Abstract

This paper is about how to solve a class of puzzles, called self-referential quizzes (SRQ), with constraint programming. An SRQ is a sequence of multiple choice questions that are about the puzzle itself. SRQs are an attractive pastime, when they provide the possibility of drawing non-trivial conclusions on the way to the solution.

We introduce a typical SRQ and represent it as a propositional satisfiability problem. Its straightforward clausal representation is too big for effective treatment using standard methods. Instead, we solve it with finite domain constraint programming. For this application of constraint programming, support of logic connectives such as conjunction and disjunction is crucial. With their small problem descriptions, SRQs are ideal candidates for benchmarks covering the implementation of 0/1 variables in constraint programming languages.

1 Introduction

Around 1993, Jim Propp invented a quiz that he called “Self-referential Aptitude Test”, or SRAT for short. It contains 20 quiz questions with 5 alternatives each almost all of which refer to the quiz itself. The problem is to find unique answers for all the questions, such that they are all correct. A typical example for a question is Question 2:

2. The only two consecutive questions with identical answers are questions
(A) 6 and 7 (B) 7 and 8 (C) 8 and 9 (D) 9 and 10 (E) 10 and 11

Distributed over the internet, this quiz attracted much attention among puzzle solvers. It is an attractive quiz, because it allows the solver to draw many non-trivial conclusions and thus reduce the search space tremendously. An experienced puzzle solver can solve SRAT within half an hour of puzzling fun.

To our knowledge, we were the first to solve SRAT automatically. We used the constraint programming language Oz to find the solution and prove it to be unique. It is surprising that the Oz program solves SRAT almost deterministically. The constraints in SRAT are so strong that only one single choice-point suffices to find a solution and prove it to be unique. This nicely reflects the design goal of the author that the solution could be found “without too much trial-and-error” [6].

In this paper, we use the Self-Referential Quiz, short SRQ, instead of SRAT. We invented SRQ on the base of SRAT for the purpose of this paper. Like SRAT, SRQ has a unique solution and contains a variety of interesting self-referential questions. However, SRQ is more suitable for this presentation, since it is composed of only 10 questions.
Assuming that exactly one alternative is true for every question, there is a unique solution to the following quiz. What is the solution?

1. The first question whose answer is A is question  
   (A) 4 (B) 3 (C) 2 (D) 1 (E) none of the above
2. Identical answers have questions  
   (A) 3 and 4 (B) 4 and 5 (C) 5 and 6 (D) 6 and 7 (E) 7 and 8
3. The next question with answer A is question  
   (A) 4 (B) 5 (C) 6 (D) 7 (E) 8
4. The first even numbered question with answer B is question  
   (A) 2 (B) 4 (C) 6 (D) 8 (E) 10
5. The only odd numbered question with answer C is question  
   (A) 1 (B) 3 (C) 5 (D) 7 (E) 9
6. A question with answer D (A) comes before this one, but not after (B) comes after this one, but not before (C) comes before and after this one (D) does not occur at all (E) none of the above
7. The last question whose answer is E is question  
   (A) 5 (B) 6 (C) 7 (D) 8 (E) 9
8. The number of questions whose answers are consonants is  
   (A) 7 (B) 6 (C) 5 (D) 4 (E) 3
9. The number of questions whose answers are vowels is  
   (A) 0 (B) 1 (C) 2 (D) 3 (E) 4
10. The answer to this question is (A) A (B) B (C) C (D) D (E) E

Figure 1: The Puzzle SRQ

making the presentation shorter, and since it is a harder problem than SRAT in a sense that it takes more choice-points to solve it, if the same solution technique is applied. Collected information on srqs can be found in [4].

2 The Self-Referential Quiz

Figure 1 states the puzzle SRQ. A few remarks may be helpful:

1. Several alternatives can be excluded immediately. For example, the answer to question 1 cannot be A, which states that question 4 is the first question whose answer is A, because then, question 1 would be the first question whose answer is A, which is a contradiction. Other such examples are the alternatives 7 C and 9 A.

2. The questions are heavily intertwined. For example, if the answer to question 1 is C, then it follows from the first five questions only that the answer to question 2 must be A, the answer to question 3 must be B, the answer to question 4 must be B, and the answer to question 5 must be A. The argument is left to the reader.

3. The reader may verify that the following is a solution:


3 SRQ as a Satisfiability Problem

Every alternative of every question of SRQ contains a statement, which is either true or false. Thus, we are going to express SRQ as a formula \( f \) of propositional calculus, using
the logical connectives $\land$ for conjunction, $\lor$ for disjunction, $\neg$ for negation and $\equiv$ for equivalence. A solution to SRQ is then an assignment of the symbols occurring in $\phi$ to truth values such that $\phi$ is satisfied.

We introduce 50 truth symbols $l_i$ stating that the answer to question $i$ is $l$, for $i \in \{1 \ldots 10\}$ and $l \in \{A, B, C, D, E\}$. For example, if $B_2$ is true, then the answer to question 4 is B.

The first sentence in SRQ states that exactly one alternative must be true for every question. Thus, for every $j \in \{1 \ldots 10\}$, the formula

$$A_j \land \neg B_j \land \neg C_j \land \neg D_j \land \neg E_j \lor \neg A_j \land B_j \land \neg C_j \land \neg D_j \land \neg E_j \lor \neg A_j \land \neg B_j \land C_j \land \neg D_j \land \neg E_j \lor \neg A_j \land \neg B_j \land \neg C_j \land D_j \land \neg E_j \lor \neg A_j \land \neg B_j \land \neg C_j \land \neg D_j \land \neg E_j$$

must hold. As an abbreviation for this formula, we introduce

$$A_j + B_j + C_j + D_j + E_j = 1 \quad (2)$$

We allow the generalization to any integer instead of 1, and the usual summation notation $\sum$.

As another convenient abbreviation, let us introduce:

$$i \equiv j := (A_i \equiv A_j) \land (B_i \equiv B_j) \land (C_i \equiv C_j) \land (D_i \equiv D_j) \land (E_i \equiv E_j) \quad (3)$$

Using this notation, Figure 2 gives the translation of the further information provided by Questions 1 through 9. Note that Question 10 provides no further information.

The problem can now be stated as follows: Find an assignment of the variables

<table>
<thead>
<tr>
<th>Question</th>
<th>Information</th>
<th>SRQ Translation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F(2, 4, 9)</td>
<td>$(D_1 \lor D_2 \lor D_3 \lor D_4 \lor D_6) \land \neg(D_1 \lor D_2 \lor D_3 \lor D_4 \lor D_6) \land (D_7 \lor D_8 \lor D_9 \lor D_{10})$</td>
</tr>
<tr>
<td>2</td>
<td>F(3, 4, 9)</td>
<td>$(D_1 \lor D_3 \lor D_4 \lor D_6 \lor D_9) \land (D_7 \lor D_8 \lor D_9 \lor D_{10})$</td>
</tr>
<tr>
<td>3</td>
<td>F(3, 4, 9)</td>
<td>$(D_1 \lor D_3 \lor D_4 \lor D_6 \lor D_9) \land (D_7 \lor D_8 \lor D_9 \lor D_{10})$</td>
</tr>
<tr>
<td>4</td>
<td>F(2, 4, 9)</td>
<td>$(D_1 \lor D_2 \lor D_3 \lor D_4 \lor D_6) \land \neg(D_1 \lor D_2 \lor D_3 \lor D_4 \lor D_6) \land (D_7 \lor D_8 \lor D_9 \lor D_{10})$</td>
</tr>
<tr>
<td>5</td>
<td>F(3, 4, 9)</td>
<td>$(D_1 \lor D_3 \lor D_4 \lor D_6 \lor D_9) \land (D_7 \lor D_8 \lor D_9 \lor D_{10})$</td>
</tr>
<tr>
<td>6</td>
<td>F(3, 4, 9)</td>
<td>$(D_1 \lor D_3 \lor D_4 \lor D_6 \lor D_9) \land (D_7 \lor D_8 \lor D_9 \lor D_{10})$</td>
</tr>
<tr>
<td>7</td>
<td>F(2, 4, 9)</td>
<td>$(D_1 \lor D_2 \lor D_3 \lor D_4 \lor D_6) \land \neg(D_1 \lor D_2 \lor D_3 \lor D_4 \lor D_6) \land (D_7 \lor D_8 \lor D_9 \lor D_{10})$</td>
</tr>
<tr>
<td>8</td>
<td>F(3, 4, 9)</td>
<td>$(D_1 \lor D_3 \lor D_4 \lor D_6 \lor D_9) \land (D_7 \lor D_8 \lor D_9 \lor D_{10})$</td>
</tr>
<tr>
<td>9</td>
<td>F(3, 4, 9)</td>
<td>$(D_1 \lor D_3 \lor D_4 \lor D_6 \lor D_9) \land (D_7 \lor D_8 \lor D_9 \lor D_{10})$</td>
</tr>
</tbody>
</table>

Figure 2: SRQ as Satisfiability Problem
$A_i, B_i, C_i, D_i, E_i, i \in \{1 \ldots 10\}$, to truth values such that the conjunction of all formulae (1) for $j \in \{1 \ldots 10\}$ and all formulae in Figure 2 holds. The general problem of satisfiability of formulae in propositional calculus (SAT) is the first problem, for which NP-completeness has been shown [1].

The representation of $f$ in clausal form as required by the standard algorithms for satisfiability [3, 2] becomes so big that it is questionable, whether these algorithms can be used here: A clausal form of the formula associated with alternative 8 A (see Figure 2) alone contains at least 2,035,800 clauses. Thus, we did not attempt to run a conventional algorithm on our formula $f$. Instead, we translate $f$ to a constraint program, making use of the fact that some constraint languages provide for propagation of arbitrary combinations of conjunction, disjunction, equivalence, and summation.

4 SRQ as a Constraint Program

We know that humans can solve SRQ; after distributing SRQ on the internet, several people reported the correct answer and a solving time of 10 minutes to half an hour. A human problem solver usually employs the following strategy:

**Propagation:** Try to exclude as many alternatives as possible.

**Distribution:** Choose one of the still possible alternatives and assume it to be true, and continue with Propagation.

When a contradiction is encountered, jump to a branch of the search tree, where there are still alternatives.

For example, a human problem solver can (among others) immediately exclude the alternative A for question 1 (see Remark 1 on page 2). Therefore, let us assume she picks alternative B for question 1. Now, 1 B states 3 A, which states 4 A, which implies 2 A. This is a contradiction, since question 2 states that there are only two consecutive questions with identical answers and we have 1 A, 2 A, and 3 A.

Thus she tries alternative C for question 1, leading to the conclusions given in Remark 2 on page 2.

Constraint programming turns exactly this principle of “propagation and distribution” into a programming paradigm.

An obvious approach to translate SRQ into a constraint program is to model every truth variable $l_i$ from the previous section as a finite domain variable ranging over values from $\{0, 1\}$, where 0 represents “false” and 1 represents “true”. Such variables, we call 0/1 variables. In the following, we are going to use the constraint language Oz as implementation language [8, 9]. In the following Oz program, we are defining a list Answers of five tuples $A, B, C, D,$ and $E$, each containing ten 0/1 variables:

`declare Answers=[A B C D E]
{ForAll Answers fun {FD.tuple q 10 0#1} end}`

The variable $B_4$ in the previous section corresponds to $B_{.4}$. Note the dot syntax for feature access and […] for procedure application. In the rest of this paper, we are going to discuss the implementation of a problem solver for SRQ given in Figure 3. In comments $$ we indicate the section that explains the respective part of the program. We refer to lines in the program by using marks of the form $%C$, implementing the corresponding alternative, here alternative C of Question 1.

For each formula in $f$, we are going to install a number of propagators, whose declarative semantics is given by the formula. The propagators concurrently inspect a constraint store, which in our case contains only basic constraints of the form $X = 0$, $X = 1$, $X \in \{0, 1\}$, and $X = Y$. During search, these propagators may amplify the store by adding basic constraints to it, which possibly triggers further propagation.
Consider for example line $1C$ in Figure 3

$C.1 = A.2 \ast \tilde{A.1}$

In slight abuse of notation, we redefined the arithmetic operators $\ast$, $\div$, and $\tilde{}$ in the third line in Figure 3 to propagators $\text{FD.conj}$ (conjunction), $\text{FD.disj}$ (disjunction), and $\text{FD.nega}$ (negation). Thus, the above line stands for

```
local N in
  {FD.nega A.1 N}
  {FD.conj A.2 N C.1}
end
```

The propagator $\{\text{FD.nega A.1 N}\}$ is straightforward: It waits until one of its arguments becomes determined (bound to 0 or 1) and binds the other one to the other value (1 or 0).

The propagator $\{\text{FD.conj A.2 N C.1}\}$ can propagate in several ways (see [5]):

1. If $A.2$ or $N$ is determined to 0, then $C.1$ is determined to 0.
2. If $A.2$ and $N$ are determined to 1, then $C.1$ is determined to 1.
3. If $A.2$ is determined to 1, then the constraint $N = C.1$ is added, and vice versa for $N$.
4. If $C.1$ is determined to 1, then both $A.2$ and $N$ are determined to 1, and
5. If $C.1$ is determined to 0 and $A.2$ determined to 1 then $N$ is determined to 0, and vice versa for $N$.

The other formulae in Figure 2 are implemented in a similar way. Note that Question 2 uses the equivalence propagator $\equiv$. Among other propagations, the propagator $B = A.I \equiv A.J$ imposes the constraint $A.I = A.J$ if $B$ becomes bound to 1. Question 6 makes use of the disjunction propagator $\text{FD.disj}$, denoted by $\div$. Questions 6, 8 and 9 make use of the procedure $\text{Sm}$, which computes the sum over all finite domain variables in a given tuple or list, using the propagator $\text{FD.sum}$. Thus, $\text{SmBCD}$ is the number of questions whose answers are consonants.

Note that adding $A.1 = 1$ will immediately result in a failure, since the conjunction propagators in $\$1A$ will trigger $\tilde{A.1} = 1$, which will try to bind $A.1$ to 0, contradicting its previous binding to 1. Compare this result with Remark 1 on page 2.

5 The General Condition

The general condition (1) on page 3 has the potential for strong constraint propagation: If one $p_i$ is 1, it allows to set all values $l_i$ with $i \neq p$ to 0.

As suggested by the notation (2) on page 3, we represent the general condition by arithmetic propagators of the form

```
{FD.sum [A.i B.i C.i D.i E.i] "\"=:\" 1}
```

As soon as one of the five variables becomes bound to 1, this propagator will bind all others to 0. The predefined procedure $\text{For}$ allows to iterate from 1 to 10. Thus, the program

```
{For 1 10 1
 proc ($\$ I) {FD.sum [A.I B.I C.I D.I E.I] "\"=:\" 1} end}
```

installs a propagator of the above form for each of the ten questions.
Don’t Be Puzzled!

With this machinery in place, we will show in this section, why determining the answer to question 1 to C leads to a propagation strong enough to yield the conclusions in Remark 2 on page 2.

What happens if we assume the answer to question 1 to be C by imposing the constraint $A.1=3$? The constraint $\%5A$ binds $A.5$ to 1. The constraint $A.1=3$ triggers the propagator $\%1C$, resulting in propagation 4 of $FD.conj$ (see Section 4), which binds $A.2$ to 1. Propagation of the general condition (see Section 5) binds $B.2$ to 0, which also binds $A.4$ to 0, due to $\%4A$. Since $A.2=1$, the conjunction propagators in Eq for $\%2A$ result in imposing the constraints $A.3=A.4$, and $B.3=B.4$, among others. Since $A.4=0$, $A.3$ is also bound to 0. Since $A.5=1$ and $A.4=0$, the conjunction propagator in $\%3B$ fires by propagation 2 in Section 4 and binds $B.3$ to 1. Since $B.3=B.4$, $B.4$ is also bound to 1.

Thus, we have shown how only assuming the answer to question 1 to be C results
in the conclusions given in 2, using only simple propagators for negation, conjunction, equivalence, and summation. The argument also nicely demonstrates the necessity of concurrency for propagators: It is impossible to determine statically the order in which they do their job.

7 The Solver for SRQ

The program in Figure 3 implements a solver, which is a unary procedure, here SRQ, abstracting from a root variable, here Answers. In the solver, constraints on this root variable are established. In our case, Answers is bound to the list [A B C D E].

The solver also determines a distribution strategy. The line

\{FD.distribute generic(value:max order:constraints) ...\}

indicates that we chose the following predefined distribution strategy: If no more propagation is possible, choose the variable on which most propagators depend, and try its maximal value first, which is always 1 in our example. This heuristic roughly corresponds to the most-constrained-first heuristic used in [2]. We choose first 1 instead of 0, since the general condition can propagate much better in this case.

The solver can be given to an inference engine, which performs the search. A particular inference engine is the Explorer tool [7]. It allows to visualize the search tree, comprised of choice nodes (circles), failure nodes (squares) and solution nodes (diamonds). The left tree in Figure 4 shows the search tree of the program in Figure 3 for all-solution search. It contains 7 choice nodes; its exploration took 117 milliseconds cpu-time on a Sparc 4 Workstation.

![Figure 4: The Oz Explorer](image)

An important programming technique in constraint programming is to allow for further pruning in the search with redundant constraints. An obvious redundant constraint is SmAE + SmBCD = 10. The right tree in Figure 4 shows the tree after inserting the propagator

\{FD.sum [SmAE SmBCD] := 10\},

which only contains 4 choice nodes.

Using the Explorer, it is straightforward to invent new puzzles of this kind, judge their difficulty by analysing the search tree and verify that they have unique solutions. In fact, we invented a sequence of three puzzles with increasing difficulty (as measured by the size
of the search tree), each having 10 questions and a unique solution [4]. We propose to
create a test-suite of srqs so that we can compare the propagation involving 0/1 variables
provided by different implementations of constraint languages.

8 Conclusion

We showed how a formulation of srq as a satisfiability problem can be translated to a
constraint program and solved efficiently using propagators for 0/1 variables provided
by Oz. To evaluate the competitiveness of constraint programming in the satisfiability
domain, an evaluation of other SAT-algorithms with respect to srq-like problems is neces-
sary. For a comparison of the implementation of propagators for 0/1 variables in different
constraint languages, a more comprehensive suite of srq-like problems is needed.

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