1 Written Assignment (50 points total)

Please submit your solution to this assignment in a plain text file named hw.4_written.txt in the submission system. Syntactic errors in program text will not be penalized in the written assignment e.g., missing semicolons, incorrect spelling of keywords, etc. Pseudo-code is acceptable so long as the meaning of your program is unambiguous.

1.1 Phasers and Atomic Integers (25 points)

Consider a desired inter-task synchronization pattern in Figure 1 followed by an incomplete HJ program in Listing 1.

1. (15 points) Complete the missing phaser declarations (SIG, WAIT, or SIG_WAIT) and phaser registrations in lines 3, 8, 11, 14, to obtain a complete HJ program that implements the inter-task synchronization pattern in Figure 1.

2. (10 points) Assume that a is a reference to a Java AtomicInteger object initialized to zero, and that each of steps A() through L() include the following code, “int n = a.getAndAdd(1);”. What are the possible values that variable n can receive in step H()?
**1.2 HJ isolated constructs vs. Java atomic variables (25 points)**

Many applications use Pseudo-Random Number Generators (PRNGs) as in class IsolatedPRNG in Listing 2. The idea is that the seed field takes a linear sequence of values obtained by successive calls to the nextInt() method as shown in line 6. The use of the HJ isolated construct in lines 4–9 ensures that there will be no data race on the seed field if nextSeed() is called in parallel by multiple tasks. The serialization of the isolated construct instances will determine which task obtains which seed in the sequence.

Since the isolated construct is not available in standard Java, class AtomicPRNG in Listing 3 attempts to implement the same functionality by using Java atomic variables instead.

1. (15 points) Assuming a scenario where nextSeed() is called by multiple tasks in parallel on the same PRNG object, state if the implementation of AtomicPRNG.nextSeed() has the same semantics as that of IsolatedPRNG.nextSeed(). If so, why? If not, why not?

By “same semantics”, we mean that for every IsolatedPRNG execution, we can find an equivalent AtomicPRNG execution that results in the same answer, and for every AtomicPRNG execution, we...
can find an equivalent IsolatedPRNG execution that results in the same answer.

2. (10 points) Why is the “while (true)” loop needed in line 5 of AtomicPRNG.nextSeed()? What would happen if the while(true) loop was replaced by a loop that executes for only iteration?

```java
class AtomicPRNG {
    private AtomicInteger seed;

    public int nextSeed() {
        int retVal;
        while (true) {
            retVal = seed.get();
            int nextSeedVal = nextInt(retVal);
            if (seed.compareAndSet(retVal, nextSeedVal)) break;
        } // while
        return retVal
    } // nextSeed()
} // AtomicPRNG
```

Listing 3: Concurrent PRNG implemented using Java’s AtomicInteger class

2 Programming Assignment (50 points total)

Many problems from artificial intelligence can be defined as combinatorial optimization problems. For example, Branch and Bound (BnB) is a widely used tool for solving large scale NP-hard combinatorial optimization problems. A BnB algorithm searches the complete space of solutions for a given problem for the best solution. Subproblems are derived from the originally given problem through the addition of new constraints. An objective function computes the lower/upper bounds for each subproblem. The upper bound is the worst value for the potential optimal solution; the lower bound is the best value. The entire tree maintains a global upper bound (GUB): this is the best upper bound of all nodes. Nodes with a lower bound higher than the GUB are eliminated from the tree because branching these sub-problems will not lead to the optimal solution. In many practical cases, the amount of pruning that occurs in this type of BnB algorithm can be very significant.

In parallel implementations, pruning the branches of the search tree may lead to terminating existing computations. The structure of the BnB search requires the ability to terminate individual subtrees of the search tree. A BnB version of our array search example is where we are interested in finding the lowest index of the goal item if it exists in the array. We can achieve this by using a MinimaEureka instance. In our EuPM, the GUB is available in the MinimaEureka instance, eu, that a speculative task is registered on and can be retrieved by a call to eu.get(). Calls to check and offer pass the current known bounds or solution, respectively, as the argument. If the argument in the offer call is lower than the GUB, the GUB is updated in the MinimaEureka instance, otherwise the current task is terminated. Similarly, calls to check terminate a task if the argument is larger than the currently known GUB in eu.

2.1 Constraint Satisfaction Search algorithms

Constraint-satisfaction problems arise frequently in several applications areas including puzzle-solving and engineering design. These problems are computationally intensive and well suited for speedup through parallel processing. This assignment explores parallelization of constraint-satisfaction search algorithms that use a game-tree search. In some puzzle-solving algorithms, the puzzle is represented as a tree of game states. Different search strategies are possible when exploring the game-tree search space, for BnB algorithms it is required to explore some monotonic property while exploring game states to ensure optimality in solutions.
An intermediate state of a constraint-satisfaction search is characterized by a *partial Problem State* in which some variables have a single assigned value, and a *Feasible Value Table* (FVT), that provides a set of possible values for the remaining *free* variables. If the set becomes empty for any variable, then it implies that no feasible solution can be derived from the given intermediate state. If an FVT has exactly one value per variable, then it can be combined with the *partial Problem State* to obtain a *complete Problem State*.

Many puzzles can be represented by a set of rules that, applied on the current state of the puzzle, decide what are the possible actions that can be performed, which lead to a new puzzle state (with an assignment of values to a subset of free variables), thereby making them amenable to constraint-satisfaction search. This assignment will focus on the use of constraint-satisfaction search in puzzle-solving, with Sudoku puzzles.

### 2.2 The Sequential Constraint-Satisfaction Solver

```java
public ProblemState search(ProblemState rootState) {  
  final Queue<ProblemState> queue = Sorted-Queue();  
  queue.push(rootState);  
  while (!queue.isEmpty()) {  
    final ProblemState loopState = queue.poll();  
    if (loopState.isSolution()) {  
      return loopState;  
    }  
    final List<ProblemState> neighbors = loopState.neighbors();  
    for (final ProblemState neighbor : neighbors) {  
      queue.add(neighbor);  
    }  
  }  
}
```

Listing 4: Game tree search in constraint-satisfaction

We have provided you an implementation of a sequential constraint-satisfaction search algorithm. In the sequential code given to you, you can find the constraint-satisfaction search code in method `computeSudoku()` of `SequentialBenchmark.java`, which is also shown in Listing 4. In this method, parameter `state` (of type `ProblemState`) contains the partial problem statement on entry. The solution maintains a queue of problem states to explore in sorted order to ensure that when a solution state is found, it is the best solution. As each state is explored, its children in the game tree are found and added into the work queue.

Sudoku is a popular puzzle game that requires players to fill in missing numbers from 0 to N-1 on a square N×N board, taking into account the following constraints:

- No square contains more than a number
- Every number appears only once on each column of the board.
- Every number appears only once on each row of the board.
- Every number appears only once in each individual region of the board. Regions are usually rectangular areas of size \( \sqrt{N} \times \sqrt{N} \) size.

Although Sudoku games are usually 9×9 with 3×3 regions, as in the 9x9.txt file, there are also variations that take larger board sizes as input, such as 16x16.txt with 4x4 regions. If 9x9 boards use the digits 0..8
to fill the board, larger sizes use 0..9, A, B, C, etc for the same purpose. Furthermore, some variations of Sudoku allow for multiple solutions, and the solver provided can find any possible solution. Using a comparison function, the solver can find the “cheapest” solution.

2.3 Your Assignment: Parallel Constraint-Satisfaction Search

Your assignment is to design and implement a parallel algorithm for constraint-satisfaction search, using the provided sequential implementation as a starting point. Your homework deliverables are as follows.

1. [Implementation of utility function in SudokuUtils (10 points)]
   Implement the following functions in SudokuUtils: setPossibleValue, countUnsolved, isSolution, isConsistent, newWorkQueue, and boardComparator. Documentation is provided in each of these methods to explain their desired functionality. Correctly implementing these functions correctly will allow the unit tests in Homework4SudokuUtilsTest to pass.

2. [Implementation of parallel search that finds a valid solution of the Sudoku board (15 points)]
   Create a new parallel version of SequentialBenchmark that uses async and finish constructs, and (possibly) Eureka or isolated constructs, to find a valid solution to the Sudoku problem in the ParallelSearchBenchmark.java file. You can focus your attention on parallelizing the computeSudoku() method. You will be graded on the correctness and speedup of your parallel version, relative to the single-threaded parallel version.

3. [Implementation of parallel search that finds a solution with the minimum lexicographic order of the Sudoku board (10 points)]
   Create a new parallel version of SequentialBenchmark that uses async and finish constructs, and (possibly) Eureka or isolated constructs, to find a solution with the minimum lexicographic (alphabetical) order to the Sudoku problem in the ParallelLexicalBenchmark.java file. While one approach is to simply reuse the solution from Part 2 above and return the solution with lowest lexicographic order, you can be smarter and reduce the work done by pruning the exploration of partial solutions that are guaranteed to never lead to a solution with lower lexicographic order than the current best solution. You will be graded on the correctness and speedup of your parallel version, relative to the single-threaded parallel version.

4. [Homework report (15 points)]
   You should submit a brief report summarizing the design of your parallel algorithms in Parts 2 and 3 above, explaining why you believe that each implementation is correct and data-race-free. Your report should also include the following measurements for both parts 2 and 3:
   (a) The number of nodes explored by the parallel versions (ParallelSearchBenchmark and ParallelLexicalBenchmark) with the inputs 16x16-9.txt and 16x16-10.txt, executed with the “-Dhj.numWorkers=1”, “-Dhj.numWorkers=4” and “-Dhj.numWorkers=8” options on a STIC compute node to run with 1, 4 and 8 workers.
   (b) Performance of the parallel versions (ParallelSearchBenchmark and ParallelLexicalBenchmark) with the inputs 16x16-9.txt and 16x16-10.txt, executed with the “-Dhj.numWorkers=1”, “-Dhj.numWorkers=4” and “-Dhj.numWorkers=8” options on a STIC compute node to run with 1, 4 and 8 workers.
   (c) Speedup obtained compared to the single-threaded version while using 4 and 8 threads in the parallel solutions.

The timings, nodes explored, and speedup values can be obtained by running the following commands: mvn clean compile exec:exec -PSudoku1 and mvn clean compile exec:exec -PSudoku2. You are also provided a sample myjob.slurm to help you run the programs on STIC. Please place the report file(s) in the top-level hw_4 directory. Please commit all files related to the homework into your
turnin svn repository. (You are not allowed to add or modify method definitions in any class that contains the following string in their documentation: “This class should not be modified”.)

Additional tips are available in the following Piazza post: https://piazza.com/class/i4ls6kwa7jh1m9?cid=245