

# Formal Methods in Software Development

## Exercise 8 (December 19)

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The result is to be submitted by the deadline stated above *via the Moodle interface* of the course as a *.zip or .tgz* file which contains

1. a PDF file with
  - a cover page with the course title, your name, Matrikelnummer, and email address,
  - the deliverables requested in the description of the exercise,
2. the JML-annotated Java files developed in the exercise,
3. the proof files generated by the KeY prover (use the menu option “Save”).

## Exercise 8: JML Verification with KeY

Take from Exercise 7 the JML-annotated program functions `minimumPosition`, `minimumElement1`, `minimumElement2`, `append`, `replace`, and `add`. Perform for each of these functions the tasks described below (you may use a single Java class file for all functions).

Annotate every loop in the function with an appropriate invariant (`loop_invariant`) and termination term (`decreases`) and check these with `escjava2/openjmlesc`. It is recommended to use multiple `loop_invariant` statements for each conjunct of the invariant; then it is easier to determine which part of an invariant failed. In the case of a `for` loop, do not forget to add the range condition for the loop variable to the invariant. If an array is modified, do not forget to specify which part of the array has remained unchanged so far.

When you are confident about these annotations, provide the loop also with an `assignable` clause (which is not standard JML but needed by the KeY prover) that lists all variables/array contents changed in the loop; in the case of a `for` loop, do not forget to add the loop variable to this clause. Then verify the method with KeY.

If your annotations are correct and sufficiently strong, the proofs should run through automatically with a few invocations of the KeY prover (be sure that in tab “Proof Search Strategy” the “Defaults” options are selected; you may want to reduce the “Max. Rule Applications” to speed up the proof search). After each proof search, you may also attempt to apply an SMT Solver (I recommend Z3) to close some proof obligations. If you cannot complete the proof, investigate the proof tree to find out what went wrong and reconsider your annotations (they may be wrong, i.e. too strong, or too weak); for this purpose, you may unselect the option “Hide intermediate proof steps” in the context menu of the proof tree in order to see all simplification steps performed by the prover. If you cannot complete the proof, explain in detail which part of the verification failed and what you believe is the reason for the failure.

The deliverables of this exercise consist of

- a nicely formatted copy of the JML-annotated Java code (the version with the `assignable` clauses used for running KeY),
- the output of `jml -Q` on the class,
- the output of `escjava2 -NoCautions/openjmlesc` on the class,
- for each function, an explicit statement where you say whether you could complete the verification or not (and how many proof branches have remained open)
- for each function, a screenshot of the KeY prover when the proof has been completed (or got stuck) illustrating the generated proof tree (without the intermediate steps) with emphasis of the still open proof branches (if any),
- for each open proof branch a screenshot of the proof obligation, an explanation of the role of this obligation in the overall verification, and your conjecture why the proof failed.

Please also report any observations or insights you have gained.