A Barrier is Worth a 1000 Locks

Problem 1: (Graded for Correctness - 30 pts)

Consider the following code written in an SPMD style. Note this is not ISPC code. It's C-like code, but assume that N threads are running the code. The threads cooperate to compute a histogram for the values in an input array `data`. You can assume that data contains random numbers between 0 and 100, the histogram has 10 bins, and that `bins[i]` is supposed to contain the count of the number of elements in `data` that fall between $10 \times i$ an $10 \times (i+1)$

```
// These variables are global variables accessible to all threads.

const int N = VERY_LARGE_NUMBER;  // assume N is a very large number
const int NUM_THREADS = 4;
int data[N];
int bins[10];  // assume initialized to 0
Lock myLock;

// This function is run in SPMD fashion by all threads

void run(int threadId) {
  int elsPerThread = N / NUM_THREADS;
  int start = threadId * elsPerThread;
  int end = start + elsPerThread;

  for (int i=start; i<end; i++) {
    int binId = data[i] / 10;
    myLock.lock();
    bins[binId]++;
    myLock.unlock();
  }
}
```

A. (15 pts) You run the program on a four core processor, and observe that it gets the correct answer, and that work is well distributed among the threads. However you don't observe a great speedup compared to a single threaded version of the code. What is a potential significant performance problem?

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B. (15 pts) Imagine that instead of locks, you are allowed to use a single `barrier()` in the code. Please give a solution that yields good work distribution onto all 4 threads, uses no locks, and uses only a single call to `barrier()`. Your solution is allowed to allocate new global or per-thread variables. **Hint: Keep in mind that N is assumed to be much, much larger than the number of bins in the histogram.**

```
const int N = VERY_LARGE_NUMBER;  // assume N is a very large number
const int NUM_THREADS = 4;
int data[N];
int bins[10];  // assume initialized to 0




void run(int threadId) {



  int elsPerThread = N / NUM_THREADS;
  int start = threadId * elsPerThread;
  int end = start + elsPerThread;




  for (int i=start; i<end; i++) {

    int binId = data[i] / 10;




  }



}
```

Particle Simulation

Problem 2: (Graded for Correctness - 30 pts)

Consider the following code that uses a simple $O(N^2)$ algorithm to compute forces due to gravitational interactions between all N particles in a particle simulation. One important detail of this algorithm is that force computation is symmetric (gravity(i,j) = gravity(j,i)). Therefore, iteration i only needs to compute interactions with particles with index j, where i<j. As a result, there are $N^2/2$ called to gravity rather than N^2.

In this problem, **assume the code is run on a dual-core processor, with infinite memory bandwidth.**

```
struct Particle {
  float force;  // for simplicity, assume force is represented as a single float
  Lock l;
};

Particle particles[N];

void compute_forces(int threadId) {

  // thread 0 takes first half, thread 1 takes second half
  int start = threadId * N/2;
  int end = start + N/2;

  for (int i=start; i<end; i++) {

    // only compute forces for each pair (i,j) once, then accumulate force
    // into *both* particle i and j

    for (int j=i+1; j<N; j++) {
      float force = gravity(i, j);

      lock(particles[i].l);
      particles[i] += force;
      unlock(particles[i].l);

      lock(particles[j].l);
      particles[j] += force;
      unlock(particles[j].l);
    }
  }
}
```

Question is on the next page...

A. (15 pts) Although the code makes $N^2/2$ calls to `gravity()` it takes N^2 locks. Modify the code so that the number of lock/unlock operations is reduced by $2\times$. You may not allocate additional variables or change how look iterations are mapped to the threads.

B. (15 pts) **(This question can be answered independently from part A)** Looking at the original code, there another major performance problem that does not have to do with the number of lock/unlock operations. Please describe the problem and then describe a solution. Clearly describing an implementable solution strategy is fine, you do not need to write precise pseudocode.

Miscellaneous Problems

Problem 3: (Graded on Effort Only - 40 pts)

A. (10 pts) A key idea in this course is the difference between *abstraction* and *implementation*. Consider two abstractions we've studied: ISPC's `foreach` and Cilk's `cilk_spawn` construct. **Briefly describe how these two abstractions have similar semantics.** (Hint: what do the constructs declare about the associated loop iterations? Be precise!). **Then briefly describe how their implementations are quite different** (Hint: consider their mapping to execution contexts and SIMD vector instructions on modern CPUs). As a reminder, we give you two syntax examples below:

```
ISPC foreach:                      Cilk:
===========================        ===========================
                                   void f(int i, float* x, float* y) {
                                     x[i] = y[i]
                                   }

foreach (i = 0 ... 100) {          for (int i=0; i<100; i++) {
  x[i] = y[i];                       cilk_spawn f(i, x, y);
}                                  }
```

B. (10 pts) When we discussed Cilk, we emphasized how `cilk_spawn foo()` differs from a normal C function call `foo()` in that the Cilk call can run asynchronously with the caller. Notice that Cilk doesn't explicitly state that the callee function runs **in parallel with the caller**. Give one reason why the designers of Cilk intentionally designed a language that does not specify when the call will run relative to the caller?

C. (10 pts) Consider a cache that contains 32 KB of data, has a cache line size of 4 bytes, is fully associative (meaning any cache line can go anywhere in the cache), and uses an LRU (least recently used—the line evicted is the line that was last accessed the longest time ago) replacement policy. Please describe why the following code will take a cache miss on every data access to the array A.

```
const int SIZE = 1024 * 64;
float A[SIZE];
float sum = 0.0;
for (int reps=0; reps<32; reps++)
  for (int i=0, i<SIZE; i++)
    sum += A[i];
```

D. (10 pts) Your friend is designing a soccer playing robot for the next RoboCup competition. The software on the robot must send a torque request to the robot's motors every 3 ms in order for the robot to successfully locomote. Unfortunately in your friend's implementation, computing torques takes 20 ms when running serially on a single core of the robot's 2 GHz single-core CPU. As a result your friend's robot constantly falls over without being touched. You laugh at your friend, and call their robot "Neymar"!

You look at your friend's code and notice that 20% of the code is inherently serial. The rest is perfectly parallelizable. You dig into your desk drawer and find two processors: Processor A is a 64-core processor that runs at 1 GHz. Processor B is a 8-core processor that runs at 4 GHz. Can you solve your friend's performance problem? Justify your answer by computing the maximum performance they can achieve.

More Practice

PRACTICE PROBLEM 1:

A. The figure below shows a "roofline" plot for a specific processor. Each point on the graph corresponds to the performance (the Y axis is ops/sec) of a different program with the given arithmetic intensity (the X-axis gives the arithmetic ops per byte read by the program. **What is the bandwidth available to the processor? Please give a number, and a 1-2 sentence explanation of your answer.**

Hint: consider why the curve slants diagonally upward in the left part of the graph. Why does the curve flatten out on the right side?
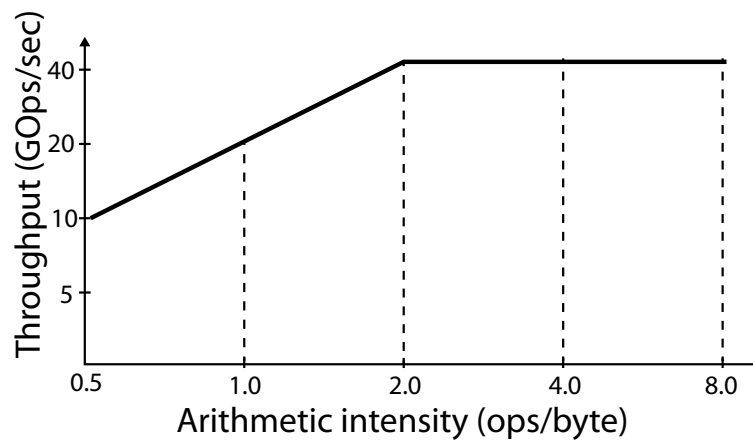
B. Your friend suspects that their program is suffering from high communication overhead, so to overlap the sending of multiple messages, they try to change their code to use asynchronous, non-blocking sends instead of synchronous, blocking sends. The result is this code (assume it is run by thread 1 in two-thread program).

```
float mydata[ARRAY_SIZE];
int dst_thread = 2;

update_data_1(mydata); // updates contents of mydata
async_send(dst_thread, mydata, sizeof(float) * ARRAY_SIZE);

update_data_2(mydata); // updates contents of mydata
async_send(dst_thread, mydata, sizeof(float) * ARRAY_SIZE);
```

Your friend runs to you to say "my program no longer gives the correct results." What is their bug?

Another exercise on understanding the behavior of caches!

PRACTICE PROBLEM 2:

Consider the following C code run by one thread on a CPU featuring a cache with 64 byte (16 float) cache lines and a total capacity of 128 KB. Assume the cache employs a least recently used (LRU) eviction policy and it is fully associative (any cache line can be placed in any available location in the cache). **The processor does not perform any data pre-fetching.**

```
const int SIZE = 1024 * 1024 * 1024;
float input[SIZE];          // sizeof(float) * SIZE bytes
float output[SIZE];         // sizeof(float) * SIZE bytes

// assume input is appropriately initialized here

for (int i=0; i<SIZE; i++) {
  output[i] = input[i] * 2.0;
}
```

    A. In the `for` loop, what fraction of loads from `input` are cache misses? Briefly explain why? **(Hint: Please keep in mind the cache line size.)**

    B. Imagine the code is changed in the following way to have a nested set of `for` loops:

```
const int SIZE = 8 * 1024;
float input[SIZE];      // sizeof(float) * SIZE bytes
float output[SIZE];     // sizeof(float) * SIZE bytes

// assume input is appropriately initialized here

for (int j=0; j<10000; j++) {
  for (int i=0; i<SIZE; i++) {
    output[i] = output[i] + input[i] * 2.0;
  }
}
```

    Assume the processor's cache is the same as in part A. In the "common case" where j>0, what fraction of accesses to `input` and `output` (both loads and stores) are cache misses? Briefly explain why?

C. Now consider the following code which works on 2D arrays:

```
const int SIZE_1 = 1024 * 1024 * 1024;
const int SIZE_2 = 1024 * 8;

float input[SIZE_1][SIZE_2];
float output[SIZE_1-1][SIZE_2];

// assume input is appropriately initialized here

for (int j=0; j<SIZE_1-1; j++) {
  for (int i=0; i<SIZE_2; i++) {
    output[j][i] = input[j+1][i] + input[j][i];
  }
}
```

Now assume that the cache still has the 64 byte line size as before, but **is now only 32 KB in size**. Please rewrite the code so that you minimize the number of cache misses. You can only modify the loop structure (you can add/remove loops and adjust loop bounds) and modify array indexing, but you cannot change the number of mathematical operations performed. **Pseudocode is fine, it need not compile. But to help the grader understand your code, please briefly (in a sentence or two) describe the rough approach used in your solution.**

PRACTICE PROBLEM 3:

Some of the CS149 CAs get organized to grade the midterm, which you can assume has five questions. To ensure fairness, they decide that each question should be graded by one CA, and that to grade each exam they will organize themselves in a pipeline. James takes question 1, Arden takes question 2, Raj takes question 3, Keshav question 4, and Edmund question 5. The CAs sit in a line at the same table, and for each exam James grades question 1, then passes the exam to Arden who grades Q2, who passes to Raj to grade Q3, etc. Pranil and Drew throw up their hands and say "there seems to only be five questions, well we guess we can sit this one out!

Assume that it takes James 5 minutes to grade each exam's Q1, Arden needs 6 minutes to grade Q2, Raj needs 15 minutes to grade Q3, Keshav needs 5 minutes to grade Q4 and Edmund needs 5 minutes to grade Q5. The CAs grade exams in a pipelined fashion to maximize their throughput.

   A. Given this configuration, what is the **latency** of completing the grading of any one exam?

   B. What is the **STEADY-STATE THROUGHPUT** of the CAs, in terms of exams per hour? Keep in mind that the CAs are pipelining grading of exams, so James grabs the next exam to grade as soon as he is done with Q1 from his current exam. (While it doesn't matter in the answer to this problem, since we are asking for steady-state throughput, it might be helpful to assume that the pile of ungraded exams between any two CAs is limited to a small fixed size.)

C. The professors start getting anxious because the CAs haven't completed grading, so they send an angry email to the staff. "Let's speed it up already!" they write. The CA's look at Pranil and Drew and, say "Quit surfing the internet reading articles about ML accelerators and please come help!" Assuming that Pranil and Drew grade questions at exactly the same speed as the other CAs, which question should they help with grading? (please choose one) Describe why? What is the new **steady state throughput** of the staff in terms of exams per hour? (Regardless of the question chosen, Assume that Pranil/Drew's help is going to come in the form of grading a different exam in parallel with the other CAs working on the same question. Their help doesn't reduce the amount of time it takes to grade one question on one exam.)

PRACTICE PROBLEM 4:

A. In class we described the usefulness of making roofline graphs, which plots the instruction through-put of a machine (gigaops/sec) as a function of a program's arithmetic intensity (ops performed per byte transferred from memory). Note moving along the X axis is changing the properties of the code being run. The Y axis plots the performane of the machine when running a specified pro-gram. Consider the roofline plot below. Please plot the roofline curve for a machine featuring a **1 GHz dual-core processor. Each core can execute one 4-wide SIMD instruction per clock**. This processor is connected to a memory system providing 4 GB/sec of bandwidth. *Hint: what is the peak throughput of this processor? What are its bandwidth requirements when running a piece of code with a specified arithmetic intensity? Recall ops/second × bytes/op is bytes/sec. Arithemetic intensity is 1/(bytes/op).*

Plot the expected throughput of the processor when running code at each arithmetic intensity on the X axis, and draw a line between the points.
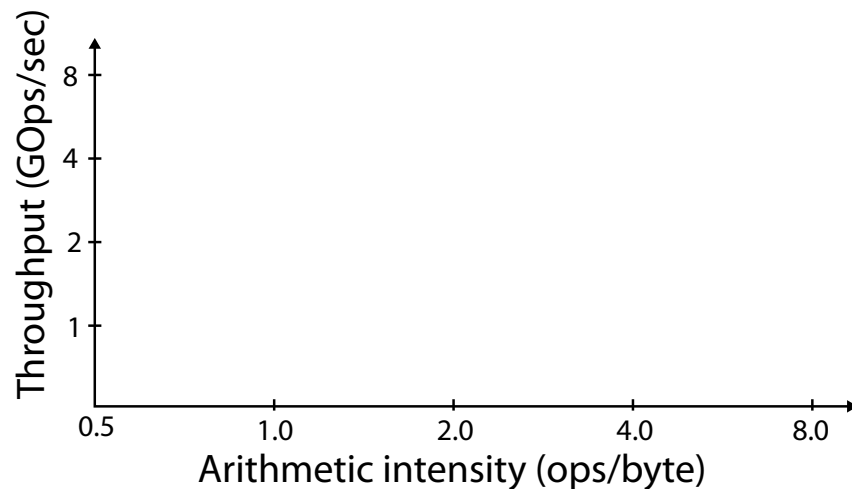
B. Consider the following piece of C code.

```
float A[VERY_LARGE];
float B[VERY_LARGE];
float C[VERY_LARGE];
float D[VERY_LARGE];
float E[VERY_LARGE];

for (int i=0; i<VERY_LARGE; i++)
  C[i] = A[i] * B[i];
for (int i=0; i<VERY_LARGE; i++)
  D[i] = C[i] + B[i];
for (int i=0; i<VERY_LARGE; i++)
  E[i] = D[i] - A[i];
```

Assume that VERY_LARGE is so large that the arrays are hundreds of MBs in size, and that the code is run on a single-core processor with a 8 MB cache. Please modify the program to maximize its arithmetic intensity. You only need to write to the output array E, you don't need to fill in C and D if it is not necessary. However, please DO NOT CHANGE the number of math operations performed. **If we assume the program before and after the modification is bandwidth bound, how much does your modification improve its performance?**

A Cardinal Processor Pipeline

PRACTICE PROBLEM 5:

The fast-growing startup Cardinal Processors, Inc. builds a single core, single threaded processor that executes instructions using a simple four-stage pipeline. As shown in the figure below, each stage of the pipeline (called if the IF, D, EX, and WB stages) performs its work for an instruction **in one clock**. To keep things simple, assume this is the case for all instructions in the program, including loads and stores (memory is infinitely fast).

The figure shows the execution of a program with six **independent instructions** on this processor. *However, if instruction B depends on the results of instruction A, instruction B will not begin the IF phase of execution until the clock after WB completes for A.*
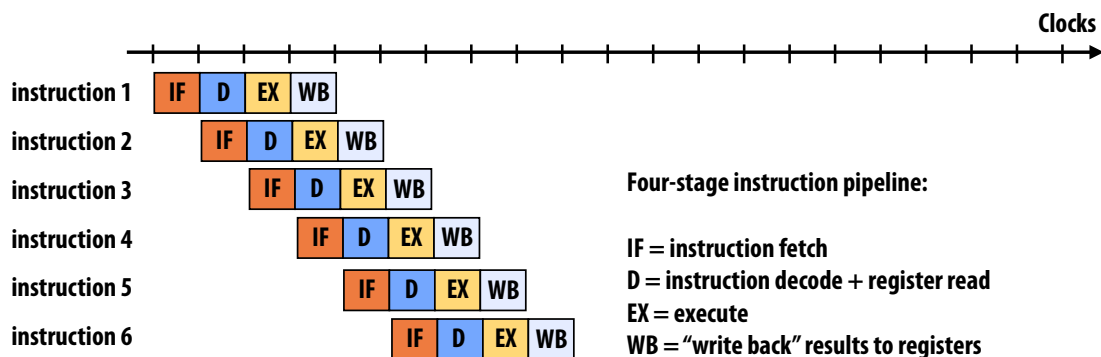
A. Assuming all instructions in a program are **independent** (yes, a bit unrealistic) what is the instruction throughput of the processor?

B. Assuming all instructions in a program are **dependent** on the previous instruction, what is the instruction throughput of the processor?

C. What is the latency of completing an instruction?

D. Imagine the IF stage is modified to improve its throughput to fetch TWO instructions per clock, but no other part of the processor is changed. What is the new overall maximum instruction throughput of the processor?

E. Consider the following C program:

```
float A[500000];
float B[500000];
// assume A is initialized here

for (int i=0; i<500000; i++) {
    float x1 = A[i];
    float x2 = 6 * x1;
    float x3 = 4 + x2;
    B[i] = x3;
}
```

Assuming that we consider only the four instructions in the loop body (for simplicity, disregard instructions for managing the loop or calculating load/store addresses), what is the average instruction throughput of this program? (Hint: You should probably consider instruction dependencies, and at least two loop iterations worth of work).

F. Modify the program to achieve peak instruction throughput on the processor. Please give your answer in C-pseudocode.

G. Now assume the program is reverted to the original code from part E, but the for loop is parallelized using a C++ language extension called OpenMP. OpenMP is a set of C++ compiler extensions that enable thread-parallel execution, and in the case of the code below, iterations of the for loop that's prefixed by `omp parallel for` will be carried out in parallel by a pool of worker threads.)

```
// assume iterations of this FOR LOOP are parallelized across multiple
// worker threads in a thread pool.
#pragma omp parallel for
for (int i=0; i<100000; i++) {
  float x1 = A[i];
  float x2 = 2*x1;
  float x3 = 3 + x2;
  B[i] = x3;
}
```

Given this program, imagine you wanted to add multi-threading to the **single-core processor** to obtain **peak instruction throughput** (100% utilization of execution resources). What is the smallest number of threads your processor could support and still achieve this goal? You may not change the program.

PRACTICE PROBLEM 6:

Consider the following ISPC code that computes $ax^2 + bx + c$ for elements x of an entire input array.

```
void polynomial(float a, float b, float c,
                uniform float x[], uniform float output[], int elementsPerTask) {
  uniform int start = taskIndex * elementsPerTask;
  uniform int end = start + elementsPerTask;

  foreach (i = start ... end) {
    output[i] = (a * x[i] * x[i]) + (b * x[i]) + c;   // 5 arithmetic ops
  }
}

// assume N is very, very large, and is a multiple of 1024
void run(int N, float a, float b, float c, float* input, float* output) {
  uniform int elementsPerTask = 1024;
  launch[N/elementsPerTask] polynomial(a, b, c, input, output, elementsPerTask);
}
```

Professor Kayvon, seeking to capture the highly lucrative polynomial evaluation market, builds a multi-core CPU packed with ALUs. "The professor with the most ALUs wins, he yells!" The processor has:

- 4 cores clocked at 1 GHz, capable of one 32-wide SIMD floating-point instruction per clock (1 addition, 1 multiply, etc.)

- Two hardware execution contexts per core

- A 1 MB cache per core with 128-byte cache lines (In this problem assume allocations are cache-line aligned so that each SIMD vector load or store instruction will load one cache line). Assume cache hits are 0 cycles.

- The processor is connected to a memory system providing a whopping 512 GB/sec of BW

- The latency of memory loads is 95 cycles. (There is no prefetching.) For simplicity, assume the latency of stores is 0.

   A. What is the peak arithmetic throughput of Prof. Kayvon's processor?

   B. What should Prof. Kayvon set the ISPC gang size to when running this ISPC program on this processor?

C. Prof. Kayvon runs the ISPC code on his new processor, the performance of the code is not good. What fraction of peak performance is observed when running this code? Why is peak performance not obtained?

D. Prof. Olukuton sees Kayvon's struggles, and sees an opportunity to start his own polynomial computation processor company that achieves double the performance of Prof. Kayvon's chip. "Oh shucks, now I'll have to double the number of cores in my chip, that will cost a fortune." Kayvon says.

TA Mario writes Kayvon an email that reads "There's another way to achieve peak performance with your original design, and it doesn't require adding cores." Describe a change to Prof. Kayvon's processor that causes it to obtain peak performance on the original workload. Be specific about how you'd realize peak performance (give numbers).

The following year Prof. Kayvon makes a new version of his processor. The new version is the **exact same quad-core processor** as the one described at the beginning of this question, except now the chip **supports 64 hardware execution contexts per core**. Also, the ISPC code is changed to compute a more complex polynomial. In the code below assume that `coeffs` is an array of a few hundred polynomial coefficients and that `expensive_polynomial` involves 100's of arithmetic operations.

```
void polynomial(uniform float coeffs[], uniform float input[],
                uniform float output[], int elementsPerTask) {
  uniform int start = taskIndex * elementsPerTask;
  uniform int end = start + elementsPerTask;
  foreach (i = start ... end) {
    output[i] = expensive_poly(coeffs, input[i]);   // 100's of arithmetic ops
  }
}

void run(int N, float* coeffs, float* input, float* output) {
  uniform int elementsPerTask = 1024;
  launch[N/elementsPerTask] polynomial(coeffs, input, output, elementsPerTask);
}
```

E. What is the peak arithmetic throughput of Prof. Kayvon's new processor?

F. Imagine running the program with $N=8\times1024$ and $N = 64\times1024$. Assuming that the system schedules worker threads onto available execution contents in an efficient manner, do either of the two values of N result in the program achieving near peak utilization of the machine? Why or why not? (For simplicity, assume task launch overhead is negligible.)

G. Now consider the case where $N=9\times1024$. Now what is the performance problem? Describe is simple code change that results in the program obtaining close to peak utilization of the machine. (Assume task launch overhead is negligible.)

PRACTICE PROBLEM 7:

In class we talked about the `barrier()` synchronization primitive. No thread proceeds past a barrier until all threads in the system have reached the barrier. (In other words, the call to `barrier()` will not return to the caller until its known that all threads have called `barrier()`. Consider implementing a barrier in the context of a message passing program that is only allowed to communicate via **blocking sends and receives**. Using only the helper functions defined below, implement a barrier. Your solution should make no assumptions about the number of threads in the system. **Keep in mind that all threads in a message passing program execute in their own address space—there are no shared variables.**

```
// send msg with id msgId and contents msgValue to thread dstThread
void blockingSend(int dstThread, int msgId, int value);

// recv message from srcThread. Upon return, msgId and msgValue are populated
void blockingRecv(int srcThread, int* msgId, int* msgValue);

// returns the id of the calling thread
int getThreadId();

// returns the number of threads in the program
int getNumThreads();
```