Implementing Constraint Handling Rules as a Domain-Specific Language Embedded in Java

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Abstract. Programming languages and techniques based on logic and constraints, such as the Constraint Handling Rules (CHR), can support many common programming tasks that can be expressed in the form of a search for feasible or optimal solutions. Developing new constraint solvers using CHR is especially interesting in configuration management for large scale, distributed and dynamic cloud applications, where dynamic configuration and component selection is an integral part of the programming environment. Writing CHR-style constraint solvers in a domain-specific language which is a subset of Java – instead of using a separate language layer – solves many integration, development cycle disruption, testing and debugging problems that discourage or make difficult the adoption of the CHR-based approach in the mainstream programming environments. Besides, the prototype implementation exposes a well-defined API that supports transactional store behavior, safe termination, and debugging via event notifications.

Keywords: Constraint Logic Programming; Constraint Handling Rules; Domain Specific Languages; Cloud Configuration Management.

1 Introduction

Programming languages and techniques based on logic and constraints [16] provide programmers with powerful high-level, declarative abstractions that are well suited for a wide spectrum of applications where the computational problem can be represented as a search for some, all, or an optimal solution (i.e., a model) that satisfies a set of logical formulas and constraints on variables [92]. Over time, several ecosystems of such languages, tools and programming practices have evolved, each with a slightly different focus and features, better suited or more specialized for one application area or another. Prolog [20][13] is probably the basis for the best known family of the Constraint Logic Programming (CLP) language implementations, and has influenced many others, such as Mercury [12], Oz [11], and Erlang [3].

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In this paper, we are concerned with replicating and reimplementing the essential features of the Constraint Handling Rules (CHR) [10], a language that has been developed for writing constraint solvers – i.e., the CLP tools themselves. CHR is actually a rule language layer on top of a host language. While in principle the choice of the host language is not restrictive, the reference implementation of CHR (and the most of the current CHR code) works on top of Prolog [19]. However, there is nothing intrinsically dependent on Prolog in the semantics of CHR rules. Several CHR systems have been implemented on top of Java, C and Haskell [14].

While there are arguably many situations where the developers using the mainstream programming environments and tools, such as those for Java, would benefit from using CHR techniques for writing custom constraint solvers, developing the CHR code together with the “main” application / library code is still a difficult and cumbersome process. Even if the CHR host language is the same as the main application language (e.g., Java), this still calls for additional intermediate compilation tools and steps, frequently disrupts the normal development workflow, and offers little if any rule debugging. These practical problems, on both unit and integration level, often discourage the use of CHR (and CLP) based techniques in the mainstream programming environments – ironically exactly for the problems for which these approaches are best suited.

We argue that an effective way to address most of these problems is to express the declarative CHR-based solver logic directly in the host language – in this case Java – without introducing an additional language layer and the intermediate compilation tools and steps. In the proposed approach, the CHR-based code is written in a domain-specific language (DSL) which is a subset of Java, and the key constraint handling components are exposed as Java objects with well-defined interfaces that support transactional behavior, event notifications, tracing and debugging. The paper is based on an implementation of the proposed system.

In the remainder of the paper, we give a motivating example in Section 2, present the DSL for the constraint handlers in Sections 3 and 4, and briefly explain their semantics in Section 5. Section 6 presents some implementation notes with the advanced transactional, debugging, and safe termination features. Finally, Section 7 offers some conclusions.

2 Motivating Example

Configuration management is one of the traditional CLP fields of application, starting from the early systems where it was used for querying a (static)
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database of available components, planning installation steps and building the dependency chains [8,6], to automatic configuration of autonomous network devices [4], to automated synthesis of complex components that meet some functional requirements [17].

A significant part of the effort to build workable cloud application platforms is related to configuration management, and relies on rich cloud software component models [7]. Additional complexities in the cloud configuration management include:

- Components that are controlled and hosted by third parties that publish only their interfaces and descriptions.
- Different component granularity – from libraries to separately deployed virtual machines and servers.
- Multiple configurations for coarse-grained deployable components that implement the same or a similar functionality.
- Quality of Service (QoS) attributes and requirements, related to performance, cost, availability, and other quality concerns.

In many cases, these aspects can be naturally addressed using constraint models that involve not only the traditional Boolean, finite and numeric domains, but also much richer and extensible ones. For instance, QoS values and their ranges can be quantified using a variety of floating point, fixed or arbitrary precision numbers with units of measurement attached. QoS value distributions as mathematical objects can be represented using data sets or analytic functions. Regular expressions can be used to restrict service identifiers and attributes. Textual version information can be converted into objects that keep hierarchic version numbering, time-stamps and release tags. Subsumption and compatibility constraints can be also placed on service interfaces based on their operations, argument and return types.

This clearly calls for constraint-solving capabilities as a part of the runtime cloud programming environment [18]. For most of the rich constraint domains mentioned above, there are well tested libraries and optimized algorithms already in place, and the object themselves are accessed through their interfaces, without looking at the data structure implementation. Therefore, from the interoperability point of view, the constraint solving components should ideally behave as the standard host language – e.g. Java – components, which are packaged and deployed in the standard way, as .jar libraries, OSGi bundles, or Web/application server packages.

Obviously, that is difficult to achieve if the constraint solver implementation language is different from the host language. But even where that is not the case, the current limitations and maturity levels of the systems that com-
pile CHR into Java (e.g. JCHR [21]), call for a simpler solutions which are more closely integrated with Java.

3 Constraint Rules as a Java DSL

CHR units that implement constraint solving functionality over some domain are called handlers, and contain constraint declarations and rule definitions, typically written in a CHR-specific syntax, which admits a subset of the host language expressions and data/object notation. One problem with that approach is the need to translate the rules from the CHR-specific syntax into the host language, before integrating it with the rest of the application and libraries. When testing and debugging, it can be difficult to trace the solver behavior back to the CHR source code. Another problem is that the CHR syntax has to be updated from time to time to keep up with the innovations in the host language, such as the introduction of generics and enumerations in Java 5, enhanced type inference in Java 7, or the forthcoming introduction of lambda-expressions in Java 8. While these new features normally do not deprecate the old ones, keeping up-to-date is certainly desirable.

To simplify and streamline the integration with the host language, we propose to express handlers, constraints, and rules in a domain-specific language which is a subset of Java. This is not unlike the inversion-of-control design pattern: instead of the CHR level controlling Java classes, we let Java code construct and configure CHR handlers using specific APIs. Instead of a static CHR-to-Java compilation, we use a transparent runtime compilation of the handler logic into the back-end Java objects that fire rules and update the store. And instead of imposing restrictions on Java constructs that are recognized by CHR, we define CHR-specific APIs callable from arbitrary Java code.

Figure 1 shows the general shape of a constraint handler in our approach. Each handler class, which may have type parameters, extends the abstract class \texttt{cr.core.Handler}, which is the part of the CHR-in-Java library. The other imported class, \texttt{cr.core.Symbol} is used to name constraints and data elements. The four main DSL-specific parts of the handler are: symbol declarations, constraint declarations, rule definitions, and guard methods.

Symbol declarations follow the simple scheme from Figure 2. Two predefined symbols in \texttt{cr.core.Handler} are \texttt{fail} (representing the unsatisfiable constraint) and \texttt{_} (the underscore, used to represent an arbitrary object). Note that the symbol fields are public, but not initialized – the \texttt{initialize()}
import cr.core.Symbol;
import cr.core.Handler;
// Other imports

public class MyHandler<...> extends Handler {

    // Symbol declarations

    public MyHandler(...) {
        // Constructor code
        initialize();
    }

    public void setup() {
        // Constraint declarations
        // Constraint rules
    }

    // Guard methods
    // Other methods
}

Fig. 1. The general form of a constraint handler.

SymbolDecl ::= public Symbol Name [ , Name ] * ;
Name ::= ⟨a valid Java field name⟩

Fig. 2. Syntax for symbol declarations.

method of cr.core.Handler – which needs to be called at the end of a custom handler constructor – uses Java reflection to initialize each public field of type cr.core.Symbol to a fresh symbol with the same name. No particular naming strategy is enforced, but it is customary to use names starting with a lowercase letter for constraints, and those starting with an uppercase letter for data objects.

One advantage of declaring symbols using public fields is that one can use the usual Java refactoring tools in modern IDEs, such as Eclipse, NetBeans, or IntelliJ/IDEA, to perform project-wide consistent renaming of constraints.

The handler class needs to implement method setup() which is called from initialize(), whose task is to declare the constraints and define the rules. Constraint need to be declared before being used in a rule, and figure 3 shows the corresponding DSL syntax. Each constraint is uniquely identified with its Name (a declared symbol), and may have zero or more key and data fields, whose classes are given in the declaration. The key fields hold
Comparable objects, and they uniquely identify a constraint literal instance, while the data fields (introduced after ".with") carry additional information (arbitrary objects) associated to the constraint literal instance, which may vary over time. Nulls are allowed in both the key and data fields.

For instance, the following statements in setup():

constraint(leq, String.class, String.class); // less-than-or-equal
constraint(lt, String.class, String.class); // less-than
constraint(eq, String.class, String.class); // equal
constraint(neq, String.class, String.class); // not equal

declare constraints named leq, lt, eq, and neq (all declared symbols) between two string keys (constrained variable names). Also:

constraint(dom, String.class).with(Integer.class, Integer.class);

declares a constraint dom which associates a range of integer values (between the limits in the data fields) to a variable whose name is given as the key.

The syntax for rules is more complex, and is given in Figure 4. In this section we present different aspects of the rule definitions with an informal explanation of their intended meaning. More detailed discussion of the rule semantics is given in the Section 5.

The simplest rule may have only a head, as in the following two examples:

when(leq, X, X);
when(eq, X, X);
which (with X a declared symbol) simply consume or throw away the trivial (in)equalities. The fields are compared on the basis of the equals() method.

Most often, rules have a body. An example of a simplification rule is:

\[
\text{when}(\text{lt}, X, Y).\text{then}(\text{leq}, X, Y).\text{and}(\text{neq}, X, Y);
\]

which converts strict inequality \(x < y\) into the equivalent conjunction of \(x \leq y\) and \(x \neq y\). Another simplification example is:

\[
\text{when}(\text{neq}, X, X).\text{then}(\text{fail});
\]

which detects inconsistencies. An example of .passive() modifier is:

\[
\text{when}(\text{leq}, X, Y)\
\text{.and}(\text{leq}, Y, X).\text{passive()}
\text{.then}(\text{eq}, X, Y);
\]

which simplifies \(x \leq y \land y \leq x\) into \(x = y\), but since the case is completely symmetric, wants to avoid firing twice, on \(y \leq x\). Another use of .passive() is to prevent proliferation of non-informative facts. For instance:

\[
\text{when}(\text{eq}, X, Y)\
\text{.and}(\text{eq}, X, Y).\text{passive()}.\text{keep();}
\]

consumes \(x = y\) if that fact is already known. Note also the modifier .keep() which prevents the known fact from being consumed too.

In fact, modifier .keep() is the mechanism for implementing propagation and simpagation rules. For instance, the following rule ensures the symmetry of eq:

\[
\text{when}(\text{eq}, X, Y).\text{keep()}
\text{.then}(\text{eq}, Y, X);
\]

and the next one propagates the domains of the equal variables:

\[
\text{when}(\text{eq}, X, Y).\text{keep()}
\text{.and}(\text{dom}, X).\text{with}(A, B).\text{keep()}
\text{.and}(\text{dom}, Y).\text{with}(C, D).\text{keep()}
\text{.where}(!\text{equals}, X, Y) // avoid the trivial case
\text{.then}(\text{dom}, X).\text{with}(C, D)
\text{.and}(\text{dom}, Y).\text{with}(A, B);
\]

In the last example, we have seen an example of a guard, introduced with ".where", whose first argument is a string that points to the corresponding guard method, with the leading bang ("!") signifying the negation. The corresponding guard method:

```java
public boolean equalsGuard(Object x, Object y) {
    return (x == null ? y == null : y != null && x.equals(y));
}
```
is built into `cr.core.Handler`. A non-negated guard succeeds when all of the arguments have the correct type, and the returned value is true (or the guard method return type is `void`). A negated guard succeeds exactly when the non-negated guard would fail.

The guard mechanism is very flexible and powerful, handles the automatic conversion between Java primitive values and objects, accepts variable argument lists, and allows the guard methods to compute new information that can be used in the body of the rule.

For instance, the following rule detects inconsistencies:

```java
when(dom, X).with(A, B)
.and("!lessOrEqual", A, B)
.then(fail);
```

using the rule method:

```java
public boolean lessOrEqualGuard(int a, int b) {
    return a <= b;
}
```

(Noe that "!lessOrEqual" guard succeeds if either of the two arguments are `null`.)

This rule ignores non-informative bounds:

```java
when(dom, X).with(A, B) // newly told
.and((dom, X).with(C, D).passive().keep() // already known, kept
.where("includes", A, B, C, D); // [C,D] already included in [A,B]
```

with the guard method:

```java
public boolean includesGuard(int a, int b, int c, int d) {
    return (a <= c) && (d <= b);
}
```

The following rule treats the informative bounds:

```java
when(dom, X).with(A, B) // newly told
.and((dom, X).with(C, D).passive()) // already known
.where("!includes", A, B, C, D) // [A,B] does not include [C,D]
.and("isect", A, B, C, D, E, F) // [E,F] is the intersection
.then((dom, X).with(E, F); // update the domain to [E,F]
```

with the new guard method that computes the intersection:

```java
public void isectGuard(int a, int b, int c, int d, @NotNull Symbol e, @NotNull Symbol f) {
    e.set(Math.max(a, c));
    f.set(Math.min(b, d));
}
```

This guard always succeeds (if no argument is null), and stores the results in `e` and `f`, used in the rule body as the updated value range. Guard method parameters of type `cr.core.Symbol` are passed not by value, but by reference.
4 Runtime rule compilation and DSL expressiveness

At this point, before proceeding to the semantics, it is useful to comment on some aspects of the proposed approach and its implementation, and to highlight and motivate the choices these are based on.

First and foremost, the elimination of the static rule compilation phase, as mentioned at the beginning of the previous section, comes at the cost of a runtime compilation of rules into Java objects. In the current implementation, this is done every time a new instance of the handler is instantiated (i.e., during and after the execution of the \texttt{setup()} method), but in a slightly improved implementation, most of this overhead can be dealt with on once-per-class basis, provided that \texttt{setup()} does not depend on the handler constructor parameters.

The first runtime rule compilation phase is building the internal rule object representations, which is done using the \texttt{constraint()}, \texttt{when()}, \texttt{where()}, \texttt{then()}, and other API methods. The most complex part here is the treatment of guards, which relies on Java reflection to ensure that the corresponding methods exist, and to create adapters that take care of the correct argument count, types, conversion, variable-argument list passing, returning result interpretation, etc. The use of strings for guard names, while not as elegant as the other parts of the DSL, allows the use of the negation prefix ("!") and avoids the need to declare guard names as symbols, and thus clutter the code.

The second runtime compilation phase is weaving the compiled rules into a per-instance index structure that is used for firing rule heads.

A handler instance can be created only if the runtime rule compilation succeeds. Otherwise, a \texttt{cr.core.HandlerException} is thrown with a fault description. Not having all the errors in the handler detected statically is arguably the greatest drawback of our scheme, although it is less critical in the context of the agile development methodologies. Any runtime rule compilation errors would be weeded out early on during the handler’s unit testing phase, before integrating it with the rest of the application modules.

It should also be noted that JVM-based languages such as Scala [15] provide much better facilities for development of DSLs than “pure” Java. In particular, Scala’s flexible system for defining operators, together with a functional representation of methods as first-class objects (on the same level as the variable and value fields) may eliminate the need for strings as guard names and run-time argument number and type checking. This makes implementing a Scala interface for the constraint rules library an interesting next step. Scala can be also used as the implementation language, but since

\footnote{Note that Java method names and field names populate different namespaces.}
it introduces its own object (reference / value) hierarchy on top of Java, this would be be more suitable when the client code is also written in Scala.

5 Semantics

The semantics of the constraint rules introduced in Section 3 as a Java DSL follows the general lines of CHR, but differs from its standard semantics with respect to the organization of the store, the firing of rules, and the absence of special built-in solvers. Each instance of the handler class (i.e., the one that extends cr.core.Handler) encapsulates five key elements: the symbols, the store, the goal (or the queue), and the rules, which are explained below.

As mentioned in the previous section, symbols are just objects with an immutable name, and are used to name the constraints and data field values in rules. (Using the same symbol for both purposes is not forbidden, but the resulting code may look confusing.) When testing guards and firing rules, symbols denoting data fields also store field values as objects. Since the rules operate on the committed-choice basis, this is done using destructive updates, by calling their .set() and .get() methods. When used as data objects outside the rules, the symbols’ values should be treated as volatile.

The handler state is a tuple \((G, S)\), where \(G\) is the goal, and \(S\) is the store. The store is an object that keeps the known facts about the declared constraints. Unlike the standard CHR where the store is a multi-set of constraint literals, we take the approach where each declared constraint \(c\) is a partial function of the form:

\[
c : K_1 \times K_2 \times \cdots \times K_n \rightarrow D_1 \times D_2 \times \cdots \times D_m
\]

where \(n, m \geq 0\). Each \(K_i\) corresponds to a Java class implementing java.lang.Comparable interface, and each \(D_j\) to an arbitrary Java class. (Each \(K_i\) and \(D_j\) is also implicitly extended to include the null reference.) If \(n\) or \(m\) is zero, the corresponding product degenerates to a singleton set containing only the unit tuple \(()\). Each constraint literal (or fact) is a statement of the form:

\[
c : (k_1, k_2, \ldots, k_n) \rightarrow (d_1, d_2, \ldots, d_m)
\]

where \(k_i \in K_i\) and \(d_j \in D_j\), which tells that \(c\) is defined at \((k_1, k_2, \ldots, k_n)\) and has value \((d_1, d_2, \ldots, d_m)\). Initially, the store is typically empty, which means that all constraints are undefined for all possible keys. For instance, if the \(dom\) constraint is declared as:

\[
dom : \forall \rightarrow \mathbb{Z} \times \mathbb{Z}
\]
where $\mathcal{V}$ is a set of variable labels (as strings), and the two integers are the pair of min/max bounds, then the partial function representation ensures that we may have at most one pair of bounds in the store for any variable label.

The partial function representation of constraints is chosen over the multisets as a more structured solution which can leverage the efficient Java data structures such as `java.util.SortedMap`, and is more powerful than the set semantics. Note that the set semantics can be simulated by taking $m = 0$ and keeping all constraint data in the key fields. Similarly, the multi-set semantics can be simulated by taking, e.g., $n = 1$ and $K_1 \equiv \text{java.lang.Integer}$, putting all constraint information into the data part, and making sure that $k_1$ is always ignored in the `when()` part of the rules (using symbol “_”), as well as initialized to a fresh value for each new fact inserted into the store.

In contrast to the store which contains the already known facts, the goal is a conjunction of newly told facts that await processing. The goal is processed one fact at a time, in a chronological (or left-to-right) order, and new facts produced by firing rules are appended to it. For these reasons, the goal is also known as the queue.

Note that our proposal does not make the distinction between the built-in and user-defined (relational) constraints. All constraints used in the solver have to be declared, and their rules explicitly specified. Also, any object inspection and matching has to be done explicitly by invoking the accessor methods in guards.

For simplicity, we present here the operational semantics of the rules using the algorithms from Figure 5 which destructively update the state. The `MAINLOOP` starts from some initial state $(G, S)$ – where $G$ is normally non-empty – and tries to reach a fixpoint state $(G', S')$ where $G'$ is empty, i.e., all possible rules have been fired and nothing else remains to be done. That is achieved by successively reading facts from the goal (in a FIFO fashion), and firing all applicable rules (or signaling a failure). `MAINLOOP` is typically initiated with a `TELL` operation which communicates a new fact to the handler.

`MAINLOOP` can return before reaching a fixpoint in two cases: when explicitly asked to do so from a rule guard (using the `forceExit()` handler method), or when it detects that the goal size has exceeded some optional and pre-configured safety level set to prevent uncontrolled memory consumption. In both cases such an early termination is safe, in the sense that no information is lost, and that the computation can always be resumed.

Procedure `FireAllRules` uses an internal index structure to iterate through all head elements of all rules that are active (i.e., not marked with `.passive()`).

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This does not mean writing huge monolithic solvers. The developers can use subclassing, delegation and other usual Java techniques for software modularization and reuse.
1 function MainLoop
2   forcedExit ← false
3   while ¬forcedExit ∧ |G| > 0 do
4     φ ← first(G); G ← rest(G)
5     if φ ≡ fail : () 7→ () then
6       signal failure
7     else
8       FIREALLRULES(φ)
9       if |G| > limit then
10      forcedExit ← true
11     end if
12   end while
13   return |G| > 0
14 end function

1 procedure FIREALLRULES(φ)
2   U ← φ
3   for each active head element H matching φ do
4     ¯H′ ← all head elements in the rule except H
5     fired ← false
6     for all facts ¯φ′ from S matched by ¯H′ do
7       if the rule guard succeeds then
8         fired ← true
9         append the rule body to G
10        U ← U ∪ { ¯φ′i | ¯H′i without .keep() }
11     end if
12   end for
13   if fired ∧ H without .keep() then
14     S ← S \ U
15   end if
16 end procedure

Fig. 5. The main loop and the rule firing algorithms.

For each such active head element, an attempt is made to fire the rule for each combination of facts from the store that correspond to the remaining head elements in the same rule (for which the rule guard succeeds if present). The facts consumed in each firing (not marked with .keep()) are marked for removal, but are not removed immediately to give chance to all other applicable rules to fire. If the firing head element is marked with .keep(), the next firing head (in the same rule or one of the following rules) is tried, otherwise the processed fact is consumed, and the processing stops. If the processed fact is not consumed by any rule, it is added to the store.

The order of rules is significant. The rules are fired in the same order in which they are defined. When an earlier rule consumes the processed fact, it effectively cuts the remaining rules off. However, those rules that do fire behave as if they do so simultaneously, since the removal of the consumed facts is performed at the end.

While the handler’s tell() method informs it of the new facts, which are added to the goal (i.e., the queue), the results of the computation are held in the store, and can be inspected using the select() method.
6 Implementation Notes and Advanced Features

The current implementation is a set of Java classes and interfaces packaged in a lightweight standalone .jar file, without external dependencies. It contains an example numerical interval solver that can be tested using the visual debugger based on the advanced features below.

6.1 Event notifications, tracing and debugging

Insufficient support for debugging is one of the key disadvantages of the current CHR implementations. In our implementation, both tracing and debugging are achieved using the publish-subscribe mechanism by which one or more event listeners can be attached to a handler instance and can observe different events, such as adding a goal to the store or firing a rule. In the latter case, the information from Java reflection relates the firing point to the handler source. An example of the full GUI debugging session is given in Figure 6, with the debugging console, source code tracing, breakpoints, and constraint views.

4 An archive with the binaries and the documentation can be downloaded from http://software.imdea.org/~idragan/cr
6.2 Transactional state behavior

It is often useful to save the state of the handler before telling more constraints, and to revert to the previous state if the problem turns out to be overconstrained or insatisfiable. A typical use would be checking if a solution to the problem exists under some additional assumptions, and if not reverting to the previous state and trying something else. Our implementation enables arbitrarily nested state savepoints, analogous to those in the transactional database, using the following operations:

- `begin()` – saves the current state and begins a new, nested transaction.
- `commit()` – closes the current nested transaction and saves its current state to the parent transaction.
- `partialCommit()` – saves the current state to the parent transaction, while keeping the nested transaction open.
- `rollback()` – discards the current nested transaction and returns to the parent transaction and its saved state.

These operations work on both components of the state (the goal and the store), and are orthogonal to the `tell()` and `select()` handler operations. The default store that is created for each new handler instance is a map-based in-memory store. We are working on an implementation where the in-memory store can be replaced with a persistent store stored in the file system.

7 Conclusions

Implementing CHR as a domain-specific language embedded in Java has several advantages over the classical approach where CHR handlers are written in an additional language layer on top of the host language, here Java. These advantages include avoiding the additional compilation steps that disrupt the usual development cycle, better leverage of the host language features, support for tracing and debugging, and the application of the existing powerful refactoring tools in the modern Java IDEs. On the overall, this can help improve the acceptance of CHR and CLP programming techniques in the component-based, Java-centric, cloud programming environment.

The future work will be directed towards more robust implementations, integration with persistent transactional store back-ends, development of a spectrum of ready-to-use constraint handlers, introduction of some CHR features [1], and exploring applications in distributed event processing.
References