Barriers for Synchronizations

1. Synchronizing Computations
   - the linear barrier
   - the tree barrier
   - the butterfly barrier
   - the `sendrecv` method of MPI
2. the Prefix Sum Algorithm
   - data parallel computations
   - the prefix sum algorithm in MPI
3. Barriers in Shared Memory Parallel Programming
   - an example illustrating the `pthread_barrier_t`

MCS 572 Lecture 18
Introduction to Supercomputing
Jan Verschelde, 3 October 2016

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the linear barrier

A barrier has two phases:

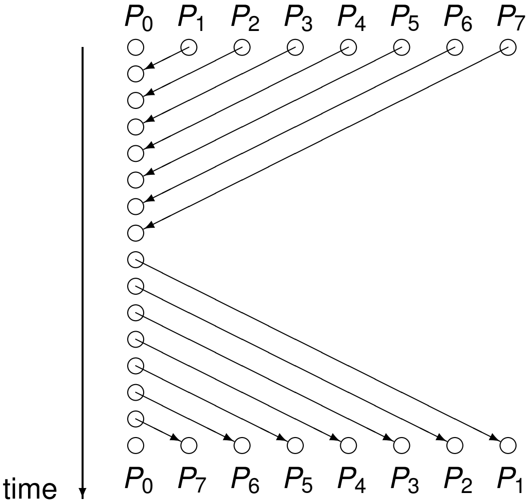
1. the arrival or trapping phase;
2. the departure or release phase.

The manager maintains a counter: only when all workers have sent to the manager, does the manager send messages to all workers.

manager	worker
for i from 1 to $p-1$ do	
receive from i	send to manager
for i from 1 to $p-1$ do	
send to i	receive from manager

The counter implementation of a barrier or linear barrier is effective but it takes $O(p)$ steps.

the linear barrier for $p = 8$



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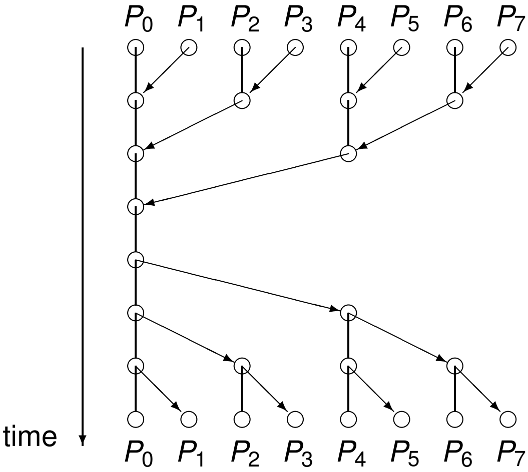
the tree barrier for $p = 8$



implementing a tree barrier

The trapping phase, for $p = 2^k$ (recall the fan in gather):

for i from $k - 1$ down to 0 do
  for j from 2^i to 2^{i+1} do
    node j sends to node $j - 2^i$;
    node $j - 2^i$ receives from node j.

The release phase, for $p = 2^k$ (recall the fan out scatter):

for i from 0 to $k - 1$ do
  for j from 0 to $2^i - 1$ do
    node j sends to $j + 2^i$;
    node $j + 2^i$ receives from node j.

The tree barrier needs $2\log_2(p)$ stages.

Number of messages: $2\sum_{i=0}^{k-1} 2^i = 2\left(\frac{2^k - 1}{2 - 1}\right) = 2^{k+1} - 2 = 2p - 2.$

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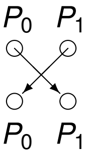
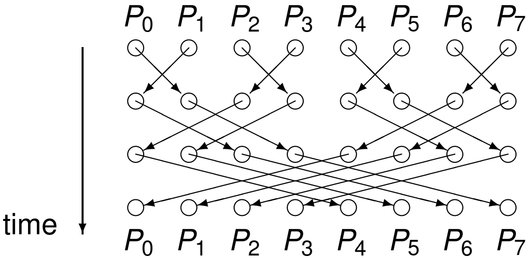
the butterfly barrier for $p = 8$

Two processors can synchronize in one step:

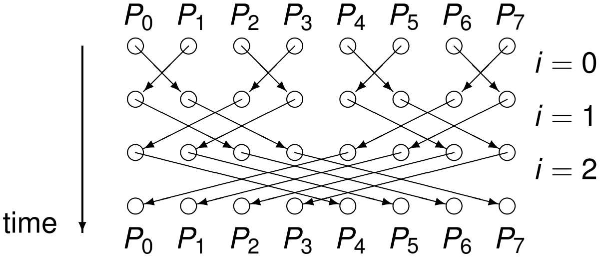


Applied to $p = 4$ and $p = 8$, observe there are no idle processors:



the algorithm for a butterfly barrier, for $p = 2^k$

for i from 0 to $k-1$ do
    $s := 0$;
    for j from 0 to $p-1$ do
        if ($j \bmod 2^{i+1} = 0$) $s := j$;
        node j sends to node $((j + 2^i) \bmod 2^{i+1}) + s$;
        node $((j + 2^i) \bmod 2^{i+1}) + s$ receives from node j.



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avoiding deadlock with `sendrecv`

$$
\begin{array}{ccccc}
P_{i-1} & & P_i & & P_{i+1} \\
 & & & & \\
\texttt{recv}(P_i) & \longleftarrow & \texttt{send}(P_{i-1}) & & \\
 & & \texttt{send}(P_{i+1}) & \longrightarrow & \texttt{recv}(P_i) \\
\texttt{send}(P_i) & \longrightarrow & \texttt{recv}(P_{i-1}) & & \\
 & & \texttt{recv}(P_{i+1}) & \longleftarrow & \texttt{send}(P_i)
\end{array}
$$

is equivalent to

$$
\begin{array}{ccccc}
P_{i-1} & & P_i & & P_{i+1} \\
 & & & & \\
\texttt{sendrecv}(P_i) & \longleftrightarrow & \texttt{sendrecv}(P_{i-1}) & & \\
 & & \texttt{sendrecv}(P_{i+1}) & \longleftrightarrow & \texttt{sendrecv}(P_i)
\end{array}
$$

the `sendrecv` in MPI

```
MPI_Sendrecv(sendbuf,sendcount,sendtype,dest,sendtag,
             recvbuf,recvcount,recvtype,source,recvtag,
             comm,status)
```

where the parameters are

`sendbuf`	initial address of send buffer
`sendcount`	number of elements in send buffer
`sendtype`	type of elements in send buffer
`dest`	rank of destination
`sendtag`	send tag
`recvbuf`	initial address of receive buffer
`recvcount`	number of elements in receive buffer
`sendtype`	type of elements in receive buffer
`source`	rank of source or `MPI_ANY_SOURCE`
`recvtag`	receive tag or `MPI_ANY_TAG`
`comm`	communicator
`status`	status object

a simple illustration

We use `MPI_Sendrecv` to synchronize two nodes:

```
$ mpirun -np 2 /tmp/use_sendrecv
Node 0 will send a to 1
Node 0 received b from 1
Node 1 will send b to 0
Node 1 received a from 0
$
```

using MPI_Sendrecv

```
#include <stdio.h>
#include <mpi.h>

#define sendtag 100

int main ( int argc, char *argv[] )
{
   int i,j;
   MPI_Status status;

   MPI_Init(&argc,&argv);
   MPI_Comm_rank(MPI_COMM_WORLD,&i);

   j = (i+1) % 2;  /* the other node */
```

a bidirectional data transfer

Processors 0 and 1 swap characters:

```
{
   char c = 'a' + (char)i; /* send buffer */
   printf("Node %d will send %c to %d\n",i,c,j);
   char d;                 /* receive buffer */

   MPI_Sendrecv(&c,1,MPI_CHAR,j,sendtag,
                &d,1,MPI_CHAR,MPI_ANY_SOURCE,
                MPI_ANY_TAG,MPI_COMM_WORLD,&status);

   printf("Node %d received %c from %d\n",i,d,j);
}

MPI_Finalize();
return 0;
```

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data parallel computations

A data parallel computation is a computation where the ***same*** operations are preformed on ***different*** data ***simultaneously***.

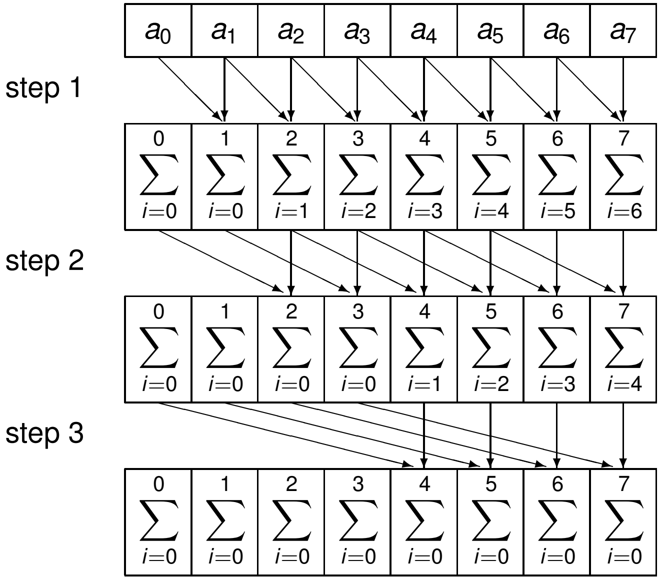
Benefits:

- easy to program,
- scales well,
- fit for SIMD computers.

Problem: compute $\displaystyle\sum_{i=0}^{n-1} a_i$ for $n = p = 2^k$.

Related problem: composite trapezoidal rule.

the prefix sum for $n = p = 8$



the prefix sum algorithm

For $n = p = 2^k$, processor i executes:

$s := 1$; $x := a_i$;
for j from 0 to $k-1$ do
    if ($j < p - s + 1$) send x to processor $i + s$;
    if ($j > s - 1$) receive y from processor $i - s$;
        add y to x: $x := x + y$;
    $s := 2 \star s$.

The speedup: $\dfrac{p}{\log_2(p)}$.

Communication overhead: one send/recv in every step.

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MPI code

```
#include <stdio.h>
#include "mpi.h"
#define tag 100                  /* tag for send/recv */

int main ( int argc, char *argv[] )
{
   int i,j,nb,b,s;
   MPI_Status status;
   const int p = 8;          /* run for 8 processors */

   MPI_Init(&argc,&argv);
   MPI_Comm_rank(MPI_COMM_WORLD,&i);

   nb = i+1;              /* node i holds number i+1 */
   s = 1;      /* shift s will double in every step */
```

the prefix sum loop

```
for(j=0; j<3; j++)              /* 3 stages, as log2(8) = 3 */
{
   if(i < p - s)      /* every one sends, except last s ones */
      MPI_Send(&nb,1,MPI_INT,i+s,tag,MPI_COMM_WORLD);
   if(i >= s)      /* every one receives, except first s ones */
   {
      MPI_Recv(&b,1,MPI_INT,i-s,tag,MPI_COMM_WORLD,&status);
      nb += b;         /* add received value to current number */
   }
   MPI_Barrier(MPI_COMM_WORLD);  /* synchronize computations */
   if(i < s)
      printf("At step %d, node %d has number %d.\n",j+1,i,nb);
   else
      printf("At step %d, Node %d has number %d = %d + %d.\n",
             j+1,i,nb,nb-b,b);
   s *= 2;                                   /* double the shift */
}
if(i == p-1) printf("The total sum is %d.\n",nb);
```

running the code

```
$ mpirun -np 8 /tmp/prefix_sum
At step 1, node 0 has number 1.
At step 1, Node 1 has number 3 = 2 + 1.
At step 1, Node 2 has number 5 = 3 + 2.
At step 1, Node 3 has number 7 = 4 + 3.
At step 1, Node 7 has number 15 = 8 + 7.
At step 1, Node 4 has number 9 = 5 + 4.
At step 1, Node 5 has number 11 = 6 + 5.
At step 1, Node 6 has number 13 = 7 + 6.
At step 2, node 0 has number 1.
At step 2, node 1 has number 3.
At step 2, Node 2 has number 6 = 5 + 1.
At step 2, Node 3 has number 10 = 7 + 3.
At step 2, Node 4 has number 14 = 9 + 5.
At step 2, Node 5 has number 18 = 11 + 7.
At step 2, Node 6 has number 22 = 13 + 9.
At step 2, Node 7 has number 26 = 15 + 11.
```

running the code continued

```
At step 3, node 0 has number 1.
At step 3, node 1 has number 3.
At step 3, node 2 has number 6.
At step 3, node 3 has number 10.
At step 3, Node 4 has number 15 = 14 + 1.
At step 3, Node 5 has number 21 = 18 + 3.
At step 3, Node 6 has number 28 = 22 + 6.
At step 3, Node 7 has number 36 = 26 + 10.
The total sum is 36.
```

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barriers and Pthreads

Recall Pthreads and the work crew model.

Often all threads must wait till on each other.

```
int count = 3;
pthread_barrier_t our_barrier;

p_thread_barrier_init(&our_barrier, NULL, count);
```

In the example above, we initialized the barrier that will cause as many threads as the value of `count` to wait.

A thread remains trapped waiting as long as fewer than `count` many threads have reached `pthread_barrier_wait(&our_barrier);`

and the `pthread_barrier_destroy(&our_barrier)` should only be executed after all threads have finished.

running an illustrative program

The shared data is the time each thread sleeps.

```
$ /tmp/pthread_barrier_example
Give the number of threads : 5
Created 5 threads ...
Thread 0 has slept 2 seconds ...
Thread 2 has slept 2 seconds ...
Thread 1 has slept 4 seconds ...
Thread 3 has slept 5 seconds ...
Thread 4 has slept 6 seconds ...
Thread 4 has data : 24256
Thread 3 has data : 24256
Thread 2 has data : 24256
Thread 1 has data : 24256
Thread 0 has data : 24256
$
```

Each thread prints only after all data is ready.

headers and global variables

```
#include <stdlib.h>
#include <stdio.h>
#include <pthread.h>

int size;    /* size equals the number of threads */
int *data;   /* shared data, as many ints as size */
pthread_barrier_t our_barrier; /* to synchronize */
```

The global variables will be initialized in the main program:

- the user is prompted to enter `size`, the number of threads;
- the array `data` is allocated with `size` elements;
- the barrier `our_barrier` is initialized.

code executed by each thread

```
void *fun ( void *args )
{
   int *id = (int*) args;
   int r = 1 + (rand() % 6);
   int k;
   char strd[size+1];

   sleep(r);
   printf("Thread %d has slept %d seconds ...\n", *id, r);
   data[*id] = r;

   pthread_barrier_wait(&our_barrier);

   for(k=0; k<size; k++) strd[k] = '0' + ((char) data[k]);
   strd[size] = '\0';

   printf("Thread %d has data : %s\n", *id, strd);
}
```

the main function

```
int main ( int argc, char* argv[] )
{
   printf("Give the number of threads : "); scanf("%d", &size);
   data = (int*) calloc(size, sizeof(int));
   {
      pthread_t t[size];
      pthread_attr_t a;
      int id[size], i;

      pthread_barrier_init(&our_barrier, NULL, size);

      for(i=0; i<size; i++)
      {
         id[i] = i;
         pthread_attr_init(&a);
         if(pthread_create(&t[i], &a, fun, (void*)&id[i]) != 0)
            printf("Unable to create thread %d!\n", i);
      }
      printf("Created %d threads ...\n", size);
      for(i=0; i<size; i++) pthread_join(t[i], NULL);

      pthread_barrier_destroy(&our_barrier);
   }
   return 0;
}
```

Summary + Exercises

We started chapter 6 in the book of Wilkinson and Allen.

Exercises:

1. Write code using `MPI_sendrecv` for a butterfly barrier.
   Show that your code works for $p = 8$.
2. Rewrite `prefix_sum.c` using `MPI_sendrecv`.
3. Consider the composite trapezoidal rule for the approximation of π (see lecture 13), doubling the number of intervals in each step. Can you apply the prefix sum algorithm so that at the end, processor i holds the approximation for π with 2^i intervals?