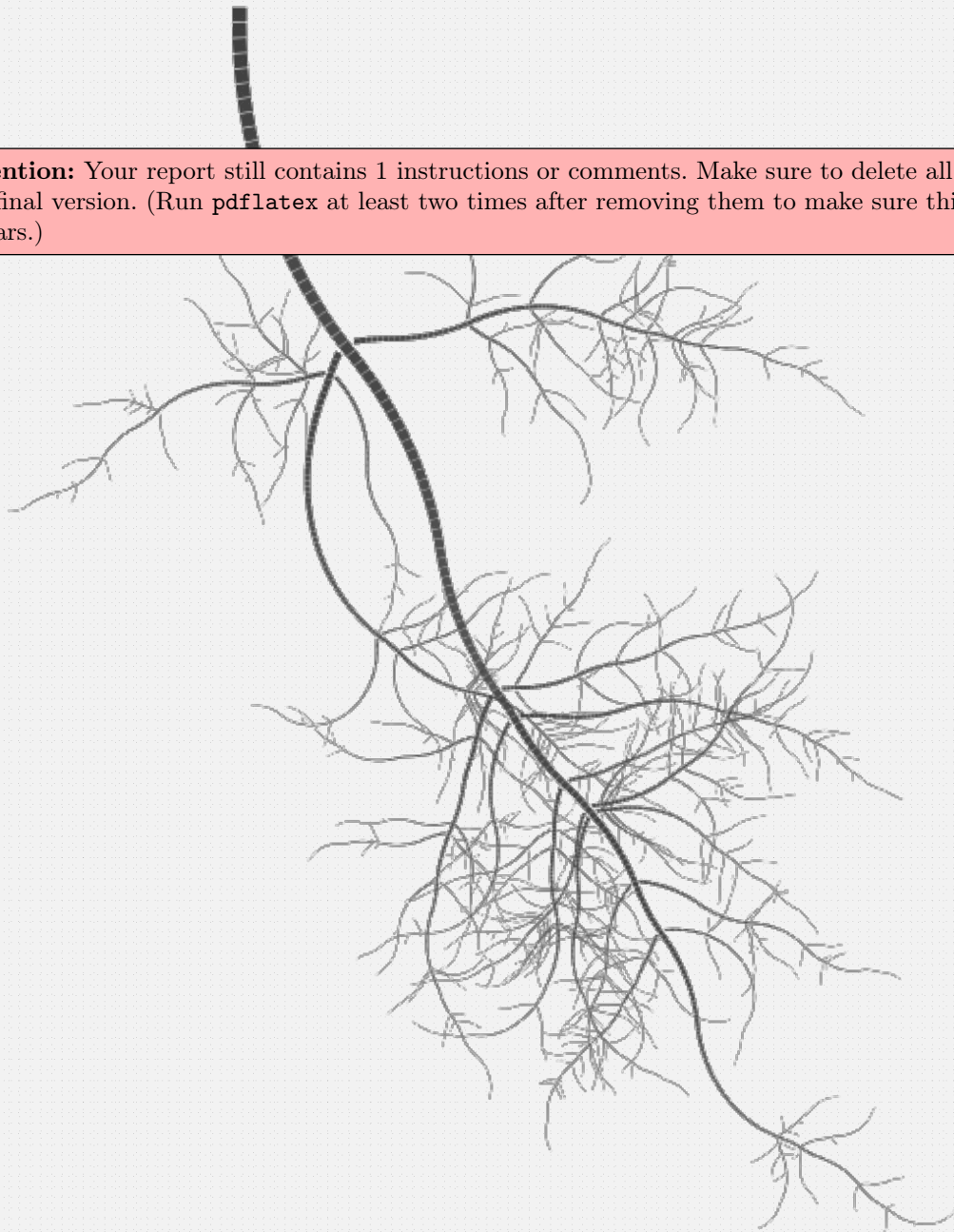# Advanced Programming Languages for A. I.

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> ⚠ **Attention:** Your report still contains 1 instructions or comments. Make sure to delete all of them for the final version. (Run `pdflatex` at least two times after removing them to make sure this warning disappears.)

Contents

*In the past decades much research has been done on the character-
ization and resolution of constraint satisfaction - and constraint
optimization problems. This report discusses three challenges ;
Sudoku puzzles, Hashiwokakero and a scheduling problem.*

1 Sudoku

Sudoku is a well-known puzzle game which needs no introduction. It is typically modelled as a constraint
satisfaction problem through the use of `all_different` constraints on rows, columns and blocks. Such global
inequalities tend to improve upon the use of binary inequalities. The constraint generating code[1] is fairly trivial
and needn't be detailed here.

There are several other ways one could model Sudoku. The widely cited study by Helmut Simonis [9] and
subsequent studies provide some ideas. Four *'dual'* models, two approaches based on a boolean characterisation,
a combination of models provided by Laburthe, a model enforcing the singular occurrence of every value in every
row, column and block, as well as a model with nothing but channeling constraints were considered[2]. Tests were
run on the provided puzzles[3] as well as some minimum puzzles provided by Gordon Royle[4]. These are puzzles
with a minimal amount of pre-filled cells (17 to be precise [7]), which does not mean that they are harder to solve.

The dual models hold a $N \times N$ array with all the decision variables. Whereas in the classic viewpoint the
rows, columns and values of this array correspond to those of the input puzzle, every one of the four dual
models changes their roles. The first two switch the role of rows or columns with those of values. In the third
model every row and column of the array corresponds to a block and a position. In the fourth dual model every
row represents a block, every column a value and every value a position within a block. For each of them it
was harder to implement the necessary constraints, usually necessitating the use of auxiliary variables together
with appropriate channeling constraints.

In one of his works Laburthe discusses various rules that can be used to resolve Sudoku puzzles, after which
he details three models that he associates with the rules [3]. He ends up proposing a model for every level of
difficulty of the input puzzle. An attempt was made at implementing his recommendation for 'difficult' puzzles.
It decreased the average number of backtracks but increased the runtime.

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[1] `ECLiPSe` and `CHR` implementations are available in `/sudoku/model/classic.pl` and in `/sudoku/chr/model/classic.pl`.

[2] These are implemented with ECLiPSe in the `/sudoku/eclipse/model/` directory, and some CHR versions are in
`/sudoku/chr/model/`.

[3] `/sudoku/benchmarks/benchmarks.pl` provides automatic benchmarking code.

[4] These are available online.

The boolean models include the natural combined model [8] and a more intuitive characterisation resembling an integer programming - or a SAT model [6] (using `occurrences/3` instead of sums, disjunctions and conjunctions). Both of them have $N \times N \times N$ boolean variables b_{rcv} which are true if the cell at row r and column c holds the value v. The natural combined model was cumbersome to implement and performed badly. It was introduced together with an algorithm which was tailored after it, and a constraint for unequality of lists isn't really supported by ECLiPSe[5].

Note that it is usually not recommended to use a boolean model when integers can be used instead (as pointed out by Rossi [4]).

The last two models were found to be the most performant. The first makes use of the previously mentioned `occurrences/3` constraint to make every value occur just once in every row, column and block.

The second one generates nothing but channeling constraints. It has been demonstrated that this can provide good results despite such constraints being less 'tight' than `all_different` constraints[6]. When Dotú discussed it he was considering QuasiGroups [2]. This was extended[7] to Sudoku puzzles by making use of three instead of two dual models (since blocks need to be considered as well). The variant in which channeling constraints between all models (one primal, three dual) are generated performed better than the one in which only channeling constraints between the primal and every dual model are applied. These variants are analogous to what Dotú referred to as *'trichanneling'* and *'bichanneling'*.

1.1 Experiments

Number of backtracks and running time for most of the models are displayed in table 1. Removal of *'big'* (`all_different`) constraints in the classic model[8] led to an increase in runtime which corroborates Demoen's experiences [1].

Figure 1: *Missing(6)* model

One interesting observation is that the two most performant models also have the same number of backtracks. One of them is the model with nothing but channeling constraints, the other uses the `occurrences/3` constraint. This constraint enforces arc consistency.

A model combining the classic viewpoint with the fourth dual model was set up. Number of backtracks and runtimes are displayed in table 1.

Algorithm 1 Dual viewpoint constraints

Code here
More code here
Even more code here

» Two tables: one with all results with ic:alldifferent and just fixed heuristics (input_order). Then a table for ic_global + heuristics for the chosen 2 models (channeling and dual3 or dual4), this time each puzzle separately. Then a small discussion of the results. Should be 3 pages in total including TOC. Note that small discussion of CHR needs to be done too.

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[5]A custom-made implementation as well as the $\sim$=/2 constraint which checks if two terms can be unified were tried. Channeling back to integers with `ic_global:bool_channeling/3` worked better.

[6]*"The reason for this difference is that the primal not-equals constraints detect singleton variables (i.e. those variables with a single value), the channelling constraints detect singleton variables and singleton values (i.e. those values which occur in the domain of a single variable), whilst the primal all-different constraint detects global consistency (which includes singleton variables, singleton values and many other situations)"*[5]

[7]The code lies in `sudoku/model/channeling.pl` in which a flag called `extended` can be used to opt for one of two variants.

[8]In his study Demoen gives several *Missing(6)* examples, models in which 6 of the `all_different` constraints are removed. *Missing(7)* models aren't Sudoku, and because of the stark rise in number of backtracks no further experimentation with the removal of *'small'* constraints was done. The `eliminate_redundancy` flag can be used to toggle redundancy elimination on and off.

	input_order	first_fail	input_order + ic_global	first_fail + ic_global
lambda				
hard17				
eastermonster				
tarek_052				
goldennugget				
coloin				
extra2				
extra3				
extra4				
inkara2012				
clue18				
clue17				
sudowiki_nb28				
sudowiki_nb49				
Total/Average				
Total/Average (minimum)				

Table 1: Results (ECLiPSe)

» Maybe for those puzzles that do better with input_order show that mirroring the puzzle leads to slower runtimes (you could do this for all puzzles, write procedure swap(Puzzle) for it). Note that value heuristics shouldn't matter much as the 'max' or 'min' isn't really meaningful in Sudoku (you can use '9,8,7, ...' instead of '1,2,3,...' for all we know

2 Hashiwokakero

📑 **TODO:** Task 2

3 Scheduling Meetings

The last challenge is the scheduling of some meetings, taking into account the preferences of the various persons involved. A constraint optimization problem where the cost is a function of the end time of the last meeting and the number of '*violations*' (people of lower rank having their meeting after that of people of higher rank). This number of violations is of secondary importance.

Weekend constraints are generated first. If a person doesn't want to meet on weekends then his or her meeting is not allowed to overlap with the first weekend that follows :

$$((S + StartingDay) \bmod 7) + D < 5$$

In the above constraint S and D represent the start and duration of the person's meeting. Making direct use of mod/3 leads to an instantiation error, necessitating the use of an auxiliary variable representing the result of the modulo operation [CODE].

Precedence constraints and constraints assuring that no meetings overlap are generated last. The corresponding code is fairly trivial[9]. The fact that the meeting with the minister should come last is equivalent to adding $N - 1$ precedence constraints with N the total number of persons.

The cost function is defined as $(V_{max} \times E) + V$ where V_{max} is the maximum number of rank violations, E is the end time of the meeting with the minister and V is the actual number of rank violations for a given

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[9]Note that all code for this third challenge can be found in `/src/scheduling/scheduling.pl`.

solution. This ensures that whenever two solutions have a different E, the solution with the smallest E will have the lowest cost (whatever the number of violations V). Yet if two solutions have the same end time E, then it's the number of violations V that will determine what solution is best. Code is displayed in [CODE].

An additional constraint was used for the cost function, stating that it cannot be smaller than $V_{max} \times D_{tot}$ with D_{tot} the sum of all meeting durations. This makes a difference[10].

Some implied constraints were added to increase performance. In case two persons have a different rank but the same meeting duration and weekend preferences, a corresponding order on their start times can safely be imposed. This mustn't override the precedence constraints. The respective implementation is displayed in [CODE].

Table 2 shows the runtime for each benchmark. Two versions are considered ; one ensures that no two meetings overlap by imposing a ($S_1+D_1 \leq S_2$ or $S_2+D_2 \leq S_1$) constraint for every such pair, the other version uses a global version of these same constraints provided by the `ic_edge_finder` library. It's clear that the global version outperforms the other one.

Instead of making use of implied constraints one can also tinker with the various heuristics provided by the `search/5` procedure. Some of those lend themselves to some benchmarks but not to others.

The `indomain_min` heuristic performed better than `indomain_max` as it is an optimisation problem after all, meaning that selecting the minimum starting time selects solutions with a smaller cost first. A solution with a lower cost will prune the search tree more.

	input_order	input_order + ic_edge_finder
bench1a		
bench1b		
bench1c		
bench2a		
bench2b		
bench2c		
bench3a		
bench3b		
bench3c		
bench3d		
bench3e		
bench3f		
bench3g		
Total/Average		

Table 2: Benchmark results for the Scheduling Meetings challenge.

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[10]In our tests the total runtime for all benchmarks was reduced by a factor of 4.

Appendix

Reflection

When implementing the Sudoku solver in CHR we took a glimpse at Thom's implementation. It's given in his book as a solution to some exercise. Once we understood his approach we had the tendency to implement the viewpoints by making use of the same strategy ; constraints representing variables, constraints representing values and a simple implementation of the `first_fail` heuristic. This worked well, but it wasn't the most creative thing to do. Implementing some other approaches (and heuristics) and trying to decrease total runtime was our way to compensate for this.

Workload

Some questions were asked online after all the code had been written. There were four of them, all about Sudoku. One on how to enforce equality of lists (we already had the solution but wanted to be sure there was no better alternative). One on looping through a list which is a subscript of an array (we found the appropriate solution ourselves). One on the inner workings of occurrences/3. And a final one on memory usage. Aside from a quick experiment with ∼=/2 no code was rewritten as a result. None of the questions mentioned Sudoku. All the viewpoints were either thought of by ourselves or come from the literature that was cited in this report.

We started working in mid-April and finished a few days before the deadline, each having worked about ??? hours in total. This includes reading (parts of) the educational material, researching, tinkering, programming, debugging and writing the report.

Overview of the Code

Folder	File	Description
`/src/sudoku/`	`utils.pl`	*Utility functions for the Sudoku code (CHR & ECLiPSe)*
`/src/sudoku/benchmarks/`	`benchmarks.pl`	*Automatic benchmarking code*
`/src/sudoku/benchmarks/puzzles`	`*`	*Benchmarks*
`/src/sudoku/chr/`	`solver.pl`	*Sudoku solver (CHR)*
`/src/sudoku/chr/model/`	`*`	*Sudoku viewpoints (CHR)*
`/src/sudoku/eclipse/`	`solver.pl`	*Sudoku solver (ECLiPSe)*
`/src/sudoku/eclipse/model/`	`*`	*Sudoku viewpoints (ECLiPSe)*
`/src/hashiwokakero/`	`jschimpf.pl`	*Hashiwokakero solution*
`/src/scheduling/`	`scheduling.pl`	*Scheduling meetings solution*

Table 3: Overview of the source code.

References

[1] Bart Demoen and Maria Garcia de la Banda. Redundant sudoku rules. *TPLP*, 14:363–377, 2014.

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[7] Gary McGuire, Bastian Tugemann, and Gilles Civario. There is no 16-clue sudoku: Solving the sudoku minimum number of clues problem. *Experimental Mathematics*, 23:190–217, 2012.

[8] T. Pay and J. L. Cox. Encodings, consistency algorithms and dynamic variable-value ordering heuris- tics for multiple permutation problems. *International Journal of Artificial Intelligence, 15(1):33-54*, 2017.

[9] Helmut Simonis. Sudoku as a constraint problem. In *CP Workshop on Modeling and Reformulating Constraint Satisfaction Problems*, 2005.