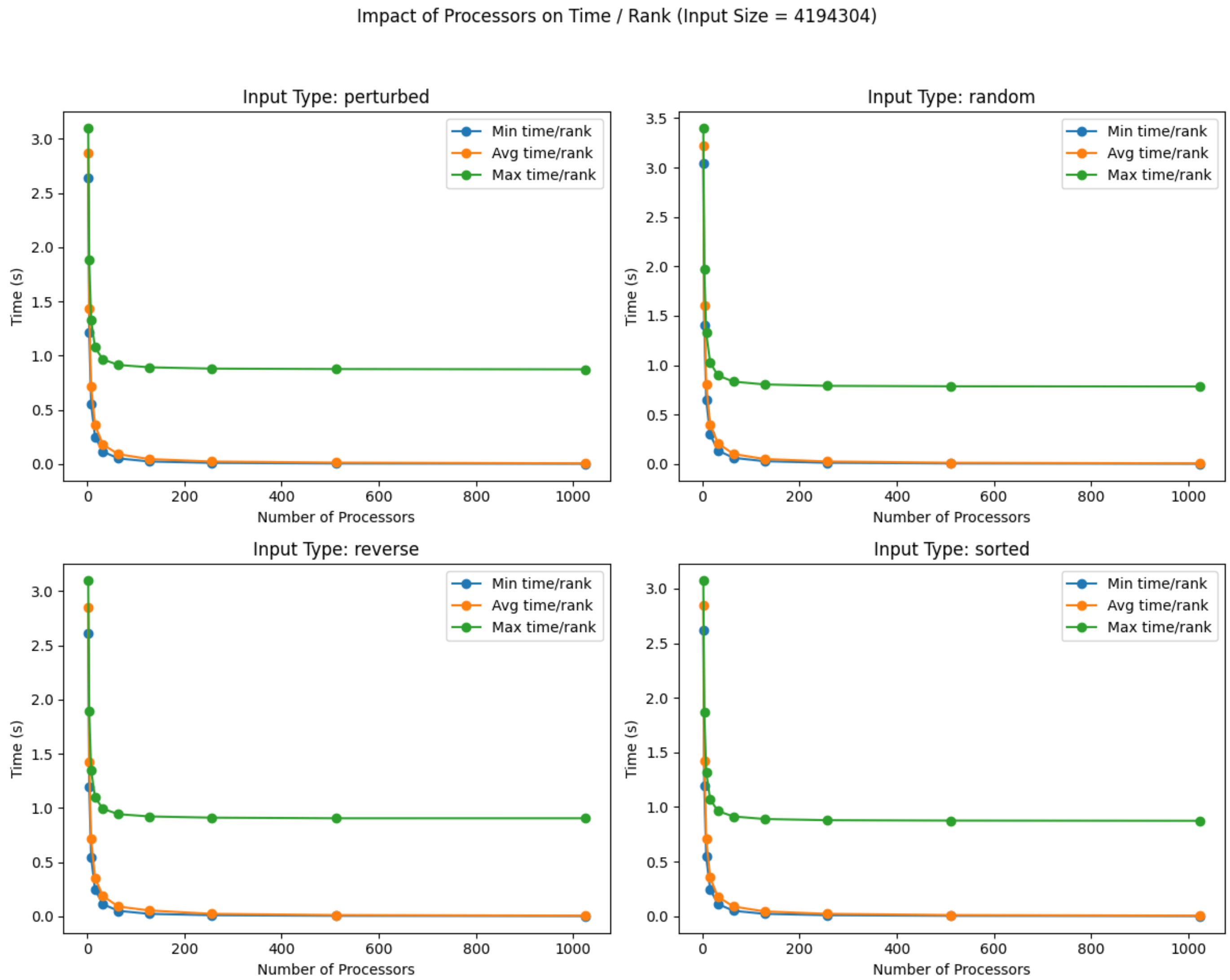
Bitonic Sort Plots:

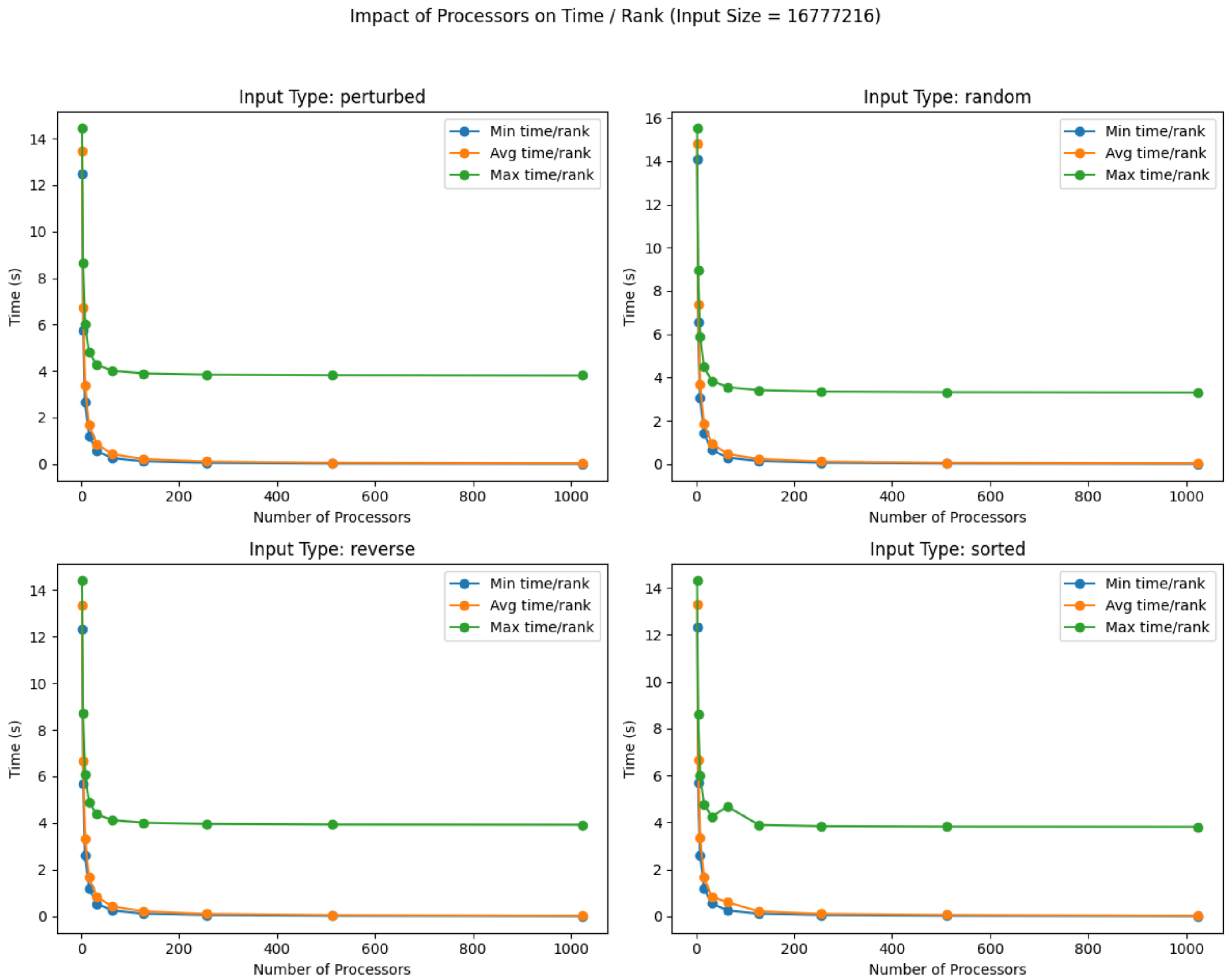

Impact of Processors on Time / Rank (Input Size = 65536)
Input Type: perturbed
Input Type: random
Input Type: reverse
Input Type: sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors

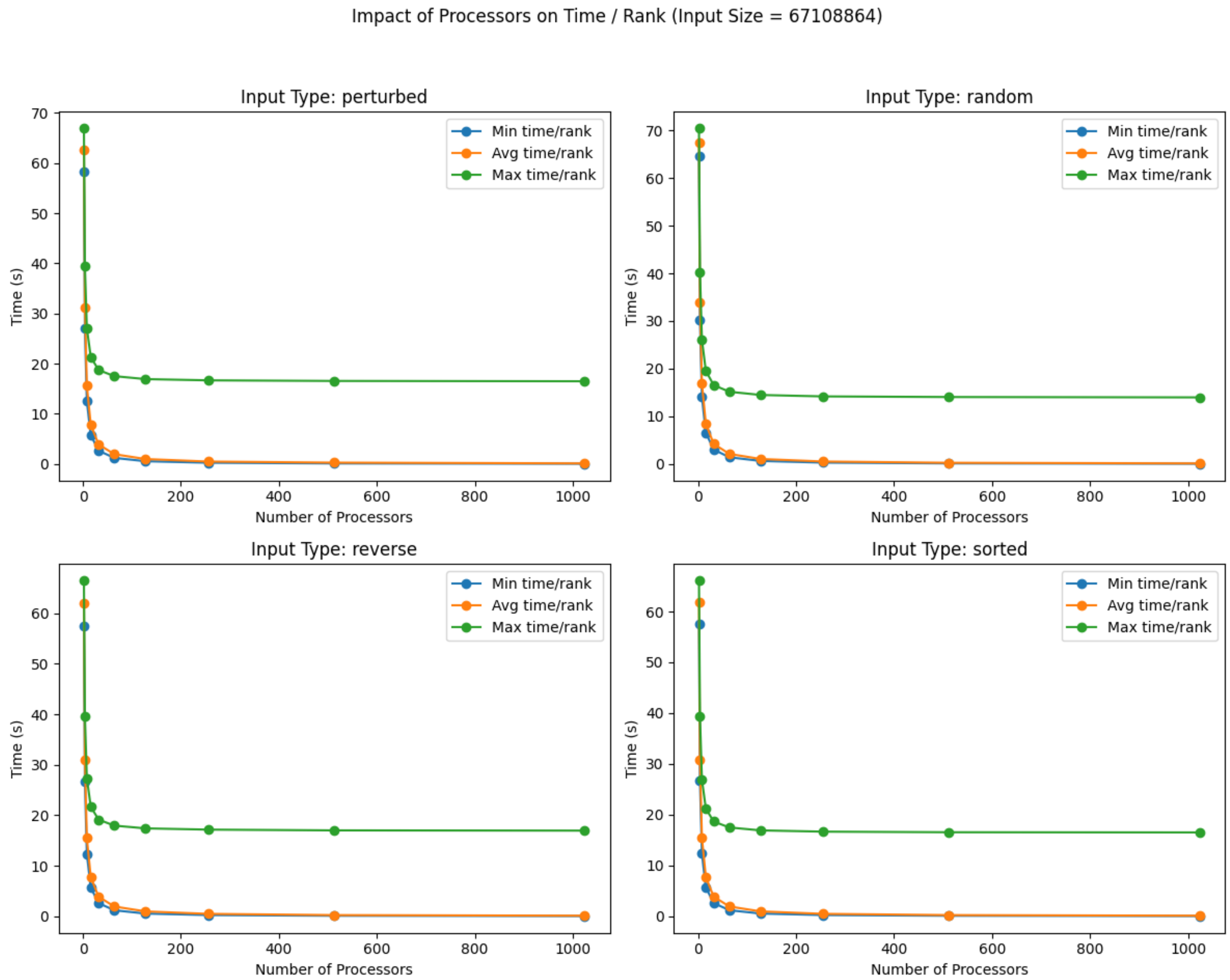

Impact of Processors on Time / Rank (Input Size = 262144)
Input Type: perturbed
Input Type: random
Input Type: reverse
Input Type: sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors

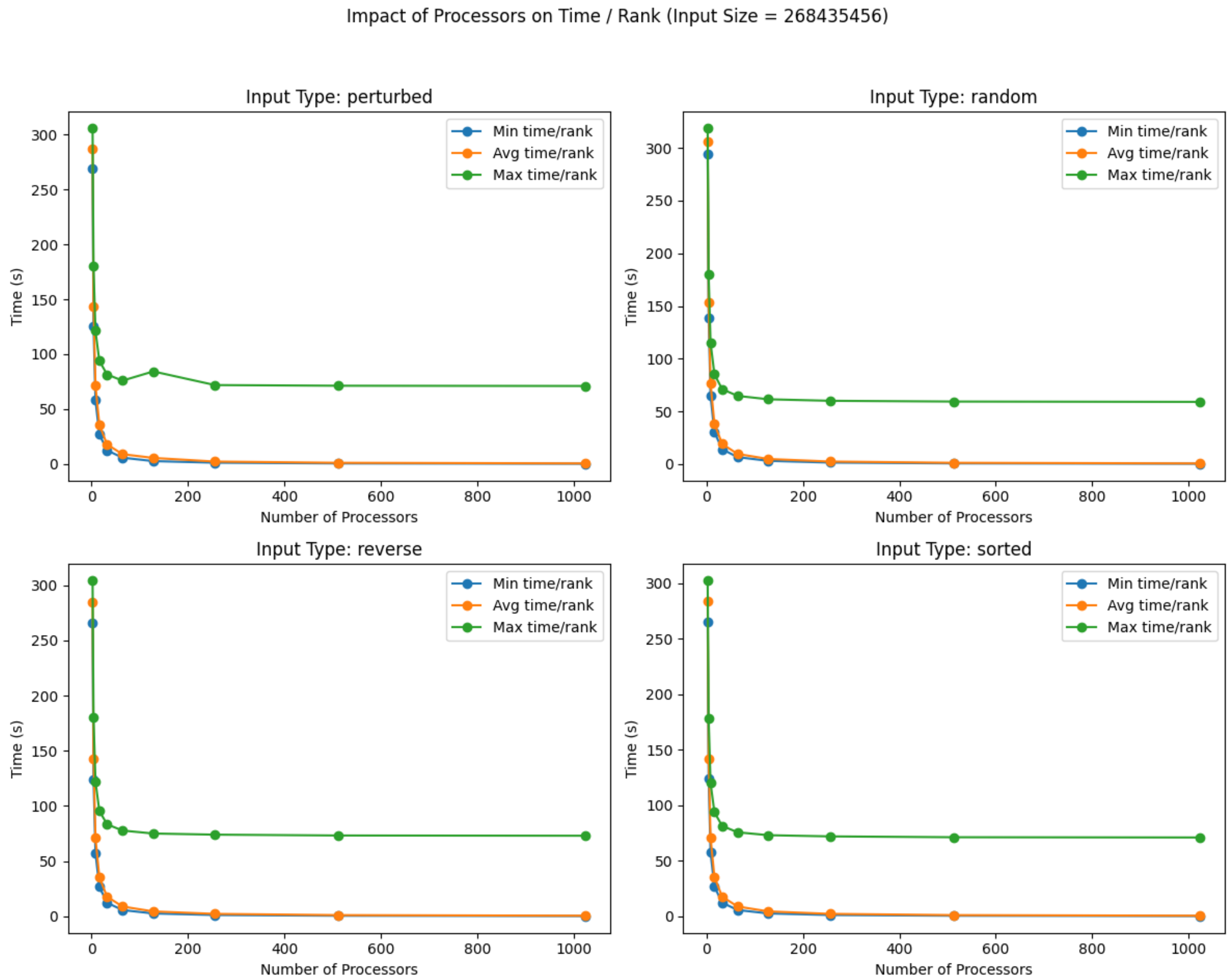

Number of Processors
Number of Processors


Impact of Processors on Time / Rank (Input Size = 1048576)
Input Type: perturbed
Input Type: random
Input Type: reverse
Input Type: sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors


Impact of Processors on Time / Rank (Input Size = 4194304)
Input Type: perturbed
Input Type: random
Input Type: reverse
Input Type: sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors


Impact of Processors on Time / Rank (Input Size = 16777216)
Input Type: perturbed
Input Type: random
Input Type: reverse
Input Type: sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors


Impact of Processors on Time / Rank (Input Size = 67108864)
Input Type: perturbed
Input Type: random
Input Type: reverse
Input Type: sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors
0
200
400
600
800
1000
10
20
30
40
50
60
70



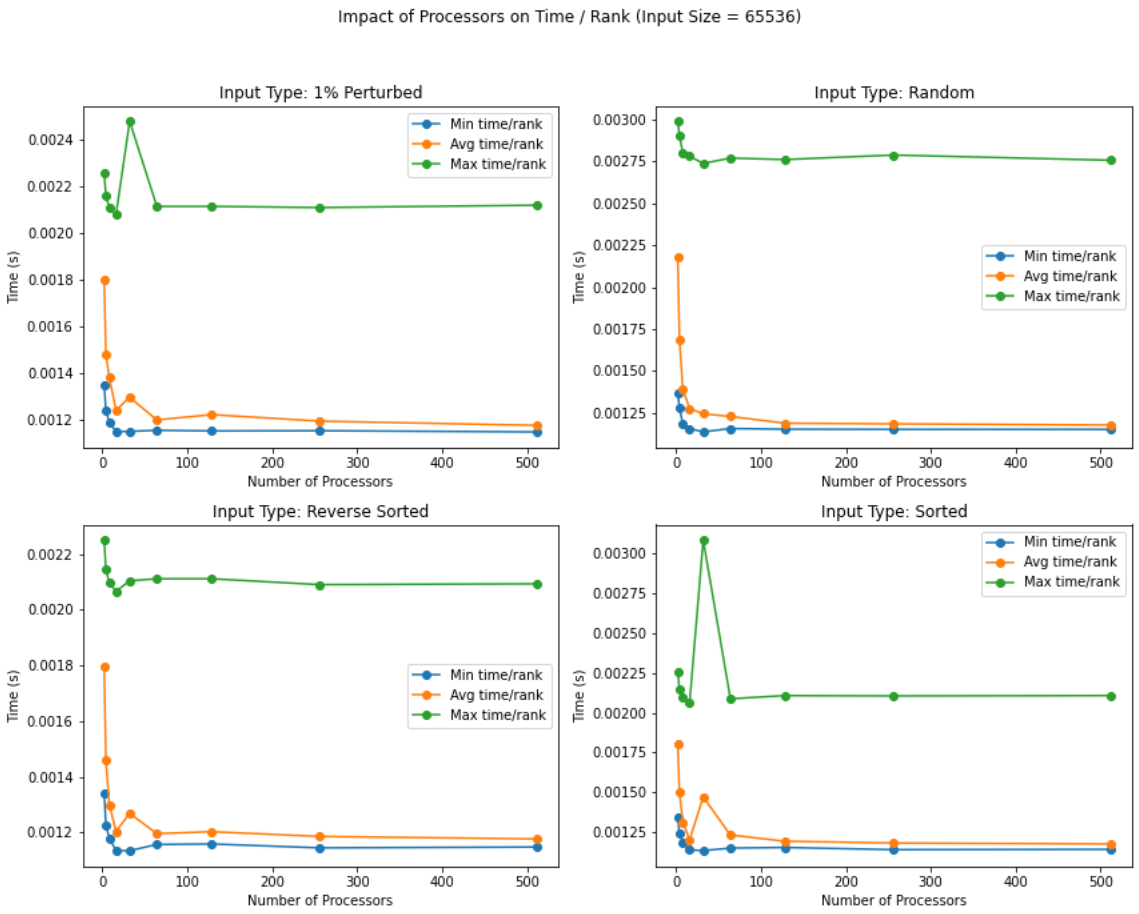
As we can see from the plots, the computation time by rank scales down negative exponentially as expected when we scale up the number of processors. This is because the bitonic sort implementation recursively divides the computational load between processors such that each only has to manage an even subarray.

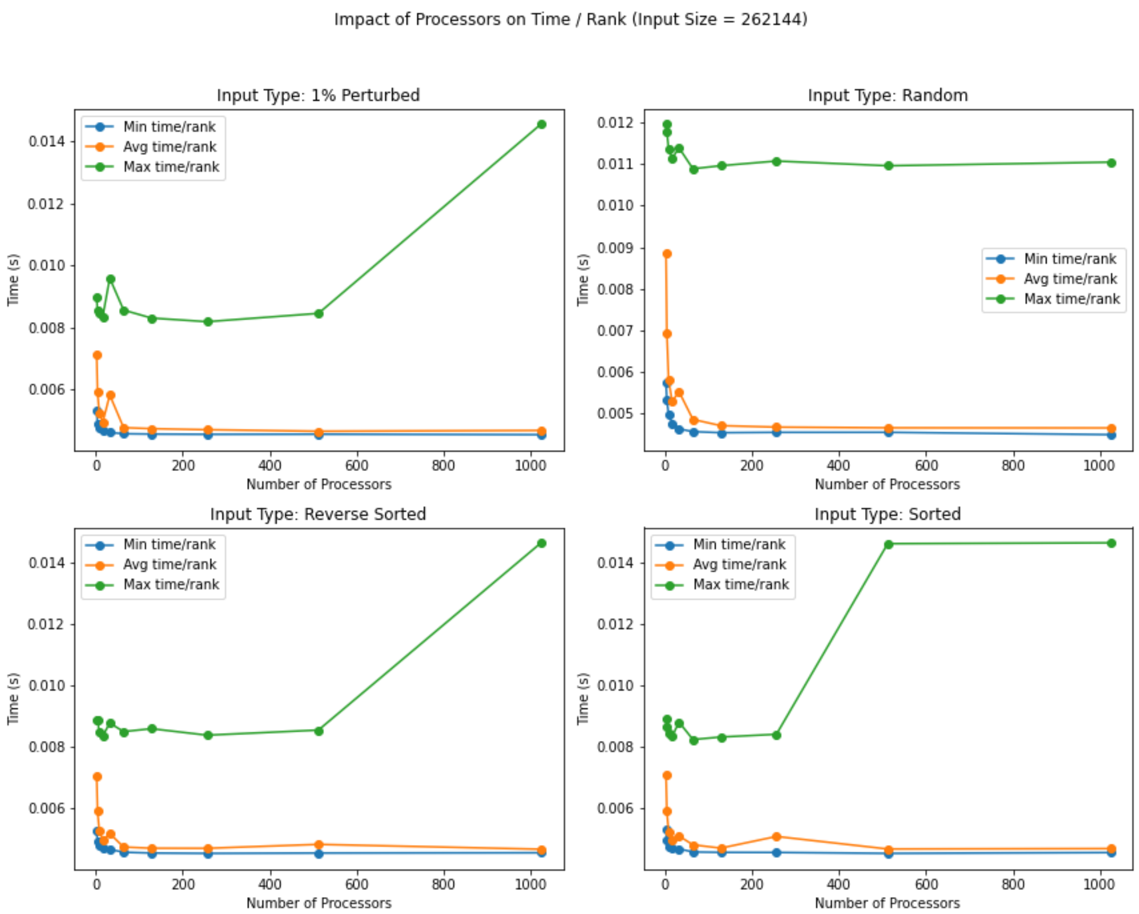
We also see that as we increase the input size, the exponential speedup by number of processes is maintained, while our total time does increase. This is expected as greater array sizes means increased computational costs per processor, additional memory allocation, and more data that needs to be communicated between processes.

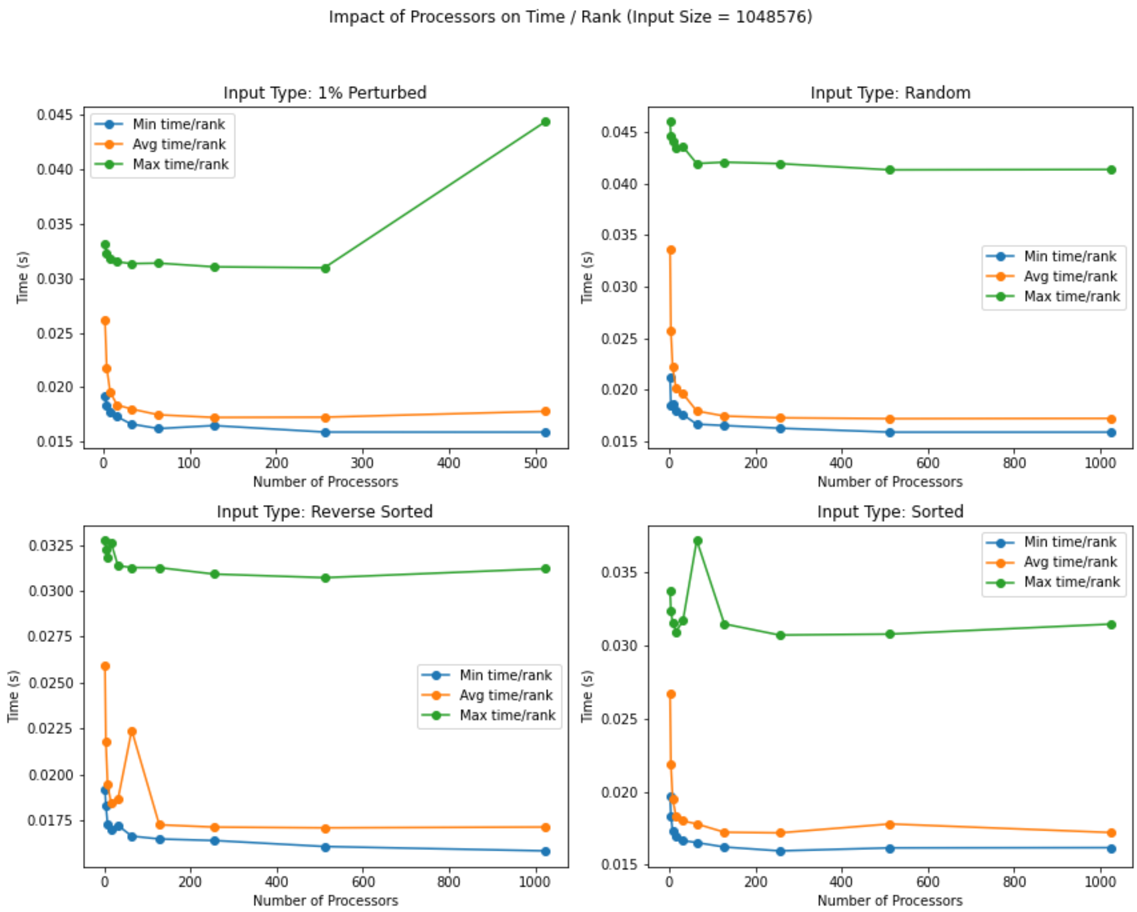
Another good indication is that the variance in computational time between processes likewise displays an exponential decay as we ramp up the number of processors. This is good news as it indicates this approach is evenly distributing the workload among processors. The key factor in this is the parallel merging algorithm I implemented that utilizes partner processes to hierarchically merge the locally sorted subarrays, trickling up into the master process's final sorted array.

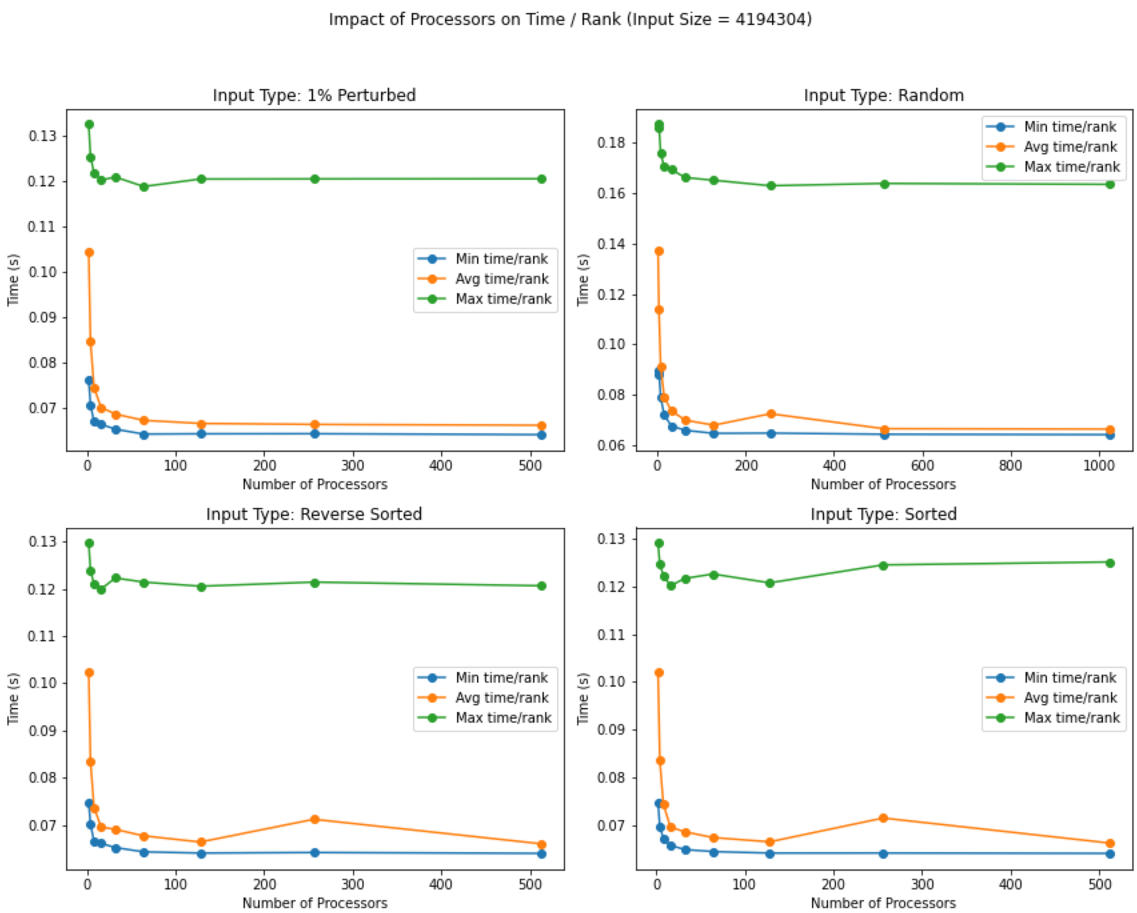
Overall, the scalability of this approach is definitely quite strong as we ramp up the number of processors and exponentiate our input size, but there is definitely still room for improvement on cutting down communication costs and complexities.

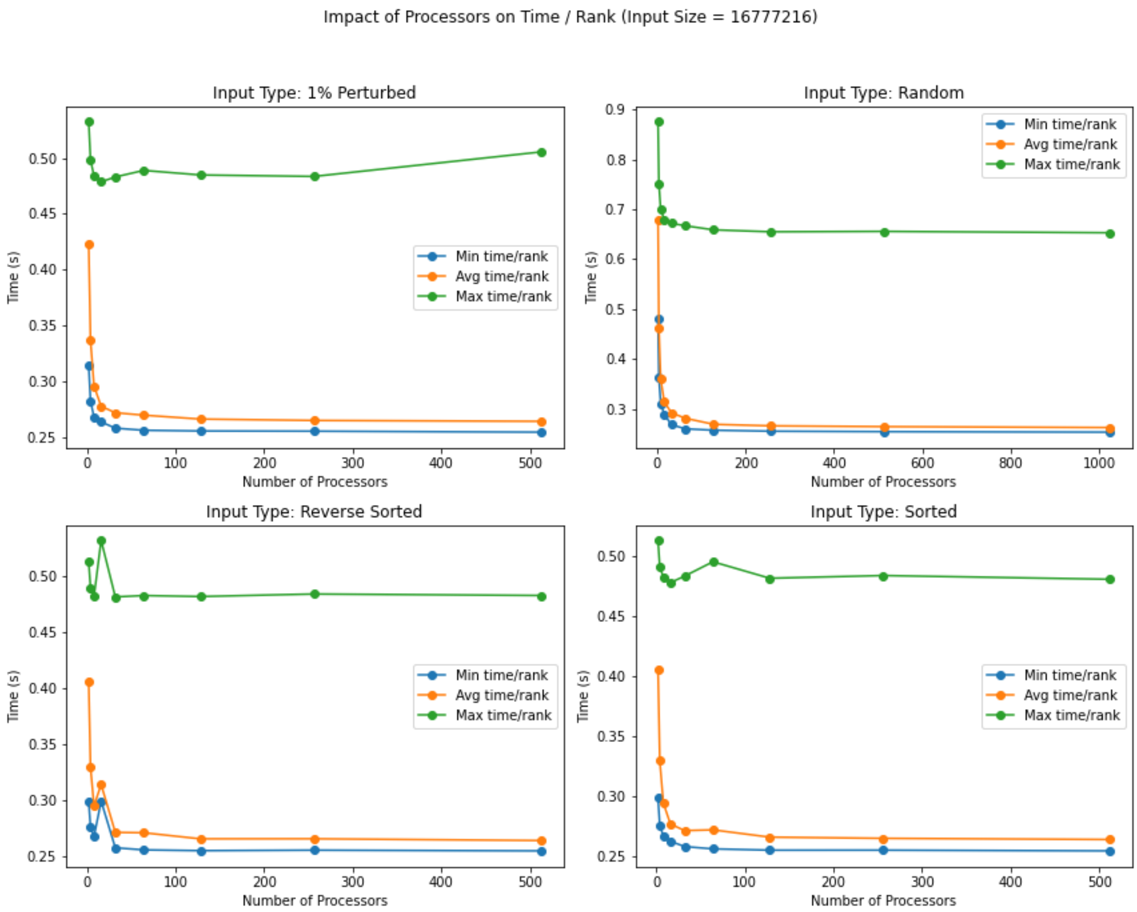
Radix Sort Plots:

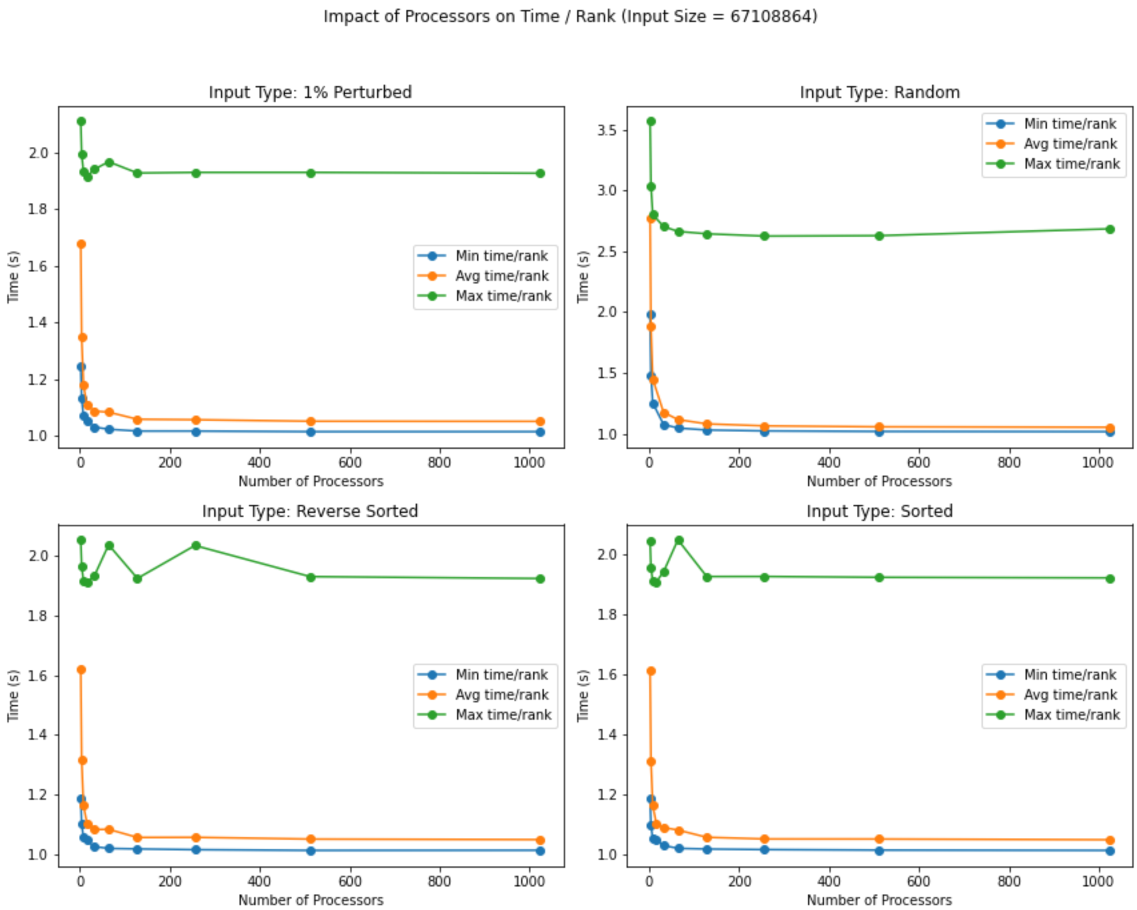

Impact of Processors on Time / Rank (Input Size = 65536)
Input Type: 1% Perturbed
Input Type: Random
Input Type: Reverse Sorted
Input Type: Sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors

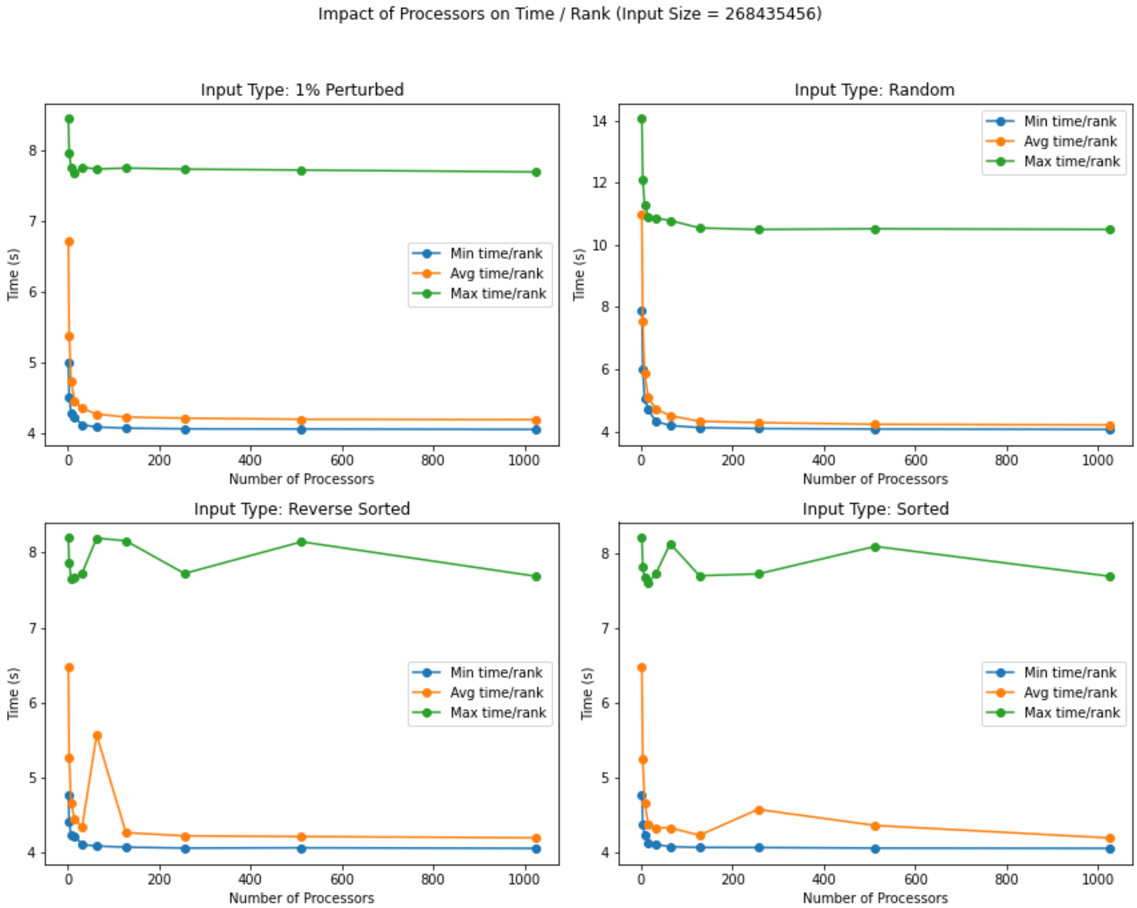

Impact of Processors on Time / Rank (Input Size = 262144)
Input Type: 1% Perturbed
Input Type: Random
Input Type: Reverse Sorted
Input Type: Sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors


Impact of Processors on Time / Rank (Input Size = 1048576)
Input Type: 1% Perturbed
Input Type: Random
Input Type: Reverse Sorted
Input Type: Sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors


Impact of Processors on Time / Rank (Input Size = 4194304)
Input Type: 1% Perturbed
Input Type: Random
Input Type: Reverse Sorted
Input Type: Sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors


Impact of Processors on Time / Rank (Input Size = 16777216)
Input Type: 1% Perturbed
Input Type: Random
Input Type: Reverse Sorted
Input Type: Sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors

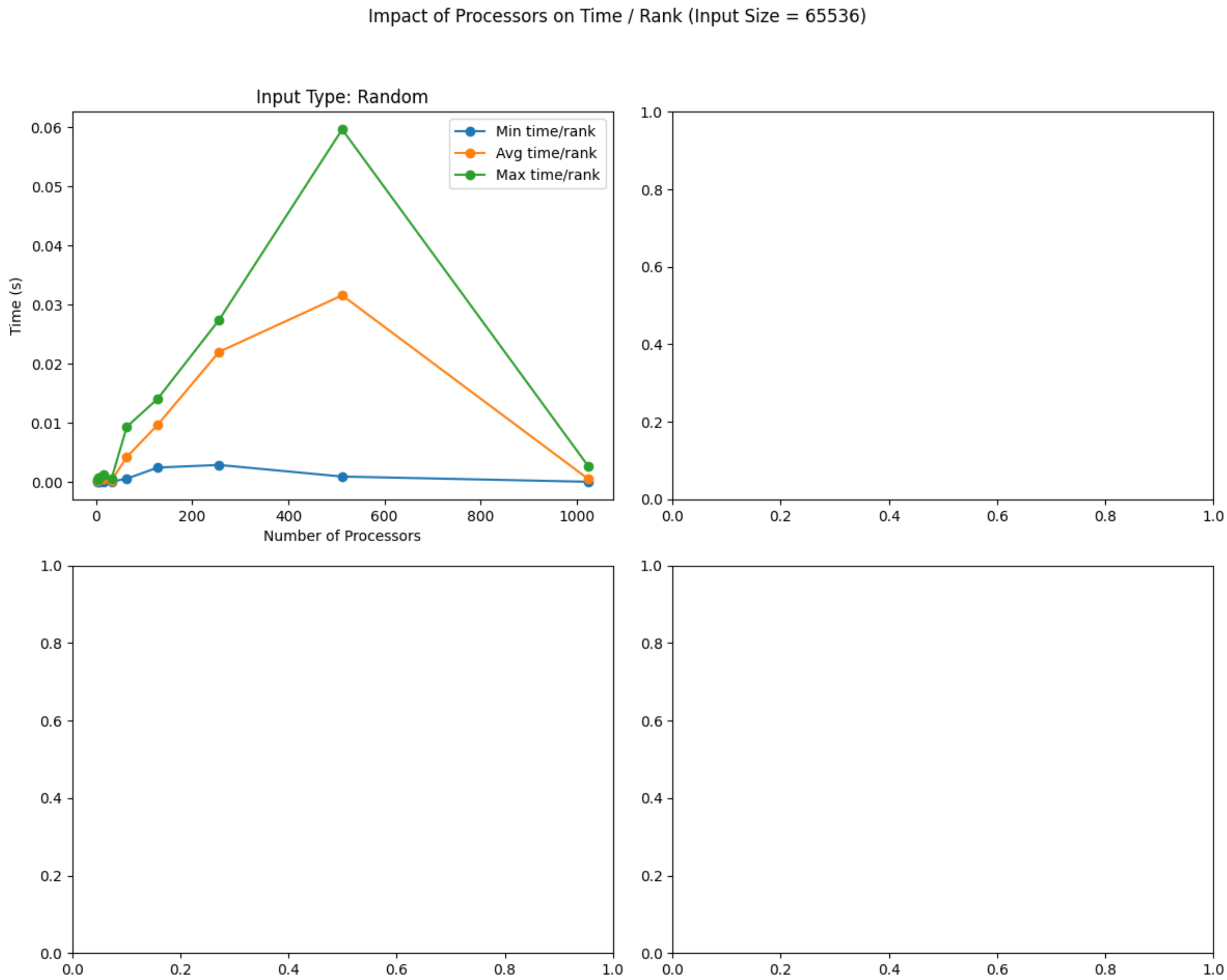

Impact of Processors on Time / Rank (Input Size = 67108864)
Input Type: 1% Perturbed
Input Type: Random
Input Type: Reverse Sorted
Input Type: Sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors

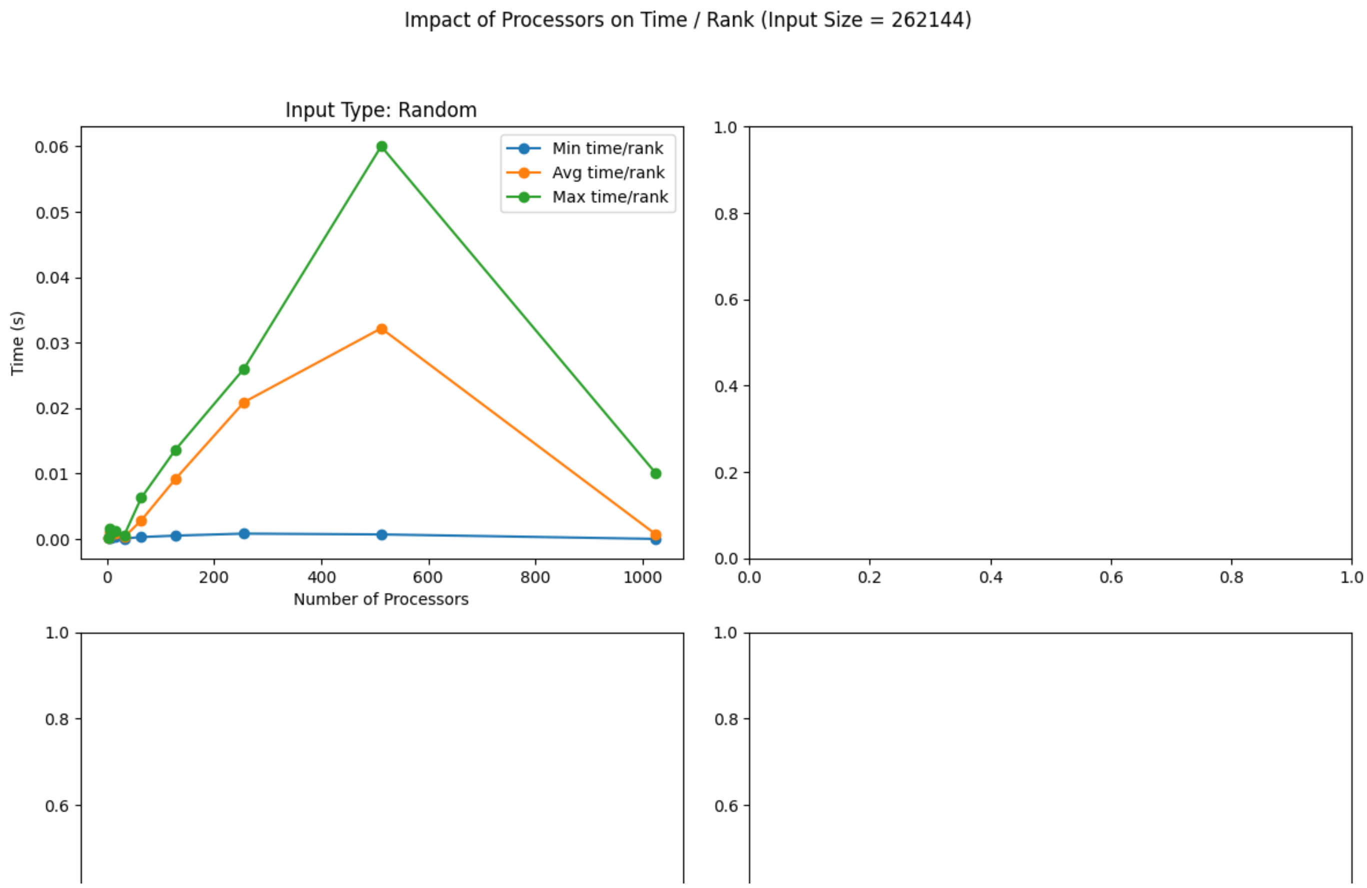


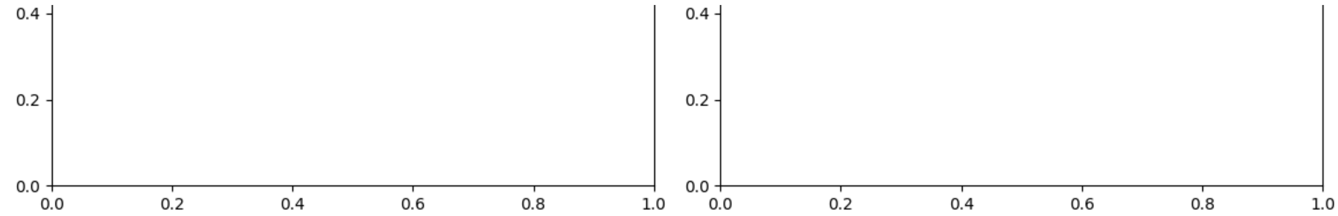
Generally speaking, we can see that the computation time of radix sort follows a negative exponential trend as the number of processors increase. However, the time difference between the varying number of processors are not as significant as others, nor is the trendline. This is because radix sort is more of a counting sort, performing linearly rather than logarithmically. Still, the trend follows this negative exponential curve since the increasing number of processors allow for smaller chunk sizes for each processor.

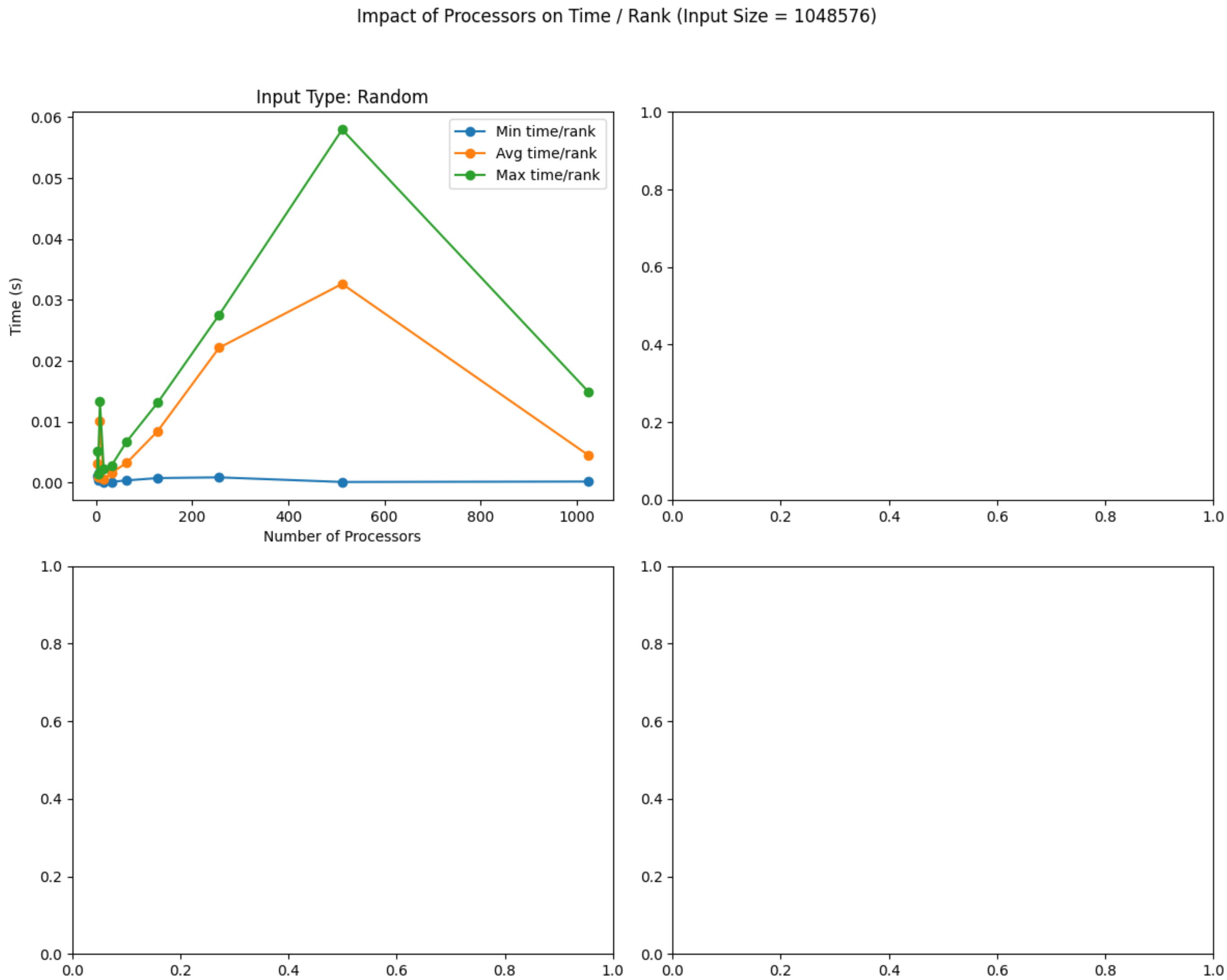
When looking at the total time, we can clearly see that there is a extreme positive linear relationship between the total time and number of processors for every input size. This indicates a weak scaling algorithm because as you add more processors and increase the problem size proportionally, the computation time should ideally remain stable or increase only slightly due to communication overhead.

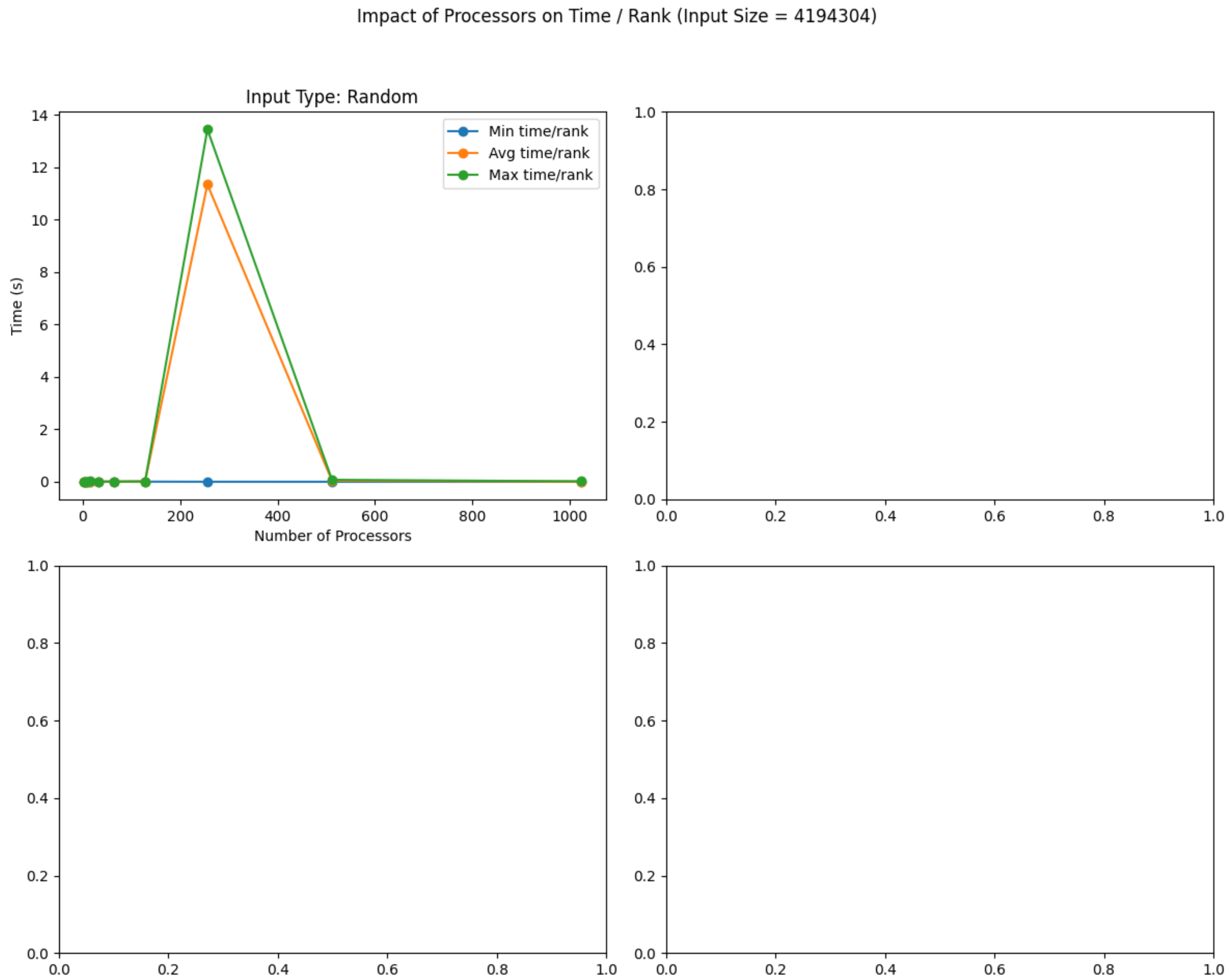
Merge Sort Plots:

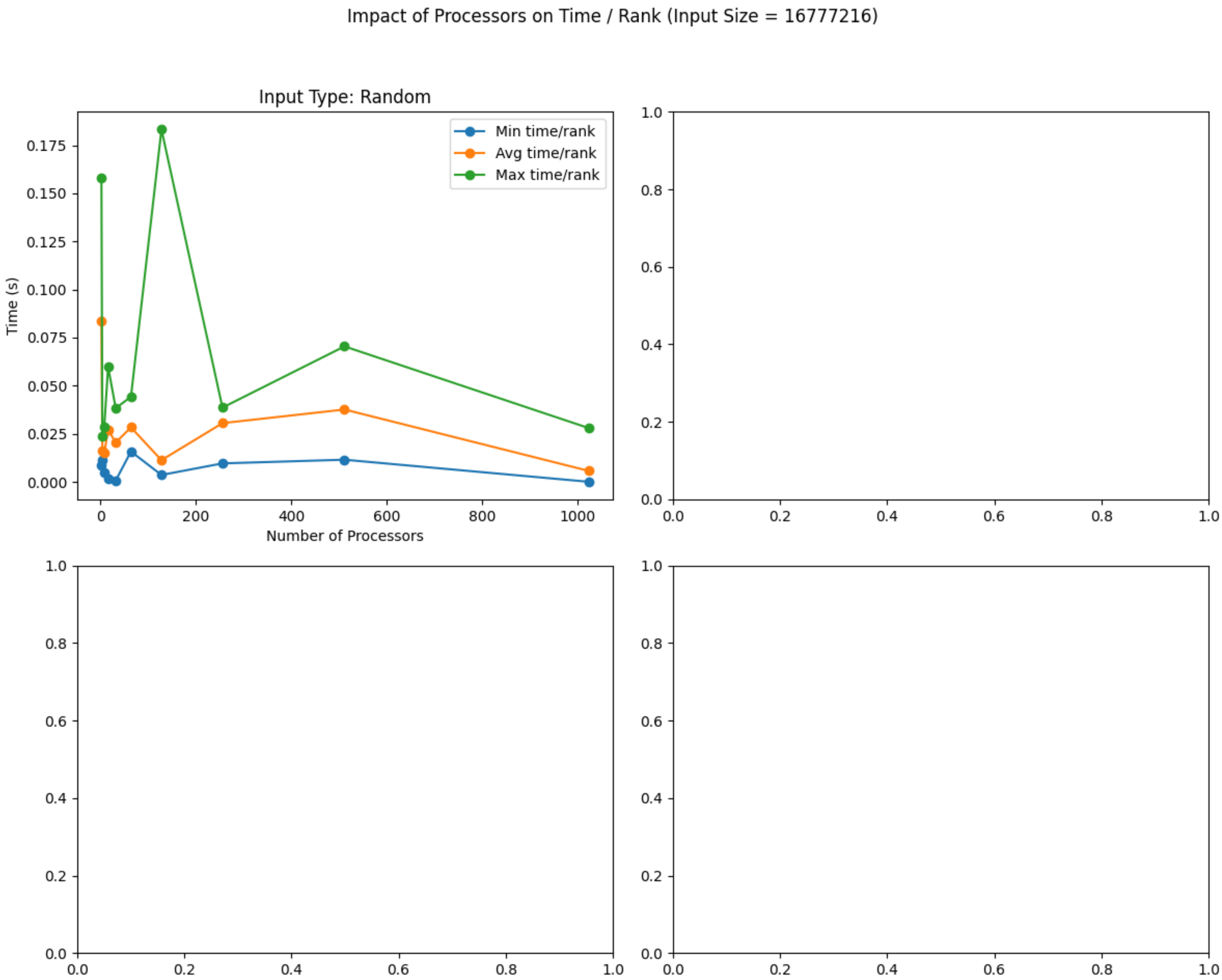

Impact of Processors on Time / Rank (Input Size = 65536)
Input Type: Random
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors

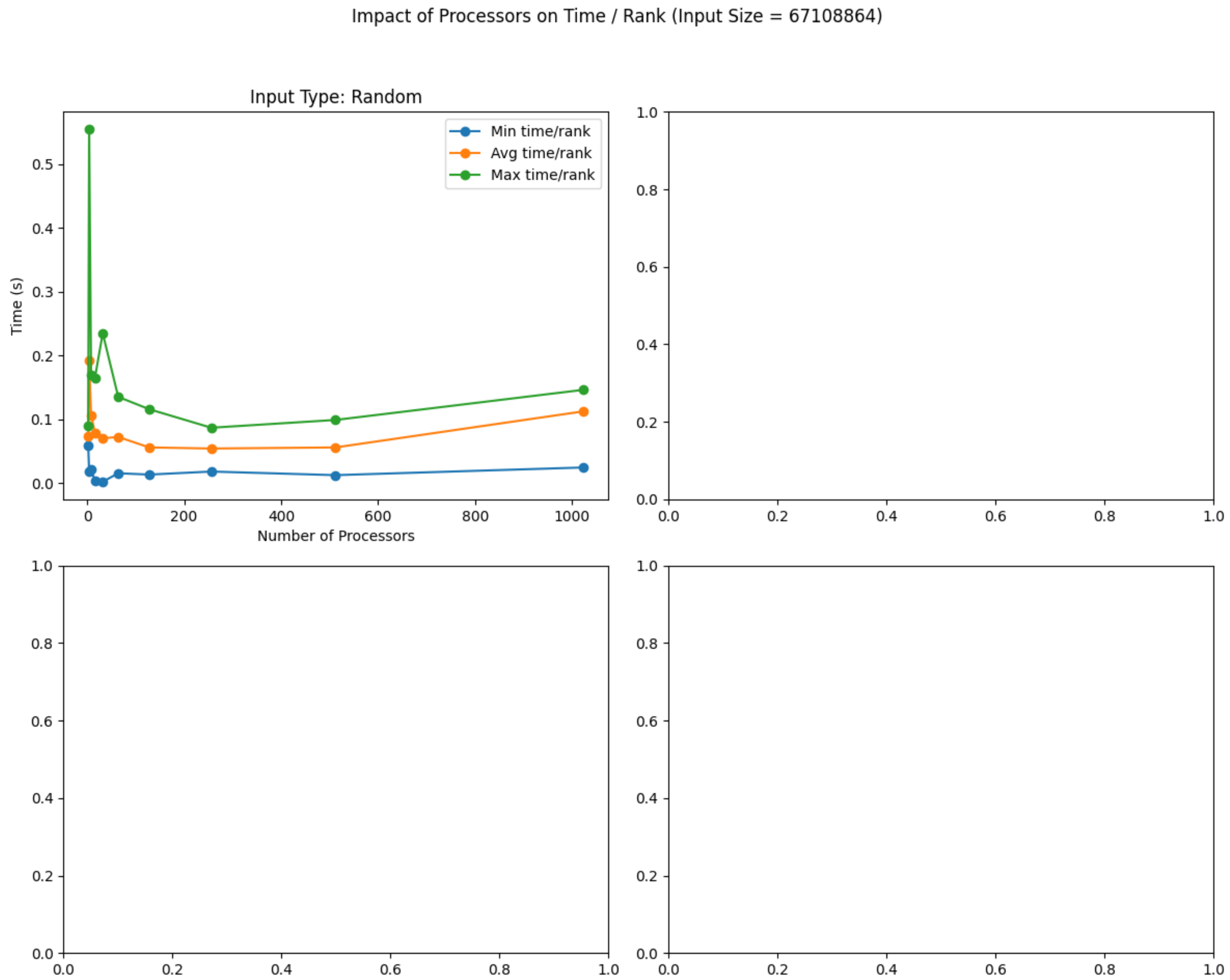

Impact of Processors on Time / Rank (Input Size = 262144)
Input Type: Random
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors

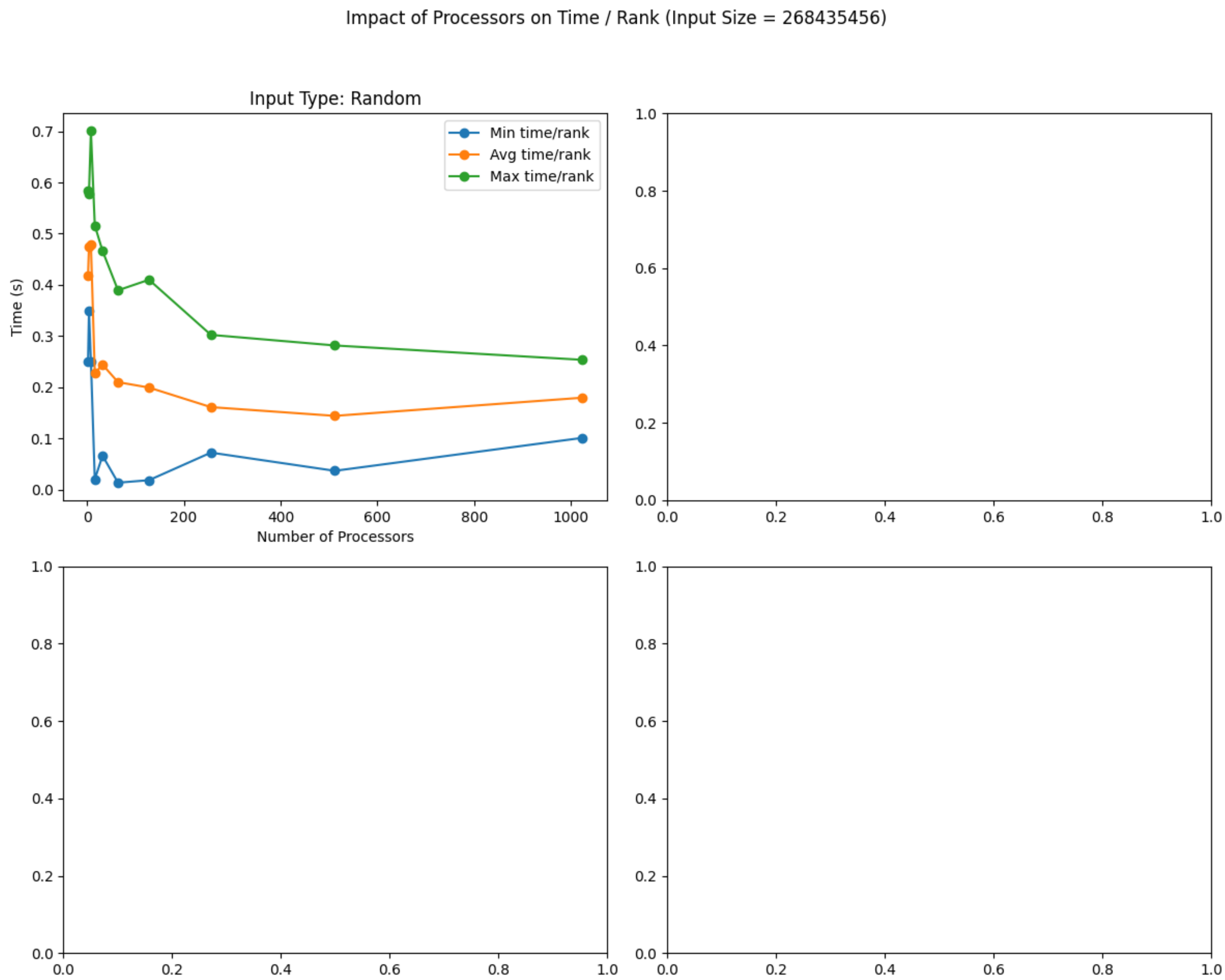



Impact of Processors on Time / Rank (Input Size = 1048576)
Input Type: Random
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors


Impact of Processors on Time / Rank (Input Size = 4194304)
Input Type: Random
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors

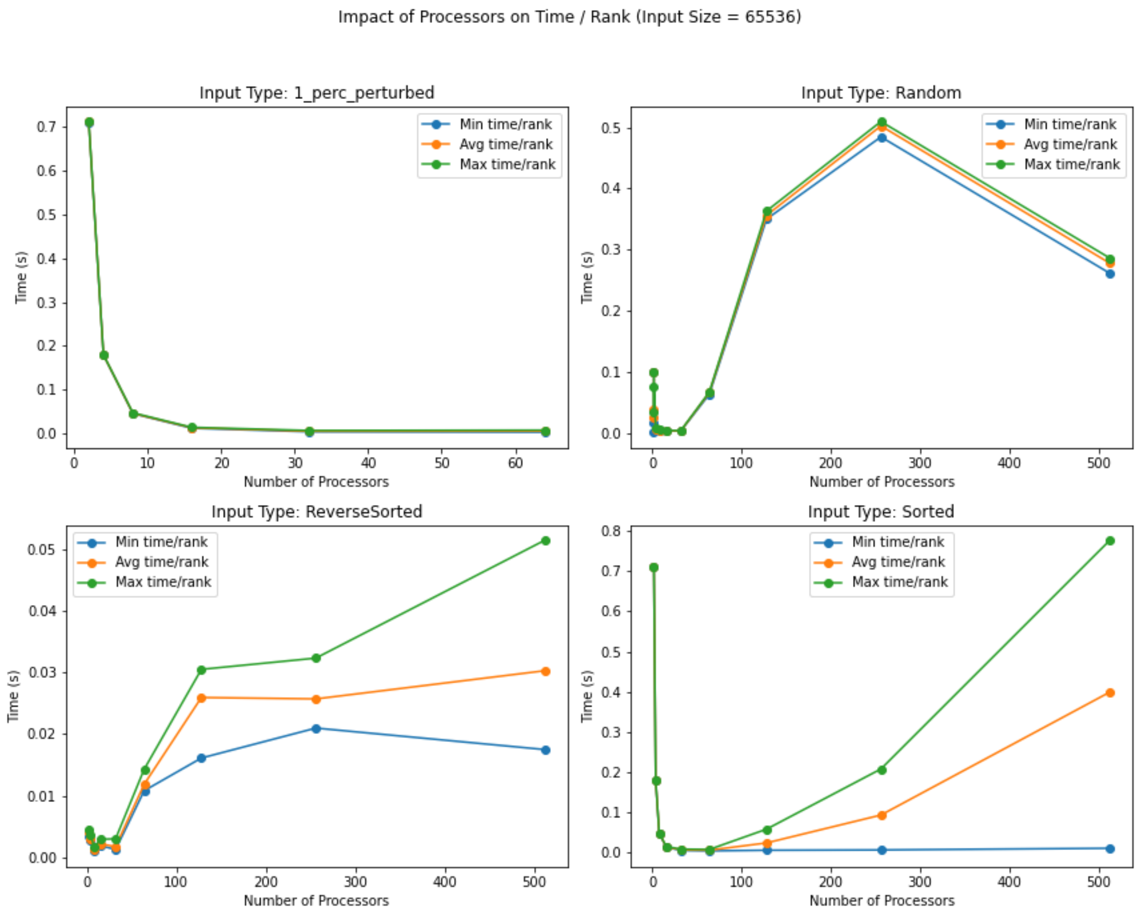

Impact of Processors on Time / Rank (Input Size = 16777216)
Input Type: Random
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors

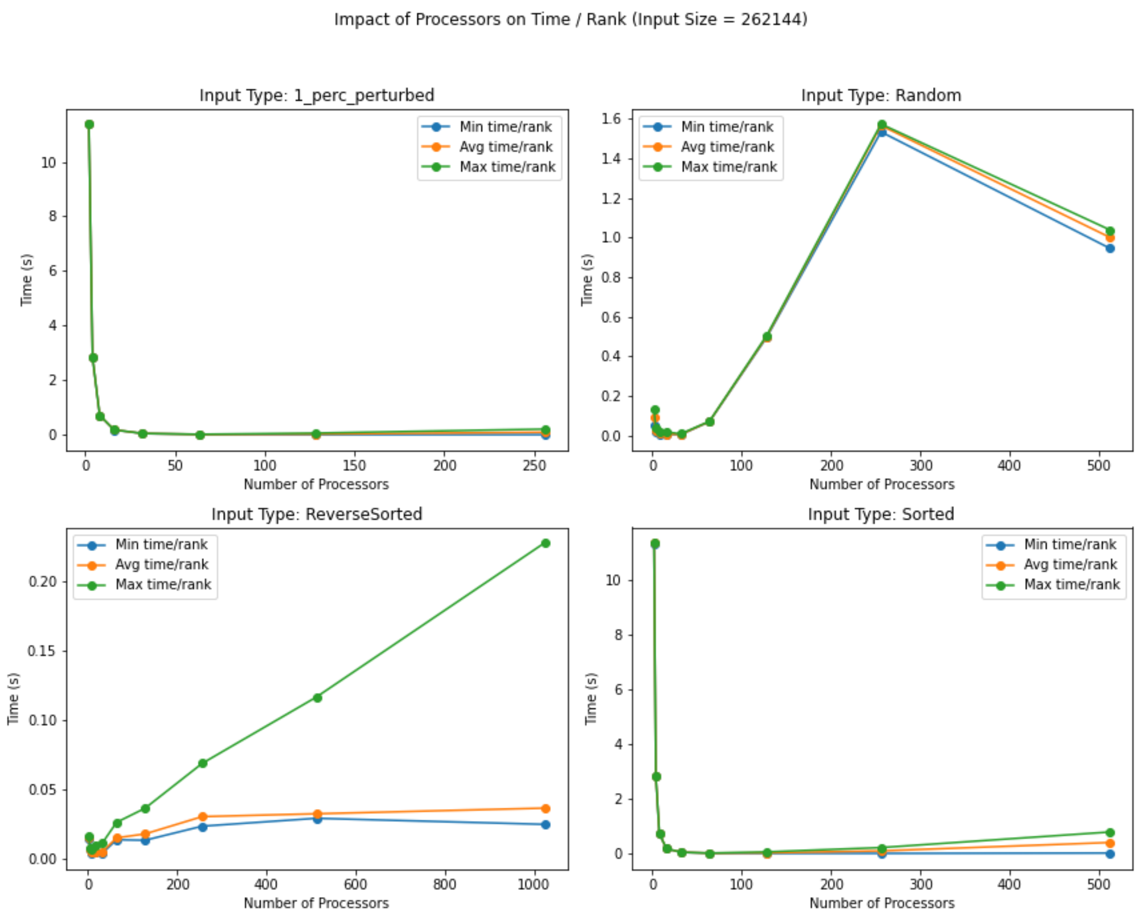

Impact of Processors on Time / Rank (Input Size = 67108864)
Input Type: Random
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors

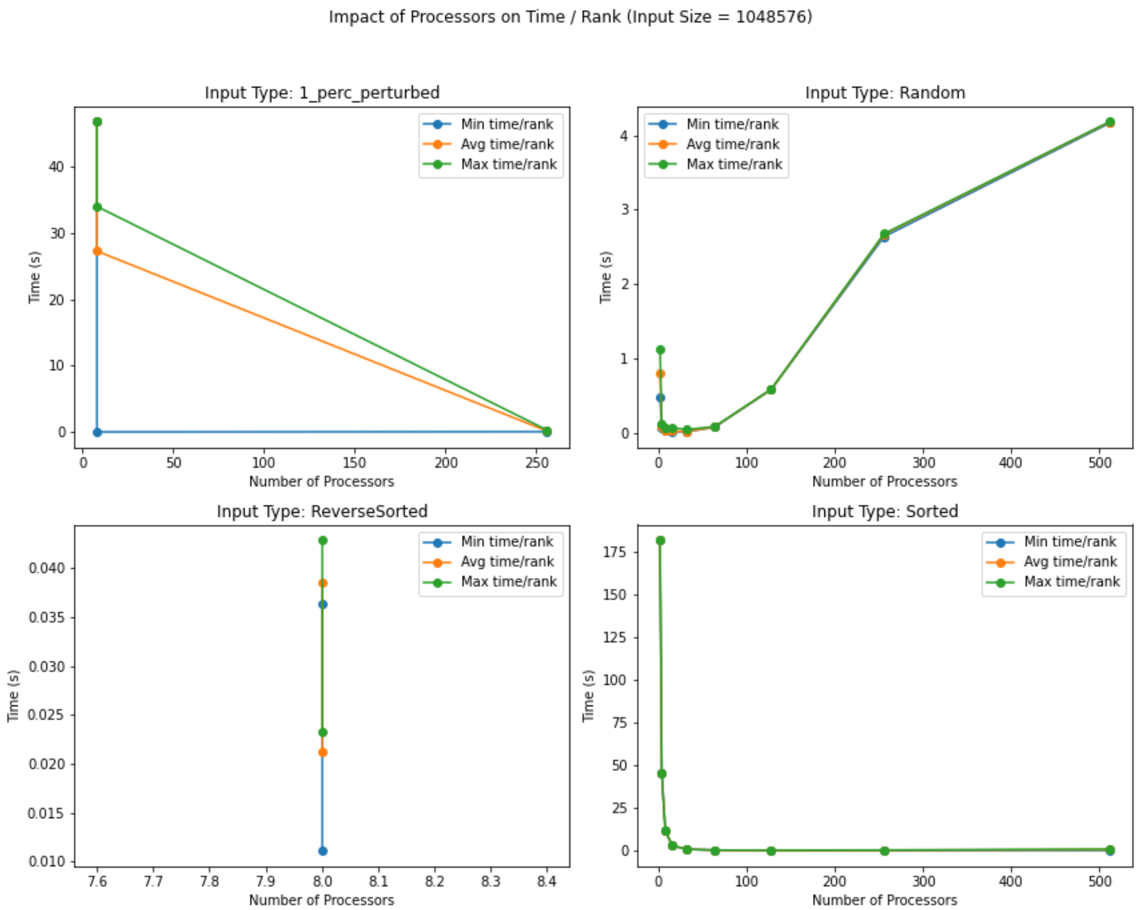


As the number of processes increases, the computational time decreases exponentially with respect to the number of processors. Conceptually, this makes sense because merge sort is a divide-and-conquer sorting algorithm. When there are more processors and the computational workload is distributed evenly, individual processors will do less computational work.

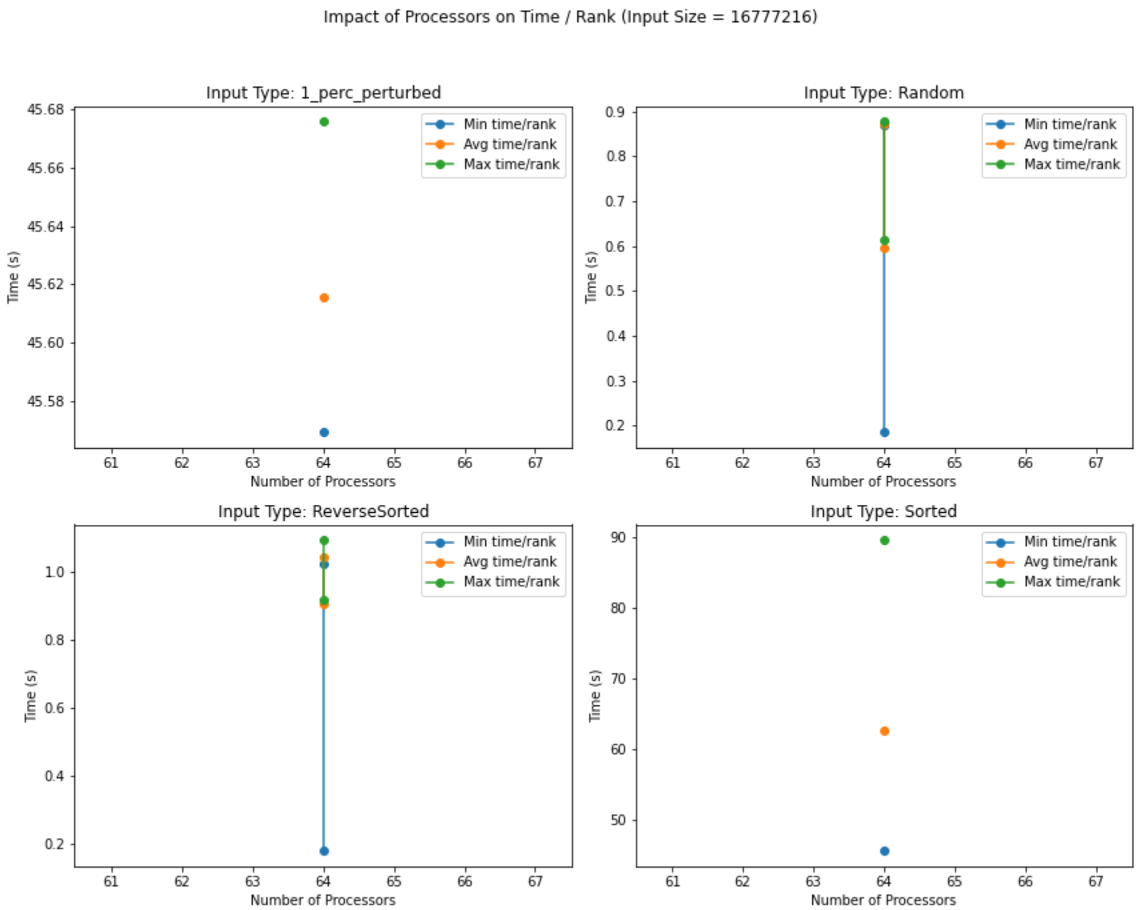
Sample Sort Plots:


Impact of Processors on Time / Rank (Input Size = 65536)
Input Type: 1_perc_perturbed
Input Type: Random
Input Type: ReverseSorted
Input Type: Sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors

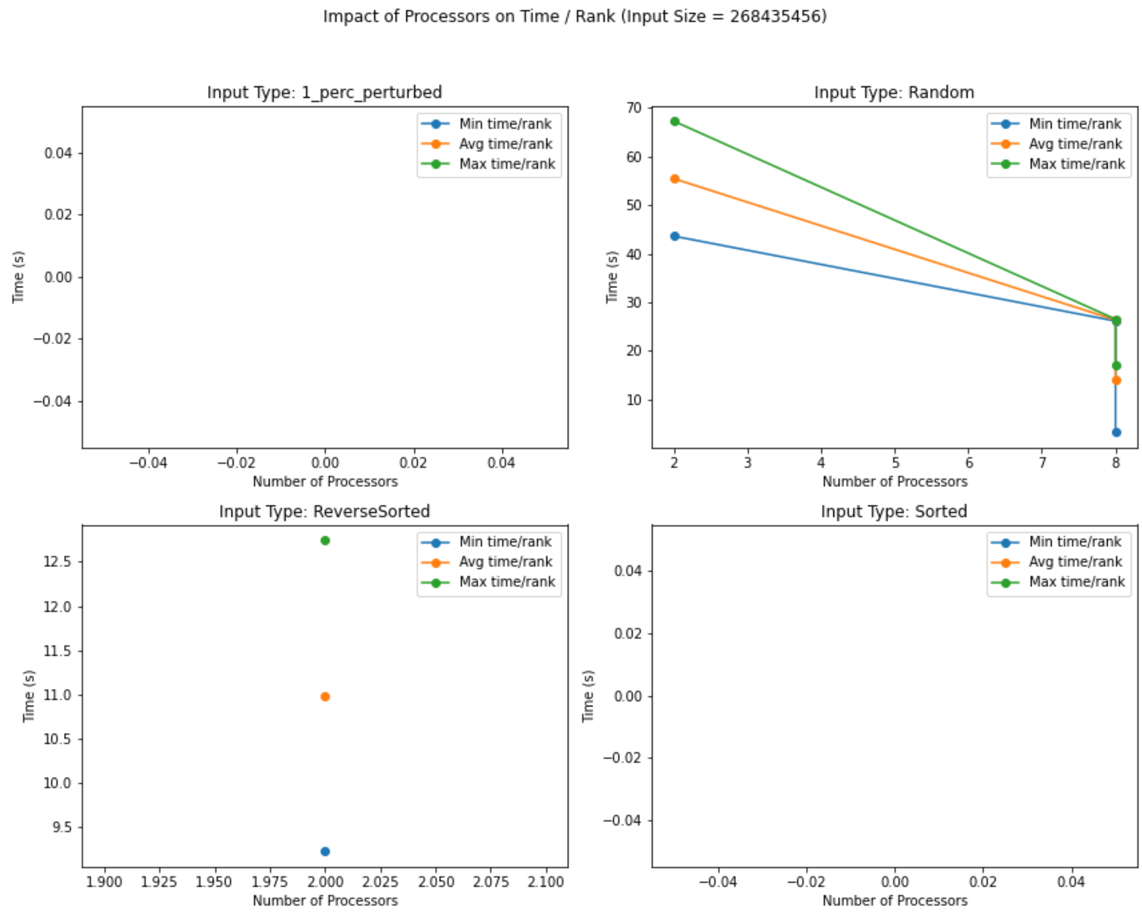

Impact of Processors on Time / Rank (Input Size = 262144)
Input Type: 1_perc_perturbed
Input Type: Random
Input Type: ReverseSorted
Input Type: Sorted
Min time/rank
Avg time/rank
Max time/rank
Time (s)
Number of Processors



sample Sort: Number of Processors vs. Time / Rank (Input Size=4194304)



sample Sort: Number of Processors vs. Time / Rank (Input Size=67108864)



The algorithm still times out and takes much longer than expected for large numbers of processes and/or sorted or perturbed input values. This along with some network issues and other possibly related errors caused a lot of jobs to not run and the data to look unexpected. On the other hand, some plots look sort of reasonable such as the plot for 2^16 for perturbed and sorted. These feature an exponentially decreasing function which seems reasonable. These unexpected trends will hopefully be fixed with a new revision of the sample sort implementation.

5. Presentation

Plots for the presentation should be as follows:

- For each implementation:
  - For each of comp_large, comm, and main:
    - Strong scaling plots for each input_size with lines for input_type (7 plots - 4 lines each)
    - Strong scaling speedup plot for each input_type (4 plots)
    - Weak scaling plots for each input_type (4 plots)

Analyze these plots and choose a subset to present and explain in your presentation.

6. Final Report

Submit a zip named `TeamX.zip` where `X` is your team number. The zip should contain the following files:

- Algorithms: Directory of source code of your algorithms.
- Data: All `.cali` files used to generate the plots seperated by algorithm/implementation.
- Jupyter notebook: The Jupyter notebook(s) used to generate the plots for the report.
- Report.md