Basic Communication Operations

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Topic Overview

- One-to-All Broadcast and All-to-One Reduction
- All-to-All Broadcast and Reduction
- All-Reduce and Prefix-Sum Operations
- Scatter and Gather
- All-to-All Personalized Communication
- Circular Shift

Basic Communication Operations: Introduction

- **Many interactions in practical parallel programs occur** in well-defined patterns involving groups of processors.
- Efficient implementations of these operations can improve performance, reduce development effort and cost, and improve software quality.
- Efficient implementations must **leverage underlying architecture**. For this reason, we refer to specific architectures here.
- We **select a descriptive set of architectures** to illustrate the process of algorithm design.

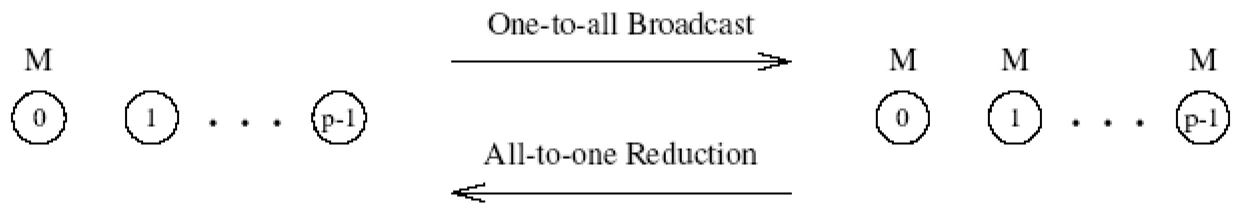
Basic Communication Operations: Introduction

- Group communication operations are built using **point-to-point messaging primitives**.
- Recall from our discussion of architectures that communicating a **message of size *m*** over an **uncongested network** takes time $t_s + t_w m$.
- We use this as the basis for our analyses. Where necessary, we take **congestion** into account explicitly by **scaling the t_w** term.
- We assume that the **network is bidirectional** and that communication is **single-ported**.

One-to-All Broadcast and All-to-One Reduction

- One processor has **a piece of data (of size *m*) it needs to send to everyone**.
- **The dual** of one-to-all broadcast is *all-to-one reduction*.
- In all-to-one reduction, each processor has *m* units of data. These **data items must be combined piece-wise** (using some associative operator, such as addition or min), and the **result made available at a target processor**.

One-to-All Broadcast and All-to-One Reduction

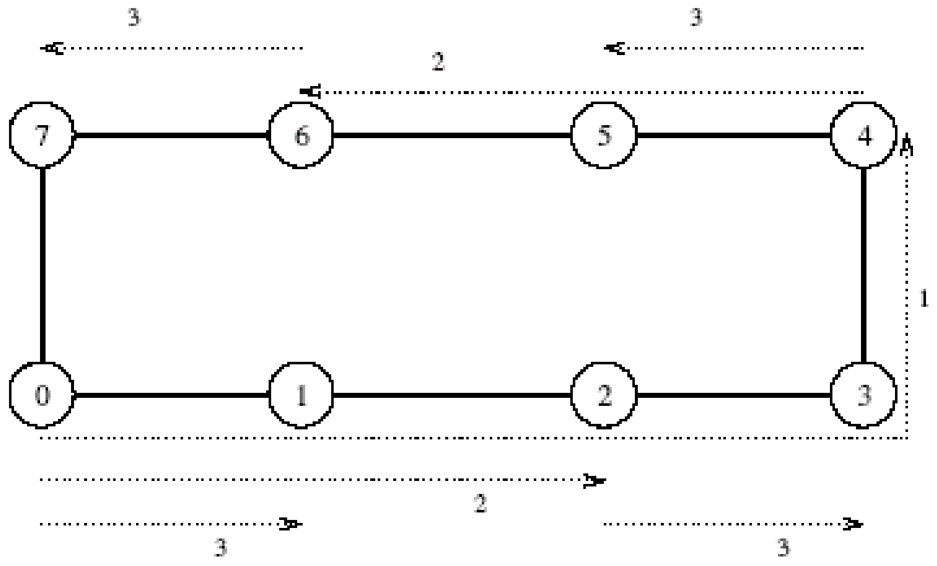


One-to-all broadcast and all-to-one reduction among processors.

One-to-All Broadcast and All-to-One Reduction on Rings

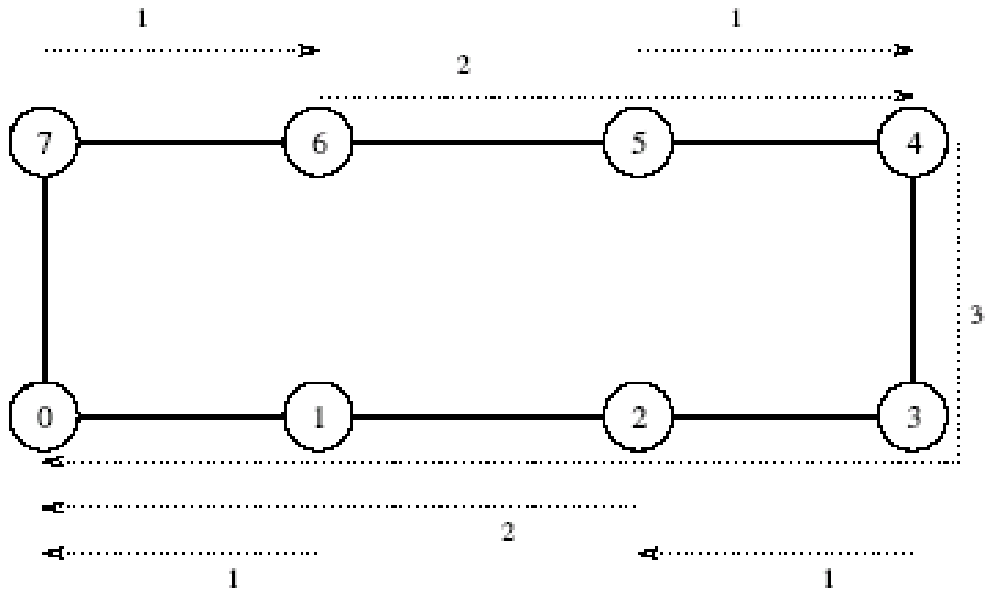
- **Simplest way** is to send *p-1* messages from the source to the other *p-1* processors - this is not very efficient.
- Use **recursive doubling**: source sends a message to a selected processor. We now have two independent problems defined over halves of machines.
- **Reduction** can be performed in an identical fashion by **inverting the process**.

One-to-All Broadcast



One-to-all broadcast on an eight-node ring. Node 0 is the source of the broadcast. Each message transfer step is shown by a numbered, dotted arrow from the source of the message to its destination. The number on an arrow indicates the time step during which the message is transferred.

All-to-One Reduction



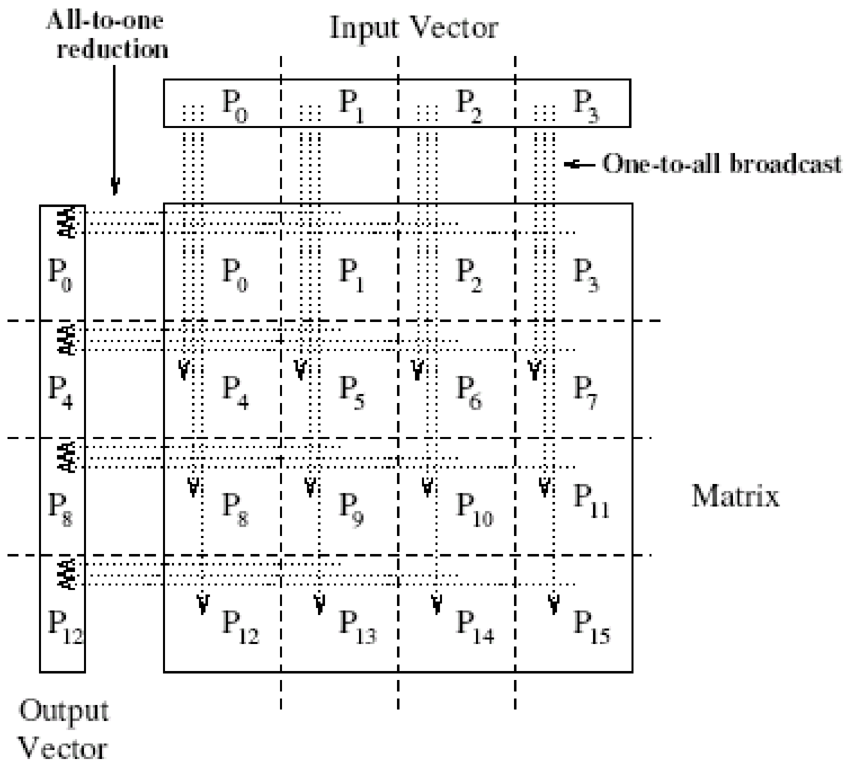
Reduction on an eight-node ring with node 0 as the destination of the reduction.

Broadcast and Reduction: Example

Consider the problem of **multiplying a matrix with a vector**.

- The ***n* x *n* matrix** is assigned to an *n x n* (virtual) **processor grid**. The vector is assumed to be on the first row of processors.
- The first step of the product requires a **one-to-all broadcast of the vector element along the corresponding column of processors**. This can be done concurrently for all *n* columns.
- The processors **compute local product** of the vector element and the local matrix entry.
- In the final step, the results of these **products are accumulated to the first row using *n* concurrent all-to-one reduction** operations along the columns (using the sum operation).

Broadcast and Reduction: Matrix-Vector Multiplication Example

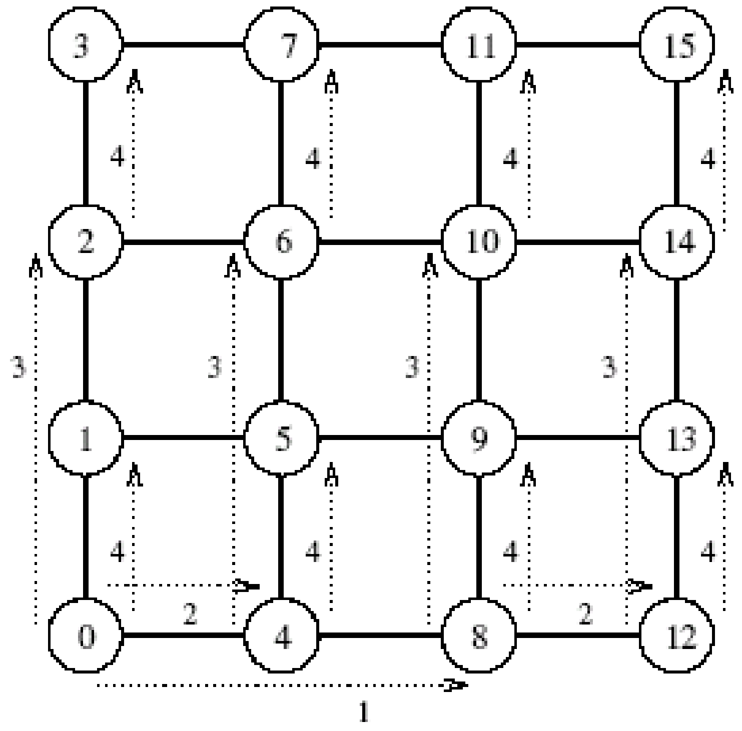


One-to-all broadcast and all-to-one reduction in the multiplication of a *4 x 4* matrix with a *4 x 1* vector.

Broadcast and Reduction on a Mesh

- We can view each row and column of a **square mesh of *p* nodes** as a **linear array of $\sqrt{p}$ nodes**.
- Broadcast and reduction operations can be performed in two steps - **the first step does the operation along a row** and **the second step along each column** concurrently.
- This process **generalizes to higher dimensions as well**.

Broadcast and Reduction on a Mesh: Example

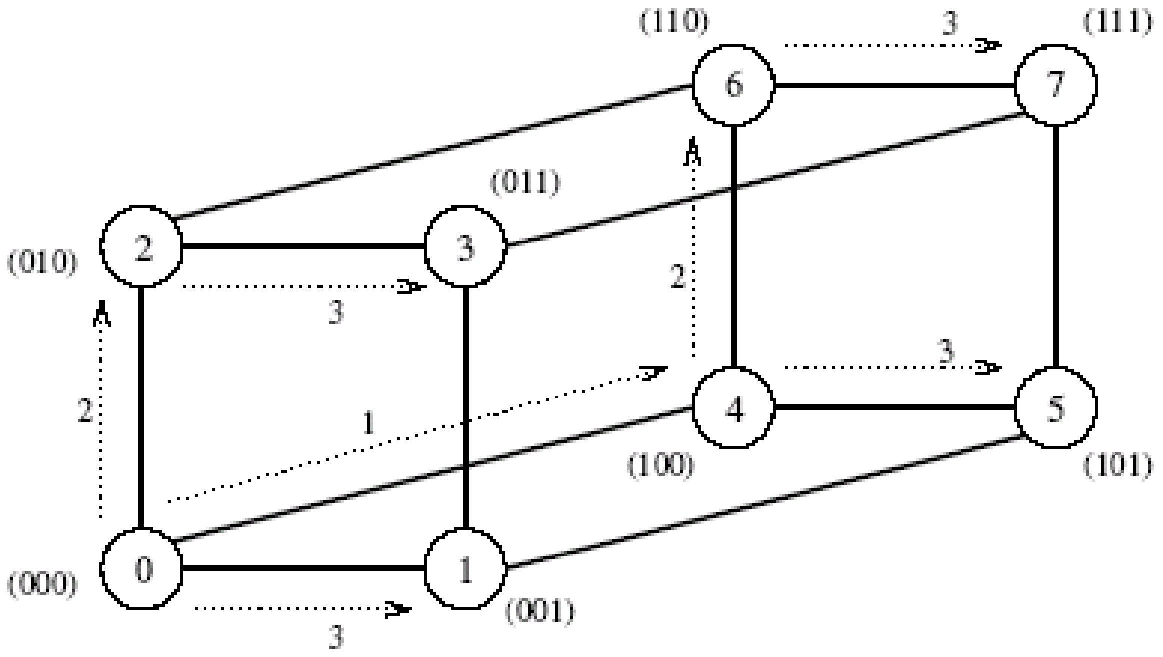


One-to-all broadcast on a 16-node mesh.

Broadcast and Reduction on a Hypercube

- A hypercube with 2^d nodes can be regarded as a ***d*-dimensional mesh** with **two nodes in each dimension**.
- The mesh algorithm can be generalized to a hypercube and the operation is **carried out in *d* (= *log p*) steps**.

Broadcast and Reduction on a Hypercube: Example



One-to-all broadcast on a three-dimensional hypercube. The binary representations of node labels are shown in parentheses.

Broadcast and Reduction Algorithms

- All of the algorithms described above are adaptations of the **same algorithmic template**.
- We illustrate the algorithm for a **hypercube**, but the algorithm, as has been seen, **can be adapted to other architectures**.
- The hypercube has ***2^d* nodes** and ***my_id* is the label** for a node.
- ***X* is the message to be broadcast**, which initially resides at the **source node 0**.

Broadcast and Reduction Algorithms

```
procedure GENERAL_ONE_TO_ALL_BC($d$, $my\_id$, $source$, $X$)
begin
    $my\_virtual\_id$ := $my\_id$ XOR $source$;
    $mask := 2^d - 1$;
    for $i := d - 1$ downto 0 do        /* Outer loop */
        $mask := mask$ XOR $2^i$;    /* Set bit $i$ of mask to 0 */
        if ($my\_virtual\_id$ AND $mask$) $= 0$ then
            if ($my\_virtual\_id$ AND $2^i$) $= 0$ then
                $virtual\_dest := my\_virtual\_id$ XOR $2^i$;
                send $X$ to (virtual_dest XOR source);
    /* Convert virtual_dest to the label of the physical destination */
            else
                $virtual\_source := my\_virtual\_id$ XOR $2^i$;
                receive $X$ from (virtual_source XOR source);
    /* Convert virtual_source to the label of the physical source */
            endelse;
    endfor;
end GENERAL_ONE_TO_ALL_BC
```

One-to-all broadcast of a message *X* from *source* on a hypercube.

Broadcast and Reduction Algorithms

```
procedure ALL_TO_ONE_REDUCE($d$, $my\_id$, $m$, $X$, sum)
begin
    for $j$ := 0 to $m-1$ do sum[$j$] := $X[j]$;
    $mask := 0$;
    for $i := 0$ to $d-1$ do
        /* Select nodes whose lower $i$ bits are 0 */
        if ($my\_id$ AND $mask$) = 0 then
            if ($my\_id$ AND $2^i$) $\neq 0$ then
                $msg\_destination := my\_id$ XOR $2^i$;
                send sum to $msg\_destination$;
            else
                $msg\_source := my\_id$ XOR $2^i$;
                receive $X$ from $msg\_source$;
                for $j := 0$ to $m-1$ do
                    sum[$j$] :=sum[$j$] + $X[j]$;
            endelse;
        $mask := mask$ XOR $2^i$;    /* Set bit $i$ of mask to 1 */
    endfor;
end ALL_TO_ONE_REDUCE
```

Single-node accumulation on a *d*-dimensional hypercube. Each node contributes a message *X* containing *m* words, and node 0 is the destination.

Cost Analysis

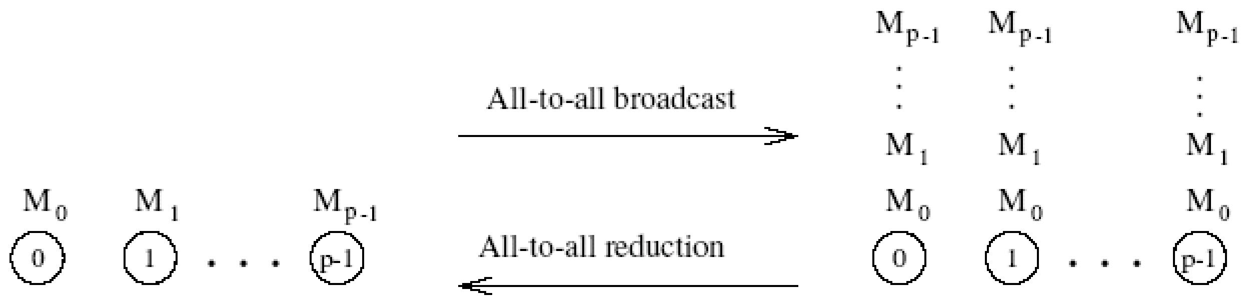
- The broadcast or reduction procedure involves ***log p*** **point-to-point simple message transfers**, each at a time cost of $t_s + t_w m$.
- The **total time** is therefore given by:

$$T = (t_s + t_w m) \log p.$$

All-to-All Broadcast and Reduction

- Generalization of broadcast in which **each processor is the source as well as destination**.
- **A process sends the same *m*-word message to every other process**, but **different processes may broadcast different messages**.

All-to-All Broadcast and Reduction

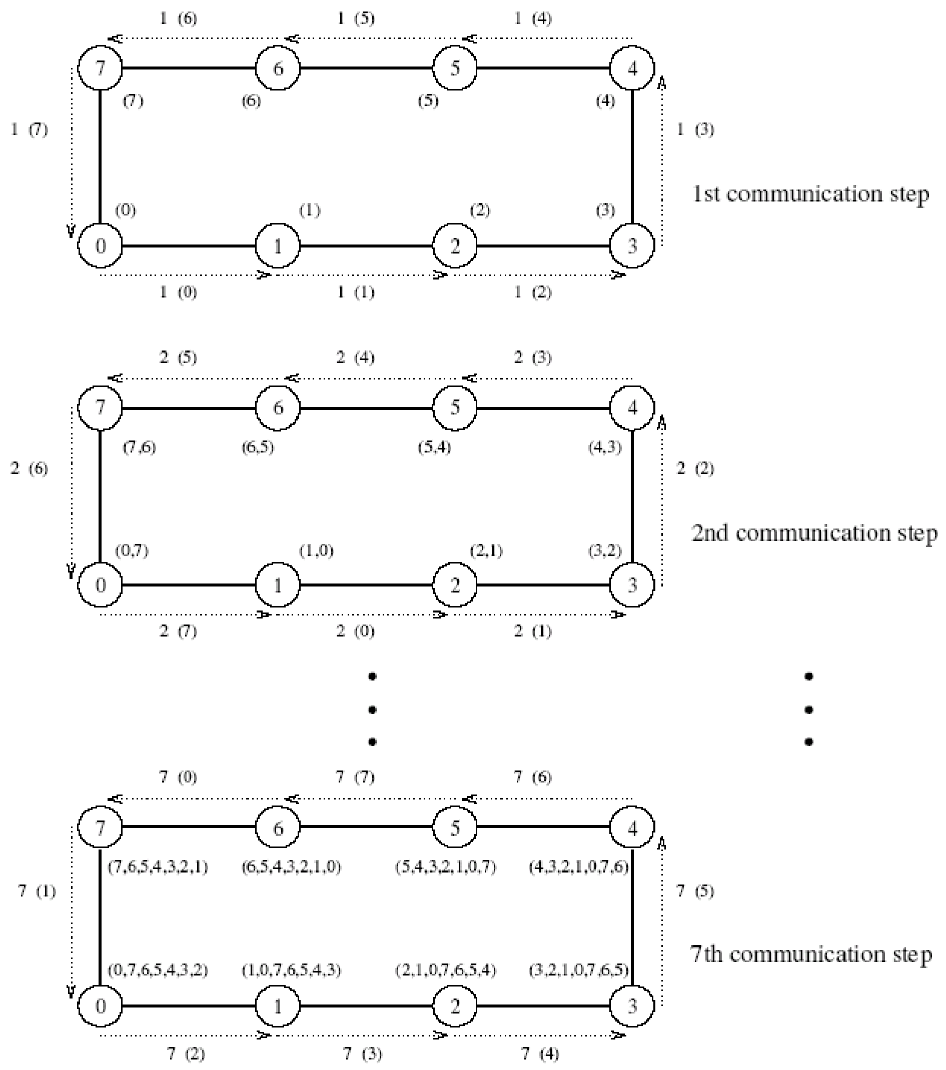


All-to-all broadcast and all-to-all reduction.

All-to-All Broadcast and Reduction on a Ring

- Simplest approach: **perform *p* one-to-all broadcasts**. This is **not the most efficient way**, though.
- Each **node first sends to one of its neighbors the data it needs to broadcast**.
- In subsequent steps, **it forwards the data received from one of its neighbors to its other neighbor**.
- The algorithm terminates in ***p-1* steps**.

All-to-All Broadcast and Reduction on a Ring



All-to-all broadcast on an eight-node ring.

All-to-All Broadcast and Reduction on a Ring

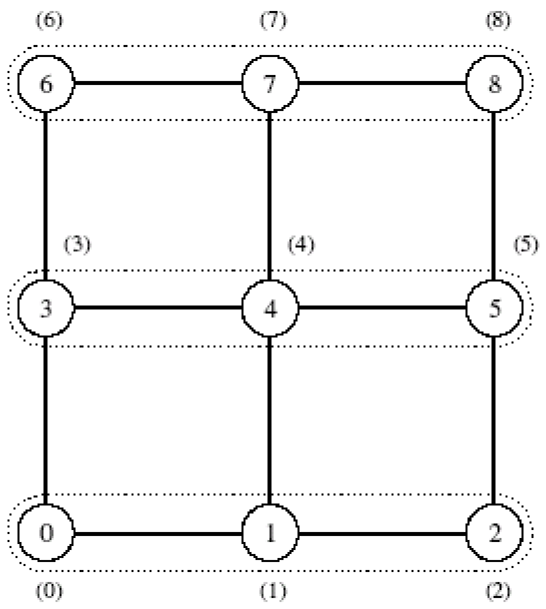
```
procedure ALL_TO_ALL_BC_RING($my\_id, my\_msg, p,$ result)
begin
    left := $(my\_id - 1)$ mod $p$;
    right := $(my\_id + 1)$ mod $p$;
    result := $my\_msg$;
    msg := result;
    for $i := 1$ to $p - 1$ do
        send msg to right;
        receive msg from left;
        result := result $\cup$ msg;
    endfor;
end ALL_TO_ALL_BC_RING
```

All-to-all broadcast on a *p*-node ring.

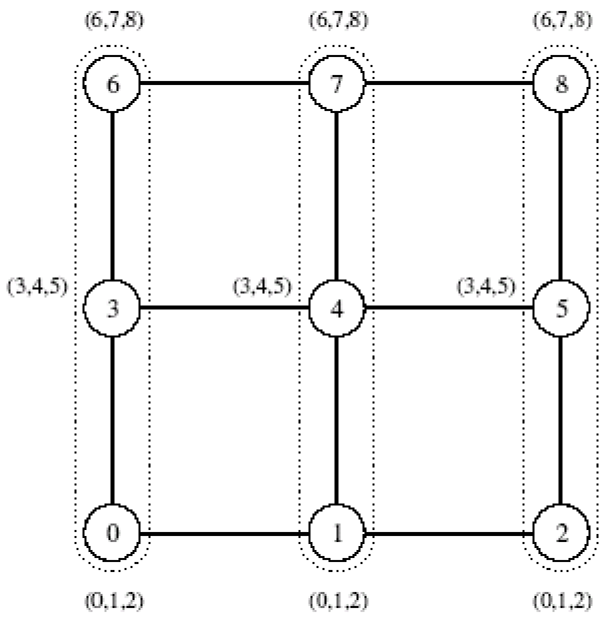
All-to-all Broadcast on a Mesh

- Performed in two phases - **in the first phase, each row of the mesh performs an all-to-all broadcast** using the procedure for the linear array.
- In this phase, all nodes **collect $\sqrt{p}$ messages** corresponding to the $\sqrt{p}$ nodes of their respective rows. Each node **consolidates this information into a single message of size $m\sqrt{p}$**.
- The second communication phase is a **columnwise all-to-all broadcast** of the consolidated messages.

All-to-all Broadcast on a Mesh



(a) Initial data distribution



(b) Data distribution after rowwise broadcast

All-to-all broadcast on a *3 x 3* mesh. The groups of nodes communicating with each other in each phase are enclosed by dotted boundaries. By the end of the second phase, all nodes get (0,1,2,3,4,5,6,7) (that is, a message from each node).

All-to-all Broadcast on a Mesh

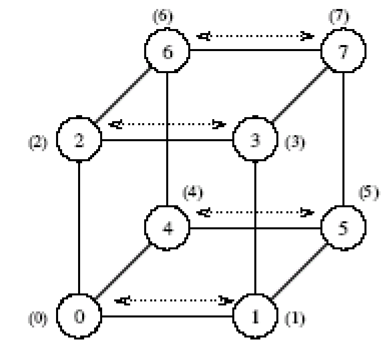
```
1.      procedure ALL_TO_ALL_BC_MESH($my\_id, my\_msg, p$, result)
2.      begin
/* Communication along rows */
3.          left := $my\_id - (my\_id \bmod \sqrt{p}) + (my\_id - 1) \bmod \sqrt{p}$;
4.          right := $my\_id - (my\_id \bmod \sqrt{p}) + (my\_id + 1) \bmod \sqrt{p}$;
5.          result := $my\_msg$;
6.          msg := result;
7.          for $i := 1$ to $\sqrt{p} - 1$ do
8.              send msg to right;
9.              receive msg from left;
10.             result := result $\cup$ msg;
11.         endfor;
/* Communication along columns */
12.         up := $(my\_id - \sqrt{p}) \bmod p$;
13.         down := $(my\_id + \sqrt{p}) \bmod p$;
14.         msg := result;
15.         for $i := 1$ to $\sqrt{p} - 1$ do
16.             send msg to down;
17.             receive msg from up;
18.             result := result $\cup$ msg;
19.         endfor;
20.     end ALL_TO_ALL_BC_MESH
```

All-to-all broadcast on a square mesh of *p* nodes.

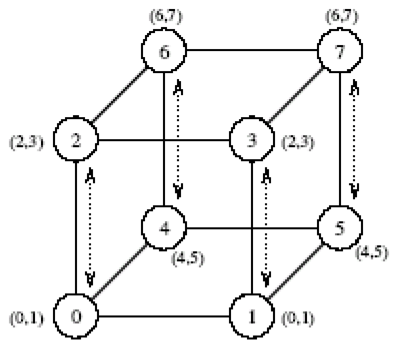
All-to-all broadcast on a Hypercube

- **Generalization of the mesh** algorithm to *log p* dimensions.
- **Message size doubles** at each of the *log p* steps.

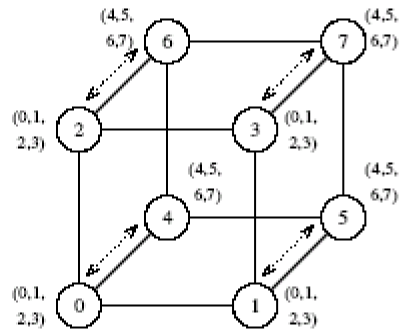
All-to-all broadcast on a Hypercube



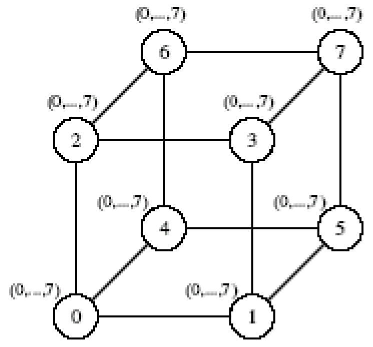
(a) Initial distribution of messages



(b) Distribution before the second step



(c) Distribution before the third step



(d) Final distribution of messages

All-to-all broadcast on an eight-node hypercube.

All-to-all broadcast on a Hypercube

```
procedure ALL_TO_ALL_BC_HCUBE($my\_id$, $my\_msg$, $d$, result)
begin
    result := $my\_msg$;
    for $i := 0$ to $d - 1$ do
        partner := $my\_id$ XOR $2^i$;
        send result to partner;
        receive msg from partner;
        result := result $\cup$ msg;
    endfor;
end ALL_TO_ALL_BC_HCUBE
```

All-to-all broadcast on a *d*-dimensional hypercube.

All-to-all Reduction

- **Similar communication pattern** to all-to-all broadcast, except in the **reverse order**.
- On receiving a message, a **node must combine it with the local copy** of the message that has **the same destination as the received message** before forwarding the combined message to the next neighbor.

Cost Analysis

- On a ring, the time is given by: $(t_s + t_w m)(p-1)$.
- On a mesh, the time is given by: $2t_s(\sqrt{p} - 1) + t_w m(p-1)$.
- On a hypercube, we have:

$$T = \sum_{i=1}^{\log p} (t_s + 2^{i-1} t_w m)$$

$$= t_s \log p + t_w m(p-1).$$

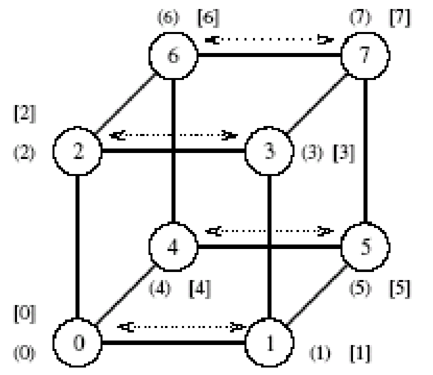
All-Reduce and Prefix-Sum Operations

- In all-reduce, **each node starts with a buffer of size *m*** and the final **results of the operation are identical buffers** of size *m* on each node that are formed by combining the original *p* buffers using an associative operator.
- Identical to **all-to-one reduction followed by a one-to-all broadcast**. This formulation is not the most efficient. Uses the pattern of all-to-all broadcast, instead. The only difference is that **message size does not increase** here. Time for this operation is $(t_s + t_w m) \log p$.
- **Different from all-to-all reduction**, in which *p* simultaneous all-to-one reductions take place, each with a different destination for the result.

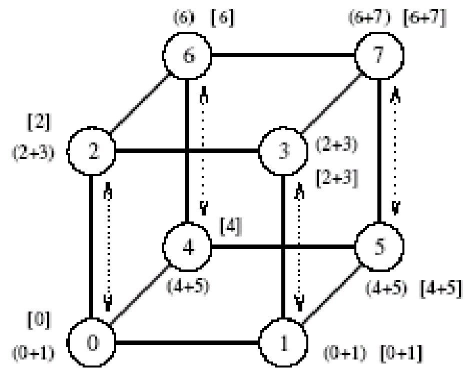
The Prefix-Sum Operation

- Given *p* numbers $n_0, n_1, \ldots, n_{p-1}$ (one on each node), the problem is to **compute the sums** $s_k = \sum_{i=0}^{k} n_i$ for all *k* between 0 and *p-1* .
- Initially, $\boldsymbol{n_k}$ **resides on the node labeled** ***k***, and at the end of the procedure, the same node holds S_k.

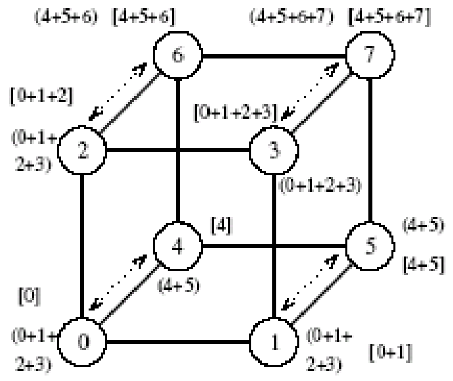
The Prefix-Sum Operation



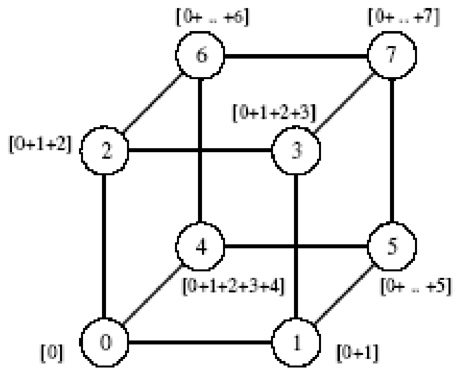
(a) Initial distribution of values



(b) Distribution of sums before second ste|



(c) Distribution of sums before third step



(d) Final distribution of prefix sums

Computing prefix sums on an eight-node hypercube. At each node, square brackets show the local prefix sum accumulated in the result buffer and parentheses enclose the contents of the outgoing message buffer for the next step.

The Prefix-Sum Operation

- The operation **can be implemented using the all-to-all broadcast kernel**.
- We must account for the fact that in prefix sums the **node with label *k* uses information from only the *k*-node subset whose labels are less than or equal to *k***.
- This is implemented using an **additional result buffer**. The content of an incoming message is added to the result buffer only if the message comes from a node with a smaller label than the recipient node.
- The **contents of the outgoing message** (denoted by parentheses in the figure) **are updated with every incoming message**.

The Prefix-Sum Operation

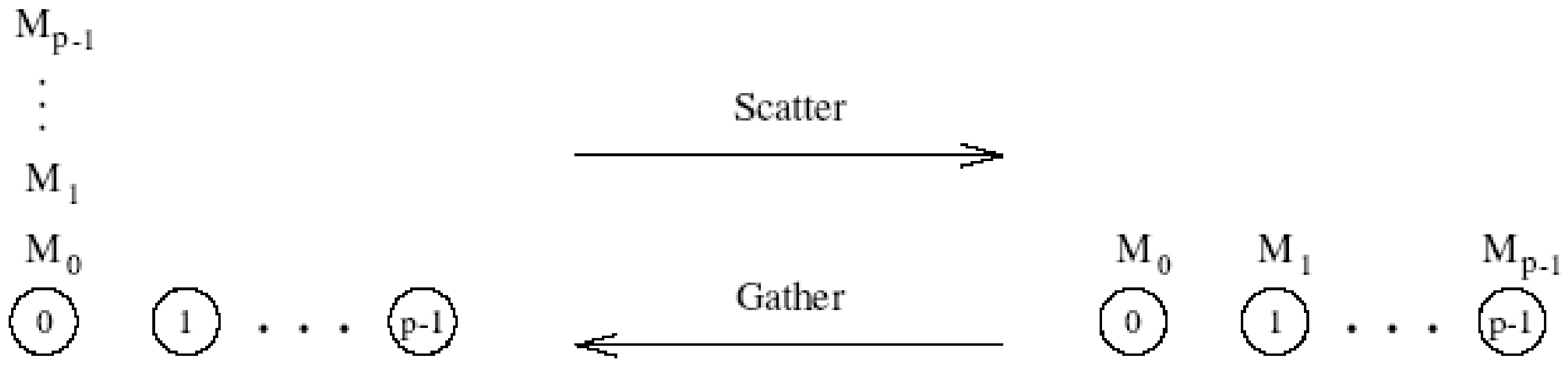
```
1.  procedure PREFIX_SUMS_HCUBE($my\_id$, $my\_number$, $d$, result)
2.  begin
3.      result := $my\_number$;
4.      msg := result;
5.      for $i := 0$ to $d - 1$ do
6.          partner := $my\_id$ XOR $2^i$;
7.          send msg to partner;
8.          receive number from partner;
9.          msg := msg + number;
10.         if (partner $<$ $my\_id$) then result := result + number;
11.     endfor;
12. end PREFIX_SUMS_HCUBE
```

Prefix sums on a *d*-dimensional hypercube.

Scatter and Gather

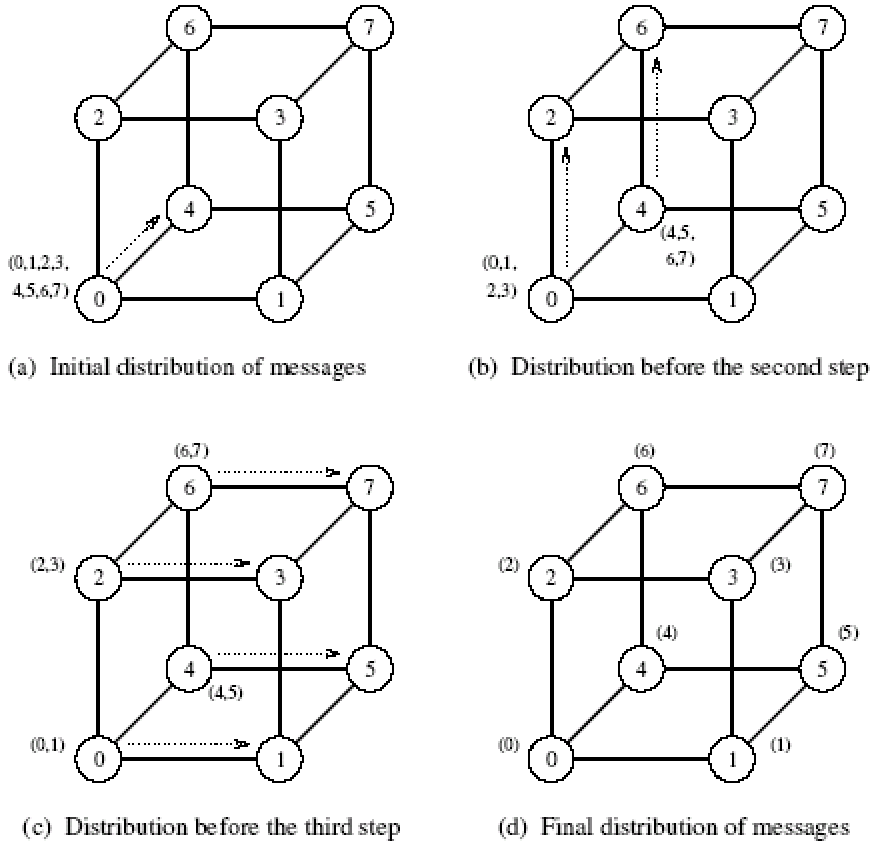
- In the *scatter* operation, **a single node sends a unique message of size *m* to every other node** (also called a one-to-all personalized communication).
- In the *gather* operation, **a single node collects a unique message from each node**.
- While the scatter operation is fundamentally different from **broadcast**, **the algorithmic structure is similar**, **except for differences in message sizes** (messages get smaller in scatter and stay constant in broadcast).
- The **gather operation is exactly the inverse** of the scatter operation and can be executed as such.

Gather and Scatter Operations



Scatter and gather operations.

Example of the Scatter Operation


(0,1,2,3,
4,5,6,7)
(a) Initial distribution of messages
(0,1,
2,3)
(4,5,
6,7)
(b) Distribution before the second step
(6,7)
(2,3)
(4,5)
(0,1)
(c) Distribution before the third step
(6)
(7)
(2)
(3)
(4)
(5)
(0)
(1)
(d) Final distribution of messages

The scatter operation on an eight-node hypercube.

Cost of Scatter and Gather

- There are ***log p*** **steps**, **in each step, the machine size halves** and **the data size halves**.
- We have the time for this operation to be:

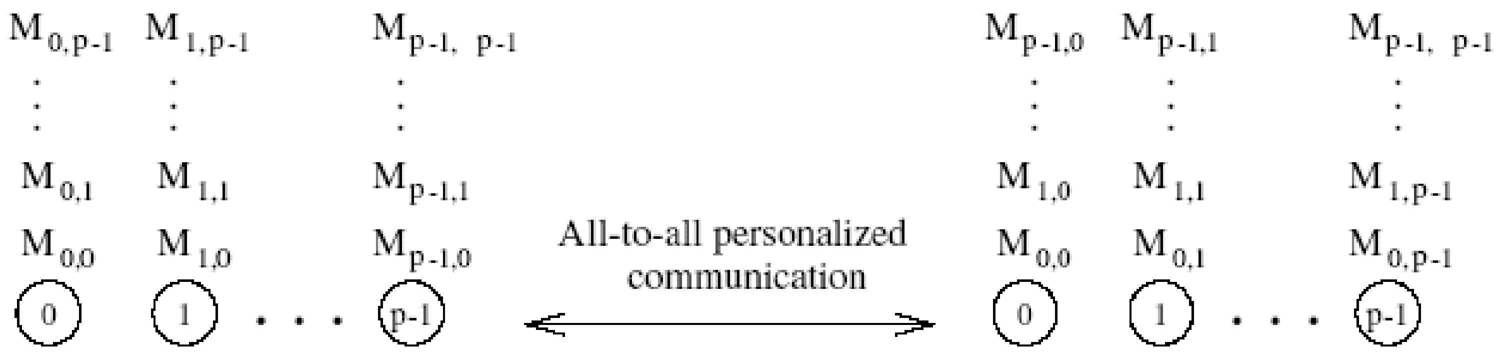
$$T = t_s \log p + t_w m(p-1).$$

- This time holds for a **linear array** as well as a **2-D mesh**.
- These times are asymptotically optimal in message size.

All-to-All Personalized Communication

- **Each node has a distinct message of size *m* for every other node**.
- This is unlike all-to-all broadcast, in which each node sends the same message to all other nodes.
- All-to-all personalized communication is also known as ***total exchange***.

All-to-All Personalized Communication

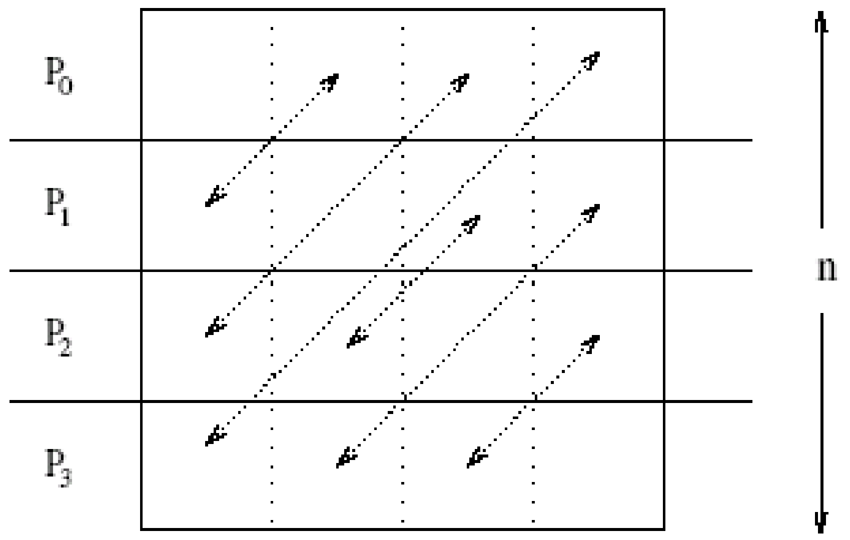


All-to-all personalized communication.

All-to-All Personalized Communication: Example

- Consider the problem of **transposing a matrix**.
- **Each processor contains one full row of the matrix**.
- The transpose operation in this case is identical to an **all-to-all personalized communication** operation.

All-to-All Personalized Communication: Example

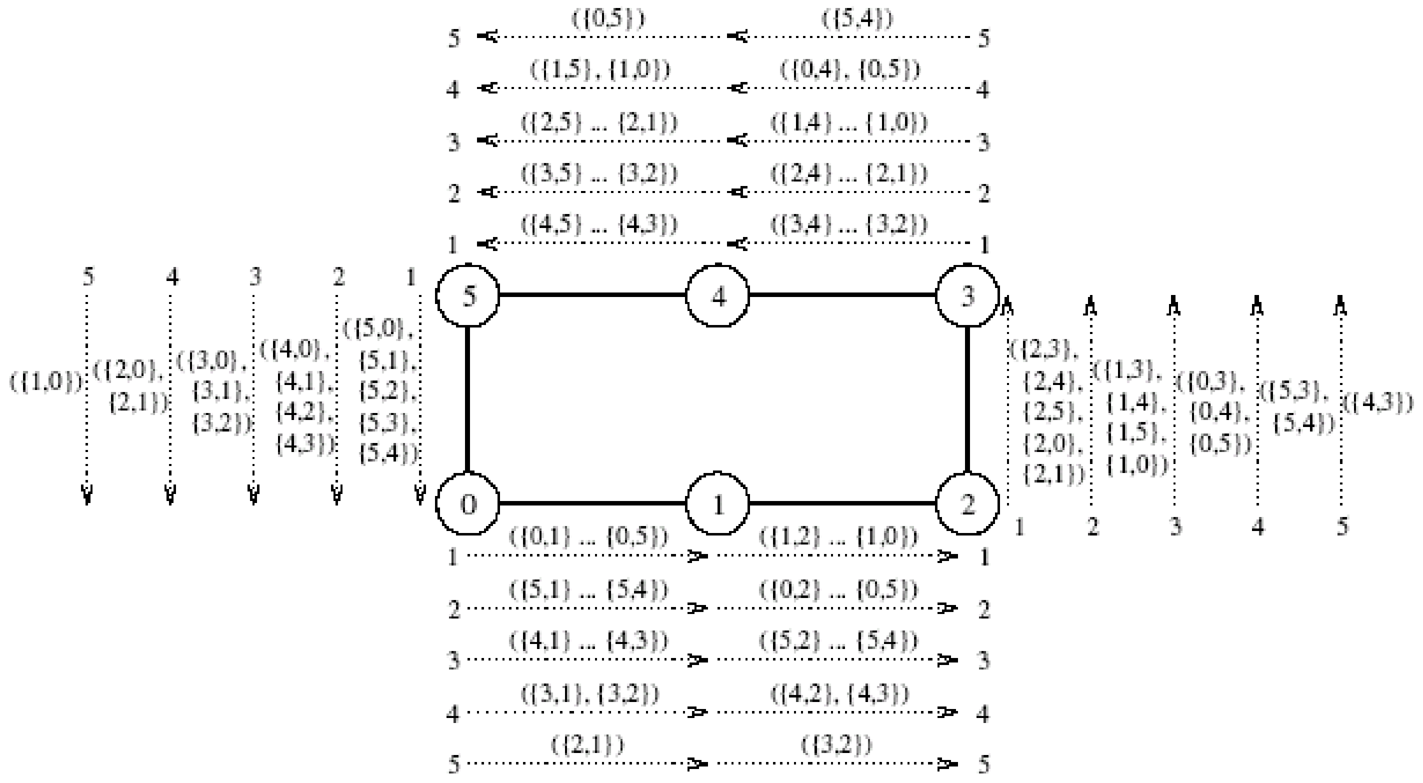


All-to-all personalized communication in transposing a *4 x 4* matrix using four processes.

All-to-All Personalized Communication on a Ring

- Each node **sends all pieces of data as one consolidated message of size *m(p – 1)* to one of its neighbors**.
- Each **node extracts the information meant for it** from the data received, and **forwards the remaining (*p – 2*) pieces of size *m* each to the next node**.
- The algorithm terminates in ***p – 1* steps**.
- The size of the **message reduces by *m* at each step**.

All-to-All Personalized Communication on a Ring



All-to-all personalized communication on a six-node ring. The label of each message is of the form *{x,y}*, where *x* is the label of the node that originally owned the message, and *y* is the label of the node that is the final destination of the message. The label *(*$\{x_1,y_1\}, \{x_2,y_2\}, \ldots, \{x_n,y_n\}$*)*, indicates a message that is formed by concatenating *n* individual messages.

All-to-All Personalized Communication on a Ring: Cost

- We have *p – 1* steps in all.
- In step *i*, the message size is *m(p – i)*.
- The total time is given by:

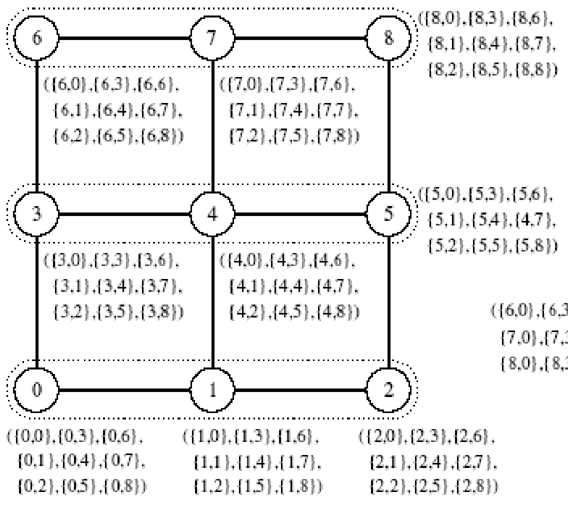
$$
\begin{aligned}
T &= \sum_{i=1}^{p-1} (t_s + t_w m(p-i)) \\
&= t_s(p-1) + \sum_{i=1}^{p-1} i t_w m \\
&= (t_s + t_w mp/2)(p-1).
\end{aligned}
$$

- The t_w term in this equation can be **reduced by a factor of 2 by communicating messages in both directions**.

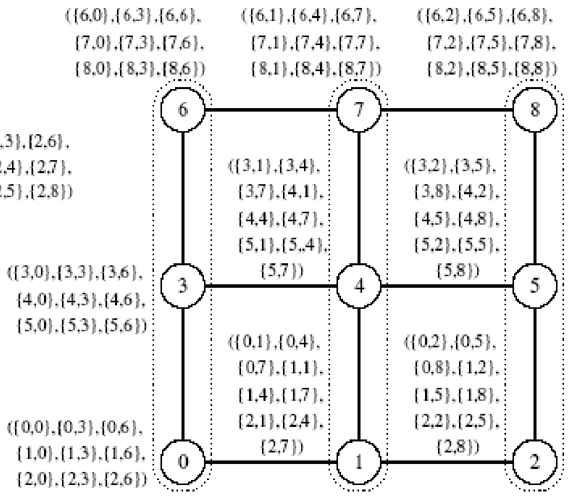
All-to-All Personalized Communication on a Mesh

- Each node **first groups its *p* messages according to the columns of their destination** nodes.
- **All-to-all personalized communication is performed independently in each row** with clustered messages of size $m\sqrt{p}$.
- Messages in each node are **sorted again**, this time **according to the rows** of their destination nodes.
- **All-to-all personalized communication** is performed independently in **each column** with clustered messages of **size** $\boldsymbol{m\sqrt{p}}$.

All-to-All Personalized Communication on a Mesh



(a) Data distribution at the beginning of first phase



(b) Data distribution at the beginning of second phase

The distribution of messages at the beginning of each phase of all-to-all personalized communication on a *3 x 3* mesh. At the end of the second phase, node *i* has messages *({0,i},…,{8,i})*, where *0 ≤ i ≤ 8*. The groups of nodes communicating together in each phase are enclosed in dotted boundaries.

All-to-All Personalized Communication on a Mesh: Cost

- Time for the **first phase** is identical to that in a ring with $\sqrt{p}$ processors, i.e., $(t_s + t_w mp/2)(\sqrt{p} - 1)$.
- Time in the **second phase is identical to the first phase**. Therefore, total time is twice of this time, i.e.,

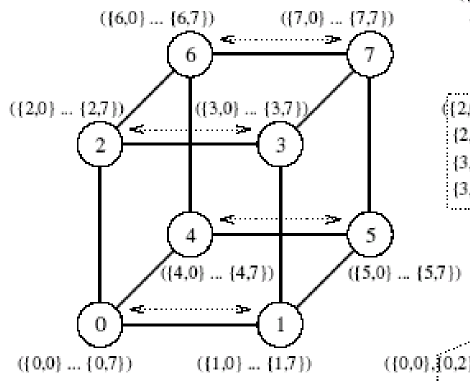
$$T = (2t_s + t_w mp)(\sqrt{p} - 1).$$

- It can be shown that the **time for rearrangement is less much less than this communication time**.

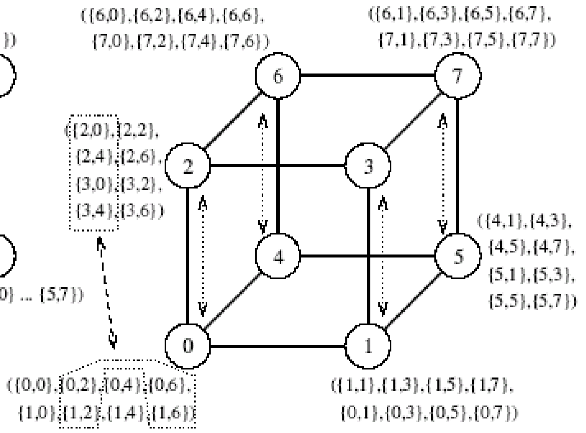
All-to-All Personalized Communication on a Hypercube

- **Generalize the mesh algorithm** to *log p* steps.
- At any stage in all-to-all personalized communication, **every node holds *p* packets of size *m* each**.
- While communicating in a particular dimension, every **node sends *p/2* of these packets** (consolidated as one message).
- A **node must rearrange its messages locally** before each of the *log p* communication steps.

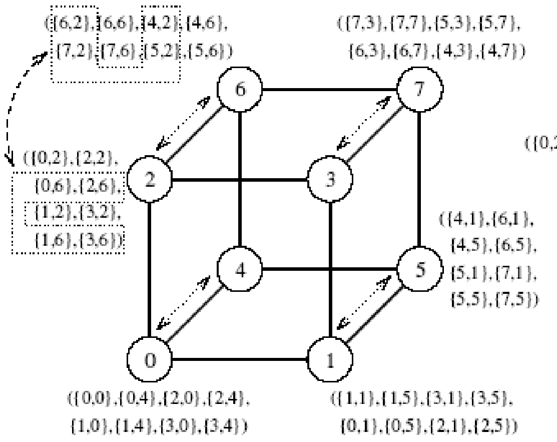
All-to-All Personalized Communication on a Hypercube



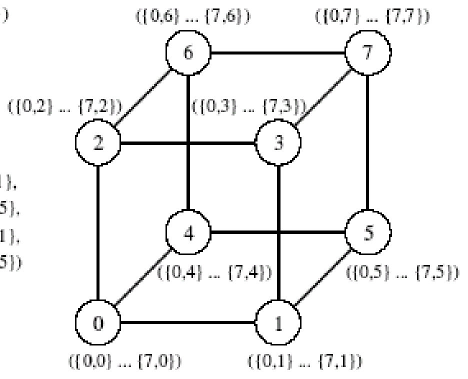
(a) Initial distribution of messages



(b) Distribution before the second step



(c) Distribution before the third step



(d) Final distribution of messages

An all-to-all personalized communication algorithm on a three-dimensional hypercube.

All-to-All Personalized Communication on a Hypercube: Cost

- We have *log p* iterations and *mp/2* words are communicated in each iteration. Therefore, the cost is:

$$T = (t_s + t_w mp/2) \log p.$$

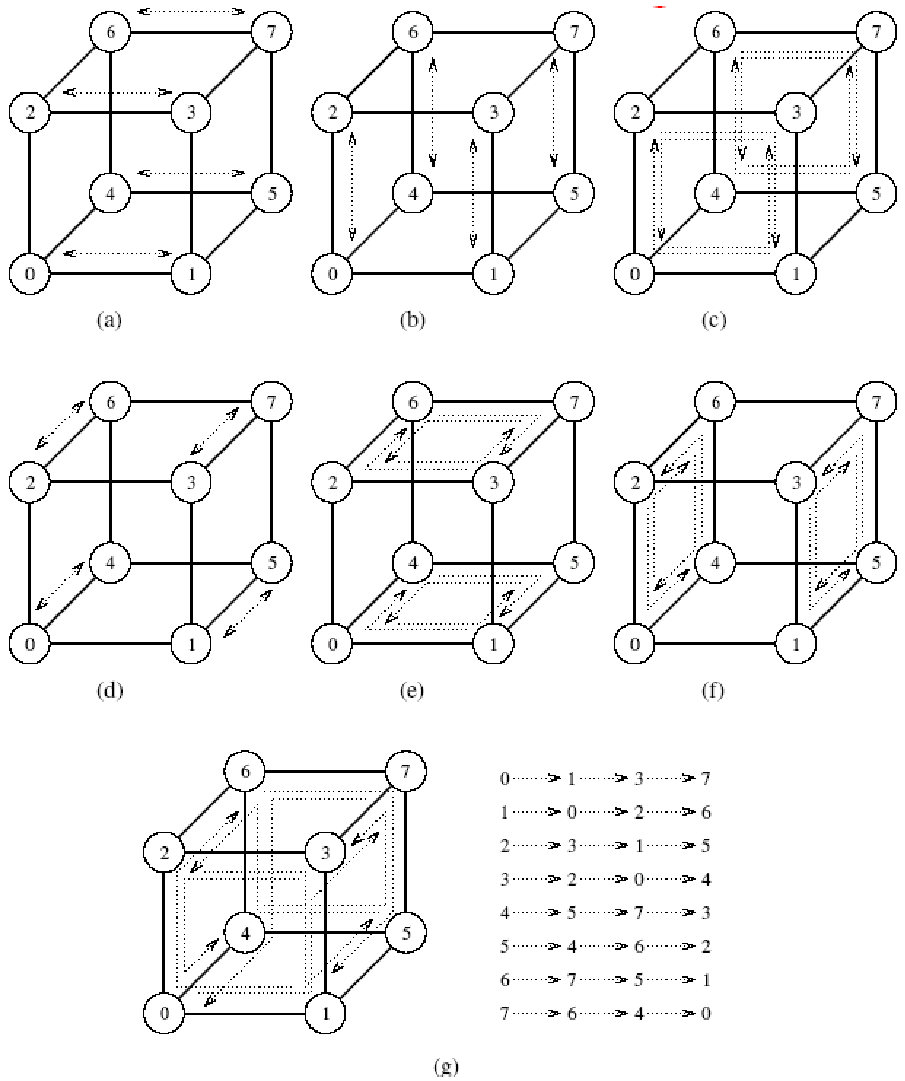
- **This is not optimal!** (Each of the p nodes **sends and receives m(p - 1) words**, the **average distance** between any two nodes on a hypercube is (log p)/2 and there is a total of (p log p)/2 **links in the hypercube** network)

$$\begin{aligned} T &= \frac{t_w pm(p-1)(\log p)/2}{(p \log p)/2} \\ &= t_w m(p-1). \end{aligned}$$

All-to-All Personalized Communication on a Hypercube: Optimal Algorithm

- **Each node simply performs *p – 1* communication steps, exchanging *m* words of data with a different node in every step**.
- A node must choose its communication partner in each step so that the **hypercube links do not suffer congestion**.
- In the j^{th} **communication step**, node *i* exchanges data with node ***(i XOR j)***.
- In this schedule, all paths in every communication step are congestion-free, and **none of the bidirectional links carry more than one message in the same direction**.

All-to-All Personalized Communication on a Hypercube: Optimal Algorithm



Seven steps in all-to-all personalized communication on an eight-node hypercube.

All-to-All Personalized Communication on a Hypercube: Optimal Algorithm

```
procedure ALL_TO_ALL_PERSONAL($d$, $my\_id$)
begin
    for $i := 1$ to $2^d - 1$ do
    begin
        partner := $my\_id$ XOR $i$;
        send $M_{my\_id,partner}$ to partner;
        receive $M_{partner,my\_id}$ from partner;
    endfor;
end ALL_TO_ALL_PERSONAL
```

A procedure to perform all-to-all personalized communication on a *d*-dimensional hypercube. The message $M_{i,j}$ initially resides on node *i* and is destined for node *j*.

All-to-All Personalized Communication on a Hypercube: Cost Analysis of Optimal Algorithm

- There are ***p* – *1* steps** and each step involves non-congesting **message transfer of *m* words**.
- We have:

$$T = (t_s + t_w m)(p - 1).$$

- This is asymptotically optimal in message size.

Circular Shift

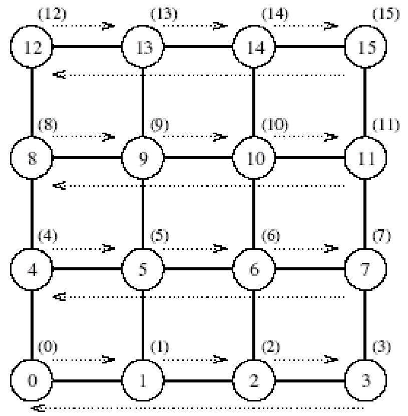
- A special permutation in which **node *i* sends a data packet to node *(i + q)* mod *p*** in a *p*-node ensemble $(0 \le q \le p)$.

Circular Shift on a Mesh

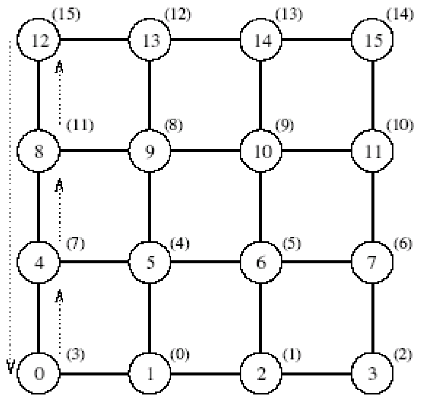
- The implementation on a ring is rather **intuitive**. It can be performed in min*{q,p – q}* neighbor communications.
- **Mesh algorithms follow from this as well**. We shift in one direction (all processors) followed by the next direction.
- The associated time has an upper bound of:

$$T = (t_s + t_w m)(\sqrt{p} + 1).$$

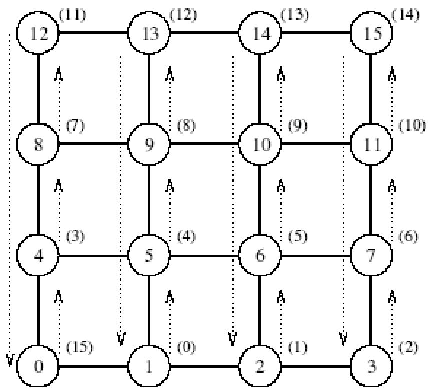
Circular Shift on a Mesh



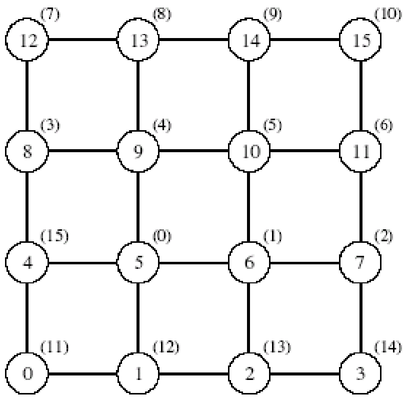
(a) Initial data distribution and the first communication step



(b) Step to compensate for backward row shift



(c) Column shifts in the third communication step



(d) Final distribution of the data

The communication steps in a circular 5-shift on a *4 x 4* mesh.

Circular Shift on a Hypercube

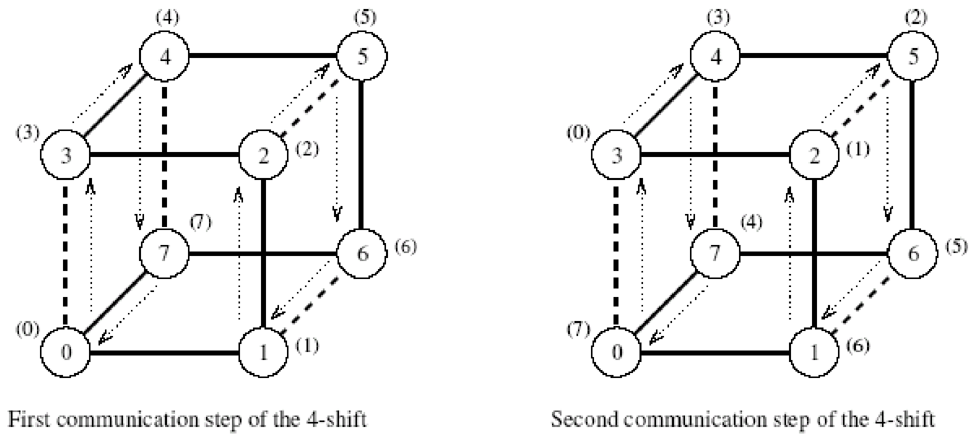
- **Map a linear array with *2^d* nodes onto a *d*-dimensional hypercube**.
- To perform a *q*-shift, we **expand *q* as a sum of distinct powers of 2**.
- If *q* is the sum of *s* distinct powers of 2, then the circular *q*-shift on a hypercube is performed in *s* phases.
- The time for this is upper bounded by:

$$T = (t_s + t_w m)(2 \log p - 1).$$

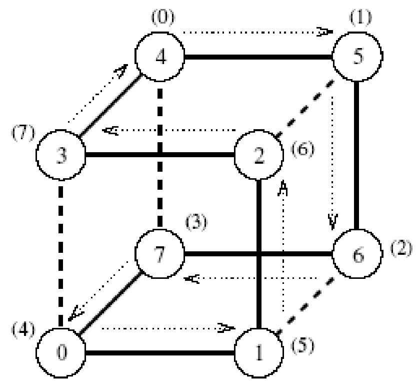
- If E-cube routing is used, this time can be reduced to

$$T = t_s + t_w m.$$

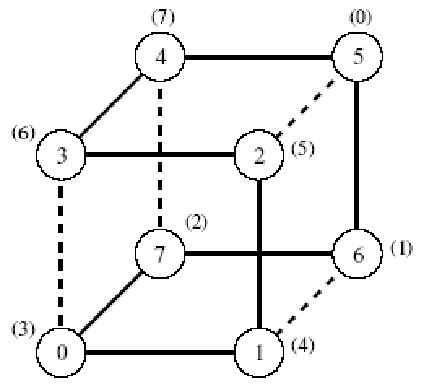
Circular Shift on a Hypercube


First communication step of the 4-shift
Second communication step of the 4-shift

(a) The first phase (a 4-shift)



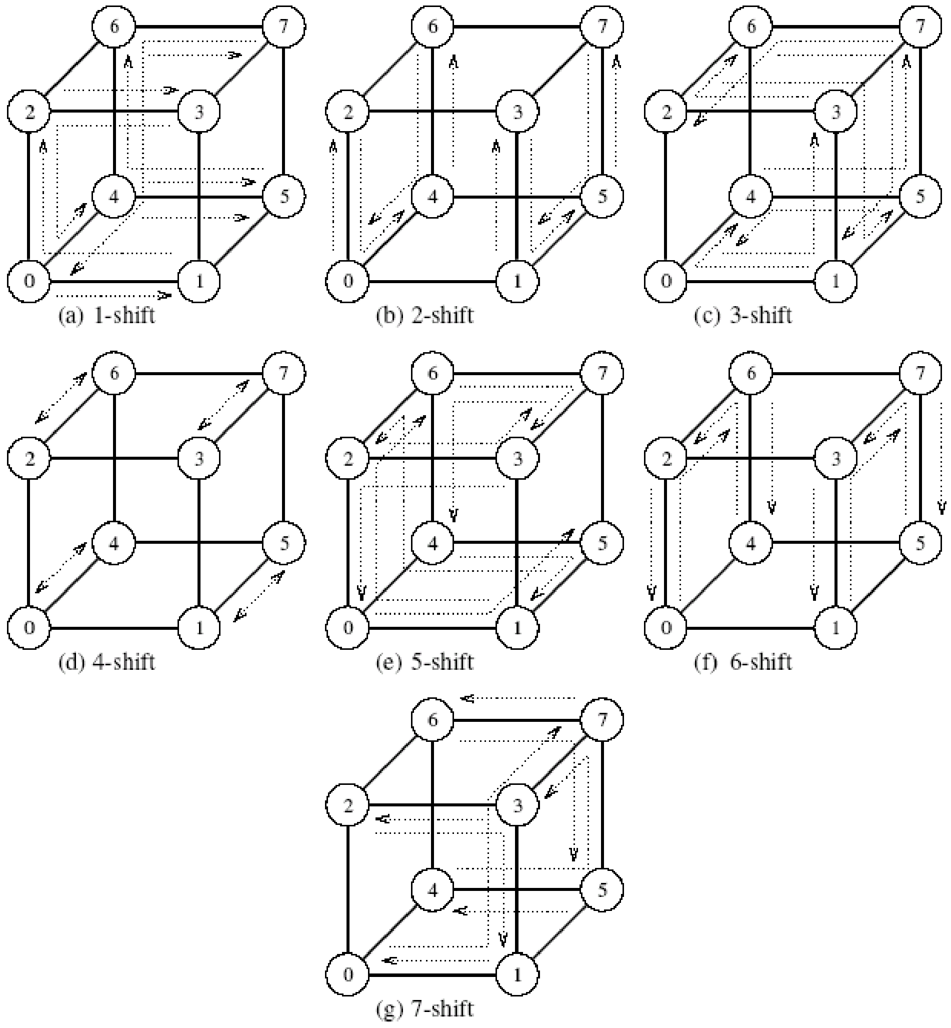
(b) The second phase (a 1-shift)



(c) Final data distribution after the 5-shift

The mapping of an eight-node linear array onto a three-dimensional hypercube to perform a **circular 5-shift** as a **combination of a 4-shift** and a **1-shift**.

Circular Shift on a Hypercube



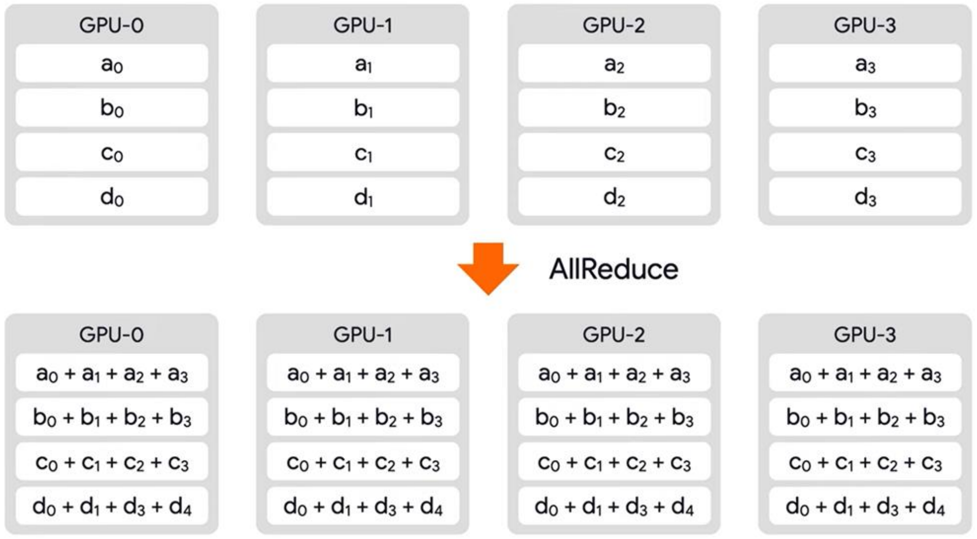
Circular *q*-shifts on an *8*-node hypercube for *1* ≤ *q* < *8*.

Summary

Operation	T (hypercube)
One-to-all broadcast	$T = (t_s + t_w m) \log p$
All-to-all broadcast	$T = t_s \log p + t_w m(p-1)$
All-reduce	$T = (t_s + t_w m) \log p$
Scatter	$T = t_s \log p + t_w m(p-1)$
All-to-all personalized	$T = (t_s + t_w m)(p-1)$
Circular shift	$T = t_s + t_w m$

Distributed ML Training

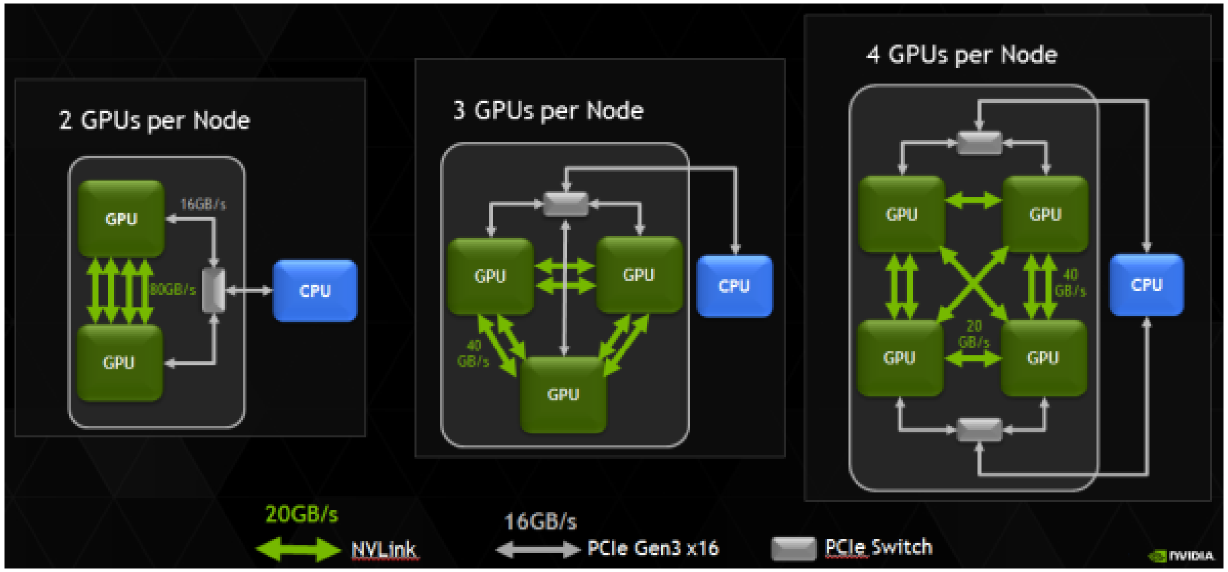
- Distributed Machine Learning (ML) training on **4 GPUs**.
- Each GPU has a different **subset of training data**.
- Each GPU computes different **gradients**.
- Gradients obtained by different GPUs are combined by **averaging**.



a, b, c, d stand for calculated gradients

Distributed ML Training

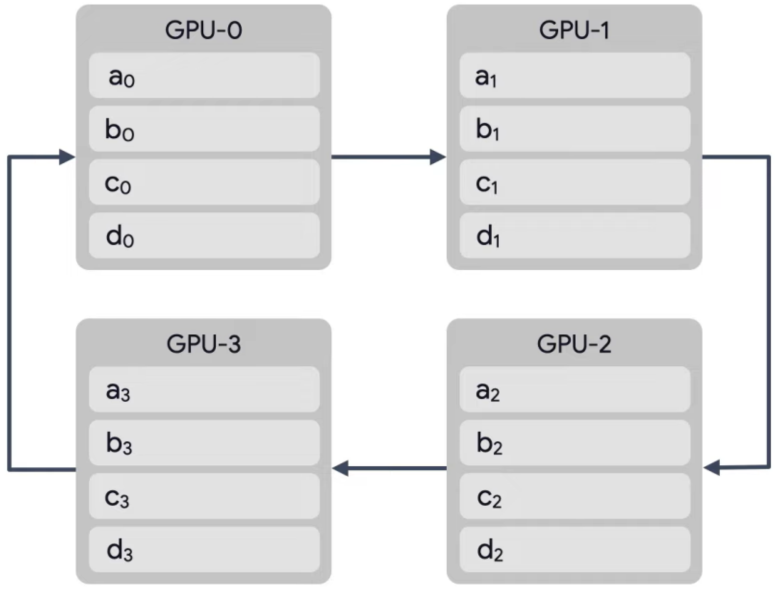
- NVIDIA's NVLink is a direct GPU-to-GPU interconnect.
- Allows one to access the memory and CUDA cores as though they were a single card.



NVLink interconnect topologies and bandwidths

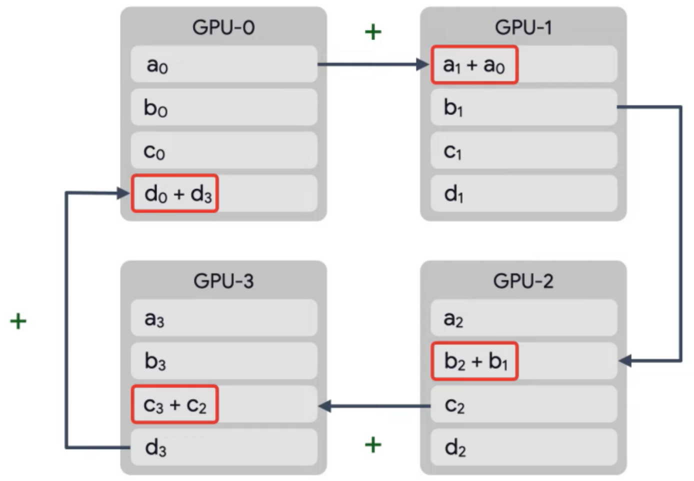
Distributed ML Training

- Communication used is **All-Reduce** on a logical **ring**.
- Two phases of communication: i) **Reduce-scatter** and ii) **All-Gather**

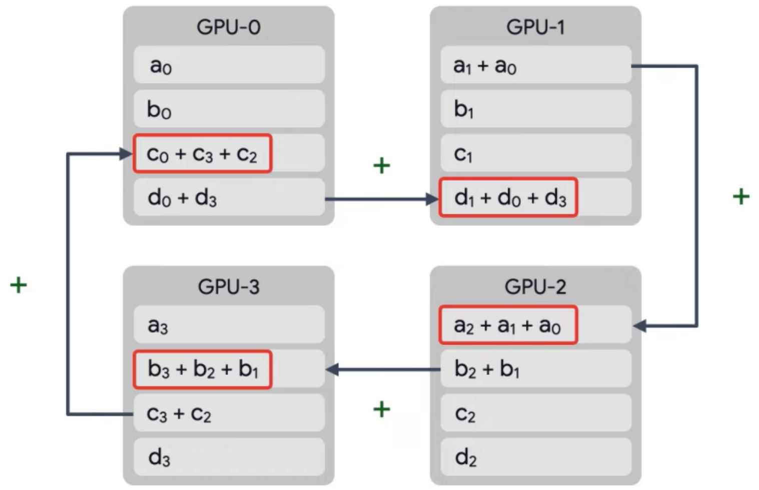


a, b, c, d stand for calculated gradients

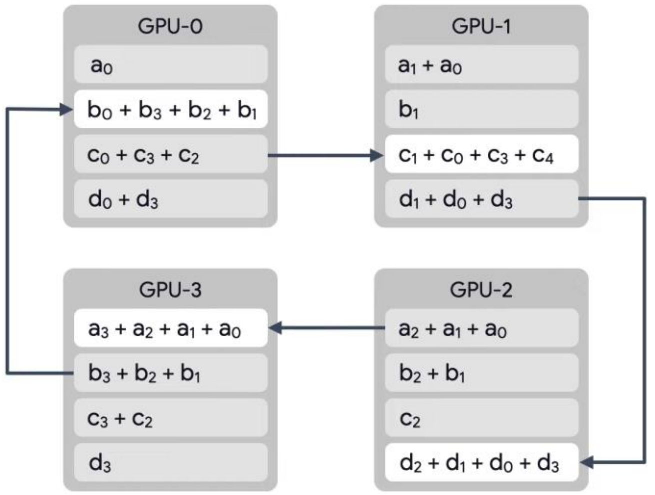
Distributed ML Training (Reduce-scatter)



Step 1

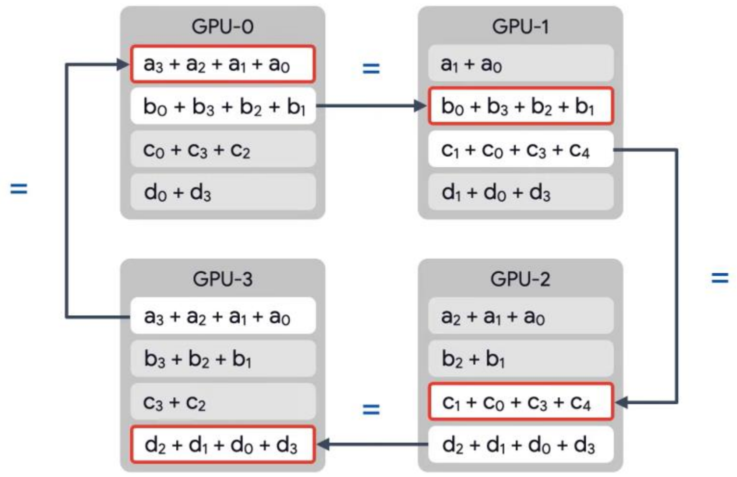


Step 2



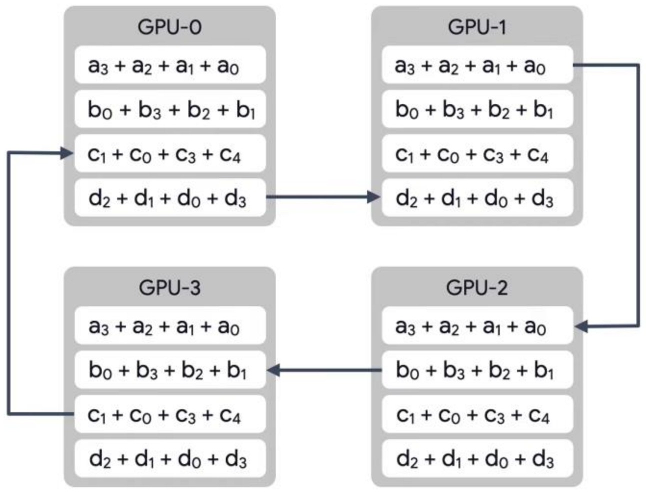
Step 3

Distributed ML Training (All-Gather)



Step 1

…



Step 3

- Finally the algorithm computes the averages.

Ref: [1] A friendly introduction to distributed training (ML Tech Talks), https://www.youtube.com/watch?v=S1tN9a4Proc, 2023.