Operating Systems, Assignment 5

This assignment includes two programming problems, one in C and one in CUDA for the ARC system that you made an account for on assignment 4. As always, be sure your code compiles and runs on the EOS Linux machines before you submit (or on the arc system for the second program). Also, remember that your work needs to be done individually and that your programs need to be commented and consistently indented. You **must** document your sources and, if you use sources, you must still write at least half your code yourself from scratch.

1. (16 pts) Paged Memory Simulation

   Consider virtual memory support through paging with a TLB. The virtual address consists of 18 bits (256KB). The physical memory size is 64KB and the page/frame size is 4KB. Using the page table and TLB shown below, please 1) calculate physical address; 2) indicate changes to the page table and TLB, also indicate when a TLB miss occurs; you should use FIFO replacement as your TLB replacement policy (starting with the first entry); 3) provide the effect on a memory reference (completion or access violation) for each of the following virtual memory references. You should assume the following accesses happen consecutively and should use the updated page table and TLB from the previous access. We also assume that we use a write-back policy for the TLB, which means the copy on the TLB only gets synced with the copy on the page table when it's the time for it to be replaced. And if the access is invalid, the page should not be brought into the TLB.

   ```
   (a) 000001000100000101 (read access)
   (b) 000000000011000100 (write access)
   (c) 000011000101100100 (write access)
   (d) 000010000101010100 (read access)
   ```

   Page numbers are encoded in the most significant bits. The status bits (valid, dirty, read only, reference) are 1 if true, 0 otherwise.

   Hints:

   dirty bit: After being modified, the dirty bit of the corresponding frame is marked as "1"

   reference bit: After most-recently access to a frame, the reference bit of this frame is marked as "1"

Page Table

virtual page	frame	valid	dirty	read-only	reference
0	2	1	0	1	0
1	0	1	0	0	1
2	1	1	0	1	1
3	5	1	0	0	1
4	3	1	0	0	0

TLB

virtual page	frame	valid	dirty	read-only	reference
2	1	1	0	1	1
1	0	1	0	0	1

For reference, your answer may take the following form:

```
000100001100000000 ( read access )
-> 000100 001100000000
page number is 4, which is mapped to frame 3 in the physical memory
TLB miss
Physical address = 000011 001100000000
paging completion

                                 Page Table
    virtual page     frame     valid     dirty    read-only      reference
        0              2         1         0          1          0
        1              0         1         0          0          1
        2              1         1         0          1          1
        3              5         1         0          0          1
        4              3         1         0          0          1

 "use" bit of entry "virtual page 4" is set to 1

                                  TLB
     virtual page   frame   valid   dirty     read-only      reference
        4             3       1       0           0           1
        1             0       1       0           0           1

 TLB replacement occurs: replace entry "virtual page 2" with the new entry "virtual page 4"
```

Write your answers into a text file, convert it to a pdf file called `hw5_p1.pdf` and submit it to HW5_Q1 on Gradescope.

2. (40 pts) We're going to implement a multi-threaded Unix client/server program in C using TCP/IP sockets for communication. The server will let users view and and update two-dimensional game board containing lower case letters (and blank spaces, like a scrabble board). A user will be able to add words to the board, going vertically or horizontally, but letters of any new words must match existing letters for words that have already been placed on the board.

   You're provided with a skeleton of the server to help get you started, `scrabbleServer.c`. You'll complete the implementation of this server, adding support for multi-threading and synchronization, and building some representation for storing the board and responding to client commands. You won't need to write a client program; for that, we're going to use a general-purpose program for network communication, `telnet`.

   Once started, your server will run perpetually, accepting connections from clients until the user kills it with ctrl-C. The program we're using as a client, `telnet`, will take the server's hostname and port number as command-line arguments. The sample execution at the end of this problems shows how to run `telnet` like this. After connecting to the server, `telnet` will just echo to the screen any text sent by the server and send any text the user enters to the server.

Scrabble Board

When the user starts the server, they will give two command-line arguments, the number of rows and columns in the board. These must be integers greater than zero. If the server is run with invalid arguments, it should print the following usage message and terminate with an exit status of 1.

```
usage: scrabbleServer <rows> <cols>
```

The server will maintain a representation of the board, adding words to it in response to user commands, printing a copy of the current board when asked to and detecting when a new word conflicts with letters already placed on the board.

Client / Server Interaction

When a client connects to the server, it will repeatedly prompt the user for a command, using the prompt, "`cmd> `". The starter code has support for prompting the user and reading commands, but it just echos each command back to the user. You're going to modify it to support the following commands:

- `across` *r c word*
  This command places a new word on the board going horizontally. The left end of the word starts at the given row, *r*, and column, *c*, on the board. Both row number and column number start from zero (the top row and left column of the board). The given word must be a sequence of 1 to 26 lower-case letters. It is placed on the board, one character per location going right from the starting location.

  The command is invalid if the given location is off the board, if the word would extend beyond the bounds of the board, if the word contains something other than lower-case letters or if the one of the characters in the word disagrees with a character already placed on the board.
- `down` *r c word*
  This command is like the `across` command, but it places a word going down from the given starting location. It has the same rules for valid words and word placement on the board.
- `board`
  This command instructs the server to print the current state of the board for the client. It should be printed with a border around the edge consisting of vertical bars on the left and right, dashes along the top and bottom and plus signs in the corners. See the sample execution below for an example.
- `quit`
  This is a request for the server to terminate the connection with this client. This behavior has already been implemented for you.

Invalid Client Input

If the client sends an invalid command, the server will print out a line saying "Invalid command", ignore that input line and then prompt for the next command.

You can assume each user command is given on a single line of input. You don't have to worry about dealing with multiple commands given on the same line, or a single command spread over multiple input lines. We won't test your program with inputs like that. This should make the user input easier to parse.

TELNET Client

For this program, we won't need to write a separate client program. The server just needs a client that can open a socket connection, send user input over the socket and write anything it reads from the socket to the terminal. There are standard programs that do this kind of thing. In this assignment, we are going to use one called `telnet`, which is already installed on the university machines. If you have your own Linux machine, you should be able to install a copy of telnet.

You can run telnet as follows. Here, hostname is the name of the system where you're running your server. The port-number is the unique port number your server is using for listening for connections (see below).

telnet *hostname port-number*

Client/Server Interaction

Client/server communication is all done in text. In the server, we're using fdopen() to create a FILE pointer from the socket file descriptor. This lets us send and receive messages the same way we would write and read files using the C standard I/O library. Of course, we could just read and write directly to the socket file descriptor, but using the C I/O functions should make sending and receiving text a little bit easier.

The partial server implementation just repeatedly prompts the client for commands and terminates the connection when the client enters "quit". You will extend the server to handle the commands described above. There's a sample execution below to help demonstrate how the server is expected to respond to these commands.

Extra Credit

Your server isn't expected to check if words entered by the user are real words. For up to 8 points of **extra credit**, you can have your server check to make sure all words on the board are always valid, dictionary words.

The starter files for this assignment include a dictionary file named "words". This is a copy of the dictionary file that's normally installed on a Linux machine, under the path `/usr/share/dict/words`. The EOS Linux machines don't have the spell checker installed, so they don't have this file. So, it's included with the starter. If you do the extra credit, at startup, your server should look for a file named "words" in the current directory with one word per line. The file could contain any number of words, but no word will be longer than 26 characters. If there's no words file in the current directory, your program should still work. It just won't check words on the board to make sure they're valid.

The standard linux dictionary has some words that contain capital letters and even some non-ASCII characters. You can discard these words as you read the "words" file, or you can keep them. Either way, they won't mach any of the words on the scrabble board, since the user can only place lower-case letters on the board.

For the extra credit, you need to check that all horizontal and vertical sequences of two or more characters make up a valid word. You don't need to check that the sequence of characters given in an `across` or `down` command constitute a valid word, only that the added characters form valid words once they are placed on the board. For example, the user could enter a command like "across 0 1 ope". By itself "ope" isn't a word, but it would still be a legal command if the "ope" came after a letter like 'c', 'h', 'm' or 'r' that had already been placed.

There are some examples of the extra credit behavior in the sample execution below.

Multi-Threading and Synchronization

In the starter code, the server uses just the main thread to accept new client connections and to communicate with the client. It can only interact with one client at a time. You're going to fix this by making it a multi-threaded server. Each time a client connects, you will create a new thread to handle interaction with that client. When it's done talking to the client, that thread can terminate. Use the pthread argument-passing mechanism to give the new thread the socket associated with that client's connection.[1]

With each client having its own thread on the server, there could be race conditions when threads try to access any state stored in the server (e.g., when they report or modify the board). You'll need to add synchronization support to your server to prevent potential race conditions. You can use POSIX semaphores or POSIX mutex locks for this. That way, if two clients enter a command at the same time, the server will make sure their threads can't access shared server state at the same time.

Detaching Threads

Previously, we've always had the main thread join with the threads it created. Here, we don't need to do that. The main thread can just forget about a thread once it has created it. Each new thread can communicate with its client and then terminate when it's done.

For this to work properly, after creating a thread, the server needs to detach it using `pthread_detach()`. This tells pthreads to free memory for the given thread as soon as it terminates, rather than keeping it around for the benefit of another thread that's expected to join with it.

Buffer Overflow

In its current state, the server is vulnerable to buffer overflow where it reads commands from the client. You'll need to fix this vulnerability in the existing code and make sure you don't have potential buffer overflows in any new code you add.[2] Your server only needs to be able to handle the commands listed above. If the user tries to type in a really long name, a really long command or a really long word, you should detect this, ignore it and print the "Invalid command" message.

Input Flushing

Because of the way we're creating our file pointer, it looks like buffered input is discarded when the server starts writing output to the socket. This ends up being fairly convenient, but its something to keep in mind as you're writing the code to parse and respond to user commands. For example, you'll need to read all parts of the user's command before you start printing a response to it (otherwise, you'll lose the parts you haven't read yet). Likewise, imagine the user types in a really long word as part of a command. Once you've detected that the word is too long, you can print out the "Invalid command" message and the rest of their command will be discarded. You wont' have to write code to read and discard the rest of the command.

Port Numbers

Since we may be developing on multi-user systems, we need to make sure we all use different port numbers our servers can listen on. That way, a client written by one student won't accidentally try to connect to a server being written by another student.

To help prevent port number collisions, I've assigned each student their own port number. You can find your randomly-assigned port number by checking the assignment named "Port Number Allocation" on our Moodle page. This isn't really an assignment for you to turn in, but clicking on this assignment should let you download a feedback file named port-number.txt. This file should tell you what port number you're supposed to use.

[1]Remember that it's easy to make a mistake in how you pass an argument to a new thread. Be careful here.

[2]As you know, a buffer overflow is really bad in a server. It could permit an attacker anywhere in the world to gain access to the system the server is running on.

Grading on this assignment will include checking to make sure you use the right port number, so be sure to get your assigned port number from this file before you start developing.

Sad Truths about Sockets on EOS Linux Hosts

Since we're using TCP/IP for communication, we can finally run our client and server programs on different hosts. You should be able to run your server on one host and then start telnet on any other Internet-connected system in the world, giving it the server's hostname and your port number on the command line. However, if you try this on a typical university Linux machine, you'll probably be disappointed. These systems have a software firewall that blocks most IP traffic. As a result, if you want to develop on a university system, you will still need to run the client and server on the same host. If you have your own Linux machine, you should be able to run your server on it and connect from anywhere (depending on how your network is set up).

If you'd like to use a machine in the Virtual Computing Lab (VCL), you should be able to run commands as the administrator, so you can disable the software firewall. I had success with a reservation for a CentOS 7 Base (64 bit VM) system. After logging in, uploading and building my server, I ran the following command to permit TCP connections via my port. Then, if I ran a server on the virtual machine, I was able to connect to it, even from off campus.

sudo /sbin/iptables -I INPUT 1 -p tcp --dport *my-port-number* -j ACCEPT

Also, if your server crashes, you may temporarily be unable to bind to your assigned port number, with an error message "Can't bind socket." Just wait a minute or two and you should be able to run the server again.

Implementation

You will complete your server by extending the file, `scrabbleServer.c` from the starter. You'll need to compile as follows:

```
gcc -Wall -g -std=gnu99 scrabbleServer.c -o scrabbleServer -lpthread
```

Sample Execution

You should be able to run your server with any number of concurrent clients, each handled by its own thread in the server. Below, we're looking at commands run in three terminal sessions, with the server running in the left-hand column and clients running in the other two columns (be sure to use our own port number, instead of 28123). I've interleaved the input/output to illustrate the order of interaction with each client, and I've added some comments to explain what's going on. If you try this out on your own server, don't enter the comments, since the server will think they're invalid commands.

Here, I'm running all three programs on the same host, but if you use a machine where you can control the firewall, you should be able to run this example on three different hosts.

```
# Run the server with an 8 x 12 board.
$ ./scrabbleServer 8 12

                # Run one client and place a word.
                $ telnet localhost 28123
                cmd> across 3 4 sunshine
                # Run another client and check the board.
                $ telnet localhost 28123
                cmd> board
                +------------+
                |            |
                |            |
                |            |
                |    sunshine|
                |            |
                |            |
                |            |
                |            |
                +------------+

                # Place a word going down.
                $ cmd> down 3 8 happy

# Check the board after the other
# client's word.
cmd> board
+------------+
|            |
|            |
|            |
|    sunshine|
|        a   |
|        p   |
|        p   |
|        y   |
+------------+

# Try a word with an illegal character.
cmd> across 2 2 CAPITAL
Invalid command

                # Try a word that starts off the board
                cmd> down 1 12 a
                Invalid command

                # Try a word that goes off the edge.
                cmd> down 5 2 excessive
                Invalid command

# Try a word that doesn't match an
# existing character.
cmd> across 7 4 sleeping
Invalid command

# Now, a word that does match an
# existing character.
cmd> across 6 4 sleeping
```

```
                # Check the board, then exit.
                cmd> board
                +------------+
                |            |
                |            |
                |            |
                |    sunshine|
                |        a   |
                |        p   |
                |    sleeping|
                |        y   |
                +------------+
                cmd> quit

# The rest of these are extra credit tests.
# try an word that's not int the dictionary.
cmd> across 0 0 alot
Invalid command

# Now, a valid word.
cmd> across 0 0 zealot

# A valid word, but it creates an
# invalid word on the board.
cmd> across 0 5 torus
Invalid command

# It's OK going the other way.
cmd> down 0 5 torus
cmd> board
+------------+
|zealot      |
|     o      |
|     r      |
|    sunshine|
|     s  a   |
|        p   |
|    sleeping|
|        y   |
+------------+

# to is a valid word, but ot (down) isn't.
cmd> across 1 4 to
Invalid command

# But, on and no are both valid.
cmd> across 1 4 no
cmd> board
+------------+
                |zealot      |
                |    no      |
                |     r      |
                |    sunshine|
                |     s  a   |
                |        p   |
                |    sleeping|
                |        y   |
                +------------+

                # Quit the client, then quit the server.
                cmd> quit

# Kill the server.
ctrl-C
```

Submitting your Work

When you're done, submit your `scrabbleServer.c` under the assignment named HW5_Q2 on Gradescope.

3. (40 points) For this problem, you're going to implement the maxsum program from assignments 1, 2 and 3 on a GPU, with lots and lots of threads. We're going to use the CUDA framework on the arc cluster at NC State. You know about arc; you should have activated your arc account as part of assignment 4. Arc has a collection of about 100 hosts running Linux, each with a general-purpose CPU and a GPU serving as a highly parallel co-processor.

Arc Filesystem

Arc doesn't share user accounts or filesystems with other university machines. To connect to it, you'll need to ssh in from another university system (e.g., remote.eos.ncsu.edu), just like you did when you activated your arc account for assignment 4. To successfully connect, you'll need to use the same machine where you made your key pair on assignment 4, or some machine that has access to NFS if you made your key pair on a machine with NFS.

Due Date Distribution

The arc system has a lot of nodes, but it doesn't have enough for all of us to have one at the same time. To make sure you get a chance to complete this problem, I'm implementing a soft due date for this assignment. You can earn up to 8 points of **extra credit** by completing this problem early. Or, if you submit your solution late, the late penalty will be applied gradually rather than all at once. I'm hoping this will help to make sure we aren't all trying to use the arc system on the same evening. Arc has a lot of compute nodes, but if we're all trying to use it at the same time, some users are going to be disappointed.

The following table shows the extra credit or late penalty based on how early or late you turn in your solution.

Bonus / Penalty	Submission Time
+8	At least 96 hours early
+6	At least 72 hours early
+4	At least 48 hours early
+2	At least 24 hours early
-2	At most 24 hours late
-4	At most 48 hours late

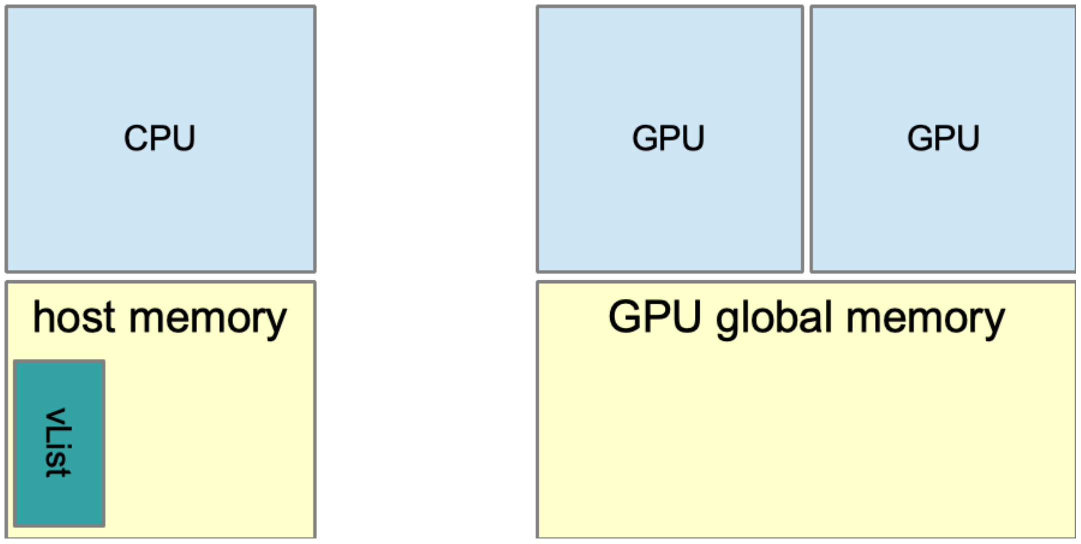
Work Partitioning

For this assignment, we're going to divide work statically among the threads. You can divide up the work however you want, and, unlike on homework 3, you will have access to the whole sequence of values before any of your worker threads start running. Each thread has a unique index, i. It computes this index based on the grid and block dimensions right after the thread starts up. You could have thread number i look at sequences starting at position i in the sequence, or maybe it could check all sequences ending at position i, or something else if you have a better idea. If the report option is given on the command line, your threads should report ranges as they find them, like we've done on previous assignments. CUDA has support for this, even though the GPU threads are running on a different device.

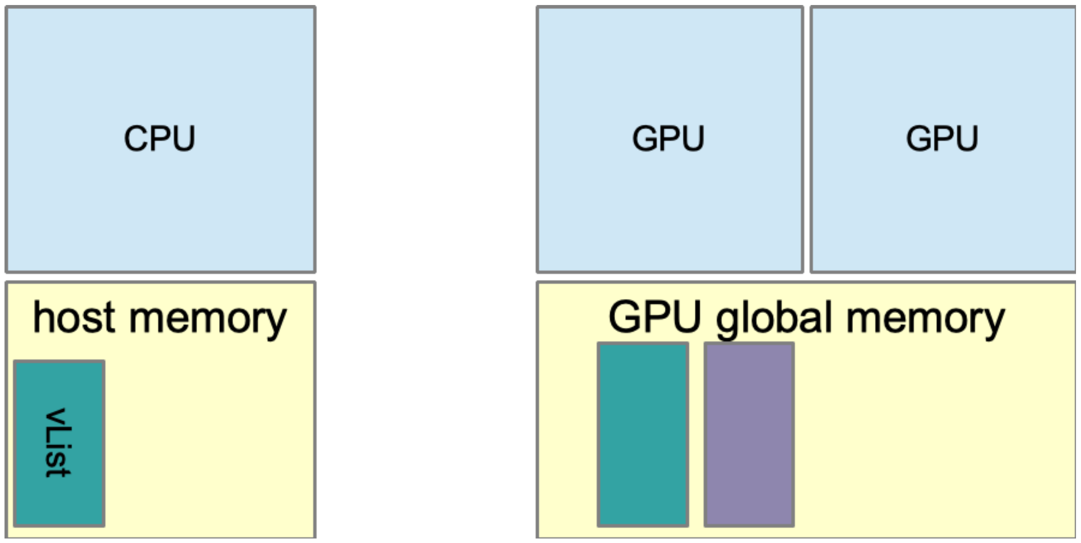
When a worker is done, it will copy the largest sum it finds to element i of an array allocated in CUDA global memory. After all the threads are finished, code from main will copy all the local largest sums to host memory and compare them to get the final largest sum.

For previous assignments, we made each process or thread responsible for several elements in the sequence. We didn't want to create too many workers. This won't be a problem on a GPU. It can handle lots of threads at once, and the CUDA software will take care of sharing the processing elements among threads if we ask for more threads than the GPU can execute at once.

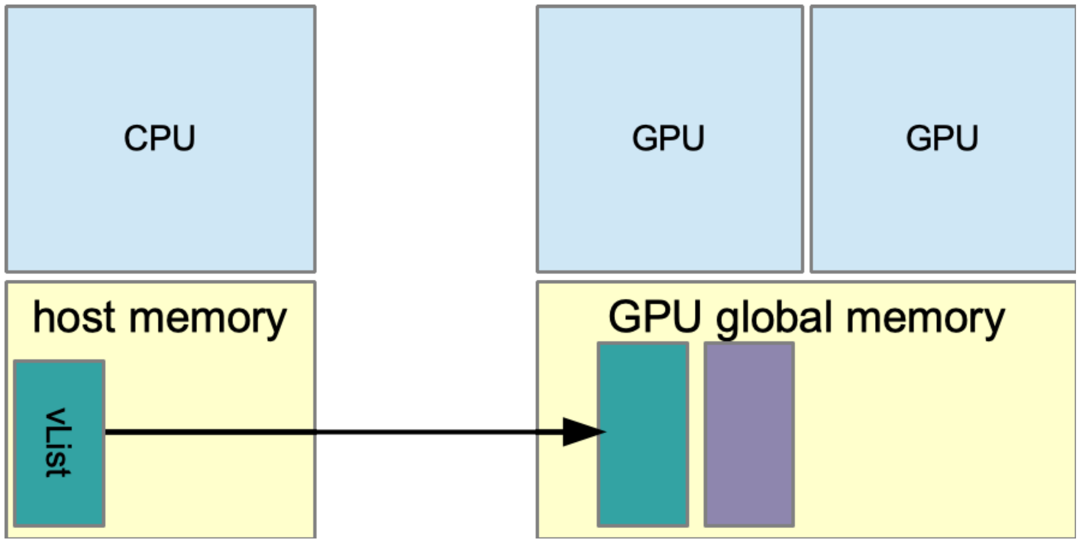
I'm providing you with a skeleton, `maxsum.cu`, to get you started. This program reads the sequence into an array on the host, `vList`.



You'll need to add code to allocate two arrays on the device, one array for holding a copy of the host's sequence and another array of integers for holding the the local largest sum computed by each thread.

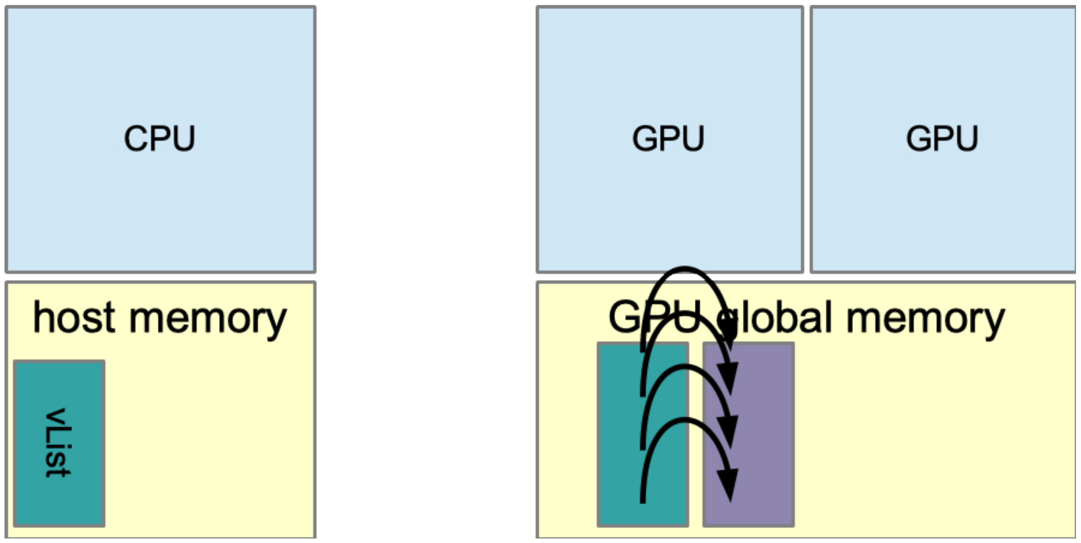


Then you'll need code to copy the sequence from the host over to the device, so threads on the GPU can access it.

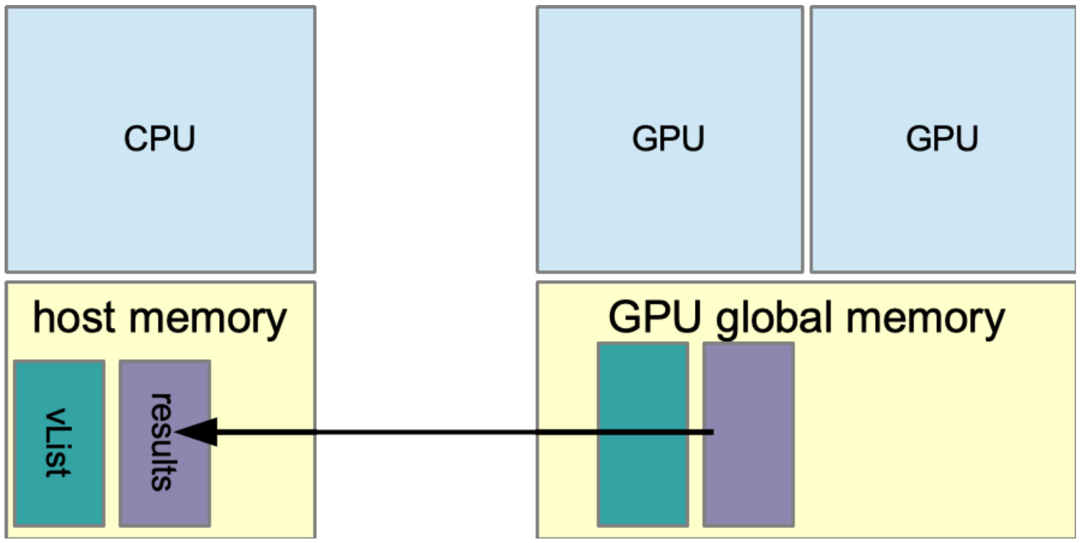


Now that the device is ready, you'll need to complete the implementation of the checkSum() kernel. Each thread will be responsible for checking for some ranges in the sequence. When it's done, it will store its largest sum in the i^{th} index of the results array in device memory.

When you run this kernel from the host, it will start a thread for each element and wait for them to finish computing their parts.



Then, the host will need to allocate host memory (malloc) and copy the results into it.



Then, the main thread on the host can quickly compare the sums from all the threads and print out a final maximum sum in the format:

```
Maximum Sum: n
```

Thread Implementation

You get to write most of the checkSum() function, the code that actually runs on the GPU. I've written some starter code for this function. Right now, each thread just computes a unique index and makes sure it has a value to work on[3] and then returns. You'll need to add parameters to the kernel function for passing in pointers to the input and output arrays, finding the largest sum in each thread's part and recording the results.

[3]If the block size doesn't evenly divide the number elements in the sequence, there may be some threads in the last block that don't actually have anything to do.

Working on Arc

To access arc, you'll have to log in from another university machine, where you've stored the key pair that you used to activate your arc account (probably remote.csc.ncsu.edu). Use your ssh client (e.g., putty or mobaXterm or ssh) to connect to remote.csc.ncsu.edu, then you can get to arc from there.

Uploading your Files

The nodes on the arc cluster share a filesystem, but they don't use the university NFS. To get files onto the machine, you'll need to upload them from another university machine. You can just upload your files to one of the university Linux machines and then transfer them from there using the `sftp` program. From one of the remote Linux machines (not from ARC), commands like the following should let you upload files. Starting from a directory containing your maxsum.cu and the input files:

```
sftp arc.csc.ncsu.edu

sftp> put maxsum.cu
Uploading maxsum.cu ...
sftp> put input-1.txt
Uploading input-1.txt
sftp> put input-2.txt
Uploading input-2.txt
<you get the idea>
sftp> bye
```

Logging in on Arc

After logging in to one of the machines at remote.eos.ncsu.edu, you should be able to enter the following to log in to the head node on arc:

```
ssh arc.csc.ncsu.edu
```

Editing, Compiling and Running

When you log in to arc, you connect to a head node that doesn't even have a GPU. From the head node, you'll need to connect to one of the compute nodes. Arc uses batch processing software to assign jobs to the compute nodes. The following commands let you connect from the head node to one of the compute nodes. Each time you want to work on arc, you should just need to run one of these commands. It will give you an interactive prompt on one of the compute nodes as soon as one is available. The comments below tell you what kind of GPU you'll get on each node. Depending on how busy the system is, you may have to wait a little while to get a prompt. Also be sure you run this from an a shell prompt (not from inside sftp command described above):

```
# there are 13 nodes with an nVidia RTX 2060
srun -p rtx2060 --pty /bin/bash

# there are 17 nodes with an nVidia rtx2070.
# Once, when I tried to use one of the rtx2070 systems, it failed
# on my first call to a cuda function.  Later, when I logged back
# in to another rtx2070 system, it worked fine.  This makes me think
# there may have been one of these nodes that had a bad GPU or maybe
# it wasn't configured correctly.  If you have this problem, you may
# want to try another system.
srun -p rtx2070 --pty /bin/bash

# there are 2 nodes with an nVidia RTX 2080
srun -p rtx2080 --pty /bin/bash

# there are 21 nodes with an nVidia RTX 2060 Super
srun -p rtx2060super --pty /bin/bash

# there are 2 nodes with an nVidia RTX 2080 Super
# I also got an error from my first CUDA call when I tried one of
# these systems.
srun -p rtx2080super --pty /bin/bash

# there are still some systems with the older, nVideo gtx480 graphics
# card.  If you can't connect to one of the newer systems above, you
# could try one of these older systems instead.
srun -p gtx480 --pty /bin/bash
```

Once you have a prompt on a compute node, you should still be able to see the files you uploaded. Arc used to require you to enter the following command before you could do any work with CUDA, but it seems like this is no longer required. If you try to run the nvcc compiler and you get a complaint that your shell can't find a program with that name, you could try running this command to see if that fixes it.

```
module load cuda
```

For editing your program, you can make edits in NFS and just use sftp to copy the modified file to arc every time you make a change. If you're comfortable editing directly on Linux machine, it may be easier for you to edit your source file directly on the arc machine. Editors vim and emacs are there, but it doesn't look like the really simple editors like pico or nano are installed (vim and emacs are better editors anyway, but it takes a little space in your brain to be ready to use them).

Once you're ready to build your program, you can compile as follows:

```
nvcc -I/usr/local/cuda/include -L/usr/local/cuda/lib64  maxsum.cu -o maxsum
```

When you're ready to run, be sure you're on a compute node (i.e., you've run one of the svrun commands above). You can run your program just like you would an ordinary program. This version of the program will still have the optional report flag, but it won't need to be told how many threads to use. It just makes a thread for every value in the input sequence. As usual, if report is enabled, then your threads will report the largest sum they find. Note that here, instead of using tid, you can number each thread using an integer starting from 0.

```
$ ./maxsum report < input-1.txt
I'm thread 0. The maximum sum I found is 2.
I'm thread 1. The maximum sum I found is 5.
I'm thread 2. The maximum sum I found is 3.
I'm thread 3. The maximum sum I found is 7.
```

```
I'm thread 4. The maximum sum I found is 8.
I'm thread 5. The maximum sum I found is 15.
Maximum Sum: 15
```

The time command is available when you want to measure the execution time for your program (especially on the larger inputs).

```
$ time ./maxsum < input-5.txt
Maximum Sum: 227655

real ?m?.???s
user ?m?.???s
sys ?m?.???s
```

Recording Execution Time

At the top of the maxsum.cu file, I've put comments for recording running times for this program on the input-5.txt file. Once your program is working, time its execution on this input file and enter the (real) execution time you got in this comment. Also, report what type of compute node you were using (i.e., what type of GPU it has). Don't use the report flag when you're measuring execution time; that would just slow it down. You'll probably notice that start-up time seems to be significant, so pushing work out to the GPU pays off most with the largest input files. The different compute nodes on arc may have different capabilities (at least, that's been the case in the past), so don't worry if you get different execution times from some of your classmates. Either way, I hope you'll find these runtimes to be faster than what you got on a general-purpose CPU.

Logging Out

When you're ready to log out, you'll have several levels to log out from. From a compute node, you can type `exit` to fall back to the head node of the arc cluster. Typing `exit` from there will drop you back to whatever machine you connected from (probably remote.eos.ncsu.edu). One more exit should get you out.

Submitting your Work

When you're done, submit a copy of your working program, `maxsum.cu`, with the runtime filled in at the top to the assignment named HW5_Q3 on Gradescope.