

Modelling Constraint Solver Architecture Design as a Constraint Problem

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Abstract. Designing component-based constraint solvers is a complex problem. Some components are required, some are optional and there are interdependencies between the components. Because of this, previous approaches to solver design and modification have been ad-hoc and limited. We present a system that transforms a description of the components and the characteristics of the target constraint solver into a constraint problem. Solving this problem yields the description of a valid solver. Our approach represents a significant step towards the automated design and synthesis of constraint solvers that are specialised for individual constraint problem classes or instances.

1 Introduction

Most current constraint solvers, such as Minion [3], are constructed to be as general as possible. They are monolithic in design, accepting a broad range of models. While this generality is convenient, it leads to a complex internal architecture, resulting in significant overheads and inhibiting efficiency, scalability and extensibility. Another drawback is that current solvers perform little analysis of an input model, so the features of an individual model cannot be exploited to produce a more efficient solving process. To mitigate these drawbacks, constraint solvers often allow manual tuning of the solving process. However, this requires considerable expertise, preventing the widespread adoption of constraint solving.

A possible solution to this problem is to automatically generate specialised constraint solvers. A given problem class or instance is analysed and the most suitable solver components identified. These components are then assembled into a solver. The artificial intelligence community has shown a lot of interest in this problem recently, especially in the context of algorithm portfolios [15, 9, 2, 4]. The solution proposed above takes the portfolio idea a step further – instead of selecting or configuring an existing solver, we aim to *synthesise* a specialised solver.

The techniques for analysing problems and identifying the most suitable solution strategies are still applicable for our approach, but in addition we are faced with the difficult problem of automatically assembling a constraint solver from a list of components and a specification of the problem it is to solve. Constraint programming itself is a natural fit for solving this configuration

problem. In the remainder of this paper, we detail a way of expressing the architecture of a constraint solver in such a way that it can be solved as a constraint problem.

2 Background

Several other approaches for generating specialised constraint solvers exist. The MULTI-TAC [7] system configures and compiles a constraint solver for a specific set of problems. It does not synthesise a new constraint solver from a library of components, but customises a base solver. The customisations are limited to heuristics and do not affect all parts of the constraint solver.

KIDS [13] is a more general system and synthesises efficient algorithms from an initial specification. The approach is knowledge-based, i.e. the user supplies the knowledge required to generate an efficient algorithm for the specific problem. Refinements are limited to a number of generic transformation operations and again are not capable of customising all parts of a solver.

A review of the literature on analysing combinatorial problems and selecting the most efficient way of solving them is beyond the scope of this paper. Some of the most prominent systems are SATzilla [15] and CPHydra [9], which select from a portfolio of SAT and constraint solvers respectively based on the characteristics of a problem using machine learning.

The synthesis of a constraint solver from components is a configuration problem, many instances of which have been discussed in the literature. An overview can be found in the Configuration chapter of the Handbook of Constraint Programming [10].

One of the earliest approaches to solving configuration problems as constraint problems is by Mittal and Falkenhainer [8] and proposes dynamic constraint problems that introduce new variables as the requirements for configured components become known. They furthermore require special constraints that express whether a variable is still relevant to the partially solved problem based on the assignments made so far.

Sabin and Freuder [11] propose solving configuration problems as composite constraint satisfaction problems where values for variables can be constraint problems themselves. Stumptner et al. [14] introduce the constraint-based configuration system COCOS. Their system requires several extensions of the standard constraint paradigm as well. Mailharro [6] proposes a constraint formulation that integrates concepts from object-oriented programming. His approach relies on many of the concepts introduced in earlier work and infinite-sized domains for variables. Hinrich et al. [5] use object-oriented constraint satisfaction for modelling configuration problems. They then transform the constraint model into first order logic sentences and find a solution using a theorem solver.

Our approach works without the need to modify an existing off-the-shelf constraint solver and a solution gives a complete configuration of a solver. There is no need to solve a series of refined constraint problems. This is crucial for us because we are aiming to do this in the context of generating a constraint solver

that is specialised to solve a particular problem more efficiently and want to keep possible overheads, such as repeatedly generating constraint models and calling a constraint solver, as minimal as possible.

3 Architecture specification

We use the generic software architecture description language GRASP [1, 12] to describe the components of a constraint solver. The advantages of using a generic architecture description language include available tools for checking architecture descriptions for consistency and that people without a background in constraint programming are able to work with it. We chose GRASP because it is being developed by a research group at our department and we are able to influence the design of the language towards meeting the requirements for modelling constraint solvers.

A full description of GRASP is beyond the scope of this paper and not necessary for our purposes. The relevant elements of the language are described below.

templates Templates are the high-level elements of the language that describe components. A single template can describe a memory manager for example. Templates may take parameters when they are instantiated to customise their behaviour further.

requires/provides Describe things a template needs and offers for other templates to use. A memory manager for example provides a facility for storing and retrieving data. This facility could be required by a variable to keep track of its domain.

properties Properties characterise components beyond the generic facilities they provide. A Boolean variable for example would have the property that the size of the domain is at most two.

checks Check statements model the interdependencies between components and restrictions of customisations of a component. A component that implements a specific constraint for example would place restrictions on the parameters it can be customised with (i.e. the variables that it constrains) by e.g. limiting the domain size.

The check statements of GRASP provide much power and flexibility. Only a small subset of this is needed to express the components of a constraint solver though. The relevant parts are explained below.

A subset of B Asserts that set B contains all the elements of set A. It is used to ensure that a certain implementation has a specific set of properties and provides a specific set of facilities. It can also be used to ensure that an implementation does *not* have a property or facility.

A accepts B Asserts that B is accepted as A, e.g. if A is the parameter given to the implementation of a constraint and B is a variable implementation, it makes sure that the constraint can be put on variables of that type.

Apart from the components that describe the building blocks of a solver, there is a top-level meta-component that describes the problem to be solved. It specifies the types of variables and constraints needed and which constraint implementation needs to work with which variable implementation.

The description of the constraint solver consists of a library of solver components specified this way and the problem meta-component. The library of solver components is not specific to any constraint problem to be solved by the generated solver and describes all the implementation options for any solver. The problem meta-component encodes the requirements for solving a particular constraint problem and links components from the library into an actual constraint solver.

4 Constraint model

The requirements of a component naturally map to variables in a constraint problem that we want to find assignments for. The domain of each of those variables is determined by the components which provide the facility required, i.e. the possible implementations. Each implementation variable has a set of provides and properties attached to it. The set of provides is necessary because an implementation may provide more than the one main facility that would be required by another component. If a variable is assigned a value which determines its implementation, it *must* provide all the facilities and have all the properties that this implementation provides and has and it *must not* provide any other facilities or have any other properties. We therefore add constraints to ensure that a component variable has a certain property or provide if and only if it is assigned an implementation that has this property or provide.

There are several cases we need to consider for converting the check statements of GRASP into constraints. The first case is of the form `list subsetof properties/provides`. This requires a component implementation to provide a list of facilities or have a set of properties. The translation into constraints is straightforward; we simply require the things in `list` to be in the set of `properties/provides`. The second case of the form `properties/provides subsetof list`. This is the opposite of the previous case and *forbids* the properties/provides which are not listed explicitly. The translation into constraints is analogous to the previous case.

The final case deals with the `accepts`. The general requirement encoded is that if a parameter to an implementation requires a certain property or facility, the implementation of the parameter must provide it. The corresponding constraints are implications that require properties and provides of an implementation that might be used as a parameter to be set if they are set for the parameter.

4.1 Conditional variables and constraints

The variables and constraints mentioned so far are only valid at the top level, i.e. for the problem meta-component. We need additional constructs that encode the requirements that arise if a component is implemented in a certain way. The

variables and constraints to encode the requirements take the same form as above, but they have prerequisites that need to be true in order for them to become relevant.

We chose an explicit representation of the prerequisites where the conditional variables encode them in their names. The names of the variables that model the requirements for an implementation of a component not at the top level are prefixed by the implementation choices for the top-level components. The constraints on these variables can be encoded as an implication, e.g. if component x is implemented as an A , its first parameter needs to have property Y . The name of the variable that models this first parameter would have a prefix that indicates that the superior component x is implemented as an A . The left-hand side of the implication is a conjunction of the implementation decisions made in the prerequisites.

4.2 Modelling language

We decided to use the modelling language of the Minion constraint solver. While it would be easier to use a more high-level language such as Essence, we need more fine-grained control over the solving process. In particular, we need to be able to specify the order of variables and values in the domains of variables to guide the solver towards the implementations we consider the most suitable ones. This enables us to analyse the constraint problem to be solved with the synthesised solver, identify the component implementations that are likely to provide the best performance and encode this in the constraint problem through the variable and value orderings.

The decision to use the Minion input language has some ramifications for the model. First, Minion only supports integer domain values and all component implementations, properties and provides must be mapped to integers. Furthermore, some of the constraints that the model uses are not provided by Minion and must be encoded with additional constraints and variables.

For the provides and the properties of each component variable, we added an auxiliary array of Boolean variables to represent the set. If the i th Boolean is set to true, the i th property or provides is present in the set. This means that two auxiliary arrays of Booleans are added for each component variable.

Almost all constraints can be encoded directly in Minion. We used the `watched-or` constraint to express that a component variable can have a property or provides if and only if it is assigned one of the implementations that have it. The conjunction to encode the conditional constraints was implemented with a `watched-and`. The only constraints which cannot directly be translated into Minion are the implications, as Minion only allows implications between a Boolean variable and a constraint. To mitigate this, we introduced channelling variables, one for each auxiliary array of Booleans that encode the properties and provides. The left hand side of the implication is linked to the channelling variable through an if and only if (`reify` in Minion) and the right hand side is connected to the channelling variable by an implication constraint (`reifyimply` in Minion).

5 Example

Consider the constraint problem below.

$$\begin{aligned}pvx + pvy &= pvw + pvc6 \\pvx &= pvz\end{aligned}$$

The GRASP specification of a solver component library and problem meta-component that corresponds to the constraint problem are shown in Figure 1. The problem meta-component requires five variables and two constraints with certain properties and restrictions. The variable and constraint implementations impose further restrictions and may in turn require a memory manager. Constant variables have domain size 1, Boolean variables domain size 2 and discrete variables arbitrary-sized domains. A GAC sum needs to be able to remove values from the domain of the variables it constrains while a Boolean sum needs its first argument to be a Boolean (domain size 2) and its second argument to be a constant variable (domain size 1). The memory manager does not have any special properties or further requirements.

Parts of the Minion model generated from this description is shown in Figure 2. The first part shows the variables generated for the requirement `IPropVariable pvw` in the GRASP model (Figure 1). Apart from the main variable, there are auxiliary variables for the properties and the provides as well as variables which model the conditional requirements of `pvw` being implemented in a particular way.

The first section of the constraints section models the properties and requires `pvw` (or one of its requirements) will have if being implemented in a particular way. We especially refer the reader to the last couple of lines before the `...` – these express what possible implementations for `pvw` would give it specific properties/provides and that some of the provides are not given by any of the candidate implementations and are therefore always not in the set (Boolean array element set to 0).

The second part of the constraints section models the check statements that affect the parameters of the sum constraint implementations. The variables for these components are not shown for space reasons, but are analogous to the variables for the `pvw` component. A pair of Minion constraints is required to model the implication of a component being implemented in a specific way, as outlined in Section 4.2. The first constraint reifies the conditions with the channelling variable while the second constraint establishes the implication between the channelling variable and the actual property or provide.

Note that some of the `check...accepts` statements are given additional properties for the variables to check in the GRASP model. Only the properties which are not explicitly given need to be checked by the generated constraints.

Minion finds a valid constraint solver architecture for the, admittedly trivial, encoded problem (the first solution to the generated constraint model) in just a couple of milliseconds.

```

architecture Solver {
  template CopyMemoryFactory() {
    provides IMemoryManager;
    provides IRawMemory;
    provides IViewHistory;
  }
  template DiscreteVariableFactory() {
    provides IPropVariable;
    provides IRemoveFromDomain;
    requires IMemoryManager domain;
    requires IMemoryManager bounds;
    property domainType = "bound";
    check domain.getProperties() subsetof [(MemoryChanges, 'Single')];
    check bounds.getProperties() subsetof [];
  }
  template BoolVariableFactory() {
    provides IPropVariable;
    provides IRemoveFromDomain;
    requires IMemoryManager bounds;
    property domainType = "bound";
    check bounds.getProperties() subsetof [(MemoryChanges, 'Single')];
    property domainSize = 2;
  }
  template ConstantVariableFactory() {
    provides IPropVariable;
    provides IRemoveFromDomain;
    property domainSize = 1;
    property domainType = "bound";
  }
  template GACSumFactory(P1, P2) {
    provides ISumEqCon;
    requires IMemoryManager m;
    check m.getProperties() subsetof [];
    check [IRawMemory] subsetof m.getInterfaces();
    check [IRemoveFromDomain, IPropVariable] subsetof P1.getInterfaces();
    check [IRemoveFromDomain, IPropVariable] subsetof P2.getInterfaces();
  }
  template BoolSumFactory(P1, P2) {
    provides ISumEqCon;
    requires IMemoryManager m;
    check m.getProperties() subsetof [];
    check [(domainSize, 2)] subsetof P1.getProperties();
    check [(domainSize, 1)] subsetof P2.getProperties();
    check [IPropVariable] subsetof P1.getInterfaces();
    check [IPropVariable] subsetof P2.getInterfaces();
  }
  template ThisProblem() {
    provides IProblem;
    requires IPropVariable pvw, pvx, pvy, pvz, pvc6;
    requires ISumEqCon scA, scB;
    check pvx.getProperties() subsetof
      [(domainType, 'bound'), (domainSize, 2)];
    check pvy.getProperties() subsetof
      [(domainType, 'bound')];
    check pvc6.getProperties() subsetof
      [(domainType, 'bound'), (domainSize, 1)];
    check scA.param(1) accepts (pvx +
      [(domainType, 'bound'), (domainSize, 2)]);
    check scA.param(1) accepts (pvx +
      [(domainType, 'bound')]);
    check scA.param(2) accepts (pvw +
      [(domainType, 'bound'), (domainSize, 1)]);
    check scA.param(2) accepts (pvc6 +
      [(domainType, 'bound'), (domainSize, 1)]);
    check scB.param(1) accepts (pvx +
      [(domainType, 'bound'), (domainSize, 2)]);
    check scB.param(1) accepts pvz;
  }
}

```

Fig. 1. Solver architecture description for simple constraint problem.

```

MINION 3
**VARIABLES**
DISCRETE pvw_1_domain {1..1}
BOOL pvw_1_domain_properties [3]
BOOL pvw_1_domain_provides [7]
DISCRETE pvw_1_bounds {1..1}
BOOL pvw_1_bounds_properties [3]
BOOL pvw_1_bounds_provides [7]
DISCRETE pvw_2_bounds {1..1}
BOOL pvw_2_bounds_properties [3]
BOOL pvw_2_bounds_provides [7]
DISCRETE pvw {1..3}
BOOL pvw_properties [3]
BOOL pvw_provides [7]
...
**CONSTRAINTS**
reify (watched-or({eq(pvw_1_domain, 1)}), pvw_1_domain_provides [0])
eq(pvw_1_domain_provides [6], 0)
eq(pvw_1_domain_provides [3], 0)
reify (watched-or({eq(pvw_1_domain, 1)}), pvw_1_domain_provides [1])
eq(pvw_1_domain_provides [4], 0)
eq(pvw_1_domain_provides [5], 0)
reify (watched-or({eq(pvw_1_domain, 1)}), pvw_1_domain_provides [2])
eq(pvw_1_domain_properties [2], 0)
eq(pvw_1_domain_properties [1], 0)
eq(pvw_1_domain_provides [0], 0)
reify (watched-or({eq(pvw_1_bounds, 1)}), pvw_1_bounds_provides [0])
eq(pvw_1_bounds_provides [6], 0)
eq(pvw_1_bounds_provides [3], 0)
reify (watched-or({eq(pvw_1_bounds, 1)}), pvw_1_bounds_provides [1])
eq(pvw_1_bounds_provides [4], 0)
eq(pvw_1_bounds_provides [5], 0)
reify (watched-or({eq(pvw_1_bounds, 1)}), pvw_1_bounds_provides [2])
eq(pvw_1_bounds_properties [2], 0)
eq(pvw_1_bounds_properties [1], 0)
eq(pvw_1_bounds_provides [0], 0)
reify (watched-or({eq(pvw_2_bounds, 1)}), pvw_2_bounds_provides [0])
eq(pvw_2_bounds_provides [6], 0)
eq(pvw_2_bounds_provides [3], 0)
reify (watched-or({eq(pvw_2_bounds, 1)}), pvw_2_bounds_provides [1])
eq(pvw_2_bounds_provides [4], 0)
eq(pvw_2_bounds_provides [5], 0)
reify (watched-or({eq(pvw_2_bounds, 1)}), pvw_2_bounds_provides [2])
eq(pvw_2_bounds_properties [2], 0)
eq(pvw_2_bounds_properties [1], 0)
eq(pvw_2_bounds_provides [0], 0)
eq(pvw_provides [0], 0)
eq(pvw_provides [6], 0)
reify (watched-or({eq(pvw, 1), eq(pvw, 2), eq(pvw, 3)}), pvw_provides [3])
eq(pvw_provides [1], 0)
reify (watched-or({eq(pvw, 1), eq(pvw, 2), eq(pvw, 3)}), pvw_provides [4])
eq(pvw_provides [5], 0)
eq(pvw_provides [2], 0)
reify (watched-or({eq(pvw, 3)}), pvw_properties [2])
reify (watched-or({eq(pvw, 2)}), pvw_properties [1])
reify (watched-or({eq(pvw, 1), eq(pvw, 2), eq(pvw, 3)}),
    pvw_properties [0])
...
reify (watched-and({eq(scA, 1)}), scA_1_param_1_provides_channel [3])
reifyimply (eq(scA_param_1_provides [3], 1),
    scA_1_param_1_provides_channel [3])
reify (watched-and({eq(scA, 1)}), scA_1_param_1_provides_channel [4])
reifyimply (eq(scA_param_1_provides [4], 1),
    scA_1_param_1_provides_channel [4])
reify (watched-and({eq(scA, 1)}), scA_1_param_2_provides_channel [3])
reifyimply (eq(scA_param_2_provides [3], 1),
    scA_1_param_2_provides_channel [3])
reify (watched-and({eq(scA, 1)}), scA_1_param_2_provides_channel [4])
reifyimply (eq(scA_param_2_provides [4], 1),
    scA_1_param_2_provides_channel [4])
...
**SEARCH**
**EOF**

```

Fig. 2. Excerpts of constraint model for Figure 1.

6 Limitations and future work

A limitation of the current system is that we are unable to express requirements which have a global effect on all components, such as whether to attach debug information. At present, we are unable to express this in GRASP and therefore cannot add it to the constraint model. We are planning on extending GRASP to support this.

We have found that in practice while solving the generated constraint problems for the first solution is quick, enumerating all solutions takes a long time because of the auxiliary variables which result in sets of separate solutions that specify the same constraint solver being found.

7 Conclusions

We have presented a way of encoding the configuration of the architecture of a constraint solver as a constraint problem such that a solution to the problem specifies a valid solver. This represents a major step towards automated synthesis of constraint solvers from a library of components for a given problem. Given a library and components and a problem specification, we can automatically and efficiently synthesis a constraint solver.

Modelling the architecture of a constraint solver as a standard constraint problem enables us to use off-the-shelf software to solve this complex configuration problem using tried and tested techniques. Instead of a single solver, we can easily generate all valid solvers by finding all solutions to the configuration problem instead of only the first one.

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