CSCE 435 Group project

0. Group number: 3

1. Group members:

1. Anjali Hole
2. Yahya Syed
3. Kyle Bundick
4. Peter Schlenker
5. Harsh Gangaramani

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

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

- **Bitonic Sort (Peter)**: A divide-and-conquer algorithm implemented using MPI that sorts data into many bitonic sequences (the first half only increasing, the second half only decreasing). It then creates alternating increasing and decreasing sequences out of the bitonic sequences to create half as many bitonic sequences, but twice the size. It keeps repeating this process until there is one large bitonic sequence left, at which point it creates one final increasing sequence. For the parallel version I'm implementing, instead of one value each process will keep a sorted list, and when two processes compare lists the smaller sequence will hold a sorted list where all the elements are smaller than the elements in the bigger sequence.
- **Sample Sort (Kyle)**: A divide-and-conquer algorithm implemented in MPI that splits the data into buckets based on data samples, sorts the buckets, and then recombines the data.
- **Merge Sort (Anjali)**: A parallel divide-and-conquer algorithm implemented using MPI for efficient data distribution and merging where each process independently sorts a portion of the data, and MPI coordinates the merging of subarrays across multiple processors on the Grace cluster.
- **Radix Sort (Yahya)**: A divide-and-conquer algorithm implemented with MPI that sorts an array of integers digit by digit, using a counting sort for each digit instead of direct comparisons to determine sorted order. Data distribution is determined by number values, with each process responsible for a certain range of values.
- **Column Sort (Harsh)**: A multi-step matrix manipulation algorithm implemented using MPI that sorts a matrix by its columns, redistributes it through a series of transpositions, and applies strategic global row shifts

Team Communication

- Team will communicate via Discord (for conferencing/meeting)
- Team will use the GitHub repo for reports, and Google Drive to share generated graphs/ report details

What versions do you plan to compare:

Communication strategies:

```
a. Point-to-point communication (as shown in the pseudocode)
b. Collective communication (using MPI_Allgather or MPI_Alltoall)
```

Parallelization strategies:

```
a. SPMD (Single Program, Multiple Data) as shown in the pseudocode
b. Master/Worker model
```

2b. Pseudocode for each parallel algorithm

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

Bitonic Sort

```
// Assumes the total list size is a power of 2, and that comm_size is a power or 2 less than or equal to the list size, and that local_data size times comm_size is the total list size
function bitonic_sort(local_data, comm_size, rank):
    local_data = sequential_sort(local_data)

    for level = 0 to log2(comm_size) - 1:
        is_increasing = !rank.bit(level + 1)

        for current_bit = level to 0:
            other_rank = rank.flip_bit(current_bit)

            // While the data lives on two processes, only one needs to do the comparison.
            // For now the lower rank process will always do the comparison, though it might speed up the algorithm if we try to balance who does the comparison more evenly.
            is_doing_comparison = rank < other_rank
            if (is_doing_comparison):
                other_data = MPI_Recv(other_rank)

                (smaller_half, larger_half) = merge(local_data, other_data)

                if (is_increasing):
                    local_data = smaller_half
                    MPI_Send(larger_half, other_rank)
                else:
                    local_data = larger_half
                    MPI_Send(smaller_half, other_rank)
            else:
                MPI_Send(local_data, other_rank)
                local_data = MPI_Recv(other_rank)

    return local_data

// Assumes data1 and data2 are the same size
function merge(data1, data2):
    array_size = sizeof(data1)

    lower_half = array size of array_size
    upper_half = array size of array_size

    index1 = index2 = 0

    while (index1 < array_size && index2 < array_size):
        output_index = index1 + index2
        choose_data1 = data1[index1] < data2[index2]

        if (choose_data1):
            value = data1[index1]
            index1++
        else:
            value = data2[index2]
            index2++

        if (output_index < array_size):
            lower_half[output_index] = value
        else:
            upper_half[output_index - array_size] = value

    // by this point we are guaranteed to be filling upper_half, since we have completely gone through one of the
input arrays
    while (index1 < array_size):
        output_index = index1 + index2
        upper_half[ouput_index - array_size] = data1[index1]
        index1++

    while (index2 < array_size):
        output_index = index1 + index2
        upper_half[ouput_index - array_size] = data2[index2]
        index2++

    return (lower_half, upper_half)

function main():
    // Initialize MPI
    MPI_Init()
    comm_size = MPI_Comm_size(MPI_COMM_WORLD)
    rank = MPI_Comm_rank(MPI_COMM_WORLD)

    // Get local data
    local_data = read_or_generate_data(rank, comm_size)

    // Sort
    local_data = bitonic_sort(local_data, comm_size, rank)

    // Verify
    verify_sorted(local_data, comm_size, rank)

    // End program
    MPI_Finalize()
```

MPI calls to be used:

```
MPI_Init()
MPI_Comm_size()
MPI_Comm_rank()
MPI_Send()
MPI_Recv()
MPI_Finalize()
```

Other functions:

```
sequential_sort(data) - exact algorithm isn't relevant
integer.bit(n) - get the value of the nth bit of the integer as a bool
integer.flip_bit(n) - returns an integer with the same bits, except the nth bit is flipped
read_or_generate_data(rank, comm_size) - data generation function used for each sorting algorithm (to be implemented later)
verify_sorted(local_data, comm_size, rank) - function to verify local data is sorted and that this sequence is smaller than the one stored in the next highest rank (to be implemented later)
```

Sample Sort

```
function main(data, data_size, oversample_factor):

    MPI_Init()
    rank = MPI_Comm_rank(MPI_COMM_WORLD)
    size = MPI_Comm_size(MPI_COMM_WORLD)

    for sample = 0 to oversample_factor - 1
        samples.add(data.get_random_element())

    MPI_Gather(source = samples, count = oversample_factor, dest = oversample, root = MASTER)
    if (rank == MASTER):
        sort(oversample)
        splitters[0] = -inf
        for sample = 1 to size - 1:
            splitters[sample] = oversample[sample * oversample_factor]
        splitters[size] = inf
    MPI_Bcast(splitters)

    for each in data:
        choose bucket | splitters[bucket] < bucket && splitters[bucket + 1] > bucket

    for process = 0 to size - 1:
        if process == rank:
            for process = 0 to size - 1:
                Recv(new_data.end, process)
        Send(buckets[process], process)

    local_data = new_data
    sort(local_data)

    MPI_Finalize()
```

MPI calls to be used:

```
MPI_Init()
MPI_Comm_size()
MPI_Comm_rank()
MPI_Gather()
MPI_Bcast()
MPI_Send()
MPI_Recv()
MPI_Finalize()
```

Merge Sort

```
function parallel_merge_sort(local_data, comm_size, rank):

    // Sort local data using sequential merge sort
    local_data = sequential_merge_sort(local_data)

    // Parallel merge phase
    for step = 1 to log2(comm_size):
        partner = rank XOR (1 << (step - 1))  // Find the partner process
        if rank < partner:
            // Send local data to the partner and receive its data
            MPI_Send(local_data, partner)
            received_data = MPI_Recv(partner)
            // Merge local and received data
            local_data = merge(local_data, received_data)
        else:
            // Send local data to the partner and receive its data
            MPI_Send(local_data, partner)
            received_data = MPI_Recv(partner)
            // Merge received data first to maintain order
            local_data = merge(received_data, local_data)

    return local_data

function main():

    // Initialize MPI
    MPI_Init()
    comm_size = MPI_Comm_size(MPI_COMM_WORLD)  // Get number of processes
    rank = MPI_Comm_rank(MPI_COMM_WORLD)       // Get process rank

    // Read or generate local data (each process generates or receives its own data)
    local_data = read_or_generate_data(rank, comm_size)

    // Perform parallel merge sort
    sorted_local_data = parallel_merge_sort(local_data, comm_size, rank)

    // Gather all sorted data at root process
    if rank == 0:
        global_sorted_data = MPI_Gather(sorted_local_data, root=0)
    else:
        MPI_Gather(sorted_local_data, root=0)

    // Finalize MPI
    MPI_Finalize()
```

MPI calls to be used:

```
MPI_Init()
MPI_Comm_size()
MPI_Comm_rank()
MPI_Send()
MPI_Recv()
MPI_Gather()
MPI_Finalize()
```

Radix Sort

```
// Function to do simple counting sort by the digit place specified by exp
function counting_sort(int arr, int n, int exp):
    output is array size n
    count is array of size 10

    for i from 0 to n:
        count[(arr[i] / exp) % 10]++

    for i from 1 to 10:
        count[i] += count[i - 1];

    for i from n-1 to 0:
        output[count[(arr[i] / exp) % 10] - 1] = arr[i];
        count[(arr[i] / exp) % 10]--;


    for i from 0 to n:
        arr[i] = output[i];


function radix_sort(local_data, local_size, comm_size, rank)
    // Transfer data between processes such that each process has a correct range of values
    local_max = max value of local_data
    local_min = min value of local_data

    // get global max and min values to determine split of numbers
    int global_max, global_min;
    MPI_Allreduce(&local_max, &global_max, 1, MPI_INT, MPI_MAX, MPI_COMM_WORLD);
    MPI_Allreduce(&local_min, &global_min, 1, MPI_INT, MPI_MIN, MPI_COMM_WORLD);

    send_counts, send_offsets, recv_counts, recv_offsets are arrays of size comm_size

    // calculate the range of values that each process will receive and send
    range_size = (global_max - global_min + 1) / comm_size;

    // vector to determine which data gets sent to which process
    vector<vector<int>> buckets(comm_size);
    for i from 0 to local_size:
        value = local_data[i];
        target_process = (value - global_min) / range_size;
        if target_process >= comm_size:
            target_process = comm_size - 1;
        buckets[target_proc].push_back(value);

    // send the data to all processes
    total_send = 0;
    for i from 0 to comm_size:
        send_counts[i] = buckets[i].size();
        send_offsets[i] = total_send;
        total_send += send_counts[i];

    send_data is array of size total_send
    index = 0;
    for i from 0 to comm_size:
        for j from 0 to buckets[i].size()
            send_data[index++] = buckets[i][j];

    MPI_Alltoall(send_counts, 1, MPI_INT, recv_counts, 1, MPI_INT, MPI_COMM_WORLD);

    // receive data from all processes
    total_recv = 0;
    for i from 0 to comm_size:
        recv_offsets[i] = total_recv;
        total_recv += recv_counts[i];

    recv_data is array of size total_recv
    MPI_Alltoallv(send_data, send_counts, send_offsets, MPI_INT, recv_data, recv_counts, recv_offsets, MPI_INT,
MPI_COMM_WORLD);

    // copy received data to local data
    local_size = total_recv;
    copy(recv_data, recv_data + total_recv, local_data);

    // radix sort now that all data are in correct processes
    local_max is max element from local data
    for exp from 1 to local_max / exp > 0, multiplying by 10:
        counting_sort(local_data, total_recv, exp);

function main():
    // initialize MPI
    MPI_Init()
    rank = MPI_Comm_rank()
    size = MPI_Comm_size()

    // provide input and sort
    input is array to sort
    input_size is input size
    radix_sort(input, input_size, rank, size)

    // finalize MPI
    MPI_Finalize()
```

MPI calls to be used:

```
MPI_Init()
MPI_Comm_rank()
MPI_Comm_size()
MPI_Finalize()
MPI_Allreduce()
MPI_Alltoall()
MPI_Alltoallv()
```

Column Sort

```
Function column_sort(local_data, local_data_size, comm_size, rank)
    Begin whole_column_sort

    // Step 1: Sort the local data
    Call sequential_sort(local_data, local_data_size)

    // Step 2: Transpose the matrix
    Initialize send_buf of size local_data_size
    Calculate subbuf_size as local_data_size / comm_size
    For i from 0 to local_data_size
        Calculate target process as i % comm_size
        Calculate target index as (subbuf_size * target process) + (i / comm_size)
        Place local_data[i] into send_buf[target index]
    Call MPI_Alltoall to redistribute send_buf into local_data using subbuf_size blocks
    Delete send_buf

    // Step 3: Sort the transposed data
    Call sequential_sort(local_data, local_data_size)

    // Step 4: "Untranspose" to restore original structure
    Call MPI_Alltoall with MPI_IN_PLACE to transpose data back in-place using subbuf_size blocks

    // Step 5: Sort the data again
    Call sequential_sort(local_data, local_data_size)

    // Step 6: Shift data to right neighboring process
    Initialize shift_buf of size (local_data_size / 2) * comm_size
    Determine half_local_size_ceil as (local_data_size + 1) / 2
    If rank == comm_size - 1
        Set target_rank to 0
    Else
        Set target_rank to rank + 1
    Calculate offset for filling shift_buf as (local_data_size / 2) * target_rank
    For i from half_local_size_ceil to local_data_size
        Place local_data[i] into shift_buf at offset + (i - half_local_size_ceil)
    Initialize receive_buf of same size as shift_buf
    Call MPI_Alltoall to exchange shift_buf into receive_buf using subbuf_size blocks
    If rank == 0
        Set receive_rank to comm_size - 1
    Else
        Set receive_rank to rank - 1
    Calculate receive offset as receive_rank * (local_data_size / 2)
    For i from half_local_size_ceil to local_data_size
        Update local_data[i] from receive_buf at receive offset + (i - half_local_size_ceil)
    Delete shift_buf and receive_buf

    // Step 7: Sort the data unless it's the first process
    If rank != 0
        Call sequential_sort(local_data, local_data_size)

    // Step 8: Reverse the shift done in step 6
    Reinitialize shift_buf and receive_buf
    Prepare data for reverse shift similar to step 6 but in opposite direction
    Call MPI_Alltoall to exchange data for unshifting
    Update local_data based on received data
    Delete shift_buf and receive_buf

    End whole_column_sort
End Function
```

MPI calls to be used

```
MPI_Init()
MPI_Comm_size()
```

```
MPI_Comm_rank()
MPI_Alltoallv()  // Used for transposing the matrix
MPI_Gather()
MPI_Finalize()
```

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

Input:

- Input Sizes
  - 2^{16}
  - 2^{18}
  - 2^{20}
  - 2^{22}
  - 2^{24}
  - 2^{26}
  - 2^{28}
- Input Types:
  - Sorted
  - Sorted with 1% perturbed
  - Random
  - Reverse sorted

Strong scaling (same problem size, increase number of processors/nodes)

- Fix problem size at 2^{24} elements
- Increase number of processors: 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024
- Measure and compare:
  - Total execution time
  - Speedup (T1 / Tn)
  - Parallel efficiency ((T1 / Tn) / n)

Weak scaling (increase problem size, increase number of processors)

- Start with 2^{16} elements per processor
- Increase both problem size and number of processors proportionally
  - (e.g., 2 processors: 2 x 2^{16}, 4 processors: 4 x 2^{16}, etc.)
- Measure and compare:
  - Execution time
  - Parallel efficiency

Performance Metrics (to be measured for all experiments):

- Total execution time
- Communication time
- Computation time
- Memory usage

3a. Caliper instrumentation

Bitonic Sort Calltree

```
0.002 main
├─ 0.000 data_init_runtime
│  └─ 0.000 data_perturbed_init_runtime
│     └─ 0.000 data_init_runtime
├─ 0.001 MPI_Recv
├─ 0.000 MPI_Send
└─ 0.000 correctness_check
   └─ 0.000 comm
      └─ 0.000 comm_small
         ├─ 0.000 MPI_Recv
         └─ 0.000 MPI_Send
0.000 MPI_Finalize
0.000 MPI_Initialized
0.000 MPI_Finalized
0.000 MPI_Comm_dup
```

Sample Sort Calltree

```
1.557 MPI_Comm_dup
0.000 MPI_Finalize
0.000 MPI_Finalized
0.000 MPI_Initialized
2.743 main
├─ 2.141 comp
│  ├─ 0.333 comm
│  │  ├─ 0.318 comm_large
│  │  │  ├─ 0.272 MPI_Recv
│  │  │  └─ 0.022 MPI_Send
│  │  └─ 0.015 comm_small
│  │     ├─ 0.014 MPI_Bcast
│  │     └─ 0.001 MPI_Gather
│  └─ 1.799 comp
│     ├─ 1.799 comp_large
│     └─ 0.000 comp_small
├─ 0.510 correctness_check
│  └─ 0.499 comm
│     └─ 0.498 comm_small
│        ├─ 0.515 MPI_Recv
│        └─ 0.000 MPI_Send
└─ 0.091 data_init_runtime
   └─ 0.091 data_init_runtime
```

Merge Sort Calltree

```
0.009 main
├─ 0.000 data_init_runtime
│  └─ 0.000 data_init_runtime
├─ 0.000 comp
│  ├─ 0.000 comp_large
│  └─ 0.000 comp_small
├─ 0.007 comm
│  ├─ 0.006 comm_small
│  │  └─ 0.006 MPI_Sendrecv
│  └─ 0.001 comm_large
│     ├─ 0.001 MPI_Sendrecv
│     └─ 0.000 MPI_Gather
└─ 0.001 correctness_check
   ├─ 0.001 MPI_Recv
   └─ 0.000 MPI_Send
0.000 MPI_Finalize
0.000 MPI_Initialized
0.000 MPI_Finalized
0.001 MPI_Comm_dup
```

Radix Sort Calltree

```
1.321 main
├─ 0.091 data_init_runtime
│  └─ 0.091 data_init_runtime
├─ 0.049 comm
│  ├─ 0.008 comm_small
│  │  └─ 0.008 MPI_Allreduce
│  └─ 0.040 comm_large
│     ├─ 0.003 MPI_Alltoall
│     └─ 0.037 MPI_Alltoallv
├─ 0.910 comp
│  └─ 0.897 comp_large
└─ 0.021 correctness_check
   └─ 0.011 comm
      └─ 0.011 comm_small
         ├─ 0.011 MPI_Recv
         └─ 0.000 MPI_Send
0.000 MPI_Finalize
0.000 MPI_Initialized
0.000 MPI_Finalized
0.131 MPI_Comm_dup
```

Column Sort Calltree

```
3.962 main
├─ 0.017 data_init_runtime
│  └─ 0.017 data_init_runtime
├─ 2.367 comp
│  └─ 2.367 comp_large
├─ 0.716 comm
│  └─ 0.716 comm_large
│     └─ 0.716 MPI_Alltoall
└─ 0.013 correctness_check
   └─ 0.002 comm
      └─ 0.002 comm_small
         ├─ 0.002 MPI_Recv
         └─ 0.000 MPI_Send
0.000 MPI_Finalize
0.000 MPI_Initialized
0.000 MPI_Finalized
0.003 MPI_Comm_dup
```

3b. Collect Metadata

Bitonic Sort Metadata

Key	Value
cali.caliper.version	2.11.0
mpi.world.size	8
spot.metrics	min#inclusive#sum#time.duration,max#inclusive#sum#time.duration,avg#inclusive#sum#time.duration,sum#inclusive#sum#time.duration,v
spot.timeseries.metrics	
spot.format.version	2
spot.options	time.variance,profile.mpi,node.order,region.count,time.exclusive
spot.channels	regionprofile
cali.channel	spot
spot:node.order	true
spot:output	p8-a2048.cali
spot:profile.mpi	true
spot:region.count	true
spot:time.exclusive	true
spot:time.variance	true
launchdate	1729130249
libraries	[/scratch/group/csce435-f24/Caliper/caliper/lib64/libcaliper.so.2, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/lib/libmpicxx.so.12, /sw/eb/sw/CUDA/12.4.0/extras/CUPTI/lib64/libcupti.so.12, /sw/eb/sw/PAPI/6.0.0-GCCcore-8.3.0/lib/libpapi.so.6.0, /lib64/ld-linux-x86-64.so.2, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libmlx-fi.so, /lib64/libucp.so.0, /sw/eb/sw/zlib/1.2.11-GCCcore-8.3.0/li /usr/lib64/libibverbs/libmlx5-rdmav34.so, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libpsmx2-fi.so, /lib64/libps /usr/lib64/ucx/libuct_ib.so.0, /usr/lib64/ucx/libuct_rdmacm.so.0, /usr/lib64/ucx/libuct_cma.so.0, /usr/lib64/ucx/libuct_knem.so.0, /usr/lib64/uc
cmdline	[./main, 0, 1, 2048]
cluster	c
algorithm	bitonic
programming_model	mpi
data_type	int
size_of_data_type	4
input_size	2048
input_type	1_perc_perturbed
num_procs	8
scalability	strong
group_num	3
implementation_source	handwritten

Sample Sort Metadata

Metadata Key	Value
cali.caliper.version	2.11.0
mpi.world.size	32
spot.metrics	min#inclusive#sum#time.duration, max#inclusive#sum#time.duration, avg#inclusive#sum#time.duration, sum#inclusive#sum#time.duration, variance#inclusive#sum#time.duration, min#min#aggregate.slot, min#sum#rc.count, avg#sum#rc.count, max#sum#rc.count, sum#sum#rc.count, min#scale#sum#time.duration.ns, max#scale#sum#time.duration.ns, avg#scale#sum#time.duration.ns, sum#scale#sum#time.duration.ns
spot.timeseries.metrics	time.variance, profile.mpi, node.order, region.count, time.exclusive
spot.format.version	2
spot.options	regionprofile
spot.channels	spot
cali.channel	true
spot:node.order	p32-a4194304.cali
spot:output	true
spot:profile.mpi	true
spot:region.count	true
spot:time.exclusive	true
spot:time.variance	true
launchdate	1729120737
libraries	/scratch/group/csce435-f24/Caliper/caliper/lib64/libcaliper.so.2, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/lib/libmpicxx.so.12, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/lib/release/libmpi.so.12, /lib64/librt.so.1, /lib64/libpthread.so.0, /lib64/libdl.so.2, /sw/eb/sw/GCCcore/8.3.0/lib64/libstdc++.so.6, /lib64/libm.so.6, /sw/eb/sw/GCCcore/8.3.0/lib64/libgcc_s.so.1, /lib64/libc.so.6, /sw/eb/sw/CUDA/12.4.0/extras/CUPTI/lib64/libcupti.so.12, /sw/eb/sw/PAPI/6.0.0-GCCcore-8.3.0/lib/libpapi.so.6.0, /lib64/ld-linux-x86-64.so.2, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/libfabric.so.1, /lib64/libutil.so.1, /sw/eb/sw/PAPI/6.0.0-GCCcore-8.3.0/lib/libpfm.so.4, /lib64/libnuma.so, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libshm-fi.so, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libmlx-fi.so, /lib64/libucp.so.0, /sw/eb/sw/zlib/1.2.11-GCCcore-8.3.0/lib/libz.so.1, /usr/lib64/libuct.so.0, /usr/lib64/libucs.so.0, /usr/lib64/libucm.so.0, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libverbs-fi.so, /lib64/librdmacm.so.1, /lib64/libibverbs.so.1, /lib64/libnl-3.so.200, /lib64/libnl-route-3.so.200, /usr/lib64/libibverbs/libmlx5-rdmav34.so, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libpsmx2-fi.so, /lib64/libpsm2.so.2, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libsockets-fi.so, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/librxm-fi.so, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libtcp-fi.so, /usr/lib64/ucx/libuct_ib.so.0, /usr/lib64/ucx/libuct_rdmacm.so.0, /usr/lib64/ucx/libuct_cma.so.0, /usr/lib64/ucx/libuct_knem.so.0, /usr/lib64/ucx/libuct_xpmem.so.0, /usr/lib64/libxpmem.so.0
cmdline	[./main, 1, 2, 4194304]
cluster	c
algorithm	sample
programming_model	mpi
data_type	int
size_of_data_type	4
input_size	4194304
input_type	Random
num_procs	32
scalability	strong
group_num	3
implementation_source	handwritten

Merge Sort Metadata

Metadata Key	Value
cali.caliper.version	2.11.0

Metadata Key	Value
mpi.world.size	32
spot.metrics	min#inclusive#sum#time.duration,max#inclusive#sum#time.duration,avg#inclusive#sum#time.duration,sum#inclusive#sum#time.duration,v
spot.timeseries.metrics	2
spot.format.version	time.variance,profile.mpi,node.order,region.count,time.exclusive
spot.options	regionprofile
spot.channels	spot
cali.channel	true
spot:node.order	p32-a4194304.cali
spot:output	true
spot:profile.mpi	true
spot:region.count	true
spot:time.exclusive	1729408207
spot:time.variance	[/scratch/group/csce435-f24/Caliper/caliper/lib64/libcaliper.so.2, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/lib/libmpicxx.so.12, /sw/eb/sw/CUDA/11.8.0/extras/CUPTI/lib64/libcupti.so.11.8, /sw/eb/sw/PAPI/6.0.0-GCCcore-8.3.0/lib/libpapi.so.6, /lib64/ld-linux-x86-64.so.2, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libmlx-fi.so, /lib64/libucp.so.0, /sw/eb/sw/zlib/1.2.11-GCCcore-8.3.0/li /usr/lib64/libibverbs/libmlx5-rdmav34.so, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libpsmx2-fi.so, /lib64/libps /usr/lib64/ucx/libuct_ib.so.0, /usr/lib64/ucx/libuct_rdmacm.so.0, /usr/lib64/ucx/libuct_cma.so.0, /usr/lib64/ucx/libuct_knem.so.0, /usr/lib64/uc
launchdate	[./main, 2, 2, 4194304]
libraries	c
cmdline	merge
cluster	mpi
algorithm	int
programming_model	4
data_type	4194304
size_of_data_type	Random
input_size	32
input_type	strong
num_procs	3
scalability	handwritten

Radix Sort Metadata

Metadata Key	Value
cali.caliper.version	2.11.0
mpi.world.size	32
spot.metrics	min#inclusive#sum#time.duration,max#inclusive#sum#time.duration,avg#inclusive#sum#time.duration,sum#inclusive#sum#time.duration,v
spot.timeseries.metrics	
spot.format.version	2
spot.options	time.variance,profile.mpi,node.order,region.count,time.exclusive
spot.channels	regionprofile
cali.channel	spot
spot:node.order	true
spot:output	p32-a4194304.cali
spot:profile.mpi	true
spot:region.count	true
spot:time.exclusive	true
spot:time.variance	true
launchdate	1729119981

Metadata Key	Value
libraries	[/scratch/group/csce435-f24/Caliper/caliper/lib64/libcaliper.so.2, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/lib/libmpicxx.so.12, /sw/eb/sw/CUDA/12.4.0/extras/CUPTI/lib64/libcupti.so.12, /sw/eb/sw/PAPI/6.0.0-GCCcore-8.3.0/lib/libpapi.so.6.0, /lib64/ld-linux-x86-64.so.2, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libmlx-fi.so, /lib64/libucp.so.0, /sw/eb/sw/zlib/1.2.11-GCCcore-8.3.0/li /usr/lib64/libibverbs/libmlx5-rdmav34.so, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libpsmx2-fi.so, /lib64/libps /usr/lib64/ucx/libuct_ib.so.0, /usr/lib64/ucx/libuct_rdmacm.so.0, /usr/lib64/ucx/libuct_cma.so.0, /usr/lib64/ucx/libuct_knem.so.0, /usr/lib64/uc
cmdline	[./main, 3, 2, 4194304]
cluster	c
algorithm	radix
programming_model	mpi
data_type	int
size_of_data_type	4
input_size	4194304
input_type	Random
num_procs	32
scalability	strong
group_num	3
implementation_source	handwritten

Column Sort Metadata

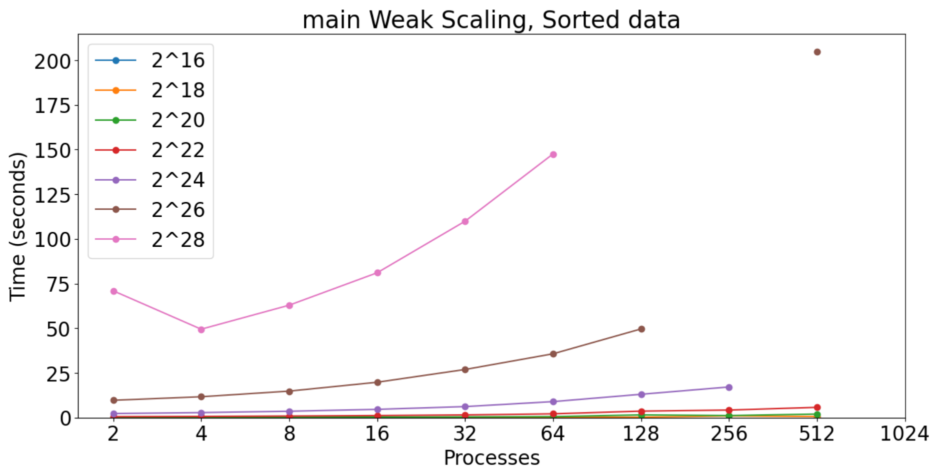
Key	Value
cali.caliper.version	2.11.0
mpi.world.size	32
spot.metrics	min#inclusive#sum#time.duration,max#inclusive#sum#time.duration,avg#inclusive#sum#time.duration,sum#inclusive#sum#time.duration,v
spot.timeseries.metrics	
spot.format.version	2
spot.options	time.variance,profile.mpi,node.order,region.count,time.exclusive
spot.channels	regionprofile
cali.channel	spot
spot:node.order	true
spot:output	p32-a4194304.cali
spot:profile.mpi	true
spot:region.count	true
spot:time.exclusive	true
spot:time.variance	true
launchdate	1729133553
libraries	[/scratch/group/csce435-f24/Caliper/caliper/lib64/libcaliper.so.2, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/lib/libmpicxx.so.12, /sw/eb/sw/CUDA/12.4.0/extras/CUPTI/lib64/libcupti.so.12, /sw/eb/sw/PAPI/6.0.0-GCCcore-8.3.0/lib/libpapi.so.6.0, /lib64/ld-linux-x86-64.so.2, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libmlx-fi.so, /lib64/libucp.so.0, /sw/eb/sw/zlib/1.2.11-GCCcore-8.3.0/li /usr/lib64/libibverbs/libmlx5-rdmav34.so, /sw/eb/sw/impi/2019.9.304-iccifort-2020.4.304/intel64/libfabric/lib/prov/libpsmx2-fi.so, /lib64/libps /usr/lib64/ucx/libuct_ib.so.0, /usr/lib64/ucx/libuct_rdmacm.so.0, /usr/lib64/ucx/libuct_cma.so.0, /usr/lib64/ucx/libuct_knem.so.0, /usr/lib64/uc
cmdline	[./main, 4, 3, 4194304]
cluster	c
algorithm	column
programming_model	mpi
data_type	int
size_of_data_type	4
input_size	4194304
input_type	ReverseSorted

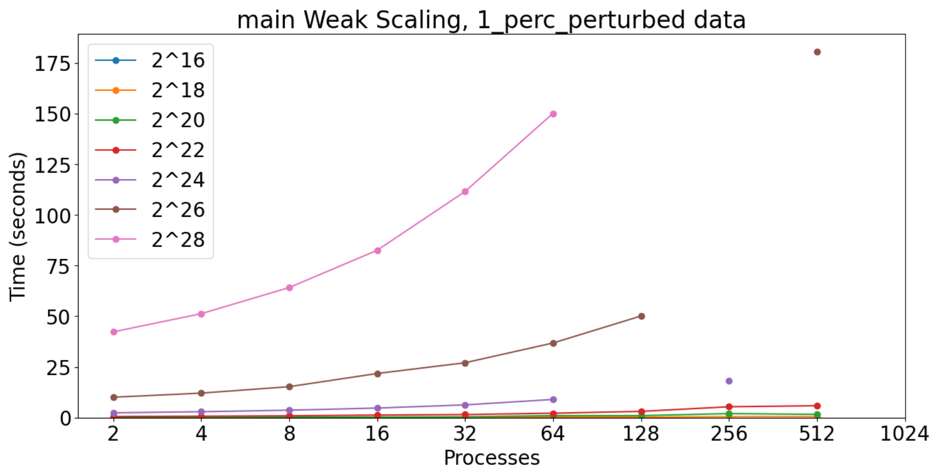
Key	Value
num_procs	32
scalability	strong
group_num	3
implementation_source	handwritten

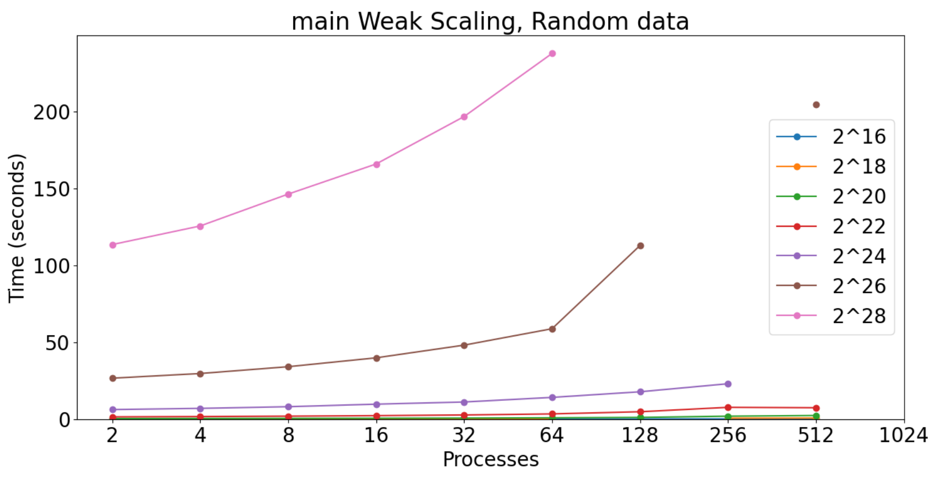
4. Performance evaluation

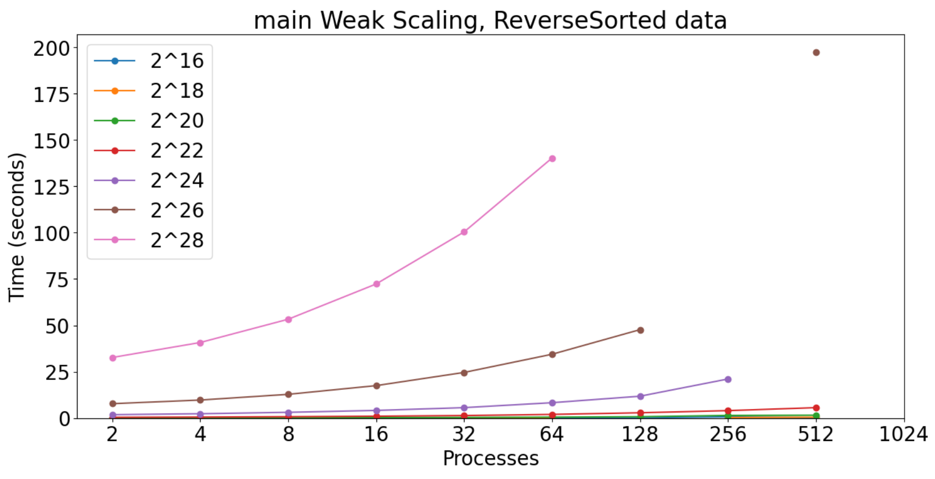
Bitonic Sort

Full Program







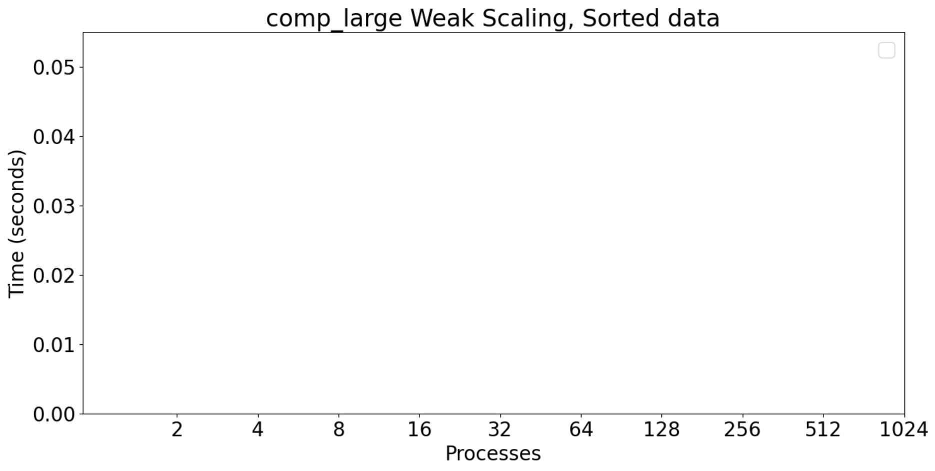


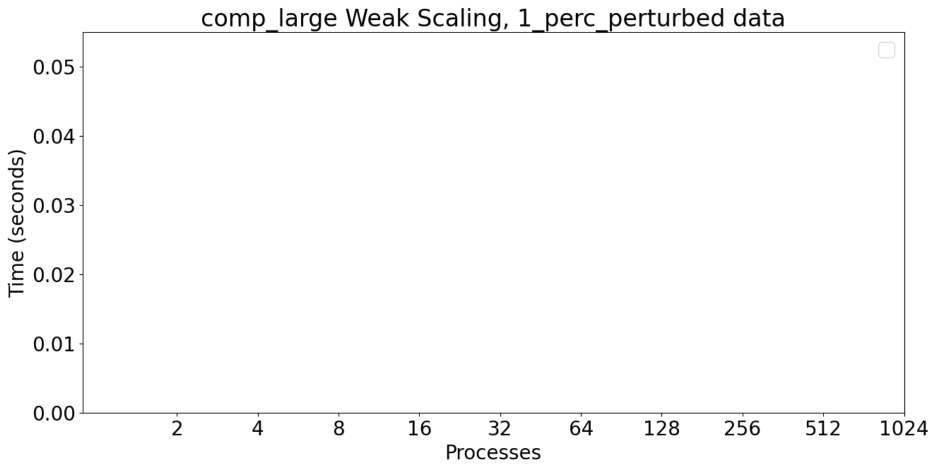
As the input size per process increases, the time required to sort the arrays increases. You can see this in the chart by looking at how the colored points line up vertically when you look at just once process number. Also, as the number of processes increases (and the total problem size along with it) the time required to sort the arrays also increases. This means the problem is not embarassingly parallel (i.e. it scales perfectly, so a flat line). The total time does not seem to increase dramatically, however, so the algorithm is fairly scalable.

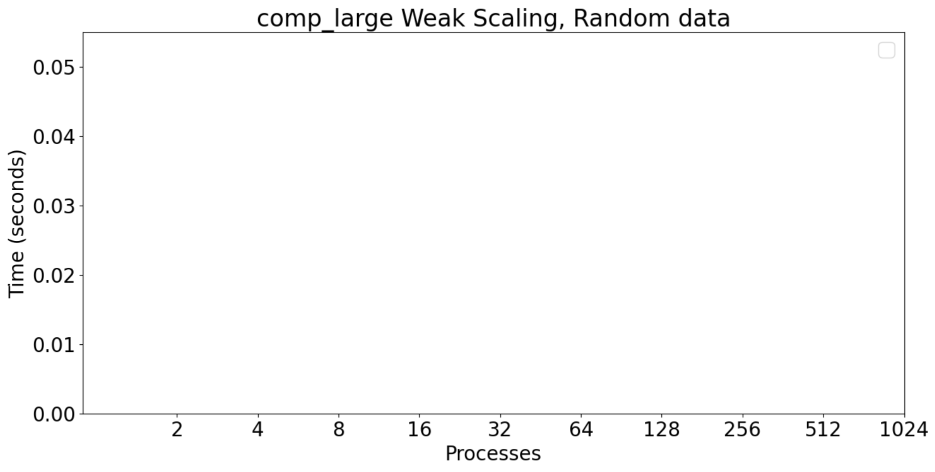
Note how the graphs look mostly identical. This is because bitonic sort does the same number of comparisons regardless of how the input data is sorted, so it makes sense that the time would be about the same for all four input types.

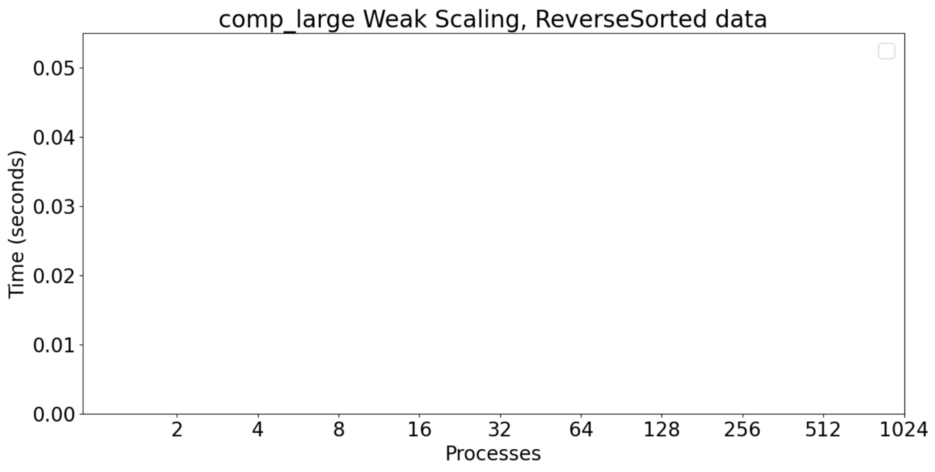
The lack of data points was caused by two things: issues with MPI communication and Hydra, and issues with gathering all the data into the first process. The first issue is with Grace, and is outside of our control. For large number of processes, the MPI communication system Hydra keeps giving error messages. As for the second issue, at the moment after the sort has occured all of the data is gathered into the central process. This is for merge sort, though in order to get it to work properly with Caliper the section of code needed to be included for all algorithms. This meant for large input sizes and large process counts the array didn't fit into memory. For the final report we are working to only use this section of code for merge sort, since there is no need to gather all of the data onto one process for bitonic sort.

Computation



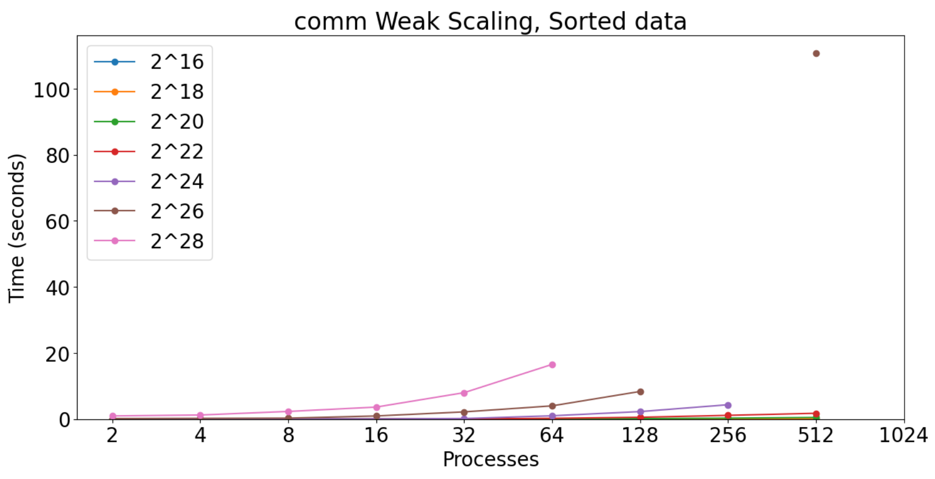


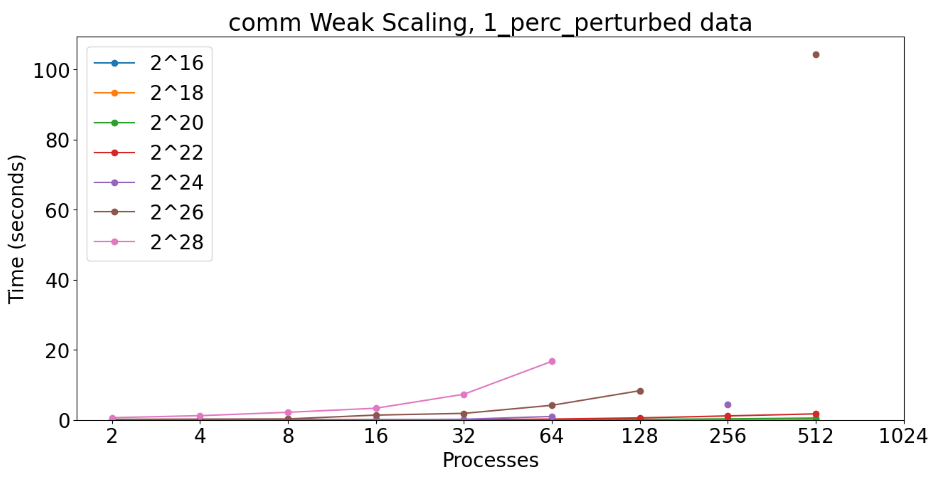


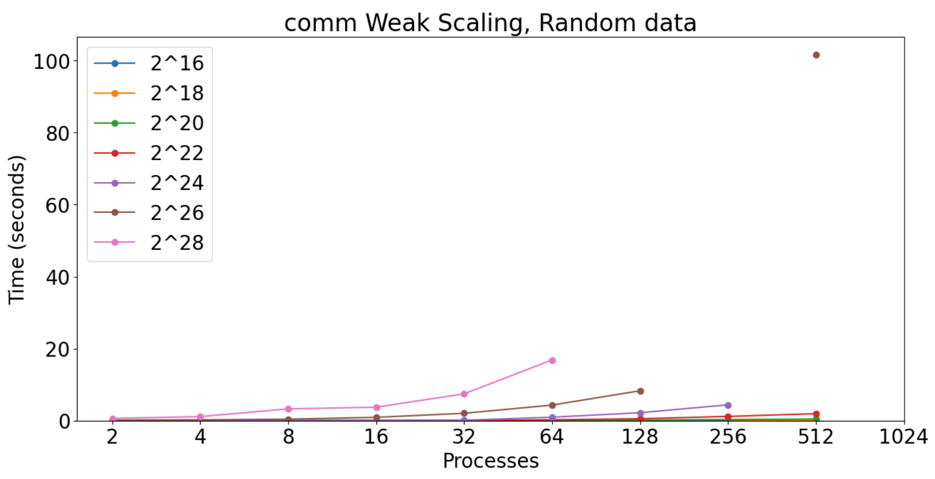


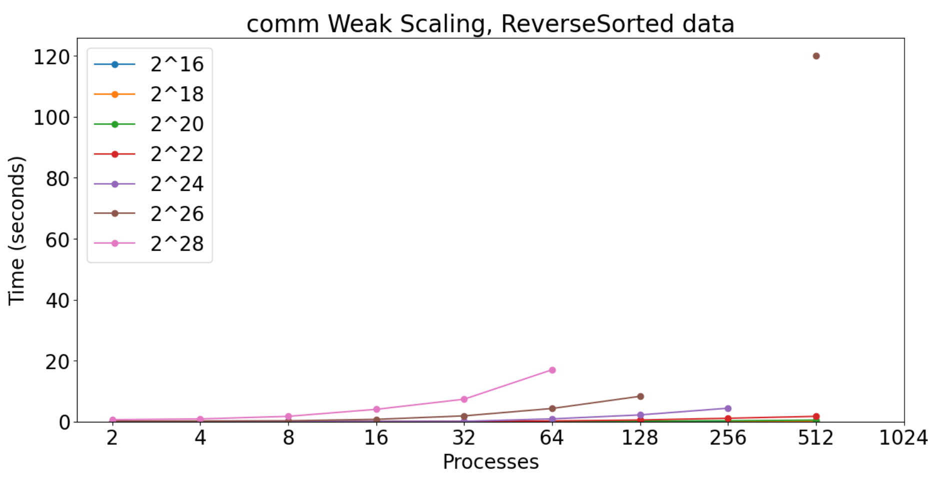
Unfortunately, when all of the trials were run the function was not properly annotated with the correct Caliper regions, so these graphs show as blank. We will fix the code, rerun all of the trials, and regenerate the graphs before the final report submission. These graphs should look similar to main.

Communication





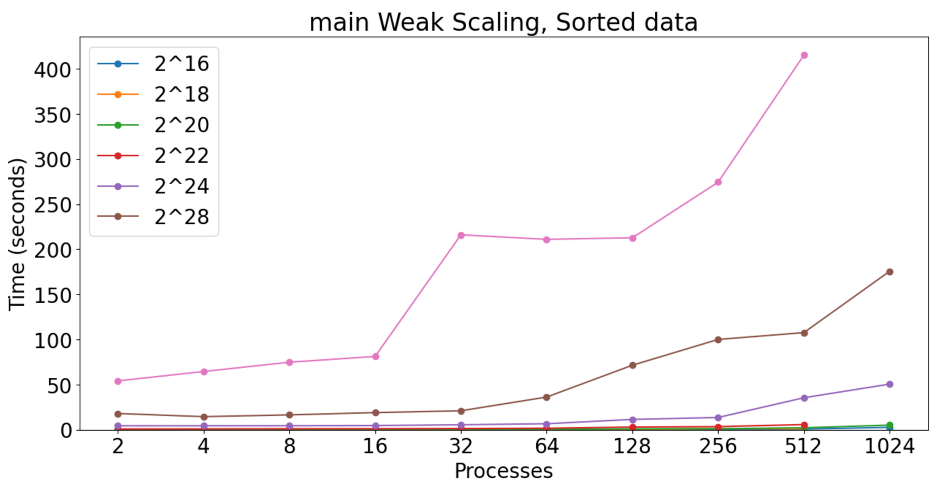


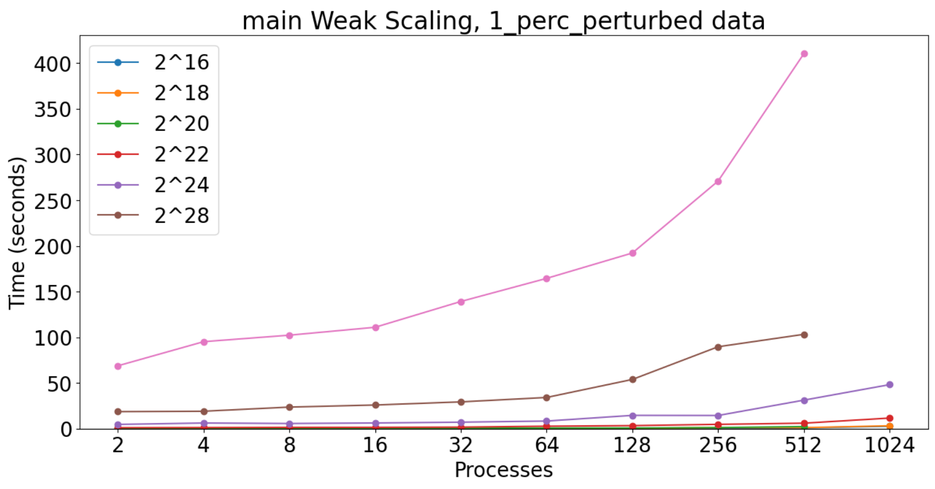


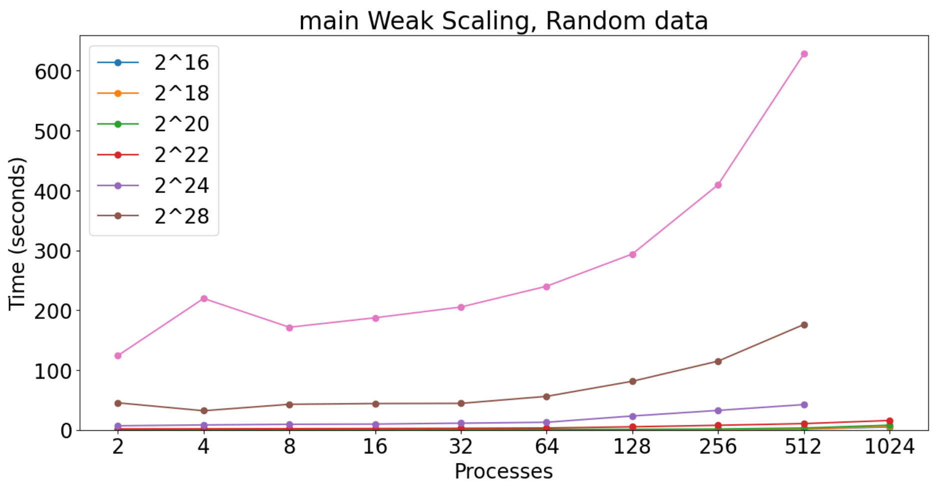
Much like with the main graphs, as the problem size increases the total time to sort the arrays also increases, and as the number of processes increases the total time to sort the arrays increases. Just like with the main graphs, the type of input doesn't affect how long it takes to sort the arrays.

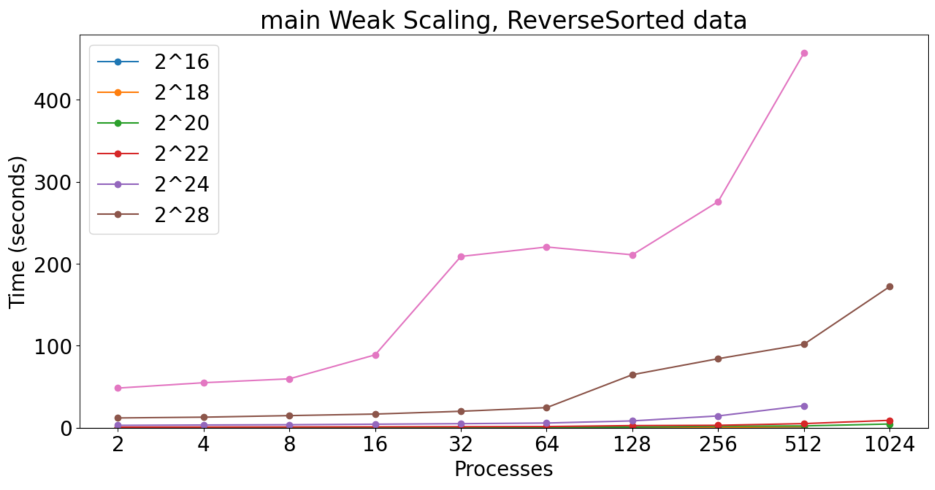
Sample Sort

Full Program



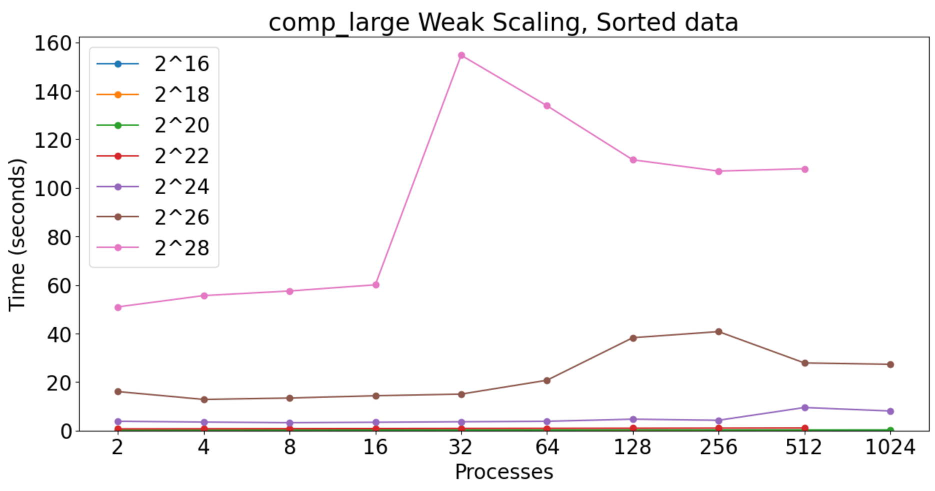


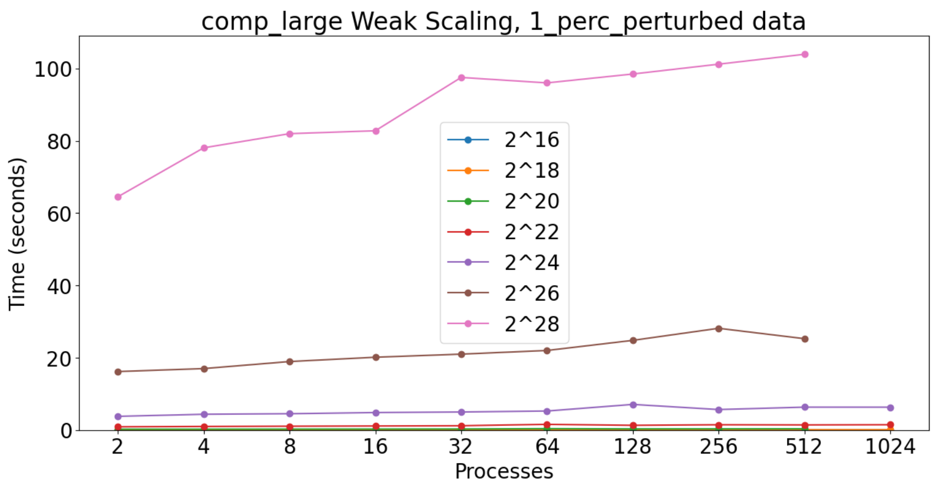


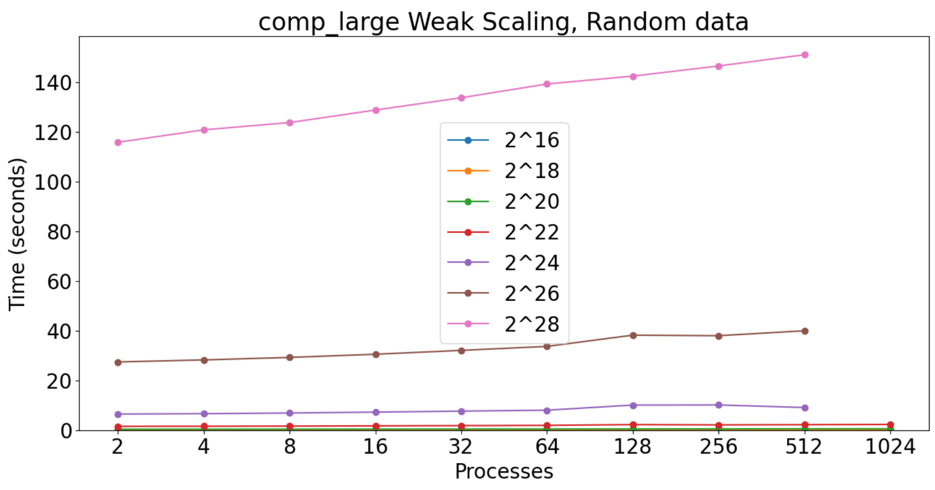


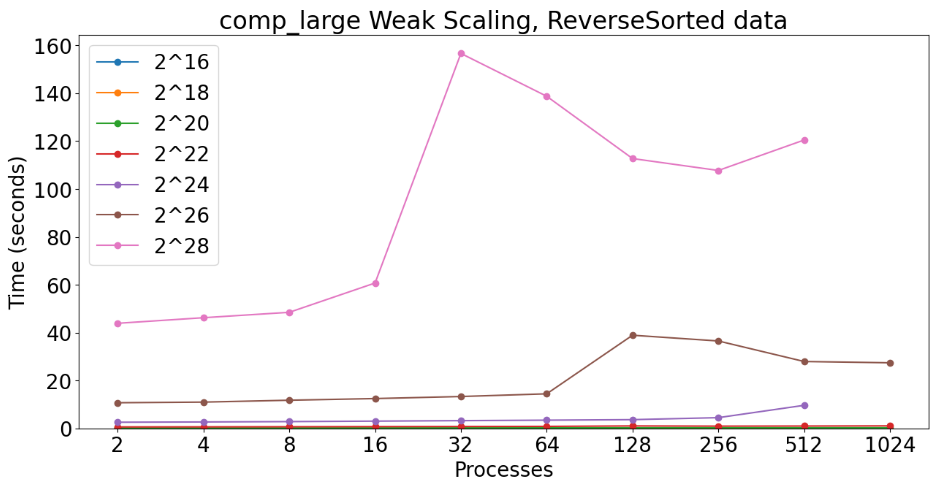
Overall, relative to the number of processors, the communication portion is the faster growing portion of the workload, so it is the portion most reflected in the main graphs. The computation portion is more significant for a lower processor count, but comparing magnitudes with the similar comm data points, it is smaller for processor amounts above about 128 processors. Because the communication time is independent of the data type, there are not many notable differences on the main graphs other than certain outliers. The random data takes significantly longer than the other three strategies, which is discussed below.

Computation



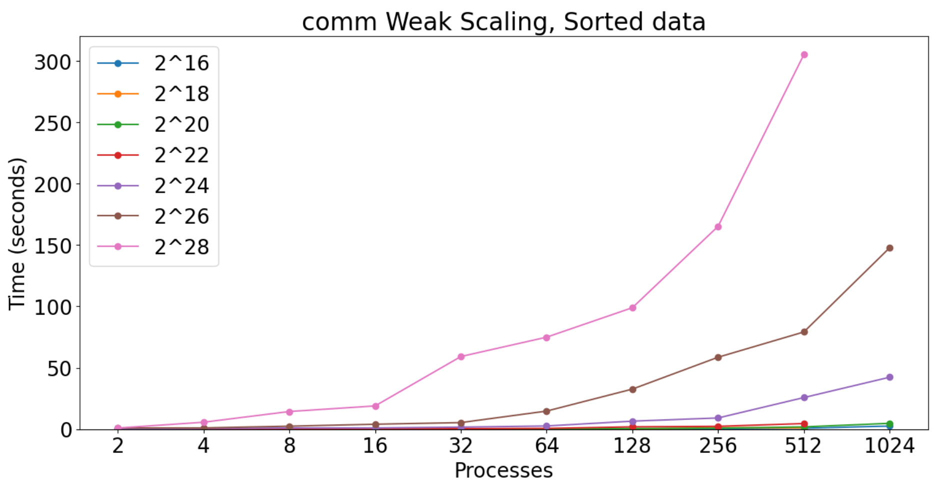


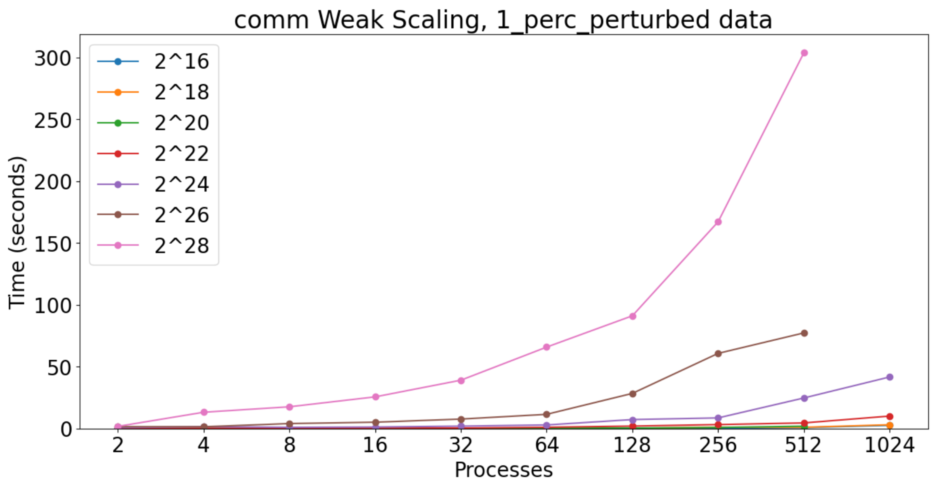


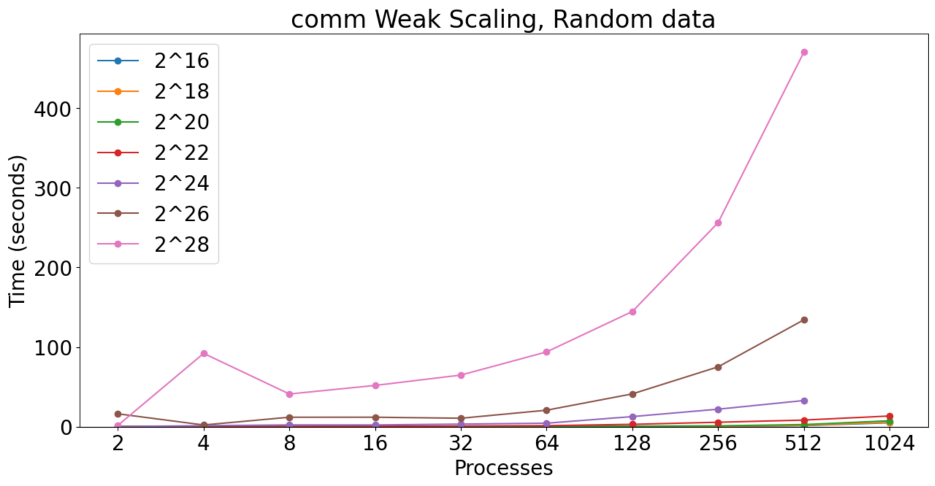


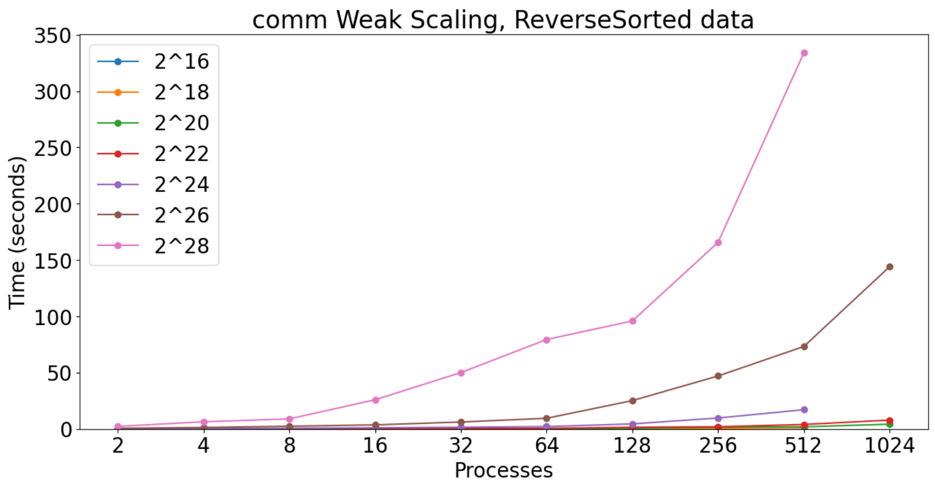
Computation time is roughly proportional to the log of the number of processors, with the random data showing the most consistent trend. There are occasional spikes in the time taken across all of the input sizes, and this is most likely because of a poor choice of splitters. If the window between two of the splitters is too wide, then one process has to sort much more data than it should, which pushes the average of sorting times up.
The time taken appears to be directly proportional to the input size; however, based on the time complexity of sequential sorting, it is actually proportional to nlogn, but the graph is not on a large enough scale to show this.
The type of data used does make a significant difference in the computation portion, and mostly applies a scale factor to the performance. Sorted and reverse sorted take about the same amount of time, with 1% perturbed taking an additional 50% time, and random taking anout 3x as long. The reason for the large spike in random is likely due to the increased randomness in choosing the correct splitter. The sampling strategy used is taking 3 samples from each process, so with sorted and reverse sorted, there is guaranteed to be exactly one splitter within each intitial array, and this will usually hold true for the 1% perturbed, while there is likely a more unbalanced workload for the random data leading to certain processes taking much longer.
The sorted and reverse sorted values do have large spikes at 32 and 1024 processors for 2^28 and 2^26 elements respectively. This is where the total number of elements exceeds the 32 bit integer limit, which then allows for more randomness in the splitter distribution since there will be two splitters within that range of data that decide where it goes.

Communication







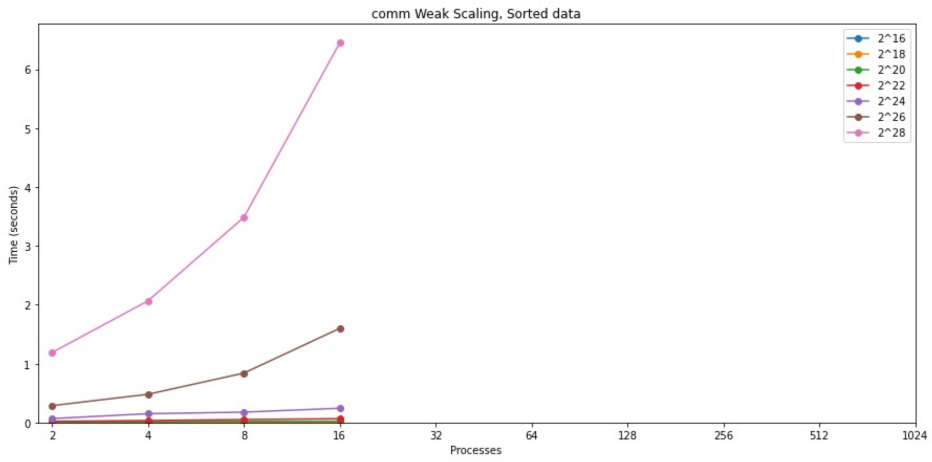


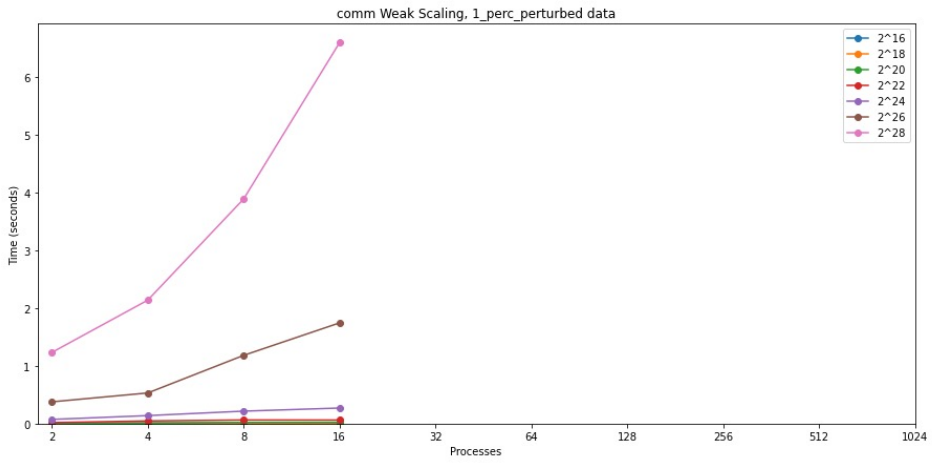
The time spent communicating is linearly proportional to the number of processes, which is expected since each additional processor must communicate with all existing processors a constant amount of times.

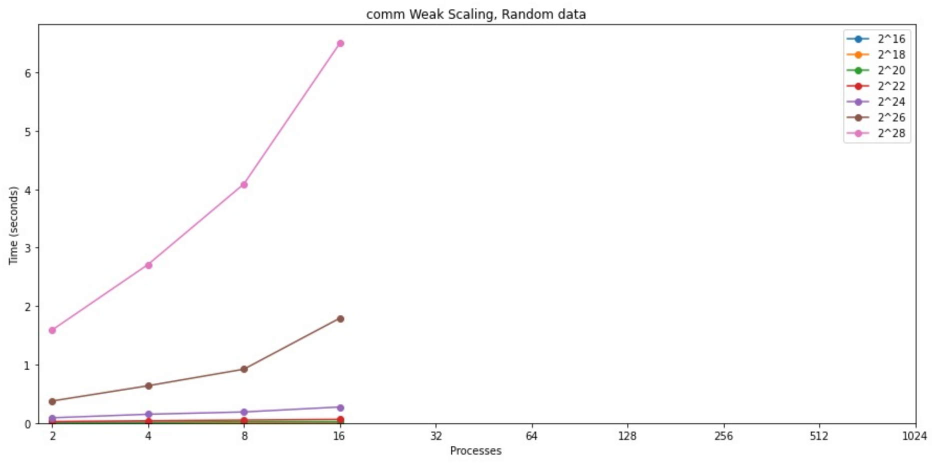
It is also directly proportional to the input size, since each new element of data needs to be sent to its corresponding process.

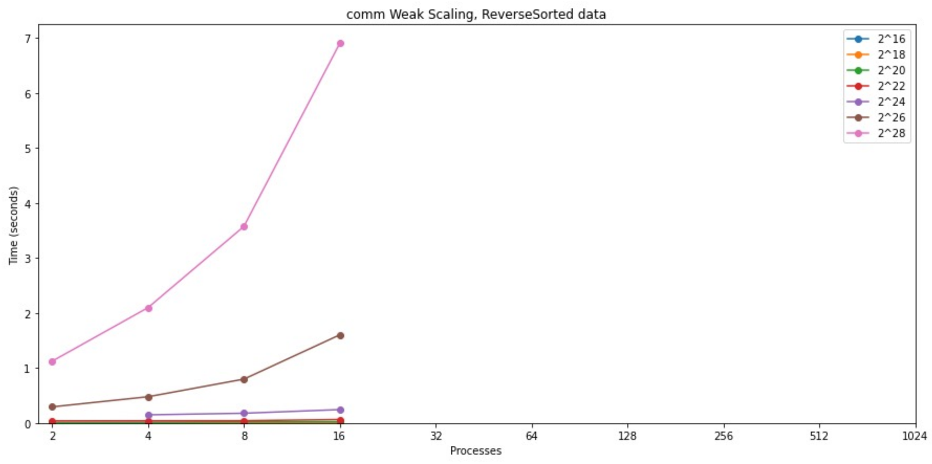
Merge Sort

Communication









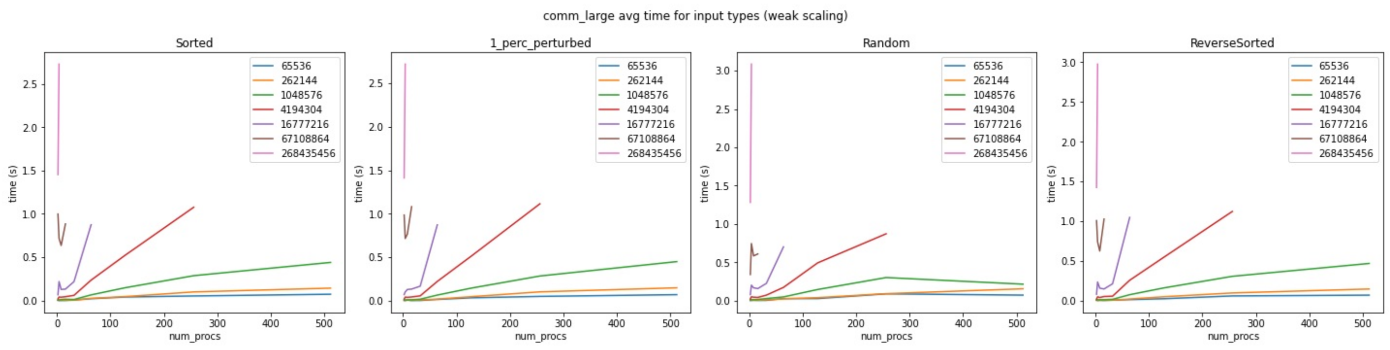
Communication time is proportional to the number of processes as expected. It is also notable that the growth in communcation time corresponds with the input sizes as well, with greater growth for larger input sizes.

Note: The number of runs at this stage are limited due to errors in job submissions.There are runs for higher num_procs, but they aren't included in the report because not all the runs for the given number of processes are there. Larger number of processes do seem to be consuming more memory and time, likely do to MPI_Gather() being utilized.

Radix Sort

A few things to mention before any analysis are that none of my 1024 process runs were able to successfully complete due to network issues with hydra within Grace itself. Furthermore, `MPI_Alltoall` is known to not scale very well due to the amount of memory and general overhead that comes with sending messages from all processes to all processes. This issue is especially apparent with high process counts and large input size. For this reason, I was not able to get outputs for 2^22 elements with 512+ processes, 2^24 elements with 128+ processes, 2^26 with 32+, and 2^28 with 8+ processes. Some proof of this is shown in the `comm_large` plot below, where graphs for all input types show that communication time scales up very quickly with input size and number of processes.

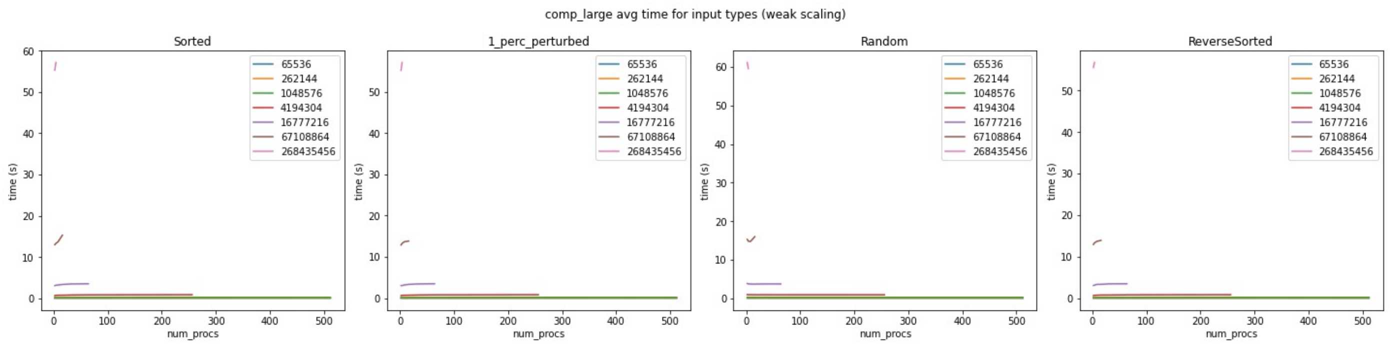
Communication



This is a graph of the average time for the `comm_large` caliper section. Since the only time communication occurs in radix sort is to send all data from all processes to all processes using `MPI_Alltoall` or `MPI_Alltoallv`, there is no `comm_small` section.

Communication time has a roughly linear relationship with the number of processes, regardless of input size and type. The magnitude of this relationship increases with input size, with larger inputs taking much longer to communicate than smaller ones. This makes sense as the algorithm uses `MPI_Alltoall` for communication, which is largely dependent on the number of processes performing the communication. There is not much difference between input types, which also makes sense because regardless of the data distribution the algorithm has to communicate its elements to all others.

Computation

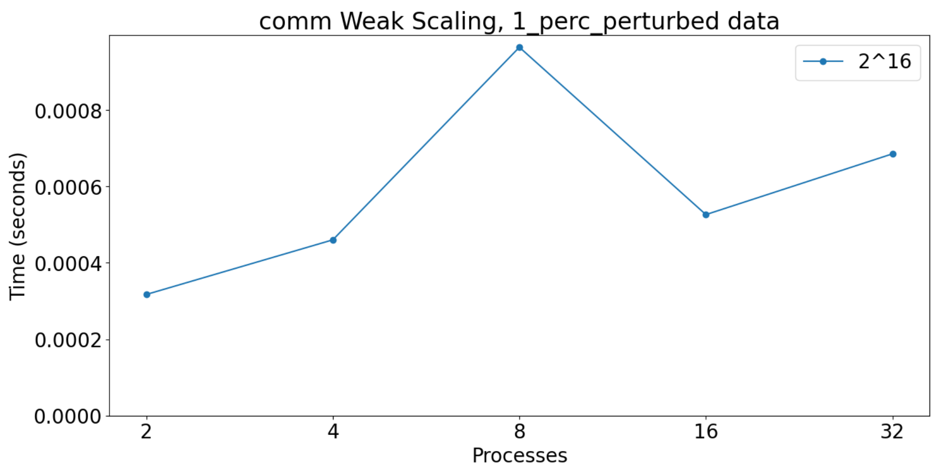


This is a graph of the average time for the `comp_large` caliper section. There is no `comp_small` caliper section since radix sort always sorts the entire local array, never just a portion of it.

Computation time doesn't really change with the number of processes--it remains a horizontal line across the number of processes for any given input size and type. Since this is weak scaling, each process is always sorting roughly the same amount of data, and since radix sort is not a comparison based sorting algorithm, it takes the same amount of time to sort every type of input. As expected, average computation time does increase with the input size because each process has more elements to sort.

Column Sort

In the development of the column sort algorithm for our project, we have successfully implemented and tested the initial eight steps as outlined in the referenced academic paper, utilizing an example with 27 elements across 3 processors (Below is a graph for this). This configuration demonstrated flawless performance, affirming the theoretical efficiency of the steps in optimizing both space complexity and the utilization of parallel processing architecture. The pseudocode provided has been meticulously updated to enhance clarity and detail concerning the operational mechanics of the algorithm, complemented by diagrams in Harsh's report that illustrate these processes.



During our implementation, we utilized the Caliper profiling tool to accurately time MPI calls, confirming the algorithm's performance efficiency during these stages. However, despite the successful execution of steps 1 through 7, we encountered an unexplained segmentation fault after step 7. This fault may be attributed to the stringent and specific requirements necessary for the proper function of column sort. Notably, the algorithm demands that the number of rows be at least double the square of one less than the number of columns (rows ≥ 2*(columns - 1)²), a condition which might not have been met under our test parameters.

To address and resolve this segmentation fault, our testing plan will systematically explore different combinations of input sizes and processor counts, ensuring they align with the algorithm's constraints. This approach will help determine the optimal configurations that prevent runtime errors and maximize efficiency. By methodically varying these parameters and observing the outcomes, we aim to pinpoint the precise conditions under which the algorithm fails and subsequently refine our implementation to ensure robust performance across a broader range of scenarios. This comprehensive testing strategy is essential to validate the algorithm's functionality and reliability in diverse operational environments.

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

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