Outline of CCL notation syntax

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Abstract. Concurrent Communicating Lists (CCL) is the novel Clojure/Java based library, which facilitates executable modeling of concurrent systems. It provides a kind of semi-formal notation modeled on the Lisp language and its modern equivalent Clojure. Models designed with the help of CCL library can be simulated and executed, as well as formally verified, using provided library tools. The main aim of this report is to briefly collect all the main syntax features of CCL and explain them by examples. The report contains several short listings of code, describing various aspects of the CCL syntax and showing how the CCL model can be built up from pieces.

Keywords: CCL, Concurrent Communicating Lists, functional programming, executable modeling, formal methods

1 Introduction

The main purpose of the report is to present in a convenient way the basic syntax mechanisms provided by the CCL library. CCL is designed as a set of Clojure language declarations, functions and macro-definitons [6] forming an algebraic-like specification language. It allows programmers to design, prototype, test and verify their concurrent control applications. Like Clojure, CCL works on the top of the Java Virtual Machine, which provides CCL portability across different hardware platforms, and brings access to the large standard libraries of both Clojure and Java. Such tight integration makes possible mixing CCL code with Clojure and Java. In particular it is possible to execute a piece of code written in Clojure and Java from the CCL model, and reversely, the CCL model execution can be initiated from Clojure and Java.

CCL is well integrated with other software components such as CCL Sim [11] and Robust [9, 12, 10]. The CCL Sim enables model debugging and simulation in a graphical environment, whilst the integration with the Robust library allows different robotic constructions to be directly controlled from the CCL executable model [13].

The CCL models are conceptually similar to those known from process algebra. For this reason, many terms defined in the context of CCL have their counterparts in many well known process algebras, such as CSP, CCS, ACP or LOTOS [14, 7, 2, 8]. In all of them, one of the basic concepts is a process understood as a “behaviour pattern of an object (…), described in terms of a limited set of
events selected as its alphabet” [7]. The concept of process may have different names. For instance, in CCS process is called agent, whilst LOTOS prefers to call the process as behavior expression [4]. Because CCL tries to be close to the Lisp programming paradigm where every single piece of code should be a correct list expression [5], the CCL expressions which are executed by CCL processes are also defined in the form of lists. Nlists are formed from actions, other processes and operators. Actions, sometimes called events (CSP) [15], in CCL convention are called primitives. Similar to the notion of action in process algebras, primitives are atomic, i.e. CCL is not interested in a primitive’s internal structure. On the other hand, since primitives are defined as Clojure functions ready to run when the model is executed, they have to be implemented so that they do not brake model execution. In particular, they should be consistent with Java’s recommendation as regards interruption handling.

One of the basic operators used for constructing more complex structures from basic ones is the prefixing operator. In CCL the precedence of expressions is determined by their order in the named list, where the expressions on the left followed before those on the right. Other operators such as choice operator or concurrent composition also are available. CCL supports interruption mechanism by introducing an interruption operator. It has a very practical prototype, and comes from Java and is similar to the threads interruption handling in Java. On the other hand, it provides the ability to declare the interruption handler as it is possible to declare a shutdown hook in the Java virtual machine. Thanks to the interruption mechanism the user has an possibility not only to raise an exception, but also correctly handle it.

2 CCL notation

CCL notation consists of several operators and constructions. The expressions presented below are sufficient to construct a CCL model sufficient for many interesting and complex problems (a few of them are presented below). The first six constructions refer to sequential processing, whilst the last four (such as concurrent composition or synchronization queues) support the modeling of concurrency in the system. Due to some similarities with popular process algebras, the semantics of these constructions should not be difficult to understand.

2.1 Named List (nlist)

A named list (nlist) is one of the fundamental constructions of CCL. Nlist is a sequence of instructions processed within a single thread, where every instruction can be: a primitive call, a condition check, a variable change, an exception rising or communication via synchronization queues. Nlist can be declared using macro def-nlist (Listing: 1, line: 1).

```clojure
1 (def-nlist list-name list-body)
```

Listing 1: Nlist definition scheme

where list-name is the name of the list and list-body is a sequence of instructions following it. For instance, a simple nlist TickTacker printing infinitely on the console “ticks” and “tacks” may look as follows (Listing: 2, line:1):

```clojure
1 (def-nlist TickTacker ((tick) (tack) TickTacker))
```

Listing 2: TickTacker nlist

A TickTacker body contains a list of two consecutive primitives, tick and tack, and ends up with a TickTacker list re-call. So, from the execution point of view, this is an infinite sequence of ticks and tacks. Tick and tack have to be defined and registered as CCL primitives. Therefore, first they have to be defined as Clojure functions (Listing: 3, lines: 1 and 2), then declared as primitives (Listing: 3, line: 3).
1 (defn tick [] (println "tick"))
2 (defn tack [] (println "tack"))
3 (reg-as-prim tick tack)

Listing 3: Tick and Tack as Clojure functions

2.2 Primitives

The tick and tack primitives are defined as Clojure functions, which take no parameters on their input and do only one Clojure action println (printing the given text on to the console).

1 (defn tt [prim-name]
2   (do
3       (println prim-name)
4       (wait 500)))
5 (reg-as-prim tt)
6
7 (def-nlist TickTacker ((tt "tick") (tt "tack") TickTacker))

Listing 4: Simple parametrized primitive

Since primitives are just Clojure functions, they can also take parameters on their input. Thus, instead of defining two different primitives, tick and tack, only one parameterized primitive can be defined (Listing: 4, lines: 1 - 4). Now, according to the Clojure syntax, the primitive tt first prints the given text, then waits 500 milliseconds. The TickTacker’s definitions also evolve and, after changes, TickTacker looks as on (Listing: 4, line: 7).

2.3 Nlist local variables

Nlist’s local variables are another syntax mechanism that supports nlist processing. A local variable is declared at the time of the first assignment. Its name must start with colon (similar to Clojure’s keywords). Local variables serve as a data interchange mechanism between different primitives and synchronization queues. They are also used in the logical conditions of the conditional choice operator. In the TickTacker example, the input data can be passed to the tt primitive as variables, not as literals. A definition of TickTacker using variables is as follows (Listing 5):

1 (def-nlist TickTacker ((:val "tick") (tt :val)
2   (:val "tack") (tt :val)
3   TickTacker))

Listing 5: Nlist local variables

After this modification, TickTacker consists of five expressions where (:val “tick”) assigns the value “tick” to :val, then in the next expression the value of :val is passed into primitive tt.

2.4 Nlist parameters

The nlist parameters are variables, which can be passed into the given nlist passage from outside. They are declared together with the name of the nlist, then in the nlist’s body they can be used in the same way as any other variables. In the case of the TickTacker example, an nlist parameter mechanism can be used to implement a tick-tack counter (Listing 6). Of course, incrementation of the variable :val is in the Lisp manner i.e. operator + precedes all of its arguments.
As a result, after every tick-tack passage a subsequent number is written. Because of the counter, every tick-tack run has its own number assigned. Thus, the next extension means that the odd runs will print *tick* before *tack*, whilst even runs behave inversely; they will print *tack* before *tick*. To do this, a *conditional choice* operator will be used.

### 2.5 Conditional Choice

*Conditional choice* allows the operator to select which *nlist* body is to be executed next. Its syntax is similar to *cond* Clojure/Lisp’s macro, although the axiom *cond* is replaced by a question mark, and the condition results are just *nlist* bodies. Another difference lies in the fact that if a conditional clause is a part of another *nlist*, no part of this *nlist* is evaluated, apart from the chosen *nlist* body. The *conditional choice* scheme is as follows (Listing: 7).

```clojure
(?
  (condition-1)
  (nlist-body-as-a-condition-result-1)
  (condition-2)
  (nlist-body-as-a-condition-result-2))
```

Listing 7: Conditional choice - scheme

Since the *TickTacker* example has been equipped with a counter :cnt, odd and even ticks can be distinguished. Let us use a conditional choice to change a *TickTacker* in a way that for odd counter values it will print “tack”, whilst for even it will print “tick”\(^1\). In the following example, the standard *Clojure* predicates such as odd? and even? are used to build condition clauses.

```clojure
(def-nlist (TickTacker :cnt) (?
  (odd? :cnt)
  ((tt "tack")
   (tt :cnt) (TickTacker (+ :cnt 1)))
  (even? :cnt)
  ((tt "tick")
   (tt :cnt) (TickTacker (+ :cnt 1)))))
```

Listing 8: Conditional choice - example

### 2.6 Random Choice

A *random choice* allows us to specify an *nlist* clause containing sub-clauses processed with some likelihood proportional to the assigned weight. The operator’s syntax is similar to the *conditional choice* operator, except for the fact that the condition clauses are replaced by weights determining sub-clause execution probability. For instance, a *TickTacker*, where “ticks” occur four times more frequently (approximately) than “tacks” can be specified as follows (Listing 9):

\(^1\)Of course, the same result can be easily achieved without using a conditional choice.
2.7 Sequential Composition

A sequential composition operator allows the specification of any number of nlists, which are processed sequentially. The operator is important mainly because of its compositional meaning. It allows the user to extract some sequences of actions into the separately named nlist definitions.

```
1 (def-nlist Ticker ((tt "tick")))
2 (def-nlist Tacker ((tt "tack")))
3 (def-nlist TickTacker (|-- Ticker Tacker) TickTacker))
```

Listing 10: Sequential composition

The sequential composition operator symbol -- follows immediately after the opening bracket. Since the sequential composition close is directly followed by the TickTacker self-recurrent declaration, it is advised to not put their self-recurrent declarations into both Ticker and Tacker. (Listing 10). Otherwise, the expressions followed the close may become unreachable.

2.8 Concurrent Composition

A concurrent composition operator allows the specification of any number of nlists, which are processed concurrently. Every nlist within the concurrent composition operator is processed independently in a separate execution thread. An inspiration for the concurrent composition operator was the composition operator in CCS [4].

```
1 (def-nlist Ticker ((tt "tick") Ticker))
2 (def-nlist Tacker ((tt "tack") Tacker))
3 (def-nlist TickTacker (| Ticker :tickProc Tacker :tackProc))
```

Listing 11: Concurrent composition

Of course, following the Lisp style the concurrent composition operator symbol follows immediately after the opening bracket and is one for any number of operands. With the help of the concurrent composition operator, our study case TickTacker can be modified so that it consists of two separate nlists: Ticker and Tacker. Each of these nlists is processed independently within the two separate processes tickProc and tackProc. The appropriate code is as follows (Listing 11).

2.9 Synchronization Queues

One of the fundamental structures mediating the communication between different processes is a buffer. Because of its importance and relative simplicity in design, it is one of the most commonly modeled artifacts [3]. Very frequently in practice a buffer communication model is implemented in the form of synchronization queues (SQ). In some languages, like Java, such a mechanism has become a part of the language standard².

CCL adopts SQ as a basic synchronization mechanism. A synchronization queue is used to synchronize two or more nlists where some of them write to the queue, while others read from the queue. All the SQs implement a common queue interface (Table 1) allowing elements to be inserted into and

²http://download.oracle.com/javase/1.5.0/docs/api/java/util/AbstractQueue.html
Table 1: A Common SQ interface - method meaning

<table>
<thead>
<tr>
<th>SQ methods</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(q-get q-name)</td>
<td>returns and removes the first element from the queue</td>
</tr>
<tr>
<td>(q-peek q-name)</td>
<td>returns the first element from the queue</td>
</tr>
<tr>
<td>(q-put q-name)</td>
<td>inserts the element at the end of the queue</td>
</tr>
<tr>
<td>(q-try-put q-name)</td>
<td>as q-put but if the queue is full, false is returned</td>
</tr>
<tr>
<td>(q-size q-name)</td>
<td>returns the number of elements in the queue</td>
</tr>
<tr>
<td>(q-capacity q-name)</td>
<td>returns the maximal size of the queue</td>
</tr>
</tbody>
</table>

Table 2: Synchronization queues

<table>
<thead>
<tr>
<th>SQ Type</th>
<th>SQ capacity</th>
<th>Read policy</th>
<th>Write policy</th>
<th>Operations ineffective</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>Non-block.</td>
<td>Non-block.</td>
<td>any</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>Blocking</td>
<td>Non-block.</td>
<td>peek, try-put</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>Non-block.</td>
<td>Blocking</td>
<td>peek, try-put</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>Blocking</td>
<td>Blocking</td>
<td>peek, try-put</td>
</tr>
<tr>
<td>5</td>
<td>n &gt; 0</td>
<td>Non-block.</td>
<td>Non-block.</td>
<td>peek, try-put</td>
</tr>
<tr>
<td>6</td>
<td>n &gt; 0</td>
<td>Blocking</td>
<td>Non-block.</td>
<td>try-put</td>
</tr>
<tr>
<td>7</td>
<td>n &gt; 0</td>
<td>Non-block.</td>
<td>Blocking</td>
<td>none</td>
</tr>
<tr>
<td>8</td>
<td>n &gt; 0</td>
<td>Blocking</td>
<td>Blocking</td>
<td>none</td>
</tr>
</tbody>
</table>

removed from the queue. There are two additional methods for reading data: q-get and q-peek and two methods for writing: q-put and q-try-put. There are also two additional methods which allow the number of elements in the queue and the capacity of the queue to be checked - q-size and q-capacity respectively.

Depending on the initial queue settings (i.e. size and blocking policy), semantics of the read/write operations may vary slightly. Due to the queue capacity and adopted blocking policy, eight types of SQ have been defined (Table: 2).

Every queue may be blocked at its (both) ends i.e.: if the queue is empty, each reader must wait for an element to be written and, correspondingly, if a queue is full, every writer must wait to get an element from the queue. If the queue is neither full nor empty, and its capacity is greater than zero, each of these conditionally blocking methods behaves in a non-blocking manner. In the case of a 0-length queue (which is always both: full and empty at the same time), every method designed as conditionally blocking is always locked up when called, and such a call must wait for synchronization with another running thread.

There are two main groups of SQ types: SQs with zero-capacity and SQs with non-zero capacity (Table: 2). The 0-length SQs do not have any internal capacity, not even a capacity of one. Thus, writing to the queue is effective only if it happens at the same time as reading. In other words, the element being inserted to the 0-capacity queue has to be immediately taken from it. To make read and write operations occur exactly at the same time, they should be mutually synchronized, so at least one of them has to be blocking. For this reason all the operations for the SQ type 1 (Table: 2) are ineffective (i.e. their result is undefined). Because of the size of zero-capacity SQs, checking whether the queue is full or empty is pointless. Thus, for any 0-capacity queues the methods which first try to check the content of the queue (i.e. as peek or try-put) are pointless as they are ineffective.

Since n-capacity queues have some storage space, calling methods which check the size of the queue are possible. A queue which has all the methods effective is a non-zero capacity both side blocking SQ (type 8, Table: 2). On the other hand, a both side non-blocking non-zero capacity queue does not have peek and try-put methods available (type 5, Table: 2). For all the types of SQ with a

\[^3\text{It is assumed that the occurrence probability of two different actions (read and write) in two independently executed threads at the same momentum of time is 0.}\]
non-blocking write, a successful-write strategy is implemented. In other words, if the queue is full, the very first item is removed and the new item is added at the end. This is due to the fact that in many practical applications the most recent data is the most important. With the help of synchronization queues, the TickTacker case study can be converted into the well-known Consumer-Producer problem [1], where ticks and tacks are provided by separate nlists called TickerProducer and TackerProducer (Listing: 12, lines: 3-6), whilst printing service is provided by the nlist: TickTackerConsumer (Listing: 12, lines: 8-9). TickerProducer and TackerProducer add appropriate messages to the tickTackerQ, call tick or tack primitive correspondingly then start the whole sequence of actions once again. TickTackerConsumer gets the message from tickTackerQ, assigns it to the local variable x, then prints the message by calling the primitive toe.

In order to connect producers and consumers at the beginning of the refreshed TickTacker case study, a tickTackerQ SQ is defined (Listing: 12, line: 1). The queue has the length 1 and a blocking input and output4.

TickTackerWithSQ prints series of “ticks” and “tacks” on the console as a result. The frequency of individual words on the output depends on the efficiency of their producers.

```
1 (def-queue tickTackerQ :size 1 :rb :wb)
2 3 (def-nlist TickerProducer
4   ((q-put tickTackerQ "tick") (tick) TickerProducer))
5 (def-nlist TackerProducer
6   ((q-put tickTackerQ "tack") (tack) TackerProducer))
7
8 (def-nlist TickTackerConsumer
9   ((:x (q-get tickTackerQ)) (toe :x) TickTackerConsumer))
10
11 (def-nlist TickTackerWithSQ (| TickTackerConsumer
12   TickerProducer
13   TackerProducer))
```

Listing 12: TickTacker with SQs - example

### 2.10 Processing Interruption

It is very often impossible to predict all the circumstances in which the actual system has to work. Sometimes there is a need to cancel the current action or postpone it for a while. Such unexpected situations are common, especially in the case of real time systems where changing external conditions (e.g. the sudden appearance of an obstacle) may force the whole system to change its plans. As a result, the system controller must interrupt the current processing and follow the rescue plan relevant to the cause of the interruption. Ways of coping with unforeseen events are present in most object-oriented and procedural languages. These are signal-sending and exception-handling mechanisms. The major difference between them is that the exception handling is closed within a single thread, whilst signal sending crosses the thread/process boundary.

---

4Keyword :rb means that the read is blocking, whilst :wb means that the write is blocking
CCL allows one nlist to interrupt another nlist. In such a case the interrupted nlist stops its current operations and may run an interruption handler containing an alternative sequence of instructions. To set the nlist’s interruption handler, at least one of its sub-lists has to start with an exclamation mark followed by the alternative list of instructions (Listing: 13, line: 2).

The nlist’s name defines only the execution scheme, not the running instance of the given nlist. Since the interruption request operates on the nlist’s instance\(^5\), another identifier for the nlist’s instance is required.

Such an identifier is defined as a keyword following the nlist’s name within the concurrent composition operator e.g. (Listing 13, line: 7). The interruption raising operator is defined by a sub-list starting with an arrow -> followed by a process name e.g. (Listing: 13, line: 5).

On listing 13 a TickTacker study case is shown, consisting of three nlists: TickerTackerWriter, Spoiler and TickTacker. This time TickerTackerWriter is responsible for writing ticks and tacks alternately to the console, although it is able to handle interruption and, in such a case, it prints the word recovery (Listing: 13, line: 2) then comes back to the standard instructions flow. The spoiler nlist contains only two primitives. The first primitive tt writes the word spoil to the console, whilst the second sends an interruption request to the TickerTackerWriter executed by the process nlid (Listing: 13, line: 7). The last nlist joins both previous nlists together, combining them with the help of the concurrent composition operator. The final run of TickTackerWithSQ results in a series of ticks and tacks printed into the console alternated by spoils and recoveries. Since every nlist can be interrupted at any time, any primitive is also susceptible to being interrupted. Thus, when developing primitives, it should be remembered that every piece of code from which an InterruptedException\(^6\) can be thrown has to be surrounded by an appropriate try-catch clause. For this reason, in the TickTacker case study (Listing 13), the primitive tt has to be rewritten in order to be ready for incoming interruption (Listing 7).

\[\text{Listing 14: Interruption ready primitive}\]

\[
(\text{defn tt \{} \text{[prim-name]} \}
\text{ do (println prim-name)}
\text{ (try}
\text{ (wait 500)}
\text{ (catch InterruptedException ex}
\text{ (println \"primitive interrupted\")))))
\]

2.11 Externalization

The fundamental way of communication in CCL is with \textit{synchronization queues}. They allow different processes defined within the same CCL model to communicate and synchronize with each other. The CCL model is also able to communicate with the external environment. This communication is carried out by \texttt{Clojure} functions registered as \textit{primitives}. This is because \textit{primitives} may get values from the

\(^5\)Many instances of the same nlist can be executed at the same time but only one needs to be interrupted.

\(^6\)Interruption of Java thread may result in raising the exception \texttt{InterruptedException}.
model and pass them to the actual hardware as well as read registers of a physical device and return them back to the model. From the CCL model perspective, primitives are a bit like a black box. Their internal implementation is not important. Their structure and correctness are not subject to the formal analysis of a model.

Although, at first glance, the perspective of many processes communicating through synchronization queues within a single model seems reasonable, sometimes, especially in the case of a large model, it is necessary to divide it into sub-models. This may be caused by compositional considerations i.e. some parts of the large model may form a consistent sub-system, but no less important are the limited possibilities of analysis. The large model is difficult to inspect manually by engineers, hard to simulate and, due to the state explosion trap, it might be very difficult to analyze by formal methods.

In CCL, creating new sub-models out of existing ones is called externalization. It relies on identifying existing synchronization queues between the model code, which is intended to be part of a new sub-model and the rest of the code. When these queues are identified, they are marked as externalized and their calls on both ends are wrapped into primitive calls. Thus, the processes, which have so far communicated through these queues, start to communicate through newly defined primitives, exactly in the same way as they communicate with the external environment. In other words, the new sub-model becomes external to the its parental (sub) model. The externalization mechanism provides a way to create a hierarchy of models. Each sub-model can be a subject of individual verification both: formal and by simulation.

In order to see how CCL supports externalization, let us go back to the example of TickTacker with SQs (Listing 12). In order to externalize the TickTackerConsumer process into a separate sub-model, the tickTackerQ queue has to be marked as externalized (Listing 15, line: 1) and wrapped into primitives (Listing 15, lines: 2). To create the queue wrapper, the appropriate macro defn-queue-wrapper is called. The user needs to define the name of the future primitive, the name of the queue and the operating policy: get, peek, put or try-put (Listing 15, lines: 2). Then, the queue access methods calls need to be replaced by wrapper calls (Listing 15, lines: 7, 9, 12). Due to the clarity of code the additional expression TickTackerProducer can be added (Listing 15, lines: 14 - 15). From this point there are two sub-models, one grouping producers: TickTackerProducer, and one consisting of TickTackerConsumer. Both of them can be verified and analyzed independently, so that when one of them is the subject of analysis it is assumed the second works correctly and vice versa.

```
(def-queue tickTackerQ :size 1 :rb :ext)
(defn-queue-wrapper tick-tack-put tickTackerQ :put)
(defn-queue-wrapper tick-tack-get tickTackerQ :get)
(req-as-prim tick-tack-put tick-tack-get)

(def-nlist TickerProducer
  ((tick-tack-put "tick") TickerProducer))
(def-nlist TackerProducer
  ((tick-tack-put "tack") TackerProducer))

(def-nlist TickTackerConsumer
  (:x (tick-tack-get)) (tt :x) TickTackerConsumer)

(def-nlist TickTackerProducers (| TickerProducer TackerProducer))

Listing 15: Externalization example (TickTacker model)
3 Summary

CCL is the Java/Clojure library facilitating executable modeling, which provides syntax modeled on formal notations, such as process algebras [3]. It offers several syntactic mechanisms, which allow the declarative construction of increasingly complex structures. These are primitives, named list (nlists), choice operators, concurrent composition operator, synchronization queues, and interruption operators. CCL is more semantically strict than non-formal modeling languages, and thus it is more susceptible to different kinds of strict model analysis. Besides formal verification, CCL models can be verified by simulation as well as executed together with other Clojure and Java components.

The report is not a complete description of the CCL library. For instance many topics connected with using CCL together with Robust and CCL Sim are not covered here. More comprehensive materials and usage examples can be found on the CCL project’s website: http://www.kulakowski.org/ccl.

References
