CMU 15-418/618: Parallel Computer Architecture and Programming
Practice Exercise 6 SOLUTIONS

Problem 1: Seeing How the Studying is Going

The night before the exam, Prof. Kayvon inspects the 15-418 web site logs to see if his students are studying. The site generates a log of all lecture slide comments, with the following format per line.

```
studentid   lecture_title   slide_number   comment
```

The log file is large (lots of studying! yay!), and is partitioned into 100 GB chunks, named `chunk_xxx.txt` stored in a shared file system accessible to all nodes on the `latedays` cluster. Below is Prof. Kayvon's correct, but inefficient, code to count the number of comments posted on a particular slide. Notice the program is written a very Spark-like style (notice pieces of code that mimick Spark's `load`, `map`, `filter`, and `count` operators generate arrays). **The code below is run by all cluster nodes.**

```
In the code below, assume vector<T> is an array of elements of type T that supports size() and append(T)

void barrier();                    is a barrier across all nodes in the cluster
int  receiveInt(int src);          receives an integer from node src
int  sendInt(int dst, int value);  sends an integer to node dst

// OPERATION 1: LOAD 100 GB FROM DISK ////////////////////////////////////////

FILE* file =  // open chunk_xxx.txt, where xxx is the id of the current node
vector<string> lines;
while (!end_of_file(file))
   lines.append( file.readLine() );

barrier(); // OPERATION 2: FILTER ////////////////////////////////////////////
           // Assume views is 30 GB after the filter (lots of long comments)

vector<string> views;
for (int i=0; i<lines.size(); i++) {
   string lecture_title;
   int    slide_number;
   parseLine(lines[i], &lecture_title, &slide_number);  // extract title and slide number
   if (lecture_title == "In-Memory Distributed Computing using Spark'' && slide_number == 28)
     views.append(lines[i]);
}

barrier();

// code continued on next page ...
```

```
// OPERATION 3: MAP: EXTRACT COMMENT ////////////////// (Assume comments is 20 GB)

vector<string> comments;
for (int i=0; i<views.size(); i++) {
   string comment;
   parseComment(views[i], &comment);
   comments.append(comment);
}

barrier();  // OPERATION 4: COUNT COMMENTS ////////////////////////////////////

if (get_node_id() == 0) {
  int count = comments.size();
  for (int i=1; i<num_nodes; i++)
     count += receiveInt(i);
  printf("%d\n'',count);
} else
  sendInt(0, comments.size());
```

A. (4 pts) Prof. Kayvon runs the program on `latedays` and it immediately fails due to running out of memory. (`latedays` nodes only have 16 GB of RAM). One answer would be to store the multi-GB intermediate arrays to disk, but there's a much better solution. Please rewrite the program so that it runs efficiently on the cluster. (**Your implementation should not exceed a node's memory capacity, and it should avoid unnecessary synchronization.** Very rough pseuocode that indicates the order of computations is fine. No need to be detailed.)

```
int count = 0;

FILE* file =  // open the chunk of the log file that is local to this node
vector<string> lines;
while (!end_of_file(file)) {
   string line = file.readLine();
   string lecture_title;
   int slide_number;
   parseLine(line, &lecture_title, &slide_number);
   if (lecture_title == "In-Memory Distributed Computing using Spark'' && slide_number == 28)
     count++;
}

if (get_thread_id() == 0) {
  for (int i=1; i<num_nodes; i++)
     count += receiveInt(i);
  printf("%d\n'',count);
} else
  sendInt(0, comments.size());
```

B. (1 pt) What is the per-node memory consumption of your implementation assuming no line of the log exceeds 1 MB? (a simple estimate is fine)

Solution: The footprint is on the order of 1 comment.

C. (4 pts) Now Prof. Kayvon wants to process the log to produce a set of files on disk where each file corresponds to a **single slide** from the Spark lecture, and contains a list of comments for that slide. In other words, there will be files for: `slide_0.txt`, `slide_1.txt`, `slide_2.txt`, etc. Please assume:

- Each file is written entirely by **exactly one node in the cluster**, which is determined by the function `hashToNode(int x)` which returns the node responsible for writing `slide_x.txt`.
- The file is written in a single call to the function `writeFile(int slideNum, vector<string> comments)`.

For simplicity, you can assume that nodes now have an infinite amount of memory. Sketch an algorithm for executing this analysis operation on the cluster. Very brief pseudocode is desired (we don't want to read very detailed code), but we do want to know the details of what (if any) data nodes exchange, and about any barriers across nodes that are required in your implementation.

*Solution: The key point is that the owner of a particular per-slide text file must wait for **all nodes** to send the comment lists for this slide. The computation can no longer be streamed, and this is fundamental due to the data dependencies in the new program. While pseudocode like the code below was not required for full credit (only a reasonable description of an approach), here's a basic solution.*

```
FILE* file =  // open the chunk of the log file that is local to this node
vector<node><string> comments;

while (!end_of_file(file)) {
  string lecture_title, line = file.readLine();
  int slide_number;
  parseLine(line, &lecture_title, &slide_number);
  if (lecture_title != "In-Memory Distributed Computing using Spark'')
    continue;

  string comment;
  parseComment(line, &comment);

  // Assign this line to the node that's responsible for it.
  comments[hashToNode(slide_number)].append(comment);
}

// Send comments to the nodes responsible for them and receive from every
// node, being careful of deadlock.
vector<string> my_comments;
for (int n = 0; n < num_nodes; n++) {
  if (my_node_id == n) {
    // Receive from all nodes.
    for (int i = 0; i < num_nodes; i++) {
      if (i == my_node_id)
        my_comments.append(comments[i]):
      else
        my_comments.append(recvString(i));
    }
  } else
    sendString(n, comments[n]);  // Send to another node.
}

// Write comments to file.
```

D. (1 pts) Contrast the amount of memory your implementation in part C uses compared to your implementation in part A. What is the fundamental reason for this difference? (in other words, why can't you achieve the footprint efficiencies observed before?)

*Solution: Instead of "streaming" over all lines in the file (as was possible in part A), now all nodes must wait to receive all comments for a given lecture slide before writing those comments to the output file (the write to the file **depends** on having all comments lists generated on all nodes). Since all comments for a single file must be memory resident on the receiving node, and the problem states there may be many GBs of comments for a single slide, the required footprint of the program has increased greatly from part A.*

Problem 2: Controlling DRAM

Consider a computer with a single DIMM containing eight 1 MB DRAM chips (8 MB total capacity). Each DRAM chip has one bank and row size 2 kilobits (256 bytes). As discussed in class, the DIMM is connected to the memory controller via a 64-bit bus, with 8-bits per cycle transferred from each chip.

Assume that:

- Contiguous 1 MB regions of the physical address space are mapped to a single DRAM chip. 256 consecutive physical address space bytes are in a row. 1048576 consecutive bytes fill a DRAM chip.
- Physical address 0 maps to chip 0, row 0, column 0. Physical address 1048576 maps to chip 1, row 0, column 0, etc.

Given these assumptions, reading a 64-byte cache line beginning at address X requires the following memory-controller logic, presented in C code below: (the data ends up in `cache_line`)

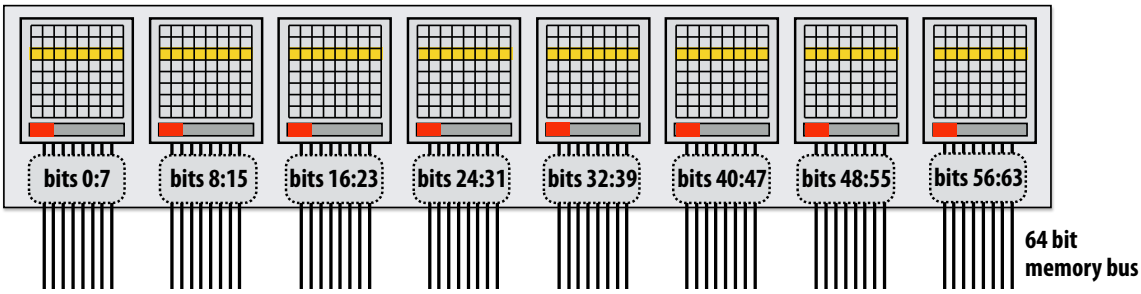
```
char cache_line[64];

// compute DRAM clip, row, col for address X
int chip = X / 1048576;
int row =  (X % 1048576) / 256;
int col =  (X % 1048576) % 256

for (int i=0; i<64; i++) {

   // Read one byte from each DRAM chip at given row and column (eight in total)
   // so that the byte from chip j ends up in 'from_dram[j]'. Assume necessary
   // DRAM row and column activations are performed inside DIMM_READ_FROM_CHIPS.

   char from_dram[8];
   DIMM_READ_FROM_CHIPS(row, column, from_dram);

   cache_line[i] = from_dram[chip];

   column++;  // move to next byte in column
}
```

Questions are on next page...

A. (2 pts) Explain why 64 iterations (64 reads from the DRAM chips) are required to populate the buffer `cache_line`.

Solution: Each read from the DRAM chips can only read 1 byte from each individual chip. Since the entire 64-byte cache line is stored on a single chip in this scheme, it must be read from 64 times to fetch the entire thing.

B. (3 pts) Now assume the address space is **byte-interleaved across the DRAM chips** as discussed in class and shown in the Figure below. (Byte X in the address space is stored on chip X % 8.) Please provide C-like pseudocode for reading the 64-byte cache line at address X from DRAM into `cache_line`. Your code should make a series of calls to `DIMM_READ_FROM_CHIPS`.



Hint: Recall that each DRAM chip row is 256 bytes.

```
int row = (X / 8) / 256;
int column = (X / 8) % 256;
for (int i=0; i<8; i++) {
   DIMM_READ_FROM_CHIPS(row, column + i, &cache_line[8*i]);
}
```

C. (2 pts) How much higher "effective bandwidth" is achieved using the interleaved mapping from part B than the original blocked mapping from part A?

Solution: 8×

D. (3 pts) Imagine the byte interleaved memory system from part B is connected to a dual-core CPU. The memory controller uses a naive **round-robin policy** to schedule incoming memory requests from the cores (it services a request from core 0, then core 1, then core 0, etc.) All requests from the same core are processed in FIFO order.

Both cores execute the following C code **on different 4 MB arrays.** Simply put, each thread is linearly scanning through different regions of memory.

```
int A[N];           // let N = 1M, so this array is 4MB
int sum = 0;        // assume 'sum' is register allocated
for (int i=0; i<N; i++)
   sum += A[i];
```

Assume that the cores request data from memory at granularity of 8 bytes. On this system, you observe that when running two threads, the overall aggregate bandwidth from the memory system *is lower* than when one thread is executing the same code. Why might this be the case? (Hint: we are looking for an answer the pertains to DRAM chip behavior: consider locality, but which kind?)

Solution: This loss is due to eliminating row-buffer locality in the DRAM. In a single-threaded system, since accesses are local, a given row will always be opened and closed exactly once. With two threads and round-robin scheduling, each row will be repeatedly closed and reopened to allow the DRAM to service the other thread's requests.