

# Homework 3: due by 11:59pm on Thursday, October 4, 2012

(Total: 100 points)

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All homeworks should be submitted using the submission system at <http://cs.hmc.edu/submit>. In case of problems using the system, please email your homework to [cs181ehelp@cs.hmc.edu](mailto:cs181ehelp@cs.hmc.edu).

*Honor Code Policy: All submitted homeworks are expected to be the result of your individual effort. You are free to discuss course material and approaches to problems with your other classmates, the teaching assistants and the professor, but you should never misrepresent someone else's work as your own. If you use any material from external sources, you must provide proper attribution.*

## 1 Written Assignment (50 points total)

Please submit your solution to this assignment in a plain text file named `hw3_written.txt` in the submission system.

### 1.1 Phasers and Atomic Integers (25 points)

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

- (15 points) Complete the missing phaser declarations 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.
- (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  finish {
2      // INSERT MISSING PHASER DECLARATIONS AND INITIALIZATIONS BELOW
3
4
5
6
7      // INSERT MISSING PHASER REGISTRATIONS BELOW
8      async phased( ----- ) { //Task T1
9          A(); next; B(); next; C(); next; D();
10     } // Task T1
11     async phased( ----- ) { //Task T2
12         E(); next; F(); next; G(); next; H();
13     } // Task T2
14     async phased( ----- ) { //Task T3
15         I(); next; J(); next; K(); next; L();
16     } // Task T3
17 } // finish

```

Listing 1: Incomplete HJ program with missing phaser declarations and registrations

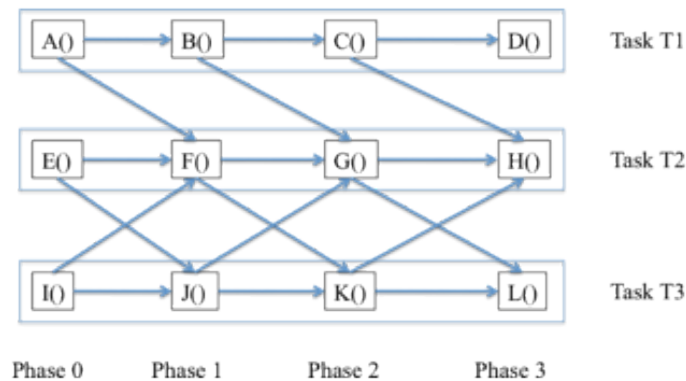


Figure 1: Desired inter-task synchronization pattern using phasers

## 1.2 HJ isolated statements 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 7. The use of the HJ isolated statement in lines 5–8 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 statement instances will determine which task obtains which seed in the sequence.

```
1  class IsolatedPRNG {
2      private int seed;
3      public int nextSeed() {
4          int retVal;
5          isolated {
6              retVal = seed;
7              seed = nextInt(retVal);
8          }
9          return retVal;
10     } // nextSeed()
11     . . . // Definition of nextInt(), constructors, etc.
12 } // IsolatedPRNG
```

Listing 2: Concurrent PRNG implemented using isolated statement

Since the isolated statement is not available in Java, the version below in class `AtomicPRNG` (Listing 3) attempts to implement the same functionality by using Java atomic variables instead.

- (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.*

- (10 points) Why is the “while (true)” loop needed in line 5 of `AtomicPRNG.nextSeed()`? What would happen if the while loop was removed?

```
1  class AtomicPRNG {  
2      private AtomicInteger seed;  
3      public int nextSeed() {  
4          int retVal;  
5          while (true) {  
6              int retVal = seed.get();  
7              int nextSeedVal = nextInt(retVal);  
8              if (seed.compareAndSet(retVal, nextSeedVal)) return retVal;  
9          } // while  
10     } // nextSeed()  
11     . . . // Definition of nextInt(), constructors, etc.  
12 } // AtomicPRNG
```

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

## 2 Programming Assignment (50 points total)

### 2.1 Habanero-Java Setup

See Section 2.1 of the Homework 0 handout for instructions on setting up a Habanero-Java installation for use in this homework. You are encouraged to read Section 8 of the handout for Module 1 to understand the different schedulers available in the HJ system.

The input files needed for this assignment can be found in [hw\\_3.zip](#). See Section 3 of this handout for available command-line options when compiling and executing HJ programs. In general, the command-line interface (rather than DrHJ) is recommended for performance measurements, since DrHJ incurs additional overhead on the machine by running in a separate JVM from the one used to execute your application.

### 2.2 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 *forward checking*. It is well known that some form of look-ahead, as in forward checking, reduces the sequential execution time for the application thereby making it a more credible candidate for parallelization than simple backtracking. This assignment will focus on the use of constraint-satisfaction search in puzzle-solving, with n-queens and Sudoku puzzles as two use cases.

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*.

In the sequential code given to you, you can find the constraint-satisfaction search code in method `search()` of `ConstraintSatisfaction.hj`, which is also shown in Listing 4 below. In this method, parameter `state` (of type `ProblemState`) contains the partial problem statement on entry, parameter `curVar` identifies the current variable to be explored in the search, and parameter `fvt` contains the FVT on entry. Line 2 checks if we are examining the last variable, in which case no further forward checking is needed; instead, `state` and `fvt` together identify one or more solutions that can be added to the set of feasible solutions. The loop body in lines 7–11 of Listing 4 is then repeated for each feasible value `v` of `curVar` in `fvt`. This can be seen in line 9 which constructs a new state in which `curVar = v`. The call to `forwardCheck()` in line 10 prunes `fvt` to obtained a reduced `newFvt` that removes values of variables that are not feasible in conjunction with `curVar = v`. If `newFvt` is `null` it means that no feasible solution is possible for `curVar = v`. Otherwise, the

```
1 public void search(ProblemState state, int curVar, FVT fvt) {
2     if (curVar == fvt.getNumVars())
3         problem.addSolution(state); // feasible solution found
4     else {
5         Iterator<Integer> itr = fvt.getValues(curVar).iterator();
6         while(itr.hasNext()) {
7             Integer v = itr.next();
8             ProblemState newState = state.copy();
9             newState.setValue(curVar, v);
10            FVT newFvt = forwardCheck(curVar, v, fvt);
11            if (newFvt != null) search(newState, curVar+1, newFvt);
12        } // while
13    } // if
14 } // search()
```

Listing 4: search() method in ConstraintSatisfaction.hj

```
1 public FVT forwardCheck(int curVar, Integer curVal, FVT fvt) {
2     FVT newFvt = new FVT(fvt.getNumVars());
3     for(int freeVar = curVar+1; freeVar < fvt.getNumVars(); freeVar++) {
4         Iterator<Integer> itr = fvt.getValues(freeVar).iterator();
5         while(itr.hasNext()) {
6             Integer v = itr.next();
7             if (problem.isConsistent(curVar, curVal, freeVar, v))
8                 newFvt.addValue(freeVar, v);
9         } // while
10        if (newFvt.getValues(freeVar).size()==0) return null;
11    } // for
12    return newFvt;
13 } // forwardCheck()
```

Listing 5: forwardCheck() method in ConstraintSatisfaction.hj

recursive call to `search()` in line 11 explores feasible values for later variables.

Listing 5 contains the sequential code for method `forwardCheck()` of `ConstraintSatisfaction.hj`, which was called in line 10 of Listing 4. Line 3 iterates through the remaining free variables starting with `curVar+1`, and line 5 iterates through the values `v` that can be taken by `freeVar`. The essence of `forwardCheck()` is captured by the call to `problem.isConsistent(curVar, curVal, freeVar, v)` in line 7, which checks if the assignment of `v` to `freeVar` is consistent with the assignment of `curVal` to `curVar`. If so, the assignment of `v` to `freeVar` is added to `newFvt` (otherwise, it is not added). Line 10 checks if the set of feasible values for `freeVar` is empty. If so, a `null` value is returned instead of `newFvt` since no feasible solution exists at this point.

### 2.3 The Sequential Constraint-Satisfaction Solver

We have provided you an implementation of a sequential constraint-satisfaction search algorithm in the `hw_3.zip` file containing the following:

1. `IConstraintSystem.hj` — this interface defines the methods that a game/puzzle should implement in order for it to be solvable by our solver.
2. `ProblemState.hj` — this class represents the state of the game.

3. `ConstraintSatisfaction.hj` — this file contains two public methods, `solve()` and `parallelSolve()`. `solve()` contains a sequential implementation of the constraint-satisfaction search algorithm. `parallelSolve()` calls `parallelSearch()` which is currently empty, and will need to be filled in by you in parts 1 and 2 of your assignment (Section 2.4). The main programs also perform a comparison test on the results returned by `solve()` and `parallelSolve()`, which should pass after you've completed the assignments (but which fails for `parallelSolve()` in the version provided).
4. `NQueens.hj` — client solver for the NQueens problem.
5. `Sudoku.hj` — client solver for Sudoku, with a `Reader` to read input problems from the disk.
6. `NQueensMain.hj` — main program that starts and validates the results of the NQueens solver.
7. `SudokuMain.hj` — main program that starts and validates the results of the Sudoku solver.

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 homework focuses on NQueens and Sudoku as two examples of such puzzles.

Alternative approaches to solving the NQueens puzzle have already been studied in class. The default size used by `NQueensMain` for this problem is  $n = 12$ .

Sudoku is a popular puzzle game that requires players to fill in missing numbers from 0 to  $N-1$  on a square  $N \times N$  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  $9 \times 9$  with  $3 \times 3$  regions, as in the `9x9.txt` file, there are also variations that take larger board sizes as input, such as `16x16.txt` with  $4 \times 4$  regions. If  $9 \times 9$  boards use the digits 1..9 to fill the board, larger sizes use 1..9, A, B, C, etc for the same purpose. Furthermore, some variations of Sudoku allow for multiple solutions, and the solver provided indeed finds all the possible solutions. If a cost function is specified, the solver must find the “cheapest” solution. The supplied serial solver already does that for you; however, it is your responsibility to keep the solver working in all case. The default input used by `SudokuMain.hj` is `9x9-2-multisol.txt`.

## 2.4 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. [Computation of all solutions (15 points)]

Create a new parallel version of `ConstraintSatisfaction.hj` that is designed to achieve the *smallest execution time* on the parallel machine (with 2 or more cores) that you use for this homework. You will be graded on the correctness and speedup of your parallel version. You can focus your attention on parallelizing the `search()` method. Keep in mind that the call to `problem.addSolution()` in line 3 of Listing 4 is not thread-safe i.e., it can lead to interference and data races if it is called multiple times (with different solutions) in parallel.

Your solution should work for any constraint-satisfaction problem, but you should test it with `NQueensMain.hj`, both for correctness and for achieving the best performance that you can relative to the sequential version. The `addSolution()` method in `NQueensCS.hj` accumulates all solutions into a single array. (It does not attempt to find the best solution according to some cost function.)

Please place all files related to this solution in a zip file named “`hw3_part1.zip`”. (You are allowed to add or modify methods in any class, so long as your implementation still works for any constraint-satisfaction problem, and the `parallelSearch()` method returns the same results as `search()`.)

## 2. [Computation of lowest-cost solution (20 points)]

Create a new parallel version of `ConstraintSatisfaction.hj` that is designed to achieve the *smallest execution time to return a single solution with lowest cost* (so long as at least one feasible solution exists). While one approach is to simply reuse the solution from Part 1 above and return the solution with lowest cost, 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 lower than the current best solution. You will be graded on the real speedup achieved by both your sequential and parallel versions relative to this brute-force approach. (The speedup will come from a combination of algorithmic improvements and from parallel computing.)

Your solution should work for any constraint-satisfaction problem with a cost function, but you should test it with `SudokuMain.hj`, both for correctness and for achieving the best performance that you can.

*To make this general, assume that the `getCost()` method provides a cost for both complete solutions and partial solutions, and that the cost of a partial solution is guaranteed to be non-decreasing as more variables in the FVT are bound to single values.*

The `addSolution()` method in `SudokuCS.hj` stores the best solution found (if any) using a (artificial) cost function that corresponds to the single `BigInteger` value obtained by scanning the digits from left-to-right and top-down in the solution. accumulates all solutions into a single array. As written, `getCost()` only provides a meaningful cost if the solution is a final Sudoku solution. *You are welcome to extend it to provide useful bounds for partial solutions, so long as it obeys the non-decreasing monotonicity constraint mentioned above.*

Please place all files related to this solution in a zip file named “`hw3_part2.zip`”. (You are allowed to add or modify method definitions in any class, so long as your implementation still works for any constraint-satisfaction problem with a cost function, and the `parallelSearch()` method returns the same result as `search()`.)

## 3. [Homework report (15 points)]

You should submit a brief report summarizing the design of your parallel algorithms in Parts 1 and 2 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 1 and 2:

- (a) Performance of the sequential version with the default input
- (b) Performance of the parallel version with the default input, executed with the “`-places 1:1`” option to run with one worker and the “`-places 1:k`” option to run with  $k$  workers (where  $k$  is the number of cores available in the machine that you used.)

*Please submit your report in a plain text file named `hw3_report.txt` in the submission system. If you prefer to submit a PDF file, that's okay too. (Send email to `cs181ehelp@cs.hmc.edu` with your report, if you have problems submitting a PDF file.)*

## 3 Compile-time and Runtime options for Habanero Java

*These options are described assuming that HJ programs are compiled and executed using the command-line interface. See DrJava's Preferences panes to select some of these options when using DrJava.*

To compile an HJ program, `Foo.hj`, type “`hjc [options] Foo.hj`”. The following command-line options are currently available for `hjc` (type “`hjc -help`” for a summary):

- racedet** Enable race-detection when program executes (off by default, only works for basic async and finish constructs)
- rt s** Compile program for work-sharing runtime (on by default, supports all HJ constructs)
- rt h** Compile program for work-stealing runtime with **help**-first policy (off by default, only works for basic async and finish constructs)
- rt w** Compile program for work-stealing runtime with **work**-first policy (off by default, only works for basic async and finish constructs)
- classpath** `<path>` Search path for class files
- sourcepath** `<path>` Search path for `hj` source files (must include `-classpath` if this option is used)
- destdir** `<path>` Set the location where output classes from `hjc` should be placed
- version** Print version number of the HJ compiler. Please include this version number when reporting any problems to comp322-staff.

To execute a compiled HJ program, `Foo.hj`, type “`hj [options] Foo [args]`”, where *args* are the command-line arguments for your program’. The following command-line options are currently available for `hj` (type “`hj -help`” for a summary):

- places** `<p>:<w>` Set number of places and workers per places. The default value is  $p = 1$  and  $w =$  number of processors in the system.  
For now, you will be working with 1 place, so you can use `-places 1:n` to run an HJ program with  $n$  workers (for  $n$  cores).
- perf=true** Output abstract execution metrics when program executes (off by default, only works for basic async and finish constructs)
- fj** Use Fork-Join variant of work-sharing runtime (off by default, assumes that program has been compiled for work-sharing execution)
- version** Print version number of the HJ runtime system. Please include this version number when reporting any problems to comp322-staff.
- mx** `<size>` set max heap size, e.g., `-mx 8000M` sets the max heap size to 8GB
- classpath** `<path>` Search path for class files
- J<arg>** Pass `<arg>` directly to Java runtime (use with caution)