Partitioning

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- At the end the solution to the overall problem may just be the collection of the solutions to the parts or we may need to combine the solutions of the parts.

- The effort here often lies in partitioning in such a way that the combining part at the end is not needed or can be simplified.
Partitioning Examples

- Parallel prefix sums
- Bottom-up parallel mergesort
- Parallel bucketsort
Parallel Prefix Sums (a.k.a Parallel Prefix)

The sequential algorithm for computing prefix sums.

```plaintext
prefix_sums(X, Sum)
//input Array: X[0...n−1]
//output Array: Sum[0...n−1]
//Sum[i] = \sum_{k=1}^{i} X[k]
1. Sum[0] ← X[0]
2. for (i=1; i<n; i++)
3. Sum[i] ← Sum[i-1] + X[i]
```
Parallel Prefix

Parallel Prefix an useful building block for various parallel algorithms. In our discussion, we will assume that the $n$ numbers are distributed across $p$ processes, with each process having $n/p$ numbers.

**Step I.** Each process computes the prefix sums of its share of numbers using the sequential algorithm.
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**Step II.** Process $i, 1 \leq i \leq p - 1$, sends its last sum ($X[n/p - 1]$) to Process 0.
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**Step II.** Process $i$, $1 \leq i \leq p - 1$, sends its last sum ($X[n/p - 1]$) to Process 0.

**Step III.** Process 0 computes prefix sums of the $p$ partial sums it receives from other processes.

**Step IV.** Process 0 ships the $i$th value from the array it just computed to Process $i + 1$, $0 \leq i \leq p - 2$.

**Step V.** Each process adds the partial value received to each element of its array of prefix sums.
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**Step I.** Each process computes the prefix sums of its share of numbers using the sequential algorithm.

**Step II.** Process \( i \), \( 1 \leq i \leq p-1 \), sends its last sum (\( X_{\lfloor n/p \rfloor-1} \)) to Process 0.

**Step III.** Process 0 computes prefix sums of the \( p \) partial sums it receives from other processes.

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Prefix Sums (a.k.a Parallel Prefix)

Step I

Step II

Step III

Step IV

Step V
Analysis of Parallel Prefix

\[ t_{\text{comm}} = (p - 1)(t_{\text{startup}} + t_{\text{data}}) + (p - 1)(t_{\text{startup}} + t_{\text{data}}) = \Theta(p) \]
Analysis of Parallel Prefix

\[ t_{\text{comm}} = (p - 1)(t_{\text{startup}} + t_{\text{data}}) + (p - 1)(t_{\text{startup}} + t_{\text{data}}) = \Theta(p) \]

\[ t_{\text{comp}} = \frac{n}{p} + (p - 1) + \frac{n}{p} = \Theta\left(\frac{n}{p} + p\right) \]
Analysis of Parallel Prefix

\[
\begin{align*}
    t_{\text{comm}} & = (p-1)(t_{\text{startup}} + t_{\text{data}}) + (p-1)(t_{\text{startup}} + t_{\text{data}}) = \Theta(p) \\
    t_{\text{comp}} & = \frac{n}{p} + (p-1) + \frac{n}{p} = \Theta\left(\frac{n}{p} + p\right) \\
    T_p(n) & = t_{\text{comm}} + t_{\text{comp}} = \Theta\left(\frac{n}{p} + p\right) \\
    T^*(n) & = \Theta(n)
\end{align*}
\]
Analysis of Parallel Prefix

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t_{\text{comm}} = (p - 1)(t_{\text{startup}} + t_{\text{data}}) + (p - 1)(t_{\text{startup}} + t_{\text{data}}) = \Theta(p)
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\]

\[
T_p(n) = t_{\text{comm}} + t_{\text{comp}} = \Theta\left(\frac{n}{p} + p\right)
\]

\[
T^*(n) = \Theta(n)
\]

\[
\text{Speedup } S_p(n) = \Theta\left(\frac{n}{\frac{n}{p} + p}\right) = \Theta\left(\frac{p}{\frac{p^2}{n} + 1}\right)
\]

\[
\lim_{n \to \infty} \frac{p}{\frac{p^2}{n} + 1} = p
\]
Mergesort is normally written as a top-down recursive algorithm. However, it can also be expressed as a bottom-up iterative algorithm. The picture on the next slide demonstrates how that works. Parallel Bottom-Up Mergesort illustrates an iterative tree-like coding technique, which is a common design pattern in parallel programs.
Mergesort is normally written as a top-down recursive algorithm. However, it can also be expressed as a bottom-up iterative algorithm. The picture on the next slide demonstrates how that works.

A bottom-up mergesort is more amenable to parallelization via partitioning. Each process starts with roughly $n/p$ elements, where $n$ is the number of elements to sort and $p$ is the number of processors. Each process then sorts them independently. From there the processes merge the sections until Process 0 has the sorted whole.
Bottom-up Mergesort

- Mergesort is normally written as a top-down recursive algorithm. However, it can also be expressed as a bottom-up iterative algorithm. The picture on the next slide demonstrates how that works.

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- Parallel Bottom-Up Mergesort illustrates an iterative tree-like coding technique, which is a common design pattern in parallel programs.
Bottom-up Parallel Mergesort (continued)

- The purple arrows show the direction of data transfer.
- At each level, the amount of data sent from one processor doubles.
- At each level, only half the number of processes remain active.

height = \lg p
parallel_mergesort(A, low, high, pid)
//Processes numbered, 0 ≤ pid ≤ p − 1
//Assume that p = 2^k
//Each process has n/p numbers at the start.

1. sort n/p elements locally
2. **for** (h=1; h ≤ lg p; h++)
3.  **if** (pid mod 2^h == 0)
4.      recv \( \frac{n}{p} 2^{h-1} \) elements from process pid + 2^{h-1}
5.  **else**
6.      send \( \frac{n}{p} 2^{h-1} \) elements to process pid – 2^{h-1}
7.  **break** //this process is done
8.  merge \( \frac{n}{p} 2^{h-1} \) elements with \( \frac{n}{p} 2^{h-1} \) local elements
Parallel Mergesort Analysis

- At each stage a total of about $n/2$ elements are transferred. There are a total of $\lg p$ stages. Hence the communication time is as shown below.

$$T_{\text{comm}}(n) = \Theta(n\lg p)$$

Notes

- Moderate to poor speedup because of large communication and because a large number of processes idle in the second phase.
- More sophisticated versions that use all the idle processes to make the merge operations faster in each stage give better speedups, especially on shared memory machines.
Parallel Mergesort Analysis

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- The total computation time includes time to initially sort \( n/p \) elements. The at each stage, half the processes merge elements. The merging time is linear to the number of elements. So this time doubles at each stage. The total computation time is shown below.
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\[
T_{\text{comp}}(n) = \Theta\left(\frac{n}{p} \lg \frac{n}{p} + \left(\frac{n}{p} + 2\frac{n}{p} + 4\frac{n}{p} + \ldots + p\frac{n}{p}\right)\right)
= \Theta\left(\frac{n}{p} \lg \frac{n}{p} + \frac{n}{p} \left(1 + 2 + 4 + \ldots + p/4 + p/2 + p\right)\right)
= \Theta\left(\frac{n}{p} \lg \frac{n}{p} + \frac{n(2p - 1)}{p}\right)
= \Theta\left(\frac{n}{p} \lg \frac{n}{p} + n\right)
\]

Notes
- Moderate to poor speedup because of large communication and because a large number of processes idle in the second phase. More sophisticated versions that use all the idle processes to make the merge operations faster in each stage give better speedups, especially on shared memory machines.
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$$= \Theta\left(\frac{n}{p} \lg \frac{n}{p} + \frac{n(2p - 1)}{p}\right)$$

$$= \Theta\left(\frac{n}{p} \lg \frac{n}{p} + n\right)$$

- **Notes.** Moderate to poor speedup because of large communication and because a large number of processes idle in the second phase. More sophisticated versions that use all the idle processes to make the merge operations faster in each stage give better speedups, especially on shared memory machines.
We have $n$ key values distributed uniformly in the range $[0..k - 1]$. 

Sequential Bucket Sort

1. Place a key value $x$ in the bucket $\lfloor x / (k / m) \rfloor$.
2. Sort each bucket using an optimal sorting algorithm.
3. Concatenate the results together into one array or list.
Sequential Bucketsort

- We have $n$ key values distributed uniformly in the range $[0..k-1]$.
- The algorithm uses $m$ buckets, with the $i$th bucket representing key values in the range $[i\frac{k}{m} \ldots (i+1)\frac{k}{m} - 1]$, for $0 \leq i \leq m-1$. 
Sequential Bucketsort

- We have \( n \) key values distributed uniformly in the range \([0..k-1]\).
- The algorithm uses \( m \) buckets, with the \( i \)th bucket representing key values in the range \([i \cdot \frac{k}{m} \ldots (i+1) \cdot \frac{k}{m} - 1]\), for \( 0 \leq i \leq m - 1 \).
- The sequential bucketsort algorithm is as follows.
  1. Place a key value \( x \) in the bucket \( \lfloor x/(k/m) \rfloor \).
  2. Sort each bucket using an optimal sorting algorithm.
  3. Concatenate the results together into one array or list.
Unsorted numbers

Place in buckets

Sort each bucket

Concatenate buckets

Sorted numbers after concatenating the buckets

Sequential Bucket sort
Analysis of Sequential Bucketsort

- **Step 1.** This step requires $\Theta(n)$ time to walk through the list and place each key value into the appropriate bucket. At the end of Step 1, each bucket has $\Theta(n/m)$ elements (assuming uniform distribution).
Analysis of Sequential Bucketsort

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- **Step 2.** Using an optimal sort in Step 2 would then take $\Theta(n/m \lg n/m)$ time per bucket. Since we have $m$ buckets to sort, the time for Step 2 is $\Theta(m n/m \lg n/m) = \Theta(n \lg n/m)$. 

- **Step 3.** This step takes $\Theta(n)$ time.
Analysis of Sequential Bucketsort

- **Step 1.** This step requires $\Theta(n)$ time to walk through the list and place each key value into the appropriate bucket. At the end of Step 1, each bucket has $\Theta(n/m)$ elements (assuming uniform distribution).

- **Step 2.** Using an optimal sort in Step 2 would then take $\Theta(n/m \lg n/m)$ time per bucket. Since we have $m$ buckets to sort, the time for Step 2 is $\Theta(m \cdot n/m \lg n/m) = \Theta(n \lg n/m)$.

- **Step 3.** This step takes $\Theta(n)$ time.

- The sequential time for bucketsort is: $T^*(n) = \Theta(n + n \lg n/m)$
Analysis of Sequential Bucketsort

- **Step 1.** This step requires $\Theta(n)$ time to walk through the list and place each key value into the appropriate bucket. At the end of Step 1, each bucket has $\Theta(n/m)$ elements (assuming uniform distribution).

- **Step 2.** Using an optimal sort in Step 2 would then take $\Theta(\frac{n}{m} \lg \frac{n}{m})$ time per bucket. Since we have $m$ buckets to sort, the time for Step 2 is $\Theta(m \frac{n}{m} \lg \frac{n}{m}) = \Theta(n \lg \frac{n}{m})$.

- **Step 3.** This step takes $\Theta(n)$ time.

The sequential time for bucketsort is:  

$$T^*(n) = \Theta(n + n\lg \frac{n}{m})$$

If we choose the number of buckets to be linear to $n$, say $m = rn$, where $r$ is a constant between 0 and 1, then the sequential run time for bucketsort is  

$$T^*(n) = \Theta(n \lg \frac{n}{rn}) = \Theta(n)$$
The bucketsort algorithm assumes that the input is uniformly distributed over a certain range. How can we use bucketsort if that is not the case? Here are some ideas.

▶ If the input fits some standard distribution (like Normal distribution, Zipf distribution etc.) then we can divide the range using the probability density function to make the buckets be approximately balanced.

▶ Use a universal hash function to randomize the data. An example of when this would be useful is if the key values are Internet URL's.
Non-uniformly Distributed Input

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- Use a universal hash function to randomize the data. An example of when this would be useful is if the key values are Internet URL’s.
Parallel Bucketsort

- Assume that the $n$ input elements are distributed across the $p$ processes, with each process initially holding $n/p$ unsorted elements. Further assume that each elements is in the range $[0\ldots k - 1]$. 
Parallel Bucketsort

- Assume that the \( n \) input elements are distributed across the \( p \) processes, with each process initially holding \( n/p \) unsorted elements. Further assume that each elements is in the range \([0\ldots k - 1]\).

- The goal is that at the end of the sorting, process \( i \) has elements that are sorted and any element on process \( i \) is greater than or equal to any element on process \( j \), where \( j < i \) and any element on process \( i \) is less than or equal to any element on process \( k \), where \( k > i \).
Parallel Bucketsort (contd.)

Each process now has multiple little buckets (one per process that it may receive data from): we refer to these little buckets as a *box*. Set the number of *boxes* on each process to be $m = p$.

**Step 1.** Each process places its $n/p$ key values into $p$ boxes with key value $x$ going to the box number $\lfloor x/(k/p) \rfloor$. 
Parallel Bucketsort (contd.)

Each process now has multiple little buckets (one per process that it may receive data from): we refer to these little buckets as a \textit{box}. Set the number of boxes on each process to be \( m = p \).

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\textbf{Step 2.} For each process \( i \), where \( 0 \leq i \leq p - 1 \), send the \( j \)th \textit{box} to process \( j \), \( 0 \leq j \leq p - 1, j \neq i \).
Each process now has multiple little buckets (one per process that it may receive data from): we refer to these little buckets as a *box*. Set the number of *boxes* on each process to be \( m = p \).

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**Step 2.** For each process \( i \), where \( 0 \leq i \leq p - 1 \), send the \( j \)th *box* to process \( j \), \( 0 \leq j \leq p - 1, j \neq i \).

**Step 3.** Each process receives \( p - 1 \) *boxes*. It combines them with its *box* and then sorts all of them together using sequential bucketsort to make one list of approximately \( n/p \) key values.
Parallel Bucketsort

Step 1

Step 2: all-to-all communication

Step 3

sort together sort together sort together sort together

process 0 process 1 process 2 process 3
Parallel Bucketsort Implementation

- Step 2 involves an **all-to-all communication** pattern (a.k.a gossip).
- The next frame shows a space-time visualization of an all-to-all communication. The example shows a parallel bucketsort program in action on a Beowulf Cluster.
Gossip (All-to-all communication)
Parallel Bucketsort Analysis

Step 1. \( t_{\text{comp}} = \Theta\left(\frac{n}{p}\right) \quad t_{\text{comm}} = \Theta(1) \)
Parallel Bucketsort Analysis

Step 1. \( t_{\text{comp}} = \Theta\left(\frac{n}{p}\right) \quad t_{\text{comm}} = \Theta(1) \)

Step 2. Assuming uniform distribution. Each box will have about \( \frac{n}{p^2} \) key values. Each process send \( p - 1 \) such boxes.

\[
\begin{align*}
  t_{\text{comp}} &= \Theta(1) \\
  t_{\text{comm}} &= \Theta(p(p - 1)(t_{\text{startup}} + \frac{n}{p^2}t_{\text{data}}))
\end{align*}
\]
Parallel Bucketsort Analysis

**Step 1.** \( t_{\text{comp}} = \Theta\left(\frac{n}{p}\right) \quad t_{\text{comm}} = \Theta(1) \)

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\end{align*}
\]

**Step 3.**

\[
\begin{align*}
    t_{\text{comp}} &= \Theta\left(\frac{n}{p} \log \frac{n}{p}\right) \\
    t_{\text{comm}} &= \Theta(1)
\end{align*}
\]

Can we cut down on the startup time?
Parallel Bucketsort Analysis

Step 1. \( t_{\text{comp}} = \Theta\left(\frac{n}{p}\right) \quad t_{\text{comm}} = \Theta(1) \)

Step 2. Assuming uniform distribution. Each box will have about \( n/p^2 \) key values. Each process send \( p - 1 \) such boxes.

\[
\begin{align*}
  t_{\text{comp}} &= \Theta(1) \\
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\end{align*}
\]

Step 3.

\[
\begin{align*}
  t_{\text{comp}} &= \Theta\left(\frac{n}{p} \log \frac{n}{p}\right) \\
  t_{\text{comm}} &= \Theta(1)
\end{align*}
\]

Total: The overall runtime for parallel bucketsort:

\[
T_p(n) = \Theta\left(\frac{n}{p} + p(p - 1)(t_{\text{startup}} + \frac{n}{p^2} t_{\text{data}}) + \frac{n}{p} \log \frac{n}{p}\right)
\]

\[
= \Theta\left(\frac{n}{p} \log \frac{n}{p} + p^2 t_{\text{startup}} + nt_{\text{data}}\right)
\]

Can we cut down on the startup time?
Parallel Bucketsort

**Step 1**

- Process 0
- Process 1
- Process 2
- Process 3

**Step 2: all-to-all communication**

- Process 0
- Process 1
- Process 2
- Process 3

**Step 3**

- Process 0
- Process 1
- Process 2
- Process 3

~n/p ~n/p ~n/p ~n/p
All-to-All Communication

Note that we can break the all-to-all communication into \( p \) rounds as shown below.

- **Round 0**: \( P_0 \rightarrow P_0 \), \( P_1 \rightarrow P_1 \), \( P_2 \rightarrow P_2 \), \( P_3 \rightarrow P_3 \)

Further improvement can be made by making use of multicasting (if supported in the underlying hardware). With multicasting, we will have \( p - 1 \) messages, each one a multicast message. This would cut down the parallel time to:

\[
T_p(n) = \Theta(n^p \log n^p + pt_{\text{start}} + nt_{\text{data}})
\]
All-to-All Communication

Note that we can break the all-to-all communication into $p$ rounds as shown below.

round 0  
$P_0 \rightarrow P_0$  $P_1 \rightarrow P_1$  $P_2 \rightarrow P_2$  $P_3 \rightarrow P_3$

round 1  
$P_0 \rightarrow P_1$  $P_1 \rightarrow P_2$  $P_2 \rightarrow P_3$  $P_3 \rightarrow P_0$

Note that in each round each process is sending out one message and receiving one message. If the processes are on nodes connected via a switch (completely connected network), then each round can be done simultaneously. This does assume that the network interface is capable of sending/receiving at the same time (which is true for most network interfaces but not all).

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$$T_p(n) = \Theta(n^p \text{lg} n^p + p_t \text{startup} + n t \text{data})$$
All-to-All Communication

- Note that we can break the all-to-all communication into \( p \) rounds as shown below.

  \[
  \begin{align*}
  \text{round 0} & \quad P_0 \rightarrow P_0 \quad P_1 \rightarrow P_1 \quad P_2 \rightarrow P_2 \quad P_3 \rightarrow P_3 \\
  \text{round 1} & \quad P_0 \rightarrow P_1 \quad P_1 \rightarrow P_2 \quad P_2 \rightarrow P_3 \quad P_3 \rightarrow P_0 \\
  \text{round 2} & \quad P_0 \rightarrow P_2 \quad P_1 \rightarrow P_3 \quad P_2 \rightarrow P_0 \quad P_3 \rightarrow P_1 
  \end{align*}
  \]

- Note that in each round each process is sending out one message and receiving one message. If the processes are on nodes connected via a switch (completely connected network), then each round can be done simultaneously. This does assume that the network interface is capable of sending/receiving at the same time (which is true for most network interfaces but not all).

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  \[
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  \]
All-to-All Communication

- Note that we can break the all-to-all communication into \( p \) rounds as shown below.

\begin{align*}
\text{round 0} & \quad P_0 \to P_0 \quad P_1 \to P_1 \quad P_2 \to P_2 \quad P_3 \to P_3 \\
\text{round 1} & \quad P_0 \to P_1 \quad P_1 \to P_2 \quad P_2 \to P_3 \quad P_3 \to P_0 \\
\text{round 2} & \quad P_0 \to P_2 \quad P_1 \to P_3 \quad P_2 \to P_0 \quad P_3 \to P_1 \\
\text{round 3} & \quad P_0 \to P_3 \quad P_1 \to P_0 \quad P_2 \to P_1 \quad P_3 \to P_2
\end{align*}

- Further improvement can be made by making use of multicasting (if supported in the underlying hardware). With multicasting, we will have \( p-1 \) messages, each one a multicast message. This would cut down the parallel time to:

\[
T_p(n) = \Theta(n p \log n p + p t_{\text{startup}} + n t_{\text{data}})
\]
All-to-All Communication

- Note that we can break the all-to-all communication into \( p \) rounds as shown below.

  round 0 \quad P_0 \rightarrow P_0 \quad P_1 \rightarrow P_1 \quad P_2 \rightarrow P_2 \quad P_3 \rightarrow P_3
  
  round 1 \quad P_0 \rightarrow P_1 \quad P_1 \rightarrow P_2 \quad P_2 \rightarrow P_3 \quad P_3 \rightarrow P_0
  
  round 2 \quad P_0 \rightarrow P_2 \quad P_1 \rightarrow P_3 \quad P_2 \rightarrow P_0 \quad P_3 \rightarrow P_1
  
  round 3 \quad P_0 \rightarrow P_3 \quad P_1 \rightarrow P_0 \quad P_2 \rightarrow P_1 \quad P_3 \rightarrow P_2

- Note that in each round each process is sending out one message and receiving one message. If the processes are on nodes connected via a switch (completely connected network), then each round can be done simultaneously. This does assume that the network interface is capable of sending/receiving at the same time (which is true for most network interfaces but not all).

Further improvement can be made by making use of multicasting (if supported in the underlying hardware). With multicasting, we will have \( p-1 \) messages, each one a multicast message. This would cut down the parallel time to:

\[
T_p(n) = \Theta(n^p \log n^p + pt_{\text{startup}} + n t_{\text{data}})
\]
All-to-All Communication

- Note that we can break the all-to-all communication into $p$ rounds as shown below.
  
  round 0 \hspace{1cm} P_0 \rightarrow P_0 \hspace{0.5cm} P_1 \rightarrow P_1 \hspace{0.5cm} P_2 \rightarrow P_2 \hspace{0.5cm} P_3 \rightarrow P_3
  
  round 1 \hspace{1cm} P_0 \rightarrow P_1 \hspace{0.5cm} P_1 \rightarrow P_2 \hspace{0.5cm} P_2 \rightarrow P_3 \hspace{0.5cm} P_3 \rightarrow P_0
  
  round 2 \hspace{1cm} P_0 \rightarrow P_2 \hspace{0.5cm} P_1 \rightarrow P_3 \hspace{0.5cm} P_2 \rightarrow P_0 \hspace{0.5cm} P_3 \rightarrow P_1
  
  round 3 \hspace{1cm} P_0 \rightarrow P_3 \hspace{0.5cm} P_1 \rightarrow P_0 \hspace{0.5cm} P_2 \rightarrow P_1 \hspace{0.5cm} P_3 \rightarrow P_2

- Note that in each round each process is sending out one message and receiving one message. If the processes are on nodes connected via a switch (completely connected network), then each round can be done simultaneously. This does assume that the network interface is capable of sending/receiving at the same time (which is true for most network interfaces but not all).

- Further improvement can be made by making use of multicasting (if supported in the underlying hardware). With multicasting, we will have $p-1$ messages, each one a multicast message. This would cut down the parallel time to:

  $$T_p(n) = \Theta\left(\frac{n}{p} \lg n + pt_{\text{startup}} + nt_{\text{data}}\right)$$