Contents

1 Introduction ............................................................. 13

2 Language Structure ..................................................... 17
  2.1 RoboChart metamodel ................................................. 17
    2.1.1 Module .......................................................... 18
    2.1.2 Controller ........................................................ 19
    2.1.3 State Machine .................................................... 20
    2.1.4 Type Declaration ............................................... 22
    2.1.5 Expression ....................................................... 22
    2.1.6 Action and Statement ........................................... 23
  2.2 Timed Primitives .................................................... 24

3 Well-formedness Conditions ........................................... 27
  3.1 Core Language ...................................................... 27
    3.1.1 Robotic Platforms .............................................. 27
    3.1.2 Interfaces ....................................................... 28
    3.1.3 Modules .......................................................... 28
    3.1.4 Connection ...................................................... 28
    3.1.5 Controllers ..................................................... 29
    3.1.6 State Machines ................................................ 29
    3.1.7 States ........................................................... 30
    3.1.8 Initial junctions ................................................. 30
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.9</td>
<td>Junction</td>
<td>30</td>
</tr>
<tr>
<td>3.1.10</td>
<td>Final states</td>
<td>30</td>
</tr>
<tr>
<td>3.1.11</td>
<td>Communications</td>
<td>30</td>
</tr>
<tr>
<td>3.1.12</td>
<td>Transitions</td>
<td>31</td>
</tr>
<tr>
<td>3.1.13</td>
<td>Operations</td>
<td>31</td>
</tr>
<tr>
<td>3.1.14</td>
<td>Variables</td>
<td>31</td>
</tr>
<tr>
<td>3.1.15</td>
<td>Expressions</td>
<td>31</td>
</tr>
<tr>
<td>3.2</td>
<td>Timed Language</td>
<td>31</td>
</tr>
<tr>
<td>3.2.1</td>
<td>State Machines</td>
<td>31</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Transitions</td>
<td>32</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Timed Expressions</td>
<td>32</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Timed Statements</td>
<td>32</td>
</tr>
<tr>
<td>3.3</td>
<td>Probabilistic Language</td>
<td>32</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Transitions</td>
<td>32</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Probabilistic Junctions</td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>Semantics</td>
<td>35</td>
</tr>
<tr>
<td>4.1</td>
<td>Detailed Semantics: Core Language</td>
<td>36</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Modules</td>
<td>36</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Controllers</td>
<td>40</td>
</tr>
<tr>
<td>4.1.3</td>
<td>State machines</td>
<td>42</td>
</tr>
<tr>
<td>4.1.4</td>
<td>NodeContainers</td>
<td>46</td>
</tr>
<tr>
<td>4.1.5</td>
<td>Transitions</td>
<td>50</td>
</tr>
<tr>
<td>4.1.6</td>
<td>Nodes</td>
<td>51</td>
</tr>
<tr>
<td>4.1.7</td>
<td>Statements</td>
<td>53</td>
</tr>
<tr>
<td>4.1.8</td>
<td>Expressions</td>
<td>56</td>
</tr>
<tr>
<td>4.2</td>
<td>Detailed Semantics: Timed Language</td>
<td>57</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Controllers</td>
<td>57</td>
</tr>
<tr>
<td>4.2.2</td>
<td>State machines</td>
<td>57</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Node containers</td>
<td>58</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Clocks</td>
<td>61</td>
</tr>
<tr>
<td>4.2.5</td>
<td>Statements</td>
<td>62</td>
</tr>
<tr>
<td>5</td>
<td>Probabilistic Semantics</td>
<td>65</td>
</tr>
<tr>
<td>5.1</td>
<td>Overview</td>
<td>66</td>
</tr>
<tr>
<td>5.2</td>
<td>Semantic Domain</td>
<td>67</td>
</tr>
<tr>
<td>5.3</td>
<td>Translation to PRISM</td>
<td>68</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Translation requirements</td>
<td>68</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Normal form</td>
<td>69</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Notions for rules</td>
<td>69</td>
</tr>
<tr>
<td>5.3.4</td>
<td>PRISM</td>
<td>69</td>
</tr>
<tr>
<td>5.3.5</td>
<td>Normalisation rules</td>
<td>73</td>
</tr>
<tr>
<td>5.3.6</td>
<td>Normal form to PRISM</td>
<td>75</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>B</td>
<td>Complete Metamodel</td>
<td>153</td>
</tr>
<tr>
<td>C</td>
<td>✓-tock and share-CSP</td>
<td>163</td>
</tr>
<tr>
<td>C.1</td>
<td>✓-tock</td>
<td>163</td>
</tr>
<tr>
<td>C.1.1</td>
<td>Timeout operator</td>
<td>163</td>
</tr>
<tr>
<td>C.1.2</td>
<td>Biased terminating parallel composition</td>
<td>164</td>
</tr>
<tr>
<td>C.2</td>
<td>share-CSP</td>
<td>164</td>
</tr>
<tr>
<td>C.2.1</td>
<td>Parallel composition</td>
<td>164</td>
</tr>
<tr>
<td>D</td>
<td>Mathematical Toolkit</td>
<td>167</td>
</tr>
<tr>
<td>E</td>
<td>OCL Well-formedness Conditions</td>
<td>173</td>
</tr>
<tr>
<td></td>
<td>Credits</td>
<td>187</td>
</tr>
<tr>
<td></td>
<td>Bibliography</td>
<td>189</td>
</tr>
<tr>
<td></td>
<td>Index of Semantic Rules</td>
<td>193</td>
</tr>
<tr>
<td></td>
<td>Index of Calls to Semantic Rules</td>
<td>199</td>
</tr>
<tr>
<td></td>
<td>Index</td>
<td>203</td>
</tr>
<tr>
<td></td>
<td>Untimed semantics</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>-------------------</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Semantics of modules</td>
<td>36</td>
</tr>
<tr>
<td>2</td>
<td>Hidden Module channels</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>Memory channels</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>Function allEvents</td>
<td>36</td>
</tr>
<tr>
<td>5</td>
<td>Function allVariables</td>
<td>37</td>
</tr>
<tr>
<td>6</td>
<td>Function requiredVariables</td>
<td>37</td>
</tr>
<tr>
<td>7</td>
<td>Function allLocalVariables</td>
<td>37</td>
</tr>
<tr>
<td>8</td>
<td>Function allConstants</td>
<td>37</td>
</tr>
<tr>
<td>9</td>
<td>Function requiredConstants</td>
<td>37</td>
</tr>
<tr>
<td>10</td>
<td>Function allLocalConstants</td>
<td>37</td>
</tr>
<tr>
<td>11</td>
<td>Function requiredOperations</td>
<td>37</td>
</tr>
<tr>
<td>12</td>
<td>Module Memory</td>
<td>38</td>
</tr>
<tr>
<td>13</td>
<td>Constants Initialisation for Controllers and Modules</td>
<td>38</td>
</tr>
<tr>
<td>14</td>
<td>Composition of controllers</td>
<td>38</td>
</tr>
<tr>
<td>15</td>
<td>Renaming controller</td>
<td>39</td>
</tr>
<tr>
<td>16</td>
<td>Renaming controller events</td>
<td>39</td>
</tr>
<tr>
<td>17</td>
<td>Buffer</td>
<td>39</td>
</tr>
<tr>
<td>18</td>
<td>Single buffer</td>
<td>40</td>
</tr>
<tr>
<td>19</td>
<td>Semantics of controllers</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>Controller Memory</td>
<td>41</td>
</tr>
<tr>
<td>21</td>
<td>Composition of machines</td>
<td>41</td>
</tr>
<tr>
<td>22</td>
<td>Renaming state machine</td>
<td>42</td>
</tr>
<tr>
<td>23</td>
<td>Renaming machine events</td>
<td>42</td>
</tr>
<tr>
<td>Number</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>24</td>
<td>Semantics of state machine</td>
<td>42</td>
</tr>
<tr>
<td>25</td>
<td>Semantics of state machine</td>
<td>42</td>
</tr>
<tr>
<td>26</td>
<td>Get and set channels</td>
<td>43</td>
</tr>
<tr>
<td>27</td>
<td>Semantics of defined operations</td>
<td>43</td>
</tr>
<tr>
<td>28</td>
<td>Semantics of undefined operations</td>
<td>43</td>
</tr>
<tr>
<td>29</td>
<td>Stateful component of state machine body</td>
<td>44</td>
</tr>
<tr>
<td>30</td>
<td>Get and set local channels</td>
<td>44</td>
</tr>
<tr>
<td>31</td>
<td>Variable memory</td>
<td>44</td>
</tr>
<tr>
<td>32</td>
<td>Constant memory</td>
<td>44</td>
</tr>
<tr>
<td>33</td>
<td>Shared variables memory</td>
<td>45</td>
</tr>
<tr>
<td>34</td>
<td>Shared constants memory</td>
<td>45</td>
</tr>
<tr>
<td>35</td>
<td>Individual variable memory</td>
<td>45</td>
</tr>
<tr>
<td>36</td>
<td>Individual constant</td>
<td>45</td>
</tr>
<tr>
<td>37</td>
<td>Individual shared variable memory</td>
<td>46</td>
</tr>
<tr>
<td>38</td>
<td>Individual shared constant memory</td>
<td>46</td>
</tr>
<tr>
<td>39</td>
<td>Node container semantics</td>
<td>46</td>
</tr>
<tr>
<td>40</td>
<td>Node container behaviour</td>
<td>46</td>
</tr>
<tr>
<td>41</td>
<td>Node container core behaviour</td>
<td>47</td>
</tr>
<tr>
<td>42</td>
<td>Rename transition trigger events</td>
<td>47</td>
</tr>
<tr>
<td>43</td>
<td>Transition events</td>
<td>47</td>
</tr>
<tr>
<td>44</td>
<td>Function usedVariables</td>
<td>48</td>
</tr>
<tr>
<td>45</td>
<td>Function usedVariables</td>
<td>48</td>
</tr>
<tr>
<td>46</td>
<td>Function vars</td>
<td>48</td>
</tr>
<tr>
<td>47</td>
<td>Function vars</td>
<td>48</td>
</tr>
<tr>
<td>48</td>
<td>Function vars</td>
<td>48</td>
</tr>
<tr>
<td>49</td>
<td>Function vars</td>
<td>49</td>
</tr>
<tr>
<td>50</td>
<td>Function vars</td>
<td>49</td>
</tr>
<tr>
<td>51</td>
<td>Function vars</td>
<td>49</td>
</tr>
<tr>
<td>52</td>
<td>Composition of nodes</td>
<td>50</td>
</tr>
<tr>
<td>53</td>
<td>Semantics of Transitions</td>
<td>50</td>
</tr>
<tr>
<td>54</td>
<td>Semantics of a Transition</td>
<td>50</td>
</tr>
<tr>
<td>55</td>
<td>Semantics of a transition’s trigger</td>
<td>51</td>
</tr>
<tr>
<td>56</td>
<td>Semantics of nodes</td>
<td>51</td>
</tr>
<tr>
<td>57</td>
<td>Semantics of junctions</td>
<td>51</td>
</tr>
<tr>
<td>58</td>
<td>Semantics of final states</td>
<td>52</td>
</tr>
<tr>
<td>59</td>
<td>Semantics of simple states</td>
<td>52</td>
</tr>
<tr>
<td>60</td>
<td>Semantics of composite states</td>
<td>53</td>
</tr>
<tr>
<td>61</td>
<td>Semantics of statements</td>
<td>53</td>
</tr>
<tr>
<td>62</td>
<td>Read state of an expression</td>
<td>54</td>
</tr>
<tr>
<td>63</td>
<td>Atomic read state of an expression</td>
<td>54</td>
</tr>
<tr>
<td>64</td>
<td>Atomic read state of an expression with initial share</td>
<td>54</td>
</tr>
<tr>
<td>65</td>
<td>Semantics of statements in context</td>
<td>55</td>
</tr>
<tr>
<td>66</td>
<td>Semantics of assignment</td>
<td>55</td>
</tr>
<tr>
<td>67</td>
<td>Semantics of call statement</td>
<td>55</td>
</tr>
<tr>
<td>68</td>
<td>Semantics of if statements</td>
<td>55</td>
</tr>
</tbody>
</table>
9 Combination of transitions of a junction ........................................ 75
10 Transition split ................................................................. 75
11 New State ......................................................................... 75
12 New Transition ................................................................. 75
13 Module ............................................................................. 76
14 Exit sequence control constants ........................................... 76
15 Robotic platforms ............................................................. 76
16 Controllers ....................................................................... 77
17 Mapping from operations required by state machines to PRISM actions ........................................... 77
18 State machines ................................................................... 78
19 State machine body ............................................................ 79
20 Composite states ............................................................... 79
21 Exit a composite state ......................................................... 80
22 Exit substates .................................................................... 80
23 Exit a substate .................................................................... 80
24 Exit a simple substate .......................................................... 81
25 Exit a composite substate ..................................................... 81
26 Enter substates (with entry actions) ....................................... 81
27 Enter a substate (with an entry action) ................................. 82
28 Constants representing states for named elements ................. 82
29 Composite substates .......................................................... 82
30 Nodes (transitions) ............................................................. 83
31 Node (transitions) .............................................................. 83
32 Probabilistic junction (transitions) ......................................... 83
33 Other nodes (initial, normal junction, and states) (transitions) ................................................................................. 84
34 Transitions from a node ......................................................... 84
35 Action and target of a transition ............................................ 84
36 Transition from a node .......................................................... 85
37 Transition from an initial junction .......................................... 85
38 Transition from a probabilistic junction ................................. 85
39 Transition from a normal junction ......................................... 86
40 Transition from a state .......................................................... 87
41 Exit composite source state ................................................... 88
42 Exit simple source state ......................................................... 88
43 Actions ............................................................................... 88
44 Statements ......................................................................... 88
45 Statement ........................................................................... 89
46 Statement (Skip) .................................................................. 89
47 Statement (ParStmt) ............................................................ 89
48 Statement (Assignment) ......................................................... 89
49 Statement (CommunicationStmt) .......................................... 90
50 Statement (if Statements) ....................................................... 90
51 Statement (Call) ................................................................... 91
52 Statement (sequential composition) ....................................... 91
53 Statement (sequence of statements) .................................... 92
Asynchronous connections ........................................ 92
Asynchronous connection ........................................... 93
Asynchronous connection ........................................... 93
Connections: events renaming ..................................... 93
Connection: events renaming ....................................... 94
Connection: events renaming ....................................... 95
Asynchronous connection: events renaming ................. 95
Buffer ................................................................. 96
Simple Buffer ........................................................ 96
Input Events .......................................................... 97
Output Events ........................................................ 98
Simple Events ........................................................ 98
Empty Events .......................................................... 99
Is an operation fully defined ................................... 99
Get all called operations (that are provided by a robotic platform) in a StateMachineBody .................. 100
Get called operations (that are provided by a robotic platform) in a NodeContainer ................. 100
Get called operations (that are provided by a robotic platform) in a statement .................. 100
Operation definitions ............................................. 101
Partially defined operation definitions ....................... 102
Call Operations nondeterministically ......................... 103
Get operation definition ........................................... 103
Call Operation definitions ........................................ 103
Events occur nondeterministically ............................ 104
Get variable lists ..................................................... 104
Get required variable lists ........................................ 104
Is a constant variable ............................................. 105
Get events ............................................................ 105
Get required operations ........................................... 105
Get the exit action ................................................... 105
Has the exit action ................................................... 105
Get the entry action ................................................ 106
Has the entry action ................................................ 106
Conjunction of boolean expressions ........................... 106
Is a state composite ............................................... 106
Get the initial junction of a node container ............... 106
Get the final state of a node container ....................... 106
Get parameters and arguments pair ......................... 107
Enumerate all values in a type ................................ 107
All possible combinations of assignments to parameters of an operation .................. 107
Variable lists ........................................................ 107
Variables ............................................................. 108
Semantics of Collections ......................................... 136
Broadcast Buffer ..................................................... 137
<table>
<thead>
<tr>
<th></th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Semantics of triggers</td>
<td>137</td>
</tr>
<tr>
<td>4</td>
<td>Semantics of send event statements</td>
<td>137</td>
</tr>
<tr>
<td>1</td>
<td>Setter channel</td>
<td>165</td>
</tr>
<tr>
<td>2</td>
<td>Setter channel</td>
<td>165</td>
</tr>
<tr>
<td>3</td>
<td>Setter channel</td>
<td>165</td>
</tr>
<tr>
<td>4</td>
<td>Setter channels</td>
<td>166</td>
</tr>
<tr>
<td>5</td>
<td>Left setter channel</td>
<td>166</td>
</tr>
<tr>
<td>6</td>
<td>Left setter channel</td>
<td>166</td>
</tr>
<tr>
<td>7</td>
<td>Left setter channels</td>
<td>166</td>
</tr>
<tr>
<td>8</td>
<td>Right setter channel</td>
<td>166</td>
</tr>
<tr>
<td>9</td>
<td>Right setter channel</td>
<td>166</td>
</tr>
<tr>
<td>10</td>
<td>Right setter channels</td>
<td>166</td>
</tr>
</tbody>
</table>
1. Introduction

The current practice of programming mobile and autonomous robots does not reflect the modern outlook of their applications. Such practice is often based on standard state machines, without formal semantics, to describe the robot controller only, with time and probabilistic properties discussed in natural language. In the design stage, the state machine guides the development of a simulation, but no rigorous connection between them is established.

In this report, we present a state-machine based notation, called RoboChart, for the specification and design of robotic systems. State machines are frequently, though informally, used in presenting and explaining the patterns of behaviours of particular robotic systems. These extra constructs embed the notions of robotic platforms and their controllers; communication between controllers can be synchronous or asynchronous. Besides state machines, RoboChart includes elements to organise specifications, fostering reuse and taming complexity.

The state-machine notation is fully specified, including an action language and constructs to specify timing and probabilistic properties. Operations used in a state machine can be taken from a domain-specific API or defined by other state machines; communication between state machines inside a controller is synchronous. Operations can be given pre and postconditions.

The time primitives of RoboChart allow time budgets and deadlines to be specified for operations and events directly as part of a state machine. Constraints can be specified in association with the relative-time elapsed since the occurrence of events or the entering of states. Our time primitives are inspired by constructs of timed automata [26] and Timed CSP [29].

UML [25] state machines are popular. RoboChart, however, is customised for robotic applications,
via the extra notions of robotic platform, controller, and a specialised API. Moreover, RoboChart provides support for time and probabilistic specifications that to make it suitable for verification and automatic generation of simulations.

In this report, we formalise the semantics of the core and timed constructs of RoboChart using CSP [7]. Importantly, CSP is a front end for a mathematical model that supports a number analysis techniques such as model-checking, which provide a high degree of automation, as well as more powerful (but not automatic) verification based on interactive and theorem proving, namely, Hoare and He’s Unifying Theories of Programming [10] (UTP). Use of CSP enables model checking with FDR [31]. On the other hand, the underlying UTP model makes our core semantics adequate for extension to deal with time [6] and probability [13].

Chapter 2 describes RoboChart models, and Chapter 3 defines their well-formedness conditions. Chapter 4 presents their semantics of RoboChart in CSP. Chapter 5 presents the probabilistic semantics of RoboChart and the translation from RoboChart to PRISM. Chapter 5 describes the API available for modelling robotic systems. Chapter 6 presents a number of models specified in RoboChart. Finally, Chapter 8 concludes with a summary of the results and future work.
2 Language Structure .......................... 17
  2.1 RoboChart metamodel
  2.2 Timed Primitives

3 Well-formedness Conditions ............. 27
  3.1 Core Language
  3.2 Timed Language
  3.3 Probabilistic Language

4 Semantics ................................. 35
  4.1 Detailed Semantics: Core Language
  4.2 Detailed Semantics: Timed Language

5 Probabilistic Semantics ................. 65
  5.1 Overview
  5.2 Semantic Domain
  5.3 Translation to PRISM
2. Language Structure

In this chapter, we first describe the metamodel of RoboChart. For an overview of the language with an example, see Appendix A.

Sections A.1 describes the features to define time properties. Finally, Section 2.1 describes the RoboChart metamodel.

2.1 RoboChart metamodel

As explained above, a model is organised in packages, with their definitions shared using an imports mechanism similar to that of Java. Figure 2.1 defines a RoboChart package RCPackage. It has an optional name, and optionally imports other packages. All elements of a model are defined in a package. So, an RCPackage can include declarations of types, interfaces, modules, robotic platforms, controllers, and state machines.

The metamodel defines a notion of a ConnectionNode, which are components that may be connected via Connections. A RCPackage may define a number of such components, including ControllerDefs, RoboticPlatformDefs, and StateMachineDefs. These are shown in Figure 2.1 and their details are presented later in Figures 2.2 to 2.5. An interface groups variableLists, operations, events and clocks.
Chapter 2. Language Structure

2.1.1 Module

The structure of a module is detailed in Figure 2.2. It comprises a number of connection nodes and connections. ConnectionNodes are elements that can be connected, namely, platforms, controllers, and state machines. In the case of module, though, the connection nodes cannot be state machines, and this is enforced via a well-formedness condition presented in the next chapter. The RoboticPlatform can be given by a RoboticPlatformDefinition or a by a RoboticPlatformReference. The other forms of ConnectionNode are detailed in later diagrams.

Connections are between a source (from) and a target (to) node, and in a module they establish the relationship between a platform and its controllers. Connections are established via a source (efrom) and a target (eto) event. They can be asynchronous and bidirectional, as indicated by the boolean attributes async and bidirec. An event may or not have a type, which is an Expression that defines the values that can be communicated via the connection, if any.

As mentioned before, a module gives a complete account of a robotic system. It defines a robotic platform, or includes a reference to a platform defined elsewhere, to indicate the facilities available. Modules associate their robotic platforms with particular controllers to specify behaviour. RoboChart state machines are not designed to model parallel or distributed behaviours. These should be modelled at the level of controllers and modules.
2.1 RoboChart metamodel

The structure of a Controller is shown in Figure 2.3. It can be specified by a ControllerDefinition or a ControllerReference, which just names a controller defined elsewhere. A ControllerDefinition encapsulates any number of state machines and defines a Context.

The structure of a Context is detailed in Figure 2.4, but briefly it defines the variables, including constants, operations, events, clocks, and provided, required, and defined interfaces of an element. Defined interfaces of an element declare the variables, clocks and events that are used for the specification of its behaviour; they are possibly shared if several elements are used to specify that behaviour. Well formedness rules establish the valid uses of interfaces in each element.

A Context is a BasicContext that has also interfaces. A BasicContext has Variables, Operations, Events, and Clocks. Variables are grouped in variable lists, with a modifier that indicates whether they are constants or indeed variables. A Variable has a name, a type (Expression), and an initial value.

Figure 2.4 also gives the metamodel for an Operation. It has an OperationSignature, which
defines its parameters, whether it terminates and its preconditions and postconditions. If there is more than one precondition, the actual precondition of the operation is their conjunction. If there is more than one postcondition, their conjunction is the actual postcondition. An Operation can also be defined by a reference or by a StateMachineBody.

### 2.1.3 State Machine

The metamodel of RoboChart state machines is similar to that of UML state machines. Features that have been removed are parallel regions, history junctions, and interlevel transitions. Whilst the state machines are designed with sequential control in mind, they may be in parallel with other machines in the same controller and with other controllers. There is also space for parallelism in the execution of during actions.

The structure of a RoboChart state machine is shown in Figure 2.5. It can be specified by a StateMachineReference or by a StateMachineDefinition. A definition gives a name to a StateMachineBody, which, as already mentioned, describes a Context. A StateMachineBody is a NodeContainer, which is composed a number of Nodes and Transitions. A State is a Node, and can be final. A Junction is also a Node and can be initial, or a ProbabilisticJunction.

An initial node indicates where the execution of a state-machine starts, a connective node provides the means for structuring more complex path between nodes, and a final node indicates the termination of the state-machine (or of the behaviour of a state). We note that a final node is a state, as the machine can stay in a final node. An initial node, however, is actually a junction, since a machine cannot remain in the initial node. A precise terminology is that the initial state is the target of the only transition that can come out of an initial junction.

States are the main components of a state machine. A State has actions: entry, during, and exit actions, executed in particular phases of its life-cycle. A State is also a NodeContainer, since it can contain nodes and transitions supporting the hierarchical feature of state machines, where
composed states have a machine to define behaviour while in that state.

Transitions are directed connections between two nodes: a source and a target. They may be triggered by an event, guarded by a condition, and contain an action that is executed when the transition is taken and its source node has exited. We can also specify a deadline for a transition to be triggered, and associate it with a number of Clocks, that are reset when the transition is taken. Additionally, a transition may have a probability value (between 0 and 1) that captures the probability of the transition being triggered.

The concrete syntax of transitions is shown in Syntax 2.1.1. A TriggerLabel defines a trigger as a Communication, or a probability value as an Expression, but not both as they are mutually exclusive in a Transition. A TimedLabel defines zero or more Clock Resets and optionally a deadline as an Expression. In Label the Expression defines the guard condition and the Statement the action of the transition.

**Syntax 2.1.1 — Transition Label.**

```
Label ::= TriggerLabel TimedLabel ('['Expression']')? ('/'Statement)?
TriggerLabel ::= (Communication|'p{'Expression'}')?
TimedLabel ::= ClockReset* ('<{'Expression'}')?
ClockReset ::= '#'Clock
```

The syntax of Communications is described in Syntax 2.1.2. It consists of an input, output, sync or simple communication. The concrete syntax of the different types of communications is shown in Table 2.1.
Chapter 2. Language Structure

Figure 2.6: Metamodel of RoboChart type declarations

### Syntax 2.1.2 — Communication.

<table>
<thead>
<tr>
<th>Communication Type</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Communication (I)</td>
<td>Receives any value from the event and stores it on the variable.</td>
</tr>
<tr>
<td>Output Communication (O)</td>
<td>Sends the value of the expression through the event.</td>
</tr>
<tr>
<td>Sync Communication (Sync)</td>
<td>Synchronises on the event with the value of the expression.</td>
</tr>
<tr>
<td>Simple Communication (S)</td>
<td>Synchronises on the event.</td>
</tr>
</tbody>
</table>

Table 2.1: Types of Communications.

A Communication has an event, which can be on its own, associated with a value, or with a variable. In the first case, we have a Communication of type SIMPLE. Communications whose events are associated with a value correspond to a synchronisation (SYNC) or output (OUTPUT). Finally, communications whose events are associated with variables model input communications (INPUT).

#### 2.1.4 Type Declaration

The metamodel for TypeDecl is given in Figure 2.6. As indicated, a TypeDecl is a NamedExpression, which means its name can be used as an expressions. The class of TypeDecl includes PrimitiveTypes (given types in Z), NamedTypes (type aliases), RecordTypes and Enumerations. The latter defines a set of Literals.

#### 2.1.5 Expression

For simplicity, RoboChart adopts the type system of the Z Standard [1, 16]. This provides a simple and solid basis for implementation of all tools, including model checkers and theorem provers. It
also means that we do not need to specify the type system for RoboChart separately. Accordingly, the Expression language is also based on that of Z.

We note that, however, tools may take a pragmatic approach to facilitate the use of the Z mathematical toolkit. For example, if there is difficulty in providing facilities to record and use a mathematical toolkit, it might be hardcoded in a tool. We might also provide syntactic sugar (such as notation for dealing with arrays and matrices) for readability of expressions by roboticists. It is, however, the responsibility of the tool providers to justify compatibility with the Z notation. Specifically, a well typed RoboChart model accepted by a tool should correspond in a clear way to a model that is described purely using Z and its standard mathematical toolkit.

Precisely, the definition of Expression for RoboChart is that for Z [1, page 32], excluding all productions for schema constructs, but including the notation for Predicate [1, page 31] except for conjunction definitions using newline and ";", and relation operator application, which is captured by Application in Expression.

### 2.1.6 Action and Statement

Similarly, the action language is very simple. Syntax 2.1.3 gives the concrete syntax of statements used to define actions in states and transitions.

#### Syntax 2.1.3 — Statements.

```plaintext
Statement ::= 'skip'
| N '(' (Expr (',' Expr)*)? ')'  -- operation call
| 'if' Expr
  'then' Statement
  'else' Statement 'end'
| N '=' Expr  -- assignment
| N '!' Expr  -- output event
| N '??' N  -- input event
| N  -- simple synchronisation
| N '.' Expr  -- synchronisation
| Statement ';' Statement  -- sequential composition
| Statement '<{ Expr '}'  -- timed statement
| 'wait' '(' Expr ')'  -- wait statement
| 'wait' '(' '[' Expr ',' Expr ']' ')'  -- nondeterministic wait
| '#' N  -- clock reset
```

Statements can be used to construct state and transition actions. The syntax of state actions is shown in Syntax 2.1.4.
2.2 Timed Primitives

The time primitives are described separately in Figure 2.8. They are shown in the previous section for completeness, and summarised and explained here. The timed primitives appear in the syntax of expressions, statements, and transitions. A ClockExpression since is a condition involving a clock. A StateClockExpression is a sinceEntry expression. A TimedStatement defines a deadline to terminate as an Expression. A Wait and ClockReset are also statements. The delay defined by Wait is that defined by the attribute duration as an Expression. Finally, a Transition may define a deadline as an Expression, and may have zero or more Clock Resets. Table 2.3 gives the concrete syntax.
2.2 Timed Primitives

We observe that a TimedStatement defines a deadline to terminate, but not a deadline to start. The possibility to specify a deadline to start was considered, however, because statements like assignment and operation calls are immediate, only an event synchronisation or a Wait statement could introduce a delayed start. For example, consider the case where we have an assignment of expression $e$ to variable $x$, sequentially composed with a call to operation $\text{op}$ as $x := e ; \text{op}()$, then a deadline to start would be imposed on the assignment, which is immediate, and thus would be redundant. Another scenario arises if, instead, we consider the example $\text{Wait}(d) ; \text{op}()$. A starting deadline could constrain $\text{Wait}(d)$, however, if we were to specify this statement as an operation $\text{waitOp}()$, then the starting deadline on $\text{waitOp}()$ would be satisfied immediately, whereas this would not be the case for $\text{Wait}(d) ; \text{op}()$.

This section has given a diagrammatic overview of the metamodel. A textual representation that specifies all the details is presented in Appendix B.

<table>
<thead>
<tr>
<th>Element</th>
<th>Concrete Syntax</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock Expression</td>
<td>$\text{since}(C)$</td>
<td>Expression counting elapsed time since the last reset of clock $C$.</td>
</tr>
<tr>
<td>State Clock Expression</td>
<td>$\text{sinceEntry}(S)$</td>
<td>Expression counting elapsed time since entry of state $S$.</td>
</tr>
<tr>
<td>Timed Statement</td>
<td>$S &lt; {e}$</td>
<td>Statement $S$ is required to terminate within $e$ time units.</td>
</tr>
<tr>
<td>Wait</td>
<td>$\text{wait}(e)$</td>
<td>Waits for $e$ units of time.</td>
</tr>
<tr>
<td>Nondeterministic Wait</td>
<td>$\text{wait}([a,b])$</td>
<td>Waits nondeterministically for $d$ units of time where $a \leq d \leq b$.</td>
</tr>
<tr>
<td>Clock Reset</td>
<td>$#C$</td>
<td>Resets clock $C$.</td>
</tr>
<tr>
<td>Trigger deadline</td>
<td>$t &lt; {e}$</td>
<td>Transition trigger $t$ is required to take place within $e$ units.</td>
</tr>
</tbody>
</table>

Table 2.3: Timed Primitives.
3. Well-formedness Conditions

The metamodel presented in the previous chapters defines models that are not meaningful. A model is characterised by a module definition, and all other definitions used there, directly or indirectly. We now define a number of well-formedness conditions for a model. They encode restrictions that are necessary for an adequate semantics to be defined.

Well formedness requires well typedness. Here, however, we do not focus on this aspect, except where this is not standard for an expression or statement. The type system of RoboChart is the type system of Z[16].

We present the conditions related to each of the elements of the core language in Section 3.1. We also provide here justifications for the restrictions. We follow that with conditions on the timed language in Section 3.2.

3.1 Core Language

3.1.1 Robotic Platforms

RP1 Robotic platforms cannot require interfaces.
RP2 Defined interfaces can only have events.
RP3 The names of variables, operations, and events are unique to the platform.
RP4 Robotic platforms cannot contain clocks.

We note that variables and operations declared directly in the platform, outside an interface, are
considered as if declared in a provided interface, for the reasons already explained above. Events declared directly in the platform, on the other hand, are defined.

### 3.1.2 Interfaces

**I1** Provided interfaces contain only variables and operations, and required interfaces contain only variables, operation and clocks.

**I2** Defined interfaces contain only variables, events and clocks.

**I3** Names of variables, events, clocks and operations are unique.

### 3.1.3 Modules

**M1** A module must contain exactly one robotic platform, at least one controller, and no state machines or operations.

**M2** All variables and operations required by the module’s controllers must be provided by the platform.

**M3** Each event on the robotic platform and controllers of a module must have at most one connection to or from it within the module.

### 3.1.4 Connection

Both modules and controllers contain connections. Their conditions restrict the types of the connected elements, the nature of the connection, and the types of the associated events, which must be the same.

**Cn1** Connections of a module must associate only events of the robotic platform and its controllers.

**Cn2** Connections involving a robotic platform are always asynchronous.

**Cn3** Connections of a controller must associate only its events and those of its state machines.

**Cn4** Only events of the same type may be connected.

**Cn5** Bidirectional connections of a module may only involve events of a controller which are connected by bidirectional connections within the controller.

**Cn6** Non-bidirectional connections of a module may only connect to events of a controller which have a non-bidirectional connection from them within the controller.

**Cn7** Non-bidirectional connections of a module may only connect from events of a controller which have a non-bidirectional connection to them within the controller.

**Cn8** Non-bidirectional connections of a controller must not connect to events that a state machine uses as an output. (An event is considered to be an output if it is used in an OUTPUT or SYNC communication, or if it is used in an OUTPUT, SYNC or SIMPLE send statement.)

**Cn9** Non-bidirectional connections of a controller must not connect from events that a state machine uses as an input. (An event is considered to be an input if it is used in an INPUT or SIMPLE communication, or if it is used in an INPUT send statement.)
3.1 Core Language

Cn10 The to-event of a connection must be an event of its to-context and the from-event of a connection must be an event of its from-context.

Cn11 Connections between state machines are always synchronous.

3.1.5 Controllers

C1 A controller must contain at least one state machine.
C2 Controllers cannot provide variables or operations to other controllers.
C3 All variables required by the controller’s state machines must be provided or required by the controller.
C4 All operations required by the controller’s state machines, including the machines that define operations, must be required or defined by the controller.
C5 The names of variables, operations, and events are unique to the controller.
C6 Each event on state machines and boundary of a controller must have at most one connection to or from it within the controller.
C7 Operations must not be declared directly in a controller, but may be defined in the controller.
C8 Operations referenced in a controller must be unique, that is, there must not be two or more references to the same operation.
C9 Controllers cannot have clocks.
C10 Controllers cannot define interfaces that contain clocks.
C11 Controllers cannot require interfaces that contain clocks.
C12 The operations defined in a controller can require only operations that are either defined or required by that controller.

Variables and events declared directly in the controller are considered as part of a defined interface.

In C3, the state machines do not include those that define operations. The restriction on provision of variables for operations are catered for STM8. In C3, we cater for provision of variables by the controller.

3.1.6 State Machines

STM1 State machines cannot have provided interfaces
STM2 Operations in state machines can only be required, not defined.
STM3 Every state machine must have exactly one initial junction.
STM4 State machines must contain at least one state (possibly a final state).
STM5 The names of variables, operations, and events are unique to the machine.
STM6 State machines must not have operations declared directly within them.
STM7 State machines must not require interfaces containing clocks (only use them).
STM8 A state machine that requires an operation, including a machine that defines another operation, must define or require all variables required by that operation.
A state machine that requires an operation, including a machine that defines another operation, must define all events defined in that operation.

Like for controllers, variables and events declared directly, outside of an interface, in a state machine are regarded as part of a defined interface.

We note that we do not require that a machine that calls an operation \( \text{Op} \) provides the operations required by \( \text{Op} \). They must be provided by the controller, either by a definition, or by requiring it (from the platform). This is ensured by C4 in Section 3.1.5. This creates a lack of uniformity in the treatment of the context of a called operation. It is needed, however, since otherwise transitivity means that the machines have to provide all data (variables) for all operations that are directly or indirectly called.

### 3.1.7 States

- **S1** If a state has a non-empty set of nodes, then conditions 3 and 4 of state machines apply.
- **S2** A state has at most one of each type of action: entry, during, and exit.

### 3.1.8 Initial junctions

- **IJ1** An initial junction does not have incoming transitions.
- **IJ2** An initial junction must have exactly one outgoing transition.
- **IJ3** All junction conditions apply.

### 3.1.9 Junction

- **J1** A junction must contain at least one outgoing transition.
- **J2** The guards of the transitions out of a junction must form a cover.
- **J3** Transitions starting in junctions cannot have triggers.

### 3.1.10 Final states

- **FS1** Final states cannot be the source of transitions.
- **FS2** Final states cannot have actions.
- **FS3** Final states cannot have states or transitions.

### 3.1.11 Communications

- **Tg1** A communication of type SIMPLE has neither the parameter attribute nor the value attribute set. This is a pure synchronisations and does not involve exchange of values.
- **Tg2** A communication of type SIMPLE must use a typeless event. This is a pure synchronisations
and does not involve exchange of values.

Tg3 A communication of type INPUT must have a parameter attribute and cannot have its value attribute set.

Tg4 A communication of type OUTPUT or SYNC must have a value attribute and cannot have its parameter attribute set.

3.1.12 \( \rightarrow \) Transitions

T1 The source and target of a transition must belong to the same container.

T2 If a transition has a trigger, it must be of type INPUT or SIMPLE.

3.1.13 \( \circ \) Operations

O1 All state-machine conditions apply to operation definitions.

O2 Recursive and mutually recursive operations are not allowed.

3.1.14 \( \times \) Variables

V1 If the initial value of a required variable or constant of a state machine or controller is defined, it must be consistent with the value of any (complementing) variable provided by the contexts (controllers or modules) where the state machine or controller is used.

3.1.15 \( \ast \) Expressions

E1 The variables declared in a set comprehension must not have initial values.

E2 Quantified variables in existential and universal quantifications must not have initial values.

E3 The variables quantified in a lambda expression must not have initial values.

3.2 Timed Language

3.2.1 State Machines

TSTM1 A state machine that requires an operation, including a machine that defines another operation, must define or require all clocks required in that operation.

We note that a state machines that does not define an operation, but defines the behaviour of a controller, cannot requires a clock (see STM7). In this case, if it requires an operation, it must define the clocks required by that operation.
3.2.2 Transitions

TT1 A transition with a deadline must have a trigger.

3.2.3 Timed Expressions

TE1 Expressions involving since(C) and sinceEntry(S) are only permitted in transition guards.

TE2 The clock C in an expression since(C) may only reference a clock declared within the expression’s containing state-machine.

TE3 The state S in an expression sinceEntry(S) may only reference a state, and not a Final state, within the containing expression’s state-machine.

TE4 The expressions since(C) or sinceEntry(S) may only occur in a comparison expression in which the other branch is an expression that does not involve other since(C2) or sinceEntry(S2). A consequence of this restriction is that no expression can compare the value of two clocks as given by since(C) or sinceEntry(S).

TE5 An expression sinceEntry(S) may only reference a state S within the same node container as the transition whose guard uses sinceEntry(S).

Name Disambiguation in State Clock Expressions

When a state name S, referenced in a state clock expression, is ambiguous, because, for instance, there is a state and a substate with the same name in the same state machine, the fully qualified name of the state S must be used.

3.2.4 Timed Statements

TS1 A clock reset #C may only reference a clock declared within the action’s containing state-machine, or in the case of a transition, within the transitions’s containing state-machine.

TS2 In a non-deterministic wait([m,n]) the condition m < n must hold.

3.3 Probabilistic Language

3.3.1 Transitions

PT1 The source of a transition with a probability value must be a probabilistic junction, that is, states, initial junctions, and normal junctions cannot be the sources of these probabilistic transitions.

PT2 The probability value of a transition must be between 0 and 1.
3.3.2 Probabilistic Junction

Probabilistic Junctions are also junctions, but with extra well-formedness conditions.

PJ1 There must be a probability value on every outgoing transition from a probabilistic junction.
PJ2 There must not be a guard on an outgoing transition from a probabilistic junction.
PJ3 The probability values of all outgoing transitions from a probabilistic junction must sum to 1.
4. Semantics

For the purpose of this semantics, the functions \( \text{vid} \), \( \text{eventId} \), and \( \text{id} \) calculate unique identifiers for their parameters, which are, respectively, variables, events and node containers (states and state machines). One possible implementation of such functions is to calculate the qualified name, and this is the implementation realised by RoboTool.

Additionally, in the semantics the set of events \( \text{Event} \) contains an event \( \text{internal} \), that corresponds to the event of a triggerless transitions. In the implementation RoboTool, this is represented in the trigger by a null value, and the semantic rules have been adapted to handle it appropriately.

Finally, we assume the existence of a function that takes an expression and returns the set of variables used in that expression.

An overview of the semantics presented here, and a detailed explanation of many of the semantic definitions can be found in [5]. The complete definition is given in the sequel.
4.1 Detailed Semantics: Core Language

4.1.1 Modules

**Rule 1. Semantics of modules**

\[
\begin{align*}
\Gamma & : \text{Context} \\
\Theta & : \text{Module} \\
\end{align*}
\]

\[
\begin{align*}
\text{modMemory}'(m) & := \\
\text{composeControllers}'(m, 
\text{ctrls}, \text{cons}) & := \\
\text{hiddenModuleChannels}'(m) & := \\
\Theta & : \text{end} \cup \{\text{Skip}\} \\
\end{align*}
\]

where

\[
\begin{align*}
\text{ctrls} & = (x : m.\text{controllers}) \\
\text{cons} & = m.\text{connections} \\
\text{asyncs} & = \{c : m.\text{connections} \mid c.\text{async} \land \{c.\text{from}, c.\text{to}\} \cap \text{RoboticPlatform} = \emptyset\} \\
\text{evasyncs} & = \{c : \text{asyncs} \cup \text{eventId}(c.\text{eto}) \cup \{c : \text{asyncs} \cup \text{eventId}(c.\text{efrom})\}
\end{align*}
\]

**Rule 2. Hidden Module channels**

\[
\text{hiddenModuleChannels}(m : \text{Module}) : \text{ChannelSet} =
\]

\[
\{c : \text{asyncs} \cup \text{eventId}(c.\text{eto}) \cup \{c : \text{asyncs} \cup \text{eventId}(c.\text{efrom})\} \cup \text{memoryChannels}'(m)
\]

where

\[
\text{asyncs} = \{c : m.\text{connections} \mid c.\text{async} \land \{c.\text{from}, c.\text{to}\} \cap \text{RoboticPlatform} = \emptyset\}
\]

**Rule 3. Memory channels**

\[
\text{memoryChannels}(m : \text{Module}) : \text{ChannelSet} =
\]

\[
\{v : \text{allLocalVariables}'(rp) \cup \text{set}_{\text{vid}}(v)\} \cup \\
\{v : \text{allLocalConstants}'(rp) \cup \text{set}_{\text{vid}}(v)\} \cup \\
\{c : m.\text{controllers} \cup \{v : \text{requiredVariables}'(c) \cup \text{set}_{\text{EXT}_{\text{vid}}}(v, c)\}
\]

where

\[
\text{rp} = \text{roboticPlatformDefinition}(m)
\]

The set channels for the constants of the platform are hidden here. If the initial value is not defined, this introduces a non-determinism as all possible initial values are considered. These sets are also synchronised with the controllers to guarantee that the constant value is the same in the controllers.

**Rule 4. Function allEvents**

\[
\text{allEvents}(c : \text{Context}) : \text{Set(\text{Event})} = \\
\text{c.events} \cup \bigcup_{i : c.\text{interfaces} \cup \text{c.events}}
\]
Rule 5. Function allVariables

\[
\text{allVariables}(c: \text{Context}) : \text{Set(Variable)} = \\
\bigcup \{ l : c.\text{variableList} \mid \text{modifier} == \text{'var' \cdot l.vars} \} \\
\bigcup \{ l : c.\text{PInterfaces} \cdot \bigcup \{ i : c.\text{variableList} \mid \text{modifier} == \text{'var' \cdot l.vars} \} \} \\
\bigcup \{ l : c.\text{RInterfaces} \cdot \bigcup \{ i : c.\text{variableList} \mid \text{modifier} == \text{'var' \cdot l.vars} \} \} 
\]

Rule 6. Function requiredVariables

\[
\text{requiredVariables}(c: \text{Context}) : \text{Set(Variable)} = \\
\bigcup \{ l : c.\text{variableList} \mid \text{modifier} == \text{'var' \cdot l.vars} \} \\
\bigcup \{ l : c.\text{PInterfaces} \cdot \bigcup \{ i : c.\text{variableList} \mid \text{modifier} == \text{'var' \cdot l.vars} \} \} 
\]

Rule 7. Function allLocalVariables

\[
\text{allLocalVariables}(c: \text{Context}) : \text{Set(Variable)} = \\
\bigcup \{ l : c.\text{variableList} \mid \text{modifier} == \text{'var' \cdot l.vars} \} \\
\bigcup \{ l : c.\text{PInterfaces} \cdot \bigcup \{ i : c.\text{variableList} \mid \text{modifier} == \text{'var' \cdot l.vars} \} \} 
\]

Rule 8. Function allConstants

\[
\text{allConstants}(c: \text{Context}) : \text{Set(Variable)} = \\
\bigcup \{ l : c.\text{variableList} \mid \text{modifier} == \text{'const' \cdot l.vars} \} \\
\bigcup \{ l : c.\text{PInterfaces} \cdot \bigcup \{ i : c.\text{variableList} \mid \text{modifier} == \text{'const' \cdot l.vars} \} \} \\
\bigcup \{ l : c.\text{RInterfaces} \cdot \bigcup \{ i : c.\text{variableList} \mid \text{modifier} == \text{'const' \cdot l.vars} \} \} 
\]

Rule 9. Function requiredConstants

\[
\text{requiredConstants}(c: \text{Context}) : \text{Set(Variable)} = \\
\bigcup \{ l : c.\text{variableList} \mid \text{modifier} == \text{'const' \cdot l.vars} \} \\
\bigcup \{ l : c.\text{PInterfaces} \cdot \bigcup \{ i : c.\text{variableList} \mid \text{modifier} == \text{'const' \cdot l.vars} \} \} 
\]

Rule 10. Function allLocalConstants

\[
\text{allLocalConstants}(c: \text{Context}) : \text{Set(Variable)} = \\
\bigcup \{ l : c.\text{variableList} \mid \text{modifier} == \text{'const' \cdot l.vars} \} \\
\bigcup \{ l : c.\text{PInterfaces} \cdot \bigcup \{ i : c.\text{variableList} \mid \text{modifier} == \text{'const' \cdot l.vars} \} \} 
\]

Rule 11. Function requiredOperations

\[
\text{requiredOperations}(c: \text{Context}) : \text{Set(Operation)} = \\
\bigcup \{ l : c.\text{PInterfaces} \cdot \text{i.operations} \} 
\]
Rule 12. Module Memory

\[
\text{modMemory}(m : \text{Module}) : \text{CSPProcess} = \\
\begin{align*}
\text{let } & \text{Memory}(vars) \equiv \forall v : \text{lvars} \bullet \text{set}\_\text{vid}(v) \Rightarrow x \rightarrow \\
& (\exists c \in \text{controllers}(v) \bullet \text{set}\_\text{Ext}\_\text{vid}(v, c) : x \rightarrow \text{Skip}) ; \\
& \text{Memory}(vars|\text{name}(v) := x)) \\
\text{within} & \\
& \text{constInit}^1(rp); \text{Memory}(\text{varvalues})
\end{align*}
\]

For each constant, in interleaving, the module memory either sets the initial value if it is defined, or queries it.

Rule 13. Constants Initialisation for Controllers and Modules

\[
\text{constInit}(\text{node} : \text{ConnectionNode}) : \text{CSPProcess} = \\
\begin{align*}
\begin{array}{c}
\iff c \in \text{consts} \bullet \\
\begin{cases}
\text{if } c.\text{initial} \neq \text{NULL} & \text{then set}_\text{vid}(c)![[c.\text{initial}]]_{\text{expr}} \rightarrow \text{Skip} \\
\text{else} & \text{set}_\text{vid}(c)?!\text{name}(c) \rightarrow \text{Skip}
\end{cases}
\end{array}
\end{align*}
\]

where
\[
\text{consts} = \text{allConstants}^1(\text{node})
\]

The function \text{initial} picks an initial value of the appropriate type for a variable. If the variable defines an initial value, this value is used.

Rule 14. Composition of controllers

\[
\text{composeControllers}(m : \text{Module}, \text{ctrls} : \text{Seq}(\text{Controller}), \text{cons} : \text{Set}(\text{Connection})) : \text{CSPProcess} = \\
\begin{cases}
\text{if } \#\text{ctrls} = 1 & \text{then renamingController}^1(m, \text{headctrls}, \text{cons}) \\
\text{else} & \text{renamingController}^2(m, \text{headctrls}, \text{cons}) \\
& \text{composeControllers}^2(m, \text{tailctrls}, \text{cons})
\end{cases}
\]

where
\[
\text{connevts} = \text{renCtrlEvts}^1(m, \text{headctrls}, \text{cons}) \cap \\
\bigcup\{c : \text{tailctrls} \bullet \text{renCtrlEvts}^2(m, c, \text{cons})\}
\]
### Rule 15. Renaming controller

renamingController(m : Module, c : Controller, cons : Set(Connection)) : CSPProcess =

\[
\begin{align*}
\text{CSPProcess} &= \left[\begin{array}{l}
\{ e : \text{internalConns} \cdot \text{eventId}(e.efrom).in \leftarrow \text{eventId}(e.efrom).out \} \\
\cup \{ e : \text{internalConns} \cdot \text{eventId}(e.efrom).out \leftarrow \text{eventId}(e.efrom).in \} \\
\cup \{ e : \text{fromPlatform} \cdot \text{eventId}(e.efrom) \leftarrow \text{eventId}(e.efrom) \} \\
\cup \{ e : \text{toPlatform} \cdot \text{eventId}(e.efrom) \leftarrow \text{eventId}(e.efrom) \} \\
\cup \{ v : \text{requiredConstants} \cdot \text{set_vid}(v) \leftarrow \text{set_vid}(v,m) \}
\end{array}\right]
\]

where

- internalConns = \{ x : \text{cons} \cdot \{ x.\text{from},x.\text{to} \} \subseteq \text{Controller} \land \neg x.\text{async} \land c \in \{ x.\text{from},x.\text{to} \} \}
- toPlatform = \{ x : \text{cons} \cdot x.\text{from} = c \land x.\text{to} \in \text{RoboticPlatform} \}
- fromPlatform = \{ x : \text{cons} \cdot x.\text{to} = c \land x.\text{from} \in \text{RoboticPlatform} \}

The controller’s *set_* events for required constants are renamed to match the *set_* event for the corresponding provided constants of the module (*container(c)*).

### Rule 16. Renaming controller events

renCtrlEvts(m : Module, c : Controller, cons : Set(Connection)) : ChannelSet =

\[
\begin{align*}
\text{ChannelSet} &= \{ x : \text{internalConns} \cdot \text{eventId}(x.\text{efrom}) \} \cup \{ \text{end} \} \cup \{ x : \text{requiredConstants} \cdot \text{set_vid}(x,m) \}
\end{align*}
\]

where

- internalConns = \{ x : \text{cons} \cdot \{ x.\text{from},x.\text{to} \} \subseteq \text{Controller} \land \neg x.\text{async} \land c \in \{ x.\text{from},x.\text{to} \} \}

Controllers that require the same constant synchronise with each other on the *set_* event of the module, as well as with the module memory.

### Rule 17. Buffer

buffer(c : Connection) : CSPProcess =

\[
\begin{align*}
\text{if } c.\text{mult} \text{ then} \\
\text{singleBuffer(c.efrom,c.eto)} \parallel \text{singleBuffer(c.eto,c.efrom)} \\
\text{else} \\
\text{singleBuffer(c.efrom,c.eto)}
\end{align*}
\]
Rule 18. Single buffer
\[\text{singleBuffer}(\text{efrom} : \text{Event}, \text{eto} : \text{Event}) : \text{CSPProcess} = \]

\[
\text{if} \ \text{efrom.type} \neq \text{null} \\text{then} \\
\text{let} \ \text{Buffer}(()) \triangleq \text{eventId}(\text{efrom}) \cdot \text{out} \? x \rightarrow \text{Buffer}(x) \\
\text{Buffer}((v)) \triangleq \text{eventId}(\text{efrom}) \cdot \text{out} \? x \rightarrow \text{Buffer}(x) \cdot \text{signal} \text{eto} \cdot \text{in} ! v \rightarrow \text{Buffer}() \\
\text{within} \ \text{Buffer}() \\
\text{else} \ \text{let} \ \text{Buffer}(\text{false}) \triangleq \text{eventId}(\text{efrom}) \cdot \text{out} \rightarrow \text{Buffer}(\text{true}) \\
\text{Buffer}(\text{true}) \triangleq \text{eventId}(\text{efrom}) \cdot \text{out} \rightarrow \text{Buffer}(\text{true}) \cdot \text{signal} \text{eto} \cdot \text{in} \rightarrow \text{Buffer}(\text{false}) \\
\text{within} \ \text{Buffer}(\text{false})
\]

4.1.2 Controllers

Rule 19. Semantics of controllers
\[
\left[\text{c} : \text{ControllerDef}\right] : \text{CSPProcess} = \\
\text{let} \\
\text{for each op : c.lOperations} : \left(\text{nproc}(\text{op})(\text{x : op.parameters} \cdot \text{x.name})\right) = \left[\text{opdef}^{\text{op}}_{\text{c}}\right]^{\text{STM}} \\
\text{for each op : requiredOperations}\ (c) : \left(\text{nproc}(\text{op})(\text{x : op.parameters} \cdot \text{x.name})\right) = \\
\text{op.name} \text{Call} \cdot \{\text{x : op.parameters} \cdot \text{x.name}\} \rightarrow \text{SKIP} \\
\text{within} \ \\
\text{composeMachines}\ (c, \text{ms}, \text{cs})^{\text{nops}} \cdot \text{ctrlMemory}\ (c) \\
\text{where} \\
\text{ms} = \{\text{x : c.machines}\} \\
\text{cs} = \{\text{c.connections}\} \\
\text{opdef} = \text{findOperationDefinition}(\text{op}, \text{c.lOperations}) \\
\text{nops} = \{\text{op : c.lOperations} \cdot \text{id}(\text{op}) \rightarrow \text{nproc}(\text{op})\} \cup \\
\{\text{op : requiredOperations}\ (c) \cdot \text{id}(\text{op}) \rightarrow \text{nproc}(\text{op})\} \\
\text{lvars} = \{\text{v : allLocalVariables}\ (c) \cdot \text{set_vid}(\text{v})\} \\
\text{rvvars} = \{\text{v : requiredVariables}\ (c) \cdot \text{setExt_vid}(\text{v})\} \\
\text{lconsts} = \{\text{v : allLocalConstants}\ (c) \cdot \text{set_vid}(\text{v})\} \\
\text{rconsts} = \{\text{v : requiredConstants}\ (c) \cdot \text{set_vid}(\text{v})\}
\]

The state machine synchronise with the memory controller on the set events of all constants of the controller (required and local), but only the set events of the local constants are hidden. The set events of the required variables are later renamed and synchronised with the memory of the module.
Rule 20. Controller Memory

ctrlMemory(c : ControllerDef) : CSPProcess =

let Memory(vars) =

\[
\begin{align*}
\forall v : lvars \bullet \text{set\_vid}(v) & \cdot \text{x} \\
(\exists m : \text{rmachines}(v) \bullet \text{set\_Ext\_vid}(v, m) & \cdot \text{x} \rightarrow \text{Skip}); \\
\text{Memory}(\text{vars}[\text{name}(v) := \text{x}])
\end{align*}
\]

within

\[\text{constinit}^2(c) : \text{Memory}(\text{varvalues})\]

where

\[
\begin{align*}
\text{ms} &= c.\text{machines} \\
lvars &= \text{allLocalVariables}^4(c) \\
rvars &= \text{requiredVariables}^4(c) \\
\text{vars} &= (v : rvars \cup lvars \bullet \text{name}(v)) \\
\text{varvalues} &= (v : rvars \cup lvars \bullet \text{initial}(v)) \\
\text{rmachines} &= \lambda v \bullet \{ m : \text{ms} | v \in \text{requiredVariables}^5(m) \}.
\end{align*}
\]

Similarly to the module memory, the controller memory initially reads the value of each constant in the controller. Both local and required constants are initialised here. The synchronisation between the controller and the module guarantee that the required constants (that are provided by the module) are initialised with the same value.

Rule 21. Composition of machines

composeMachines(c : Controller, ms : Seq(StateMachineDef), cons : Set(Connection))^{nops} : CSPProcess =

if \#ms = 1 then

renamingMachine^1(c, headms, \text{cons})^{nops}

else

renamingMachine^2(c, headms, \text{cons})^{nops}

\[\text{connevts}\]

composeMachines^2(c, tailms, \text{cons})^{nops}

where

\[\text{connevts} = \text{renStmEvts}^1(c, \text{headms}, \text{cons}) \cup \bigcup \{ m : \text{tailms} \bullet \text{renStmEvts}^2(c, m, \text{cons}) \} \]
**Rule 22. Renaming state machine**

\[
\text{renamingMachine}(c \colon \text{Controller}, m \colon \text{StateMachineDef}, \text{cons} \colon \text{Set(Connection)}))^{\text{tops}} : \text{CSPProcess} =
\[
\begin{array}{c}
\{ e \colon \text{internalConns} \bullet \text{eventId}(e.e.to), \text{in} \leftarrow \text{eventId}(e.e.from), \text{out} \} \\
\cup \{ e \colon \text{internalConns} \bullet \text{eventId}(e.e.to), \text{out} \leftarrow \text{eventId}(e.e.from), \text{in} \} \\
\cup \{ e \colon \text{fromController} \bullet \text{eventId}(e.e.to) \leftarrow \text{eventId}(e.e.from) \} \\
\cup \{ e \colon \text{toController} \bullet \text{eventId}(e.e.from) \leftarrow \text{eventId}(e.e.to) \} \\
\cup \{ v \colon \text{requiredConstants}^x(m) \bullet \text{set}_\text{vid}(v) \leftarrow \text{set}_\text{vid}(v,c) \}
\end{array}
\]

where

\[
\text{internalConns} = \{ x \colon \text{cons} \bullet \{ \text{x.from,x.to} \} \subseteq \text{StateMachine} \wedge m \in \{ \text{x.from,x.to} \} \}
\]

\[
\text{toController} = \{ x \colon \text{cons} \bullet \text{x.from} = m \wedge \text{x.to} \in \text{Controller} \}
\]

\[
\text{fromController} = \{ x \colon \text{cons} \bullet \text{x.to} = m \wedge \text{x.from} \in \text{Controller} \}
\]

**Rule 23. Renaming machine events**

\[
\text{renStmEvts}(c \colon \text{Controller}, m \colon \text{StateMachineDef}, \text{cons} \colon \text{Set(Connection)})) : \text{ChannelSet} =
\]\[
\begin{array}{c}
\{ x \colon \text{internalConns} \bullet \text{eventId}(x.e.from) \} \cup \{ \text{end} \} \\
\cup \{ x \colon \text{requiredConstants}^x(m) \bullet \text{set}_\text{vid}(x,c) \}
\end{array}
\]

where

\[
\text{internalConns} = \{ x \colon \text{cons} \bullet \{ \text{x.from,x.to} \} \subseteq \text{StateMachine} \wedge m \in \{ \text{x.from,x.to} \} \}
\]

### 4.1.3 State machines

**Rule 24. Semantics of state machine**

\[
\text{[[stm : StateMachineBody]]}^{\text{tops}} : \text{CSPProcess} =
\]

The rule is split according to the type of \( \text{stm} \).

**Rule 25. Semantics of state machine**

\[
\text{[[stm : StateMachineDef]]}^{\text{tops}} : \text{CSPProcess} =
\]\[
\begin{array}{c}
\left( \begin{array}{c}
\left( \text{stateful} \ (\text{stm}) \ \text{\&} \ \{ \text{end} \} \ ; \ \text{SStop} \ \triangle \ \text{end} \rightarrow \text{Skip} \right) \\
\text{[[v : requiredVariables}^x(\text{stm}) \mid \text{share} \leftarrow \text{set}_\text{EXT}\_\text{vid}(v)]] \\
\text{[[\{\text{shared}\}]]} \\
\text{Skip} \\
\text{sharedVarSync} \cup \text{sharedConstSync} \cup \{ \text{end} \} \\
\left( \text{sharedVarMemory}^x(\text{stm}) \mid \{ \text{end} \} \right) \text{sharedConstMemory}(\text{stm}) \\
\end{array} \right) \\
\text{\&} \text{sharedVarHide} \cup \text{sharedConstSync}
\end{array}
\]

where

\[
\text{sharedVarSync} = \{ v : \text{requiredVariables}^x(\text{stm}) \bullet \text{get}_\text{vid}(v), \text{set}_\text{vid}(v), \text{set}_\text{EXT}\_\text{vid}(v) \}
\]

\[
\text{sharedVarHide} = \{ v : \text{requiredVariables}^x(\text{stm}) \bullet \text{get}_\text{vid}(v) \}
\]

\[
\text{sharedConstSync} = \{ v : \text{requiredConstants}^x(\text{stm}) \bullet \text{get}_\text{vid}(v) \}
\]

The semantic rule for operations is simpler, in that it does not have a model of the shared variables.
This is because the memory for state machines needs to conform to the semantics of Controllers, whereas operations do not engage in set_{\text{EXT}} events directly. Instead, they synchronise on shared events, as well as on set and get events for all required variables.

**Rule 26. Get and set channels**

getsetChannels(s : StateMachineDef) : ChannelSet =

\[
\{\forall v : \text{allVariables}^1(s) \cdot \text{get}_{\text{vid}}(v)\} \cup \{\forall v : \text{allVariables}^2(s) \cdot \text{set}_{\text{vid}}(v)\} \cup \\
\{\forall v : \text{allConstants}^2(s) \cdot \text{get}_{\text{vid}}(v)\} \cup \{\forall v : \text{allConstants}^3(s) \cdot \text{set}_{\text{vid}}(v)\}
\]

**Rule 27. Semantics of defined operations**

\[
[[\text{stm} : \text{OperationDef}]_{\text{STM}} : \text{CSPProcess} = \]

\[
\text{stateful}^2(\text{stm}) \setminus \{\text{end}\} \\
\text{where} \\
\text{stm.nodes} > 0
\]

**Rule 28. Semantics of undefined operations**

\[
[[\text{stm} : \text{OperationDef}]_{\text{STM}} : \text{CSPProcess} = \\
\text{let} \\
\quad \text{Aux} = \text{SS} \triangle (\text{Skip} \triangledown \text{Stop} \triangledown (\langle \text{Events} \triangledown \text{Variables} : \text{Aux} \rangle) \\
\quad \text{Variables} = \begin{cases} 
\text{if} \#\text{vars} > 0 \text{ then } & \exists e : \text{vars} \cdot \text{set}_{\text{vid}}(v) \rightarrow \text{Skip} \triangledown \text{get}_{\text{vid}}(v) \rightarrow \text{Skip} \\
\text{else} & \text{Stop} 
\end{cases} \\
\quad \text{Events} = \begin{cases} 
\text{if} \#\text{events} > 0 \text{ then } & \exists e : \text{events} \cdot e \rightarrow \text{Skip} \\
\text{else} & \text{Stop} 
\end{cases} \\
\text{within} \\
\text{Aux} \\
\text{where} \\
\text{stm.nodes} = 0 \\
\text{stm.terminates} = \text{false} \\
\text{vars} = \text{allVariables}^3(\text{stm}) \\
\text{events} = \text{allEvents}^1(\text{stm})
\]

**Rule 29. Stateful component of state machine body**

\[
\text{stateful}(\text{stm} : \text{StateMachineBody})^{\text{nops}} : \text{CSPProcess} = \\
\text{let} \\
\text{Stateful} = \left( \begin{array}{c} \\
\text{MachineBody} \\
\text{let} \text{getsetLocalChannels}^{1}(\text{stm}) \cup \{\text{end}\} \\
\text{varMemory}^{1}(\text{stm}) \cup \{\text{end}\} \text{ constMemory}^{1}(\text{stm}) \\
\text{getsetLocalChannels}^{2}(\text{stm}) \\
\text{MachineBody} = \left( \begin{array}{c} \\
\text{nops} [\{\text{interrupt}\}] \text{ Skip} \right) \ \text{ \ enteredSS} \\
\end{array} \right) \\
\text{within} \\
\text{Stateful} \\
\text{where} \\
\text{enteredSS} = \{x : \text{stm}.\text{nodes} \ast \text{entered}.\text{id}(x)\}
\]

**Rule 30. Get and set local channels**

\[
\text{getsetLocalChannels}(s : \text{StateMachineBody}) : \text{ChannelSet} = \\
\{v : \text{allLocalVariables}^{5}(s) \ast \text{get}.\text{vid}(v), \text{set}.\text{vid}(v)\} \cup \\
v : \text{allLocalConstants}^{3}(s) \ast \text{get}.\text{vid}(v), \text{set}.\text{vid}(v)\}
\]

The state machine hides all \textit{get} events for both constants and variables, but only hides the \textit{set} events for local constants and variables.

**Memory**

**Rule 31. Variable memory**

\[
\text{varMemory}(\text{stm} : \text{Context}) : \text{CSPProcess} = \\
\text{if} \ #\text{allLocalVariables}^{6}(\text{stm}) > 0 \\
\{\text{end}\} \ v : \text{allLocalVariables}^{7}(\text{stm}) \ast \text{Memory}^{1}(v) \\
\text{else} \\
\text{end} \rightarrow \text{Skip}
\]

**Rule 32. Constant memory**

\[
\text{constMemory}(\text{stm} : \text{Context}) : \text{CSPProcess} = \\
\text{if} \ #\text{allLocalConstants}^{4}(\text{stm}) > 0 \\
\{\text{end}\} \ v : \text{allLocalConstants}^{5}(\text{stm}) \ast \text{Constant}^{1}(v) \\
\text{else} \\
\text{end} \rightarrow \text{Skip}
\]
Rule 33. Shared variables memory

\[
\text{sharedVarMemory}(\text{stm} : \text{Context}) : \text{CSPProcess} =
\]

\[\begin{align*}
\text{if } \# \text{requiredVariables}^{\text{v}}(\text{stm}) &> 0 \\
\left[\text{\{end\} v : \text{requiredVariables}^{\text{v}}(\text{stm}) \cdot \text{sharedMemory}^{\text{v}}(v)\right] & \text{else} \\
\text{end} & \rightarrow \text{Skip}
\end{align*}\]

Rule 34. Shared constants memory

\[
\text{sharedConstMemory}(\text{stm} : \text{Context}) : \text{CSPProcess} =
\]

\[\begin{align*}
\text{if } \# \text{requiredConstants}^{\text{v}}(\text{stm}) &> 0 \\
\left[\text{\{end\} v : \text{requiredConstants}^{\text{v}}(\text{stm}) \cdot \text{sharedConst}^{\text{v}}(v)\right] & \text{else} \\
\text{end} & \rightarrow \text{Skip}
\end{align*}\]

Rule 35. Individual variable memory

\[
\text{Memory}(v : \text{Variable}) : \text{CSPProcess} =
\]

\[\begin{align*}
\text{let } \\
\text{Memory}(x) = & \text{get}_{\text{vid}}(v) !x \rightarrow \text{Memory}(x) \Box \text{set}_{\text{vid}}(v) ?x \rightarrow \text{Memory}(x) \Box \text{end} \rightarrow \text{Skip} \\
\text{within} \\
\text{if } v.\text{initial} \neq \text{null} & \text{ Memory} \left(\left[\text{x.initial}\right]_{\text{Expr}}\right) \\
\text{else} & \prod i : \left[\text{v.type}\right]_{\text{Expr}} \cdot \text{Memory}(i)
\end{align*}\]

Rule 36. Individual constant

\[
\text{Constant}(v : \text{Variable}) : \text{CSPProcess} =
\]

\[\begin{align*}
\text{let } \\
\text{Constant}(x) = & \text{get}_{\text{vid}}(v) !x \rightarrow \text{Constant}(x) \Box \text{end} \rightarrow \text{Skip} \\
\text{within} \\
\text{if } v.\text{initial} \neq \text{null} & \text{ Constant} \left(\left[\text{v.initial}\right]_{\text{Expr}}\right) \\
\text{else} & \prod i : \left[\text{v.type}\right]_{\text{Expr}} \cdot \text{Constant}(i)
\end{align*}\]
4.1.4 NodeContainers

The semantics of a node container is split into three rules for convenience.

**Rule 39. Node container semantics**
\[
\llbracket nc : \text{NodeContainer} \rrbracket^{\text{nops}} : \text{CSPProcess} =
\]
\[\text{ncBehaviour}^{1}(nc)^{\text{nops}}\]

**Rule 40. Node container behaviour**
\[
\text{ncBehaviour}(nc : \text{NodeContainer})^{\text{nops}} : \text{CSPProcess} =
\]
\[(\text{ncCoreBehaviour}^{1}(nc)^{\text{nops}} \{ \text{enter, exit, exited, internal} \})^{\text{nops}} \cdot \text{renameTriggerEvents}^{1}(nc)^{\text{nops}}\]
We observe that in the meta parallel composition, the variables that are considered to be written in parallel by the semantics of the transitions is the empty set. This assumption is possible given that there is sequentiality between the moment a transition is taken (and some node is interrupted) and the possibility to change a variable in a transition, either via an InputCommunication trigger, or as a Transition’s action.
Rule 44. Function usedVariables

\[
\text{usedVariables}(s : \text{Statement}) : \text{Set}(\text{Variable}) = \\
\begin{align*}
\text{if } s & \in \text{Assignment} \text{ then} \\
\text{usedVariables}^2(s.\text{right}) \\
\text{else if } s & \in \text{Call} \text{ then} \\
\bigcup \{ x : s.\text{args} \bullet \text{usedVariables}^3(x) \} \\
\text{else if } s & \in \text{IfStatement} \text{ then} \\
\text{usedVariables}^4(s.\text{expression}) \\
\text{else if } s & \in \text{CommunicationStmt} \land s.\text{communication.type} \in \{ \text{SYNC}, \text{OUTPUT} \} \text{ then} \\
\text{usedVariables}^5(s.\text{communication.value}) \\
\text{else if } s & \in \text{ParStmt} \\
\text{usedVariables}^6(s.\text{stmt}) \\
\text{else if } s & \in \text{SeqStatement} \\
\text{usedVariables}^7(s.\text{statements}) \\
\text{else if } s & \in \text{TimedStatement} \\
\text{usedVariables}^8(s.\text{stmt}) \cup \text{usedVariables}^9(s.\text{deadline}) \\
\text{else} \\
\emptyset
\end{align*}
\]

Rule 45. Function usedVariables

\[
\text{usedVariables}(e : \text{Expression}) : \text{Set}(\text{Variable}) = \\
\text{The definition of this function is standard and omitted for now.}
\]

Rule 46. Function vars

\[
\text{vars}(ns : \text{PNode}) : \text{Set}(\text{NamedElement}) = \\
\bigcup \{ n : ns \bullet \text{vars}^2(n) \}
\]

Rule 47. Function vars

\[
\text{vars}(ts : \text{PTransition}) : \text{Set}(\text{NamedElement}) = \\
\bigcup \{ t : ts \bullet \text{vars}^3(t) \}
\]

Rule 48. Function vars

\[
\text{vars}(s : \text{Node}) : \text{Set}(\text{NamedElement}) = \\
\text{if } s \in \text{State} \\
\bigcup \{ a : s.\text{actions} \bullet \text{vars}^4(a.\text{action}) \} \cup \text{vars}^5(s.\text{nodes}) \cup \text{vars}^6(s.\text{transitions}) \\
\text{else} \\
\emptyset
\]
4.1 Detailed Semantics: Core Language

**Rule 49. Function vars**

\[
\text{vars}(t : \text{Transition}) : \text{Set}(	ext{NamedElement}) = \\
\text{vars}^7(t.\text{condition}) \cup \text{vars}^8(t.\text{action}) \cup \text{vars}^9(t.\text{deadline})
\]

The following definition is similar to usedVariables\(^{10}\), but takes into account the variables required by operations called in statements. This is required in order to ensure that operations can synchronise on state updates via share.

**Rule 50. Function vars**

\[
\text{vars}(s : \text{Statement}) : \text{Set}(	ext{NamedElement}) = \\
\begin{array}{l}
\text{if } s \in \text{Assignment} \\
\quad \text{usedVariables}^1(s.\text{left}) \cup \text{usedVariables}^2(s.\text{right}) \\
\text{else if } s \in \text{Call} \\
\quad \bigcup \{ x : s.\text{args} \} \cup \text{requiredVariables}^1(s.\text{operation}) \\
\text{else if } s \in \text{IfStatement} \\
\quad \text{usedVariables}^4(s.\text{expression}) \cup \text{vars}^10(s.\text{then}) \cup \text{vars}^11(s.\text{else}) \\
\text{else if } s \in \text{CommunicationStmt} \land s.\text{communication.type} \in \{\text{SYNC, OUTPUT}\} \\
\quad \text{usedVariables}^5(s.\text{communication.value}) \\
\text{else if } s \in \text{ParStmt} \\
\quad \text{vars}^12(s.\text{stmt}) \\
\text{else if } s \in \text{SeqStatement} \\
\quad \text{vars}^13(s.\text{statements}) \\
\text{else if } s \in \text{TimedStatement} \\
\quad \text{vars}^14(s.\text{stmt}) \cup \text{vars}^15(s.\text{deadline}) \\
\text{else} \\
\quad \emptyset
\end{array}
\]

**Rule 51. Function vars**

\[
\text{vars}(s : \text{Seq}(\text{Statement})) : \text{Set}(	ext{NamedElement}) = \\
\begin{array}{l}
\text{if } s \neq \langle \rangle \\
\quad \text{vars}^16(\text{head}(s)) \cup \text{vars}^17(\text{tail}(s)) \\
\text{else} \\
\quad \emptyset
\end{array}
\]

**Composition**

The composition of nodes in a NodeContainer is the replicated generalised parallel composition of the semantics of nodes \( n \) in \( \text{nc.nodes} \), synchronising on events share and end.
Chapter 4. Semantics

**Rule 52. Composition of nodes**

\[
\text{composeNodes}(\text{nodes} : \text{Set}(\text{Node}))^{\text{nops}} : \text{CSPProcess} = \\
\begin{align*}
\text{if nodes} &= \emptyset \\
S\text{Stop} \triangle \text{end} &\rightarrow \text{Skip} \\
\text{else} \\
\{\{\text{share}, \text{end}\} \parallel n : \text{nodes} \bullet [n]^{\text{nops}}
\end{align*}
\]

4.1.5 Transitions

**Rule 53. Semantics of Transitions**

\[
\text{transitions}(\text{nc} : \text{NodeContainer})^{\text{nops}} : \text{CSPProcess} = \\
\begin{align*}
\text{let} \\
\begin{align*}
\text{Trans} &= \text{readStateA} \\
\text{vguards}, \\
\begin{align*}
\square t : \text{nc.transitions} \bullet [t]_{\text{Expr}} \\
\text{share} \rightarrow \text{Skip} \\
\square \text{interrupt}.\text{id}(\text{nc}) \rightarrow (S\text{Stop} \triangle \text{exit} \rightarrow \text{Skip}); \\
(S\text{Stop} \triangle \text{exited} \rightarrow \text{end} \rightarrow \text{Skip})
\end{align*}
\end{align*}
\end{align*}
\]

\begin{align*}
\text{within} \\
\text{Trans} \\
\text{where} \\
\begin{align*}
\text{vguards} &= \{t : \text{nc.transitions}, v : \text{NamedElement} | v \in \text{usedVariables}(t.\text{condition}) \bullet v\}
\end{align*}
\end{align*}

Observe that in \(\text{Trans}\), the process also offers the possibility to engage in the event \(\text{interrupt}.\text{id}(\text{nc})\), so that a parent \text{NodeContainer} of \text{nc} may also interrupt the current state, and \(\text{end}\), so that a final state may offer to terminate.

**Rule 54. Semantics of a Transition**

\[
[t : \text{Transition}]^{\text{nops}} : \text{CSPProcess} = \\
\begin{align*}
\text{if src} &\in \text{State} \land t.\text{condition} \neq \text{null} \\
&\begin{align*}
\left(\begin{array}{c}
\langle t.\text{condition}\rangle_{\text{Expr}} \\
&\& \text{trigger}(t) ; (S\text{Stop} \triangle \text{exit} \rightarrow \text{Skip}); \\
(S\text{Stop} \triangle \text{exited} \rightarrow [t.\text{action}]^{\text{nops}} ; \text{enter}.\text{id}(t.\text{target}) \rightarrow \text{Skip})
\end{array}\right)
\end{align*}
\end{align*}
\]

\begin{align*}
\text{else if src} &\in \text{State} \land t.\text{condition} = \text{null} \\
&\begin{align*}
\left(\begin{array}{c}
\text{trigger}^2(t) ; (S\text{Stop} \triangle \text{exit} \rightarrow \text{Skip}); \\
(S\text{Stop} \triangle \text{exited} \rightarrow [t.\text{action}]^{\text{nops}} ; \text{enter}.\text{id}(t.\text{target}) \rightarrow \text{Skip})
\end{array}\right)
\end{align*}
\end{align*}

\begin{align*}
\text{else if src} &\notin \text{State} \land t.\text{condition} \neq \text{null} \\
&\begin{align*}
\left(\begin{array}{c}
\langle t.\text{condition}\rangle_{\text{Expr}} \\
&\& \text{tevent}^3(t) \rightarrow [t.\text{action}]^{\text{nops}} ; \text{enter}.\text{id}(t.\text{target}) \rightarrow \text{Skip}
\end{array}\right)
\end{align*}
\end{align*}

\begin{align*}
\text{else if src} &\notin \text{State} \land t.\text{condition} = \text{null} \\
&\begin{align*}
\text{tevent}^4(t) \rightarrow [t.\text{action}]^{\text{nops}} ; \text{enter}.\text{id}(t.\text{target}) \rightarrow \text{Skip}
\end{align*}
\end{align*}
Rule 55. Semantics of a transition’s trigger

\[ \text{trigger}(t : \text{Transition}) : \text{CSPProcess} = \]
\[
\begin{align*}
\text{if } t.\text{trigger} &= \text{null} \\
\quad &\quad \text{internal}.\text{id}(t.\text{source}) \to \text{Skip} \\
\text{else if } t.\text{trigger}.\text{type} &= \text{CommunicationType}.\text{INPUT} \\
\quad &\quad \text{eventId}(t.\text{event}).\text{id}(t.\text{source}).\text{in}\{x\} \to (\text{SStop} \triangle \text{set}_{\text{vid}}(t.\text{trigger}.\text{parameter})!x \to \text{Skip}) \\
\text{else if } t.\text{trigger}.\text{type} &= \text{CommunicationType}.\text{SIMPLE} \\
\quad &\quad \text{eventId}(t.\text{event}).\text{id}(t.\text{source}).\text{in} \to \text{Skip}
\end{align*}
\]

4.1.6 Nodes

The semantics of nodes is split according to the type of node. The CSP events used to control the execution flow of nodes are:

- \text{enter}.\text{id}(n), to request the activation of a node \(n\);
- \text{interrupt}.\text{id}(n), to interrupt the execution of a node \(n\);
- \text{end}, to terminate.

Rule 56. Semantics of nodes

\[ [n : \text{Node}]^{\text{ops}} : \text{CSPProcess} = \]

This function is split in multiple rules according to the type of \(n\).

Junctions (including Initial)

The semantics of an \text{Initial} node is exactly that of a Junction.

Rule 57. Semantics of junctions

\[ [n : \text{Junction}]^{\text{ops}} : \text{CSPProcess} = \]
\[
\begin{align*}
\text{let} \\
\quad \text{Inactive} &= \text{SStop} \triangle (\text{Activation} \Box \text{Termination}) \\
\quad \text{Activation} &= \text{enter}.\text{id}(n) \to \text{Active} \\
\quad \text{Termination} &= \text{end} \to \text{Skip} \\
\quad \text{Active} &= (\text{SStop} \triangle \text{interrupt}.\text{id}(n) \to \text{Skip}); \text{Inactive} \\
\text{within} \\
\quad \text{Inactive}
\end{align*}
\]

Final States

In addition to the CSP events \text{enter}, \text{interrupt} and \text{end}, States also engage in the following events: \text{entered}.\text{id}(n), used to indicate that a state \(n\) has entered; \text{exit}, used to synchronise the execution of a state’s exit action (if any); and \text{exited} to indicate that a state has finished exiting.
Chapter 4. Semantics

Rule 58. Semantics of final states
\[
[n : \text{Final}]^{\text{nops}} : \text{CSPProcess} =
\]
\begin{align*}
\text{let} & \quad \text{Inactive} \triangleq S\text{Stop} \triangle (\text{Activation} \otimes \text{Termination}) \\
\text{Activation} & \triangleq \text{enter}, \text{id}(n) \rightarrow \text{Entering} \\
\text{Termination} & \triangleq \text{end} \rightarrow \text{Skip} \\
\text{Entering} & \triangleq \text{entered}, \text{id}(n) \rightarrow \text{Active} \\
\text{Active} & \triangleq (S\text{Stop} \triangle (\text{Termination} \otimes \text{interrupt}, \text{id}(n) \rightarrow \text{Interrupted})) \\
\text{Interrupted} & \triangleq (S\text{Stop} \triangle \text{exit} \rightarrow \text{exited} \rightarrow \text{Inactive})
\end{align*}
\]

within

\text{Inactive}

The possibility to terminate a state machine is enforced at the level of the semantics of a state machine, thus making the semantics of a final state independent from its context.

Simple States

We observe that \textit{exited} and \textit{exit} are parameterless, as the execution flow of states (other than via the use of during actions) is sequential. Only one state may be interrupted at each level of the hierarchy, and so after an interruption, only that state is prepared to synchronise on the events \textit{exit} and \textit{exited}.

Rule 59. Semantics of simple states
\[
[s : \text{State}]^{\text{nops}} : \text{CSPProcess} =
\]
\begin{align*}
\text{let} & \quad \text{Inactive} \triangleq S\text{Stop} \triangle (\text{Activation} \otimes \text{Termination}) \\
\text{Activation} & \triangleq \text{enter}, \text{id}(s) \rightarrow \text{Active} \\
\text{Termination} & \triangleq \text{end} \rightarrow \text{Skip} \\
\text{Active} & \triangleq ([s.]^{\text{nops}} \text{entry})_{\text{Action}} \text{; Behaviour; Exiting} \\
\text{Behaviour} & \triangleq \text{entered}, \text{id}(s) \rightarrow \text{During} \\
\text{During} & \triangleq ([s.]^{\text{nops}} \text{during})_{\text{Action}} \text{; } S\text{Stop} \triangle \text{interrupt}, \text{id}(s) \rightarrow \text{Skip} \\
\text{Exiting} & \triangleq (S\text{Stop} \triangle \text{exit} \rightarrow \text{Skip}) \text{; } ([s.]^{\text{nops}} \text{exit})_{\text{Action}} \text{; exited} \rightarrow \text{Inactive}
\end{align*}

within

\text{Inactive}

where

\#s.nodes = 0

Composite states

The process Behaviour accounts for the behaviour within the state, which is a composition of \([s]^{\text{nops}}\), that defines the behaviour of \(s\) as a node container, including that of its states and transitions, and \textit{During} that defines the semantics of the during action.
4.1 Detailed Semantics: Core Language

Rule 60. Semantics of composite states

\[s : \text{State} \]

\[\text{nops} : \text{CSPProcess} =\]

let

\[\text{Inactive} \equiv SStop \triangle (\text{Activation} \square \text{Termination})\]

\[\text{Activation} \equiv \text{enter},\text{id}(s) \rightarrow \text{Active}\]

\[\text{Termination} \equiv \text{end} \rightarrow \text{Skip}\]

\[\text{Active} \equiv \left(\left[\left[ s \right]\right] \text{nops}^{\text{Action}^{\text{s}}}; \text{Behaviour}; \text{Exiting}\right)\]

\[\text{Behaviour} \equiv \left(\left[\left[\left[ s \right]\right] \text{nops}^{\text{ vars}^{18}(s\text{.nodes}) | \text{enteredSS}(s) \cup \{\text{end}, \text{interrupt}\}| \text{vars}^{19}(s\text{.during})]\right]\right)\]

\[\text{During} \equiv \left(\left[\left[\left[ s \right]\right] \text{nops}^{\text{ entered}\text{id}(s) \rightarrow \text{RUN(enteredSS(s))} \ || \ \left[\left[ s \right]\right] \text{nops}^{\text{Action}^{\text{s}}}; \text{SStop}\right)\right] \triangle \text{interrupt},\text{id}(s) \rightarrow (\text{SStop} \triangle \text{end} \rightarrow \text{Skip})\right)\]

\[\text{Exiting} = (\text{SStop} \triangle \text{exit} \rightarrow \text{Skip}); \left[\left[\left[ s \right]\right] \text{nops}^{\text{exited} \rightarrow \text{Inactive}}\right]\]

within

\[\text{Inactive}\]

where

\[#s\text{.nodes} > 0\]

\[\text{enteredSS}(s) = \{x : s\text{.nodes} \bullet \text{entered},\text{id}(x)\}\]

4.1.7 Statements

Rule 61. Semantics of statements

\[s : \text{Statement} \]

\[\text{nops} : \text{CSPProcess} =\]

This rule is split in multiple rules according to the subtype of the statement.

The semantics of statements, in general, has the format

\[\text{SStop} \triangle \text{get}_{x_1}?x_1 \rightarrow \ldots \rightarrow \text{SStop} \triangle \text{get}_{x_n}?x_n \rightarrow P\]

where the channels get_{x_i} read values from the memory and the process P models the actual statement. The input events get_{x_i}?x_i build a context where all the state components used in the expressions of the statement are declared, while SStop captures the possibility for state to be changed. The process P is then run on this context.

In order to simplify our semantic rules, we use the following function that helps in building the context.
Chapter 4. Semantics

**Rule 62. Read state of an expression**

\[
\text{readState}(\text{vs} : \text{seq}(\text{Variable}), P : \text{CSPProcess}) : \text{CSPProcess} = \\
\begin{align*}
\text{if }(\#\text{vs} = 0) \text{ then} & \\
& P \\
\text{else} & \\
& S\text{Stop} \triangle \text{get}_\text{vid}((\text{headvs})?((\text{headvs}).\text{name} \rightarrow \text{readState}^1(\text{tailvs}, P))}
\end{align*}
\]

This function reads a list of state variables and executes a process in that context. The variables must be read in sequence so that the final process can be executed in the full context. The order in which the variables are read is not important because the memory is always prepared to respond to a get event.

The function \text{readState}^2 allows state updates, handled via synchronisation on \text{share}, to take place while individual variables are read. In cases where this lack of atomicity is undesirable, instead the following function \text{readStateAtomic}^1 is used, which refuses to engage in \text{share} initially if \text{vs} is non-empty.

**Rule 63. Atomic read state of an expression**

\[
\text{readStateAtomic}(\text{vs} : \text{seq}(\text{Variable}), P : \text{CSPProcess}) : \text{CSPProcess} = \\
\begin{align*}
\text{if }(\#\text{vs} = 0) \text{ then} & \\
& P \\
\text{else} & \\
& \text{get}_\text{vid}((\text{headvs})?((\text{headvs}).\text{name} \rightarrow \text{readStateAtomic}^2(\text{tailvs}, P))
\end{align*}
\]

The following is a version of \text{readStateAtomic}^3 that allows the state to be changed, via \text{share}, before any synchronisation on \text{get} happens.

**Rule 64. Atomic read state of an expression with initial share**

\[
\text{readStateA}(\text{vs} : \text{seq}(\text{Variable}), P : \text{CSPProcess}) : \text{CSPProcess} = \\
\begin{align*}
\text{if }(\#\text{vs} = 0) \text{ then} & \\
& P \\
\text{else} & \\
& S\text{Stop} \triangle \text{get}_\text{vid}((\text{headvs})?((\text{headvs}).\text{name} \rightarrow \text{readStateAtomic}^4(\text{tailvs}, P))
\end{align*}
\]

We define the function \text{[}\_\text{]}_{\text{StatementInContext}} to separate the application of \text{readState} from the core semantics of the statement given by the rule \text{[}\_\text{]}_{\text{Statement}}. We additionally use the function \text{usedVariables} that takes a statement and calculates the set of variables used by the expressions in the statement.
4.1 Detailed Semantics: Core Language

Rule 65. Semantics of statements in context
\[ [s : Statement]^{nops}_{StatementInContext} : CSPProcess = \]
\[
\text{readState}^{3} \left( \text{usedVariables}^{17}(s), [s]^{nops}_{Statement} \right)
\]

Rule 66. Semantics of assignment
\[ [s : Assignment]^{nops}_{Statement} : CSPProcess = \]
\[
S\text{Stop} \triangle \text{set\_vid}(s.\text{left})!\![s.\text{right}]_{Expr} \rightarrow \text{Skip}
\]

Rule 67. Semantics of call statement
\[ [s : Call]^{nops}_{Statement} : CSPProcess = \]
\[
\text{op}\_\text{name}(\{x : s.\text{args} \bullet [x]_{Expr}\})
\]
where
\[
op = s.\text{operation}
\]

Rule 68. Semantics of if statements
\[ [s : IfStatement]^{nops}_{Statement} : CSPProcess = \]
\[
\left( \text{if} \left[ [s.\text{expression}]_{Expr} \text{then} \left[ [s.\text{then}]^{nops}_{StatementInContext} \right] \right. \text{elseif} \left( s.\text{else} \neq \text{null} \right) \text{then} \left[ [s.\text{else}]^{nops}_{StatementInContext} \text{else} \text{Skip} \right] \right)
\]

Rule 69. Semantics of communication statements
\[ [s : CommunicationStmt]^{nops}_{Statement} : CSPProcess = \]
\[
\text{if} \left( \text{type} = \text{INPUT} \right) \text{then} \quad S\text{Stop} \triangle \text{event\_id}(\text{event}).\text{in}?\text{par}\_\text{name} \rightarrow \left( S\text{Stop} \triangle \text{set\_vid}(\text{par}\_\text{name}) \rightarrow \text{Skip} \right)
\]
\[
\text{if} \left( \text{type} = \text{OUTPUT} \right) \text{then} \quad S\text{Stop} \triangle \text{event\_id}(\text{event}).\text{out}!\text{value}\_\text{Expr} \rightarrow \text{Skip}
\]
\[
\text{if} \left( \text{type} = \text{SIMPLE} \right) \text{then} \quad S\text{Stop} \triangle \text{event\_id}(\text{event}).\text{out} \rightarrow \text{Skip}
\]
\[
\text{else} \quad S\text{Stop} \triangle \text{event\_id}(\text{event}).\text{out} \rightarrow \text{Skip}
\]
where
\[
type = s.\text{communication}\_\text{type}
\]
\[
event = s.\text{communication}\_\text{event}
\]
\[
\text{value} = s.\text{communication}\_\text{value}
\]
\[
\text{par} = s.\text{communication}\_\text{parameter}
\]
**Rule 70. Semantics of sequential composition**

\[
\begin{align*}
[s : \text{SeqStatement}]_{\text{Statement}}^{\text{nops}} &: \text{CSPProcess} = \\
\langle x : s.\text{statements} \bullet [x]_{\text{Statement} \text{EnCon}}^{\text{nops}} \rangle
\end{align*}
\]

**Rule 71. Semantics of Skip**

\[
\begin{align*}
[s : \text{Skip}]_{\text{Statement}}^{\text{nops}} &: \text{CSPProcess} = \\
\text{SStop} \triangledown \text{Skip}
\end{align*}
\]

**Rule 72. Semantics of ParStmt**

\[
\begin{align*}
[s : \text{ParStmt}]_{\text{Statement}}^{\text{nops}} &: \text{CSPProcess} = \\
[s.\text{stmt}]_{\text{Statement} \text{EnCon}}^{\text{nops}}
\end{align*}
\]

**Rule 73. Semantics of actions**

\[
\begin{align*}
[a : \text{Action}]_{\text{Action}}^{\text{nops}} &: \text{CSPProcess} = \\
\text{if } a \neq \text{null} & \quad [a.\text{action}]_{\text{Statement} \text{EnCon}}^{\text{nops}} \\
\text{else} & \quad \text{Skip}
\end{align*}
\]

### 4.1.8 Expressions

The translation of expressions is standard. We note, however, that the expression language of Z is much richer than that of CSP. So, in some cases, we require user input to translate the expressions. Notably, this is the case of function applications. If the function is defined in RoboChart using pre and postconditions, the user needs to provide a CSP definition.
The semantics of modules is the same as the untimed semantics. Here we describe the rules of the timed semantics to accommodate the timed constructs of RoboChart, namely clocks and deadlines. The untimed semantics of controllers, state machines, operations, and nodes is largely reused, and so we present the rules by focusing on the changes required to accommodate the timed semantics.

4.2.1 Controllers

Rule 74. Semantics of controllers

\[
[c : \text{ControllerDef}][c : \text{CSPProcess} =
\]

let

\[
\text{for each op : c.IOperations} \rightarrow
\text{nproc}(\text{op})(\{x : \text{op.parameters \& x.name}\}) = \text{opdef}^{\text{nops}}_{\text{STM}}
\]

\[
\text{for each op : requiredOperations}^4(c) \rightarrow
\text{nproc}(\text{op})(\{x : \text{op.parameters \& x.name}\}) =
\]

\[
\text{Stop} \triangleq \text{Stop} \sqcup \text{o.name@Call.\{x : \text{op.parameters \& x.name}\} \rightarrow Skip}
\]

within

\[
\text{composeMachines}^3(c, ms, cs)^{\text{nops}}_\Theta[\text{end} Skip]
\]

where

\[
\text{ms} = \{x : \text{c.machines}\}
\]

\[
\text{cs} = \text{c.connections}
\]

\[
\text{opdef} = \text{findOperationDefinition}(\text{op}, \text{c.IOperations})
\]

\[
\text{nops} = \{\text{op : c.IOperations} \rightarrow \text{id}(\text{op}) \rightarrow \text{nproc}(\text{op})\} \cup
\]

\[
\{\text{op : requiredOperations}^4(c) \rightarrow \text{id}(\text{op}) \rightarrow \text{nproc}(\text{op})\}
\]

\[
\text{lvars} = \{v : \text{allLocalVariables}^3(c) \rightarrow \text{vid}(v)\}
\]

\[
\text{rvars} = \{v : \text{requiredVariables}^2(c) \rightarrow \text{Extvid}(v)\}
\]

\[
\text{lconsts} = \{v : \text{allLocalConstants}^2(c) \rightarrow \text{vid}(v)\}
\]

\[
\text{rconsts} = \{v : \text{requiredConstants}^2(c) \rightarrow \text{vid}(v)\}
\]
### Rule 75. Timed stateful component of state machine behaviour

\[
\text{stateful}(\text{stm} : \text{StateMachineBody})^{\text{nops}} : \text{TimedCSPProcess} = \\
\begin{align*}
& \text{let} \\
& \quad \text{Stateful} = \\
& \quad \quad \left( \begin{array}{c}
\quad \text{MachineBody} \\
\quad \quad \left( \text{setqLocalChannels}^{3}(\text{stm}) \cup \text{clockSync} \cup \{ \text{end} \} \right) \\
\quad \quad \left( \text{varMemory}^{2}(\text{stm}) \left| \{ \text{end} \} \right| \text{constMemory}^{3}(\text{stm}) \right) \\
\quad \quad \text{clocks}^{2}((\text{stm}.\text{clocks}) \setminus \text{getsetLocalChannels}^{4}(\text{stm}) \cup \text{clockSync}) \\
\quad \quad \text{\{getsetLocalChannels}^{4}(\text{stm}) \cup \text{clockSync} \\
& \quad \quad \left( \text{\{getsetLocalChannels}^{4}(\text{stm}) \cup \text{clockSync} \right)
\end{array} \right) \\
& \quad \text{\{MachineBody} \\
& \quad \quad \left( \text{\{stm}\}^{\text{nops}} \cup \text{\{interrupt\}} \cup \text{\{Skip\}} \setminus \text{\{enteredSS\}} \right)
\end{align*}
\]

within \text{Stateful}

where

\[
\text{clockSync} = \{\text{c} : \text{stm}.\text{clocks} \bullet \text{get}_\text{id}(\text{c}), \text{clockReset}_\text{id}(\text{c})\}
\]

\[
\text{enteredSS} = \{\text{x} : \text{stm}.\text{nodes} \bullet \text{\{entered\}_id}(\text{x})\}
\]

---

#### 4.2.3 Node containers

The semantics of node container is changed to account for \$\text{sinceEntry}\$ expressions by defining clocks that count the timed since entering states, with the exception of final states.

### Rule 76. Semantics of node container

\[
[\text{nc} : \text{NodeContainer}]^{\text{nops}} : \text{TimedCSPProcess} = \\
\begin{align*}
& \left( \begin{array}{c}
\quad \text{ncBehaviour}^{2}(\text{nc})^{\text{nops}} \\
\quad \quad \left( \text{\{stateClockSync}^{\text{nc}(\text{nc})} \cup \{ \text{end} \} \right) \\
\quad \quad \text{clocks}^{3}(\text{stateClocks}(\text{nc}))
\end{array} \right) \\
& \quad \{\text{stateClockSync}^{\text{nc}(\text{nc})} \setminus \{ \text{\{entered\}} \}
\end{align*}
\]

where

\[
\text{stateClocks}(\text{nc}) = \{\text{s} : \text{nc}.\text{nodes} | \text{s} \in \text{State} \land \text{s} \notin \text{Final} \}
\]

\[
\text{stateClockSync}(\text{nc}) = \{\text{n} : \text{stateClocks}(\text{nc}) \bullet \text{\{entered\}}(\text{n}), \text{\{get\}}(\text{n})\}
\]

The core semantics of node containers is changed to take into account deadlines on transitions.
Rule 77. Node container core behaviour
\( \text{ncCoreBehaviour}(\text{nc} : \text{NodeContainer})^{\text{nops}} : \text{TimedCSPProcess} = \)
\[
\left( (\text{composeTimedNodes}(\text{nc})^{\text{nops}}[\text{tidsR}(\text{nc})]) \right)
\]
\[
\left. \left[ \left[ \text{vars}^{20}(\text{nc}.\text{nodes}) \ | \ \text{flowevts} \cup \text{transSync}(\text{nc}) \cup \{\text{end}\} \ | \ \text{vtguards}(\text{nc}) : \emptyset \right] \right| \right.
\]
\[
\left( (\text{enter}.\text{initial}(\text{nc}.\text{nodes}) \rightarrow \text{transitions}^{3}(\text{nc})^{\text{nops}}) \right)
\]
where
\[
\text{tidsR}(\text{nc}) = \left\{ t : \text{nc}.\text{transitions} \bullet \text{interrupt}.\text{id}(t.\text{src}) \leftarrow \text{tevent}^{5}(t) \right\} \\
\bigcup \left\{ n : \text{nc}.\text{nodes} \ | \ n \in \text{State} \bullet \text{interrupt}.\text{id}(n) \leftarrow \text{interrupt}.\text{id}(\text{nc}) \right\}
\]
\[
\text{flowevts} = \{\text{enter}, \text{exit}, \text{exited}, \text{interrupt}\}
\]
\[
\text{transSync}(\text{nc}) = \{t : \text{nc}.\text{transitions} \bullet \text{tevent}^{6}(t)\}
\]
\[
\text{vtguards}(\text{nc}) = \{t : \text{nc}.\text{transitions} | \exists v \in \text{usedVariables}^{18}(t.\text{condition}) \bullet v\}
\]

Rule 78. Composition of nodes
\( \text{composeTimedNodes}(\text{nc} : \text{NodeContainer})^{\text{nops}} : \text{TimedCSPProcess} = \)
\[
\left\{ \left[ \{\text{share}, \text{end}\} \right] n : \text{nc}.\text{nodes} \bullet \text{nodeD}^{1}(n, \{t : \text{nc}.\text{transitions} | \text{t.source} = n\})^{\text{nops}} \right\}
\]

Rule 79. Node with deadline
\( \text{nodeD}(\text{nc} : \text{NodeContainer}, \text{ts} : \text{Set(Transition)})^{\text{nops}} : \text{TimedCSPProcess} = \)
\[
\left\{ \left[ \{\text{share}, \text{end}\} \right] n : \text{nc}.\text{nodes} \bullet \text{nodeD}^{1}(n, \{t : \text{nc}.\text{transitions} | \text{t.source} = n\})^{\text{nops}} \right\}
\]
where
\[
\text{tds}(x) = \{t : x | \text{t.deadline} \neq \text{null}\}
\]
\[
\text{vt}(x) = \left\{ \begin{array}{l}
\{t : \text{tds}(x), v : \text{NamedElement}\} \\
\{v \in \text{usedVariables}^{19}(t.\text{condition}) \cup \text{usedVariables}^{20}(t.\text{deadline}) \bullet v\}
\end{array} \right\}
\]
Chapter 4. Semantics

Rule 80. Transition deadlines of a state
\[ \text{stateDeadlines}(n : \text{State}, ts : \text{PTransitions}) : \text{TimedCSPProcess} = \]
\[
\begin{align*}
\text{if } ts = \emptyset & \\
\quad \text{let} & \\
\quad \begin{align*}
P &= \text{SStop} \triangledown \left( \text{end} \to \text{Skip} \boxdot \text{entered}.\text{id}(n) \to P \boxdot \text{interrupt}.\text{id}(n) \to P \right) \\
\quad \text{within} & \notag \\
\quad P & 
\end{align*} \\
\text{else} & \\
\quad \text{let} & \\
\quad \begin{align*}
\{\text{entered}.\text{id}(n), \text{end}, \text{interrupt}.\text{id}(n), \text{share}\} & \triangledown ts \bullet \text{transitionDeadline}^1(t) 
\end{align*}
\end{align*}
\]

Rule 81. Transition deadline
\[ \text{transitionDeadline}(t : \text{Transition}) : \text{TimedCSPProcess} = \]
\[
\begin{align*}
\text{let} & \\
\quad \text{Inactive} &= \text{SStop} \triangledown (\text{Activation} \boxdot \text{Termination}) \\
\quad \text{Termination} &= \text{end} \to \text{Skip} \\
\quad \text{Activation} &= \text{entered}.\text{id}(t.\text{source}) \to (\text{Active} \triangle \text{interrupt}.\text{id}(t.\text{source}) \to \text{Inactive}) \\
\quad \text{Active} &= \begin{cases}
\text{UntilTrue}; & \\
\text{readState}^1 \left( \text{usedV}(t.\text{end}), \left( \text{UntilFalse} \triangledown \left( \text{Wait} \left( [t.\text{deadline}]_{\text{Expr}} \right); \text{UStop} \right) \right) \right) \\
\text{Active} & 
\end{cases} \\
\quad \text{UntilTrue} &= \text{readStateA}^1 \left( \left( \text{not} [t.\text{condition}]_{\text{Expr}} \right) \& \text{Skip} \right) \\
\quad \text{UntilFalse} &= \text{readStateA}^2 \left( \left( \text{not} [t.\text{condition}]_{\text{Expr}} \right) \& \text{Skip} \right) \\
\quad \quad \text{\text{\triangledown}_1 \text{UntilFalse}} & \\
\quad \text{within} & \notag \\
\quad \text{Inactive} & 
\end{align*}
\]

Transitions

The rule \text{} is changed here to accommodate the passage of time, where via the use of the timeout operator (\text{\triangledown}_1) the state of conditions is evaluated after the passage of every time unit. This is required to ensure that the values of time elapsed in conditions involving $\text{since}(C)$ is updated.
4.2 Detailed Semantics: Timed Language

**Rule 82. Semantics of Transitions**

\[
\text{transitions(nc : NodeContainer) \text{\textsuperscript{nops}}. TimedCSPProcess =}
\]

\[
\text{let}
\]

\[
\text{Trans} \equiv \text{readStateA}^2
\]

\[
\left(\begin{array}{c}
\text{vtguards(nc),} \\
\left(\begin{array}{c}
\Box t : nc.transition \cdot \llbracket t \rrbracket_T \\
\Box \text{share} \rightarrow \text{Skip} \\
\text{interrupt.id(nc)} \\
\Box \text{end} \rightarrow \text{Skip}
\end{array}\right) \\
\end{array}\right) \\
\left(\begin{array}{c}
\Delta (\text{SStop} \triangle \text{exit} \rightarrow \text{Skip}) \\
\Delta (\text{SStop} \triangle \text{exited} \rightarrow \text{end} \rightarrow \text{Skip}) \\
\end{array}\right)
\]

\[
\text{within}
\]

\[
\text{Trans}
\]

where

\[
\text{vtguards(nc)} = \{ t : nc.transition | \exists v \cdot v \in \text{vars(t.condition)} \cdot v \}
\]

**Rule 83. Semantics of a Transition**

\[
\llbracket t : \text{Transition} \rrbracket_{T \text{\textsuperscript{nops}}}. \text{CSPProcess} =
\]

if \(\text{src} \in \text{State} \land \text{t.condition} \neq \text{null}\)

\[
\left(\begin{array}{c}
\llbracket \text{t.condition} \rrbracket_{\text{Expr}} & \text{trigger} \llbracket t \rrbracket ; \text{clockResets} \llbracket t \rrbracket ; (\text{SStop} \triangle \text{exit} \rightarrow \text{Skip}) \\
(\text{SStop} \triangle (\text{exited} \rightarrow \llbracket \text{t.action} \rrbracket_{\text{nops}} ; \text{enter.id}(\text{tgt}) \rightarrow \text{Skip}))
\end{array}\right)
\]

else if \(\text{src} \in \text{State} \land \text{t.condition} = \text{null}\)

\[
\left(\begin{array}{c}
\text{trigger} \llbracket t \rrbracket ; \text{clockResets} \llbracket t \rrbracket ; (\text{SStop} \triangle \text{exit} \rightarrow \text{Skip}) \\
(\text{SStop} \triangle (\text{exited} \rightarrow \llbracket \text{t.action} \rrbracket_{\text{nops}} ; \text{enter.id}(\text{tgt}) \rightarrow \text{Skip}))
\end{array}\right)
\]

else if \(\text{src} \notin \text{State} \land \text{t.condition} \neq \text{null}\)

\[
\left(\begin{array}{c}
\llbracket \text{t.condition} \rrbracket_{\text{Expr}} & \text{internal.id}(\text{src}) \rightarrow \llbracket \text{t.action} \rrbracket_{\text{nops}} ; \text{enter.id}(\text{tgt}) \rightarrow \text{Skip}
\end{array}\right)
\]

else if \(\text{src} \notin \text{State} \land \text{t.condition} = \text{null}\)

\[
\left(\begin{array}{c}
\text{internal.id}(\text{src}) \rightarrow \llbracket \text{t.action} \rrbracket_{\text{nops}} ; \text{enter.id}(\text{tgt}) \rightarrow \text{Skip}
\end{array}\right)
\]

where

\[
\text{src} = \text{t.source} \\
\text{tgt} = \text{t.target}
\]

**Rule 84. Semantics of clock resets for transitions**

\[
\text{clockResets(t : Transition) : TimedCSPProcess =}
\]

if \(\# \text{reset} > 0\)

\[
\llbracket \{ \text{share} \} \rrbracket \llbracket t \rrbracket \text{\textsuperscript{\text{reset}}} \cdot \text{clockReset.id(t.clock)} \rightarrow (\text{SStop} \triangle \text{Skip})
\]

else

\[
\text{SStop} \triangle \text{Skip}
\]

### 4.2.4 Clocks
Rule 85. Clocks
\[
\text{clocks}(cs : \text{NamedElement}) : \text{TimedCSPProcess} = \\
\text{if } \#cs = 0 \\
\text{then } \text{end} \rightarrow \text{Skip} \\
\text{else } \\
\text{||} \text{end} || c : cs \cdot \text{clock}^1(c)
\]

Rule 86. Clock
\[
\text{clock}(c : \text{NamedElement}) : \text{TimedCSPProcess} = \\
\text{This rule is split in multiple rules according to the subtype of NamedElement.}
\]

The function \( \text{clock} \) is defined over the type \( \text{NamedElement} \), for elements of type \( \text{State} \) and \( \text{Clock} \). Increments happen every time unit, as defined using the timeout operator \( \triangleright 1 \).

Rule 87. Clock
\[
\text{clock}(c : \text{Clock}) : \text{TimedCSPProcess} = \\
\text{let} \\
\text{Memory}(x) = \\
\begin{align*}
\text{clockReset}.id(c) & \rightarrow \text{Memory}(0) \\
\Box \text{get}_\text{id}(c)!x & \rightarrow \text{Memory}(x) \\
\Box \text{end} & \rightarrow \text{Skip}
\end{align*} \\
\triangleright 1 \text{Memory}(x + 1) \\
\text{within} \\
\text{Memory}(0)
\]

Rule 88. Clock
\[
\text{clock}(s : \text{State}) : \text{TimedCSPProcess} = \\
\text{let} \\
\text{Memory}(x) = \\
\begin{align*}
\text{entered}.id(s) & \rightarrow \text{Memory}(0) \\
\Box \text{get}_\text{id}(\text{?x}) & \rightarrow \text{Memory}(x) \\
\Box \text{end} & \rightarrow \text{Skip}
\end{align*} \\
\triangleright 1 \text{Memory}(x + 1) \\
\text{within} \\
\text{Memory}(0)
\]

4.2.5 Statements

Rule 89. Read state of an expression
\[
\text{readState}(vs : \text{seq}(\text{Variable}), P : \text{CSPProcess}) : \text{TimedCSPProcess} = \\
\text{if } \#vs = 0 \text{ then } P \\
\text{else } \\
S\text{Stop} \triangle (\text{Stop}U \Box \text{get}_\text{vid}(\text{head} vs)!\text{?(head} vs).\text{name} \rightarrow \text{readState}^2(\text{tail} vs, P))
4.2 Detailed Semantics: Timed Language

**Rule 90.** Atomic read state of an expression

\[ \text{readStateAtomic}(vs : \text{seq}(\text{Variable}), P : \text{CSPProcess}) : \text{TimedCSPProcess} = \]

\[
\begin{align*}
\text{if} & (\#vs = 0) \text{ then } \\
& P \\
\text{else} & \\
& \text{ (StopU ⊗ get.vid(headvs)?(headvs).name → readStateAtomic}'(\text{tailvs}, P))
\end{align*}
\]

**Rule 91.** Atomic read state of an expression with initial share

\[ \text{readStateA}(vs : \text{seq}(\text{Variable}), P : \text{CSPProcess}) : \text{TimedCSPProcess} = \]

\[
\begin{align*}
\text{if} & (\#vs = 0) \text{ then } \\
& P \\
\text{else} & \\
& \text{ SStop} \triangle (\text{StopU} ⊗ \text{get.vid(headvs)?(headvs).name → readStateAtomic}'(\text{tailvs}, P))
\end{align*}
\]

**Rule 92.** Semantics of assignment

\[ [s : \text{Assignment}]^{\text{nops}} : \text{Statement} : \text{TimedCSPProcess} = \]

\[
\text{SStop} \triangle (\text{StopU} ⊗ \text{set.vid}(s.\text{left})! [s.\text{right}]_{\text{Expr}} → \text{Skip})
\]

**Rule 93.** Semantics of statements

\[ [s : \text{Statement}]^{\text{nops}} : \text{Statement} : \text{TimedCSPProcess} = \]

This rule is split in multiple rules according to the subtype of the statement.

**Rule 94.** Semantics of statement deadlines

\[ [s : \text{TimedStatement}]^{\text{nops}} : \text{Statement} : \text{TimedCSPProcess} = \]

\[
\text{[sstmt]}^{\text{nops}} \triangle (\text{Wait}([s.deadline]_{\text{Expr}}); \text{StopU})
\]

**Rule 95.** Semantics of wait statement

\[ [s : \text{Wait}]^{\text{nops}} : \text{Statement} : \text{TimedCSPProcess} = \]

\[
\text{[[s.duration]}_{\text{Expr}}] \triangle \text{Wait}
\]

**Rule 96.** Semantics of Wait

\[ [e : \text{Expression}]_{\text{Wait}} : \text{TimedCSPProcess} = \]

This rule is split in multiple rules according to the subtype of the expression.
Chapter 4. Semantics

**Rule 97. Semantics of Wait**
\[
\[e : P \tau]_{Wait} : \text{TimedCSPProcess} = \\
SStop \triangleq \bigcap n : \emptyset \bullet Wait(n)
\]

**Rule 98. Semantics of Wait**
\[
\[e : A \]_{Wait} : \text{TimedCSPProcess} = \\
SStop \triangleq Wait(e)
\]

**Rule 99. Semantics of clock reset**
\[
\[s : \text{ClockReset}\]_{\text{nops}} : \text{TimedCSPProcess} = \\
SStop \triangleq clockReset.id(s.clock) \rightarrow Skip
\]

**Rule 100. Semantics of deadline over statements**
\[
\[s : \text{TimedStatement}\]_{\text{nops}} : \text{CSPProcess} = \\
readState^3 \left( \underbrace{\text{usedVariables}^2(s.deadline),}_{\text{Statement}^7} \underbrace{\text{readState}^1(s.deadline)}_{\text{nops}} \right) \triangleq \left( Wait\left(s.deadline,_{\text{Expr}}\right) ; UStop \right)
\]

**Rule 101. Semantics of clock reset**
\[
\[s : \text{ClockReset}\]_{\text{nops}} : \text{CSPProcess} = \\
SStop \triangleq clockReset.id(s.clock) \rightarrow Skip
\]
This chapter describes and defines the probabilistic semantics of RoboChart. We give an overview of probabilistic semantics in Section 5.1, and present its UTP semantics in Section 5.2. Then in Section 5.3, we define a translation from RoboChart to PRISM [19] (the language supported by the probabilistic model checker PRISM) in order to use PRISM to analyse RoboChart models.
5.1 Overview

The long-term plan for RoboChart is to support automated verification by both model checking and theorem proving. The RoboChart semantics for its core language and its timed language presented in Chapter 4 is formalised using CSP and its dialect, tock-CSP [8]. The semantic underpinning that is UTP, but our use of CSP is primarily as a front end to enable model checking with FDR.

The semantics for the probabilistic language of RoboChart is also based on UTP, and so RoboChart has a unified semantic base. Ultimately, we aim to support its verification using the theorem prover Isabelle/UTP [27], a mechanisation of UTP in the Isabelle/HOL theorem prover [32].

To enable model checking of the probabilistic behaviour of RoboChart, we translate RoboChart models to PRISM, and then use PRISM to analyse the generated models. The translation is formalised in Section 5.3. We present the metamodel of PRISM and a set of rules to translate RoboChart models.
The probabilistic denotational semantics for RoboChart [33] is based on the weakest completion semantics [14] in UTP. The general idea is to use a forgetful function to embed standard designs into probabilistic designs. This embedding preserves program structure of a probabilistic programming language which includes abort, skip, assignment, conditional, nondeterministic choice, probabilistic choice, sequence, and recursion constructors. We are mechanising the UTP theory for probabilistic designs in Isabelle/UTP. The next step is to lift probabilistic designs into UTP’s reactive design to develop a theory of reactive probabilistic designs.
5.3 Translation to PRISM

We structure the translation from RoboChart models to PRISM models in two steps: normalisation of the RoboChart model and transformation of normalised RoboChart models to PRISM. In Section 5.3.2, we define our probabilistic normal form, namely a restricted version of RoboChart models in which all transitions between two states are probabilistic. We then define the normalisation of a RoboChart model in Section 5.3.5, and then the translation from a RoboChart model in normal form to a PRISM model in Section 5.3.6 by a set of rules. We present the notions used in rules in Section 5.3.3 and the PRISM metamodel in Section 5.3.4.

Not all features of RoboChart are currently supported. Section 5.3.1 presents our assumptions.

5.3.1 Translation requirements

We list the conditions that need to be satisfied by a RoboChart model for our technique to be applicable.

TR-TP1  *Time primitives are not used.* In DTMCs and MDPs, transitions occur in discrete-time steps. Every transition takes one unit of time. Time primitives [23] in RoboChart, however, are capable of capturing budgets and deadlines using clocks and constructs like \(\text{wait}(n)\), which defines a waiting period of \(n\) units of time, and \(\text{read?x}<2\), in which reading a value \(x\) through an event \(\text{read}\) has a deadline to take place within 2 units of time. DTMCs and MDPs do not intrinsically support clocks, time budgets and deadlines to model the corresponding RoboChart constructs.

In addition to DTMCs and MDPs, the PRISM notation also supports probabilistic timed automata (PTAs) [17, 21], which extend MDPs with the ability to model real-time behaviour through real-valued clocks [20]. The timed semantics of RoboChart, however, are based on time units [23], instead of real-valued time. The default verification method (quantitative abstraction refinement [18]) for PTAs in PRISM, therefore, cannot be used. Instead, we can use the digital clocks [22] method which uses an *integral* time model. We will extend our transformation to support PTAs in order for time primitives in RoboChart, which is part of our future work.

TR-CN1  *Connections between controllers are not asynchronous.*

TR-OP1  *Operations cannot be defined by state machines.*

TR-ST1  *States cannot have during actions.*

To cater for these constructs, the PRISM model needs to include extra modules to deal with shared variables, buffers for asynchronous communication, operation calls, and interruptions of during actions by outgoing transitions. Dealing with these extra constructs is part of our agenda for future work.
5.3 Translation to PRISM

Only primitive types and enumerations, sequences of these types, or sequences of sequences of these types are used.

Quantification, lambda, and definite description expressions cannot be used since the PRISM notation is concrete.

PRISM supports only integer, boolean, and real numbers. Refinement techniques [2, 16] are a possible solution to deal with abstract data types and constructs in RoboChart. Support of more abstract data types and expressions is part of our plans for future work.

5.3.2 Normal form

A normalised RoboChart model satisfies the following extra conditions on transitions and junctions.

- NFM-1 A state has at least one outgoing transition.
- NFM-2 A transition that is from a state or a normal junction to a normal junction has an action.
- NFM-3 A transition can have a trigger or an action, but not both together.

5.3.3 Notions for rules

See Table 5.1.

5.3.4 PRISM

Metamodel

See Figure 5.1 to 5.8.
Figure 5.2: Metamodel of PRISM types

Figure 5.3: Metamodel of PRISM expressions

Figure 5.4: Metamodel of PRISM boolean expressions
5.3 Translation to PRISM

Figure 5.5: Metamodel of PRISM unary and manyary expressions

Figure 5.6: Metamodel of PRISM binary expressions

Figure 5.7: Metamodel of PRISM modules
### Table 5.1: Summary of construct syntax in rules

<table>
<thead>
<tr>
<th>Form</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Junction</strong></td>
<td>The class name from the metamodel also represents a collection of objects that have the <em>Junction</em> type. Similarly, <em>State</em>, <em>ProbabilisticJunction</em>, <em>Controller</em>, and so on. Particularly, <em>ProbJunc</em> is an abbreviation for <em>ProbabilisticJunction</em> for a compact space.</td>
</tr>
<tr>
<td><strong>Class_{rc}</strong></td>
<td>Subscripts indicate classes of different metamodels, where <em>rc</em> stands for RoboChart, and <em>pr</em> for PRISM. For example, <em>Transition_{rc}</em> and <em>ModuleDef_{pr}</em> denote the Transition in RoboChart, and the ModuleDef in PRISM.</td>
</tr>
<tr>
<td><strong>P</strong></td>
<td>Power set of <em>X</em>.</td>
</tr>
<tr>
<td><strong>X × Y</strong></td>
<td>Cartesian product.</td>
</tr>
<tr>
<td><strong>seq X</strong></td>
<td>Finite sequences.</td>
</tr>
<tr>
<td>{ <em>x</em> : <em>T</em></td>
<td><em>P</em></td>
</tr>
<tr>
<td>{ <em>x</em> : <em>T</em></td>
<td><em>P</em> }</td>
</tr>
<tr>
<td>{ <em>x</em> : <em>T</em></td>
<td><em>e</em> }</td>
</tr>
<tr>
<td>( μ x : T</td>
<td><em>P</em> )</td>
</tr>
<tr>
<td>( \bigcup { <em>x</em> : <em>T</em></td>
<td><em>e</em>( <em>x</em>) } )</td>
</tr>
<tr>
<td><strong>p.n</strong></td>
<td>Selection of <em>n</em>th element from the tuple <em>p</em>.</td>
</tr>
<tr>
<td><strong>obj.v</strong></td>
<td>Selection of value of component <em>v</em> from object <em>obj</em>.</td>
</tr>
<tr>
<td>([f_1 \sim v_1, \cdots]_C)</td>
<td>Record where <em>f_i</em> is a component name and <em>v_i</em> is the value associated to that component. It represents an object of the class <em>C</em> with its components instantiated. If a component is not specified, it is set to null or 0 (if it is a set) by default.</td>
</tr>
<tr>
<td><strong>R{ S }</strong></td>
<td>Relational image of a relation <em>R</em> under a set <em>S</em>.</td>
</tr>
<tr>
<td>[ i : T ]_X ]</td>
<td>Transformation of <em>i</em> to PRISM in the context <em>X</em>. For example, [ \cdot ]_M denotes the module context.</td>
</tr>
<tr>
<td><strong>uname</strong></td>
<td>This function constructs a fresh unique identifier for a new element from the supplied construct <em>par</em> (of type <em>NamedElement</em>) and the name <em>m</em> (a string) of the element.</td>
</tr>
<tr>
<td><strong>uname</strong></td>
<td>Similar to <strong>uname</strong>(<em>par</em>, <em>m</em>), but this function has three parameters where both <em>m</em> and <em>n</em> are of type string.</td>
</tr>
<tr>
<td><strong>id</strong></td>
<td>This function defines a unique identifier for an existing construct <em>n</em> (of type <em>NamedElement</em>). If <em>n</em> is null, it gives an empty name. One possible implementation is to use qualified names.</td>
</tr>
<tr>
<td><strong>id</strong></td>
<td>This function defines a unique identifier for an existing event <em>e</em> (of type <em>Event</em>) when considering it for input (<em>out</em> = false) or output (<em>out</em> = true). If <em>e</em> is null, it gives an empty name. One possible implementation is to use qualified names with a suffix “IN” or “OUT”.</td>
</tr>
<tr>
<td><strong>fname</strong></td>
<td>This is a function declaration with the last parameter <em>p_n</em> of type <em>T_n</em> and the result of type <em>T_r</em>. It is commonly used to create a curried version of the function, an application of the function having all arguments except the last one.</td>
</tr>
</tbody>
</table>
5.3.5 Normalisation rules

**Rule 102. Normalisation of state machines**

\[
\begin{align*}
\text{where} & \quad \text{transnodes} = \left\{ [\text{stm}] \right\}_{\text{CS}} \\
\end{align*}
\]

**Rule 103. Normalisation of states**

\[
\begin{align*}
\text{where} & \quad \text{transnodes} = \left\{ [\text{s}] \right\}_{\text{CS}} \\
\end{align*}
\]

**Rule 104. Normalisation of NodeContainer**

\[
\begin{align*}
\end{align*}
\]

Figure 5.8: Metamodel of PRISM rewards
Chapter 5. Probabilistic Semantics

Rule 105. Normalisation of states without outgoing transitions

\[
\text{addLoopStateTrans}(stm : \text{NodeContainer}) : \text{PState} \times \text{PTransition} =
\]

\[
\begin{align*}
\text{if } & \exists n : \text{stm.nodes} \land n \in \text{State} \land (\forall t : \text{stm.transitions} \land t.\text{source} \neq n) \text{ then} \\
& \left(\{\text{loopstate}\}, \{\text{looptran}\} \cup \text{newtrans}\right) \\
\text{else} & \left(0, 0\right)
\end{align*}
\]

where

\[
\text{loopstate} = \text{newState}^1(\text{uname}(\text{stm}, \text{"loop"}))
\]

\[
\text{looptran} = \text{newTransition}^1(\text{uname}(\text{stm}, \text{"loop_self"}), \text{loopstate}, \text{loopstate})
\]

\[
\text{newtrans} = \bigcup \left\{ n : \text{stm.nodes} \mid n \in \text{State} \land (\forall t : \text{stm.transitions} \land t.\text{source} \neq n) \right\} \text{newTransition}^2(\text{uname}(n, \text{"to_loop"}), n, \text{loopstate})
\]

Rule 106. Normal junctions whose incoming transitions are combinable

\[
\text{inTransCombinableJuncs}(stm : \text{NodeContainer}) : \text{PJunction} =
\]

\[
\left\{ n : \text{stm.nodes} \mid n \in \text{Junction} \land n \notin \text{Initial} \land n \notin \text{ProbJunc} \land \\
(\exists t : \text{stm.transitions} \land t.\text{target} = n \land \text{isCombinableTran}^1(t)) \right\}
\]

Rule 107. Combinable transition

\[
\text{isCombinableTran}(t : \text{Transition}) : \text{boolean} =
\]

\[
t.\text{action} = \text{null} \land t.\text{source} \notin \text{Initial} \land t.\text{source} \notin \text{ProbJunc}
\]

Rule 108. Incoming and outgoing transitions of a node

\[
\text{transitionsOf}(trans : \text{PTransition}) : n : \text{Node} \rightarrow \text{PTransition} =
\]

\[
\{t : trans \mid t.\text{source} = n \lor t.\text{target} = n\}
\]

Rule 109. Combination of transitions of junctions

\[
\text{combTransJunctions}(juncs : \text{PJunction}, trans : \text{PTransition}) : \text{PJunction} \times \text{PTransition} \times \text{PTransition} =
\]

\[
\begin{align*}
\text{if } & \text{juncs} = 0 \text{ then } (0, 0, 0) \text{ else } (jtrans.1 \cup \text{ojstrans}.1, jtrans.1 \cup \text{ojstrans}.2, jtrans.3 \cup \text{ojstrans}.3) \\
\text{where} & \text{j} \in \text{juncs} \\
\text{jtrans} & = \text{combTransJunction}^1(j, \text{transitionsOf}^2(\text{trans}, j)) \\
\text{ojstrans} & = \text{combTransJunctions}^2(\text{juncs} \setminus \{j\}, \\
& \bigcup \left(\text{transitionsOf}^3((\text{trans} \setminus \text{jtrans}.2) \cup \text{jtrans}.3) \setminus \{j\}\right))
\end{align*}
\]
Rule 110. Combination of transitions of a junction

\[
\text{combTransJunction}(j : \text{Junction}, \text{trans} : \mathbb{P} \text{Transition}) = \mathbb{P} \text{Junction} \times \mathbb{P} \text{Transition} \times \mathbb{P} \text{Transition} = \\
\begin{cases} 
\text{if } \text{intransother} \neq \emptyset \text{ then } (\emptyset, \text{intranscomb}, \text{newtrans}) \text{ else } (\{j\}, \text{trans}, \text{newtrans}) \\
\end{cases}
\]

where

\[
\text{intranscomb} = \{ t : \text{trans} | t.\text{target} = j \wedge \text{isCombinableTrans}(t) \}
\]
\[
\text{intransother} = \{ t : \text{trans} | t.\text{target} = j \} \setminus \text{intranscomb}
\]
\[
\text{outtrans} = \{ t : \text{trans} | t.\text{source} = j \}
\]
\[
\text{newtrans} = \{ 
\begin{align*} 
& t_i : \text{intranscomb}, t_j : \text{outtrans} \mapsto \\
& \begin{cases} 
& \text{name} \mapsto \text{uname}(t_i, t_j, \text{name}), \text{source} \mapsto t_i.\text{source}, \\
& \text{target} \mapsto t_j.\text{target}, \text{trigger} \mapsto t_i.\text{trigger}, \\
& \text{condition} \mapsto t_i.\text{condition} \land t_j.\text{condition}, \text{action} \mapsto t_j.\text{action} \\
& \text{Transition}
\end{cases}
\end{align*}
\}
\]

Rule 111. Transition split

\[
\text{splitTrans}(t : \text{Transition}) : \mathbb{P} \text{Transition} \times \mathbb{P} \text{ProbJunc} = \\
\begin{cases} 
\text{if } t.\text{trigger} \neq \emptyset \land t.\text{action} \neq \emptyset \text{ then } \\
\begin{align*} 
& \begin{cases} 
& \text{name} \mapsto \text{uname}(t, \text{sp}_1), \text{source} \mapsto t.\text{source}, \text{target} \mapsto \text{pj}, \\
& \text{trigger} \mapsto t.\text{trigger}, \text{condition} \mapsto t.\text{condition} \\
& \text{Probability} \mapsto 1, \text{action} \mapsto t.\text{action}
\end{cases} \\
& \text{Transition}, \{\text{pj}\}
\end{align*}
\end{cases}
\]

\[
\text{else } (\{t\}, \emptyset)
\]

where

\[
\text{pj} = |\text{name} \mapsto \text{uname}(t, \text{sp}_2)|.\text{ProbJunc}
\]

Rule 112. New State

\[
\text{newState}(n : \text{String}) : \text{State} = \\
\begin{cases} 
\text{name} \mapsto n, \text{nodes} \mapsto \emptyset, \text{transitions} \mapsto \emptyset, \text{actions} \mapsto \emptyset
\end{cases}_\text{State}
\]

Rule 113. New Transition

\[
\text{newTransition}(n : \text{String}, \text{source} : \text{Node}, \text{target} : \text{Node}) : \text{Transition} = \\
\begin{cases} 
\text{name} \mapsto n, \text{source} \mapsto \text{source}, \text{target} \mapsto \text{target}, \text{trigger} \mapsto \emptyset, \\
\text{condition} \mapsto \emptyset, \text{probability} \mapsto \emptyset, \text{action} \mapsto \emptyset
\end{cases}_\text{Transition}
\]

5.3.6 Normal form to PRISM

\[
\text{MODEL_TYPE}
\]

\text{MODEL_TYPE} is a parameter to this translation and can have two values: “DTMC” and “MDP”;
Chapter 5. Probabilistic Semantics

Rule 114. Module
\[ [m : \text{Module}]_\mathcal{M} : \text{Model}_\mathcal{M} = \]
\[
\begin{align*}
\text{modelType} & \leftarrow \begin{cases}
\text{if MODEL\_TYPE} = \text{"MDP" then } \text{"MDP" else } \text{"DTMC"} & , \\
\text{constants} & \leftarrow ((r : \text{ctrlrets} \cdot r.1) \cup \text{rprets.1} \cup \text{exitconsts}, \\
\text{globals} & \leftarrow ((r : \text{ctrlrets} \cdot r.2) \cup \text{rprets.2}, \\
\text{modules} & \leftarrow ((r : \text{ctrlrets} \cdot r.3) \cup \text{rprets.3} \cup \text{bufmodules}
\end{cases}
\end{align*}
\]

Rule 115. Exit sequence control constants
\[ \text{exitSeqCtrlConsts}() : \mathbb{P} \text{Constant} = \]
\[
\begin{align*}
\{ \text{inv, act\_p, act\_t, exited, sub\_act, sub\_waiting, sub\_exited} \}
\end{align*}
\]

Robotic platforms

Rule 116. Robotic platforms
\[ \left( \begin{array}{l}
\text{rp} : \text{RoboticPlatformDef}, \text{outevents} : \mathbb{P} \text{Event}, \text{opmaps} : \text{OperationSig} \leftrightarrow \text{Action}_\mathcal{P}, \\
\text{namemap} : (\text{Event}\_\text{Name} \times \text{Boolean}) \rightarrow \text{String} \\
\end{array} \right) \]
\[ : \mathbb{P} \text{Constant} \times \mathbb{P} \text{VarDecl} \times \text{Module} = \]
\[
\begin{align*}
\left( \bigcup (r : \text{constvars} \cdot r.1), \bigcup (r : \text{constvars} \cdot r.2), \text{module} \right)
\end{align*}
\]

where
\[
\begin{align*}
\text{constvars} & \leftarrow \bigcup_{r \in \mathcal{R}} \{ \text{getStyleLists}(rp) \} \\
\text{localvars} & \leftarrow \{ e : \text{outevents} \times \text{EVT}\_\text{namemap}(e) \rightarrow \text{true} : \text{[e.type]} \} \\
\text{eventcmds} & \leftarrow \begin{cases}
\text{if } e \in \text{outevents} \text{ then} \\
\{ \text{[namemap}(e \rightarrow \text{true}) \rightarrow \text{EVT}\_\text{namemap}(e \rightarrow \text{true}) \} = y; \\
\} \\
\end{cases}
\end{align*}
\]

\[
\begin{align*}
\text{opcmds} & \leftarrow \{ \text{act}. \text{ran omaps} \rightarrow \{ \text{act.name} \rightarrow \text{true} \} \\
\text{module} & \leftarrow \text{module}(i, \text{opmaps}, \text{localvars}, \text{commands} : (\bigcup \text{eventcmds} ) \cup \text{opcmds}) \text{endmodule}
\end{align*}
\]
Rule 117. Controllers

\[
\begin{align*}
\text{controllers} & : \text{ControllerDef} 	imes \text{namemap} : (\text{Event} \times \text{Boolean}) \to \text{String} \\
& = \\
& \{ \text{constvars} \mid r.1 \} \cup \{ \text{stmsrets} \mid r.1 \} \cup \{ \text{constvars} \mid r.2 \} \\
& \cup \{ \text{stmsrets} \mid r.2 \} \cup \text{bufmodules}, \text{rops}
\end{align*}
\]

where

\[
\begin{align*}
\text{constvars} & = \{ \text{getVariableLists} (\text{ctrl}) \} \\
\text{newnamemap} & = \text{renameEventsConns} (\text{ctrl}, \text{ctrl}.\text{connections}, \text{namemap}) \\
\text{bufmodules} & = \text{asyncConnectedEvents} (\text{ctrl}, \text{ctrl}.\text{connections}, \text{newnamemap}) \\
\text{allops} & = \text{getRequiredOperations} (\text{ctrl}) \cup \{ \text{op} : \text{ctrl}.\text{Operations} \mid \begin{cases} \text{if op} \in \text{OperationDef} & \text{then op} \\ \text{else op}.\text{ref} & \end{cases} \}
\end{align*}
\]

\[
\begin{align*}
\text{stmrets} & = \\
& \{ \text{c : ctrl.connections} \mid \begin{cases} \text{if c}.\text{bidirec} \land \text{c}.\text{from} = \text{stm} \\ \text{c}.\text{from} = \text{stm} \\ \text{c}.\text{efrom}.\text{type} \neq \text{null} & \text{then c}.\text{efrom} \\ \text{else c}.\text{eto} & \end{cases} \}
\end{align*}
\]

\[
\begin{align*}
\text{stminevents} & = \\
& \{ \text{c : ctrl.connections} \mid \begin{cases} \text{if c}.\text{bidirec} \land \text{c}.\text{from} = \text{stm} \\ \text{c}.\text{from} = \text{stm} \\ \text{c}.\text{efrom}.\text{type} \neq \text{null} & \text{then c}.\text{eto} \\ \text{else c}.\text{from} & \end{cases} \}
\end{align*}
\]

\[
\begin{align*}
\text{allops} & = \{ \text{op} : \text{ctrl}.\text{Operations} \mid \begin{cases} \text{if op} \in \text{OperationDef} & \text{then op} \\ \text{else op}.\text{ref} & \end{cases} \}
\end{align*}
\]

\[
\begin{align*}
\text{rops} & = \{ \text{stm : ctrl.machines} \mid \begin{cases} \text{opToActionMaps} (\text{stm}, \text{stmoutevents}) \\
\text{let stmoutevents} = \\
\{ \text{c : ctrl.connections} \mid \begin{cases} \text{if c}.\text{bidirec} \land \text{c}.\text{from} = \text{stm} \\ \text{c}.\text{from} = \text{stm} \\ \text{c}.\text{efrom}.\text{type} \neq \text{null} & \text{then c}.\text{efrom} \\ \text{else c}.\text{eto} & \end{cases} \}
\end{align*}
\]

Rule 118. Mapping from operations required by state machines to PRISM actions

\[
\text{opToActionMaps} (\text{stm} : \text{StateMachineDef}) : \text{OperationSig} \leftrightarrow \text{Action} = \\
\{ \text{op} : \text{getRequiredOperations} (\text{stm}) \mid \begin{cases} \text{if op} \in \text{OperationDef} & \text{then op} \\ \text{else op}.\text{ref} & \end{cases} \}
\]
**Rule 119. State machines**

\[
\begin{align*}
\text{stm}: & \text{StateMachineDef}, \\
\text{outevents}: & \mathbb{P} \text{Event}, \\
\text{inevents}: & \mathbb{P} \text{Event}, \\
\text{ctrlops}: & \text{OperationSig}, \\
\text{namemap}: & (\text{Event} \times \text{Boolean}) \rightarrow \text{String}
\end{align*}
\]

\[
\begin{align*}
\text{STM} & \equiv \\
U \{ \text{r}: \text{constvars} \cdot \text{r}.1 \}; \\
U \{ \text{r}: \text{opdefsret} \cdot \text{r}.1 \}; \\
\text{stmret.0}; \\
\text{module id(STM)} \\
Y \{ \text{r}: \text{constvars} \cdot \text{r}.2 \}; \\
\text{outeventvars}; \\
\text{ineventvars}; \\
\text{stmret.1}; \\
\text{ropsvars}; \\
U \{ \text{r}: \text{opdefsret} \cdot \text{r}.2 \}; \\
\text{stmret.2}; \\
U \{ \text{r}: \text{opdefsret} \cdot \text{r}.3 \}; \\
\text{endmodule}
\end{align*}
\]

where

\[
\begin{align*}
\text{constvars} & = U \{ \text{getVariableLists}^{3} (\text{stm}) \} \\
\text{outeventvars} & = \{ \text{e}: \text{outevents} \cdot \text{EVT} \cdot \text{namemap}(\text{e} \rightarrow \text{true}); [\text{e.type}] \}; \\
\text{ineventvars} & = \{ \text{e}: \text{inevents} \cdot \text{FIN} \cdot \text{namemap}(\text{e} \rightarrow \text{false}); \text{boolInittrue} \}; \\
\text{rops} & = \text{getRequiredOperations}^{3} (\text{stm}) \\
\text{calledops} & = \text{getAllCalledOperations}^{1} (\text{stm}, \text{ctrlops}) \\
\text{ropsvars} & = U \{ \text{op} : \text{getRequiredOperations}^{4} (\text{stm}) \mid \text{op} \in \text{calledops} \cdot \\
& \{ \text{p} : \text{op.parameters} \cdot \text{uname} (\text{stm}, \text{op.name}, \text{p.name}) : [\text{p.type}] \}; \} \\
\text{ctrlopdefs} & = \{ \text{op} : \text{ctrlops} \mid \text{op} \in \text{OperationDef} \} \\
\text{opdefsret} & = \{ \text{op} : \text{ctrlops} \mid (\exists \text{rop} : \text{rops} \cdot \text{rop.name} = \text{op.name}) \land \\
& \{ \text{op} : \text{ctrlopdefs} \cdot \text{namemap} \} \} \\
\text{stmret} & = \{ \text{stm}, \text{namemap} \}^{3}
\end{align*}
\]
5.3 Translation to PRISM

Rule 120. State machine body

\[
\begin{bmatrix}
\text{stm} \colon \text{StateMachineBody},
\text{ctroldefs} : \mathbb{I} \text{OperationDef},
\text{namemap} : (\text{Event}_{\mathbb{I}} \times \text{Boolean}) \to \text{String}
\end{bmatrix}
\]

\[\text{STB} \]

\[\bigcup \{ r : \text{constvars} \cap r.1 \} \cup \{ \text{lockfree} \} \cup \text{stmret.2},
\bigcup \{ r : \text{constvars} \cap r.2 \} \cup \{ \text{lockvar} \} \cup \text{stmret.3},
\text{stmret.4} \]

where

\[
\text{constvars} = \bigcup
\begin{bmatrix}
\text{getVariableLists}^{6}(\text{stm})
\end{bmatrix}
\]

\[\text{stmret} = [\text{stm}, \text{stm}, 0, 1, \text{ctroldefs}, \text{namemap}] \]

\[\text{lockfree} = \text{const int id(\text{stm}).LOCK\_FREE} = 0;\]

\[\text{lockvar} = \text{id(\text{stm}).lock} : [0..(\text{stmret.1} - 1)] = \text{id(\text{stm}).LOCK\_FREE};\]

Rule 121. Composite states

\[
\begin{bmatrix}
\text{cs} : \text{NodeContainer},
\text{stm} : \text{StateMachineDef},
\text{pccons} : \mathbb{I} \text{BoolExp}_{\mathbb{I}},
\text{trnumber} : \text{int},
\text{ctroldefs} : \mathbb{I} \text{OperationDef},
\text{namemap} : (\text{Event}_{\mathbb{I}} \times \text{Boolean}) \to \text{String}
\end{bmatrix}
\]

\[\text{S} \]

\[\text{subcssret.1},
\begin{bmatrix}
\{ \text{const0} \} \cup \text{exitcsret} \cup \text{exitssret.2} \cup \text{enterstatesret.2} \cup
\begin{bmatrix}
\text{constsnodesret} \cup \text{transret.3} \cup \text{subcssret.2}
\end{bmatrix},
\{ \text{scpc, exit} \} \cup \text{subcssret.3},
\text{exitssret.3} \cup \text{exitssret.3} \cup \text{enterstatesret.3} \cup \text{transret.4} \cup \text{subcssret.4}
\end{bmatrix}
\]

where

\[
\text{const0} = \text{const int id(\text{cs}).INACTIVE} = 0;
\]

\[\text{id} = \text{getInitial}^{1}(\text{cs})\]

\[\text{f0} = \text{getFinal}^{1}(\text{cs})\]

\[\text{scpcname} = \text{id(\text{cs}).scpc}\]

\[\text{scpc} = \text{scpcname} : [0..(\text{if} \text{f0} \neq \text{null} \text{then} \text{transret.1} \text{else} (\text{transret.1} - 1))],\]

\[\text{if} \text{cs} \in \text{StateMachineDef} \text{then} \text{id}(0) \text{else} \text{const0}.name;\]

\[\text{exit} = \text{id(\text{cs}).exit} : [0..6] = \text{Exit\_NONE};\]

\[\text{exitcsret} = \begin{bmatrix}
\text{if} \text{cs} \in \text{StateMachineBody} \text{then} (1, 0, 0)
\text{else exitCompState}^{1}(\text{cs}, \text{exits}, \text{scpcname}, \text{pccons}, \text{transret.1}, \text{ctroldefs}, \text{namemap})
\end{bmatrix}\]

\[\text{exitssret} = \text{exitSubstates}^{1}(\{ \text{s} : \text{cs.nodess} \in \text{State} \}
\text{scpcname}, \text{pccons}, \text{transret.1}, \text{ctroldefs}, \text{namemap})\]

\[\text{enterstatesret} = \text{enterSubstates}^{1}(\{ \text{s} : \text{cs.nodess} \in \text{State} \}
\text{scpcname}, \text{pccons}, \text{transret.1}, \text{ctroldefs}, \text{namemap})\]

\[\text{constsnodesret} = \text{constantsOfNamedElems}^{1}(\text{cs.nodess}, \text{enterstatesret.1})\]

\[\text{transret} = [\text{cs.nodess}, \text{cs}, \text{stm}, \text{exit}, \text{scpcname}, \text{pccons},
\text{constsnodesret.1}, \text{trnumber}, \text{ctroldefs}, \text{namemap}] \]

\[\text{cstates} = \{ \text{s} : \text{cs.nodess} \in \text{State} \}
\text{isComposite}^{1}(\text{s})\]

\[\text{subcssret} = [\text{cstates}, \text{stm}, \text{scpcname}, \text{pccons}, \text{transret.2}, \text{ctroldefs}, \text{namemap}]\]
The extra assignment \( \text{exit.name} = \text{Exit.NE} \) in \text{cmd2} in Rule 21 is to clear \text{exit} to avoid this command re-enabled.

### Rule 122. Exit a composite state

\[
\text{exitCompState} \left( \begin{array}{c}
\text{cs : NodeContainer}, \text{exit : VarDeclP}, \text{scpcname : Name}, \\
\text{pcconstrs : } \mathbb{P} \text{ BoolExprP}, \text{stnumber : int}, \text{ctrlopdefs : } \mathbb{P} \text{ OperationDef}, \\
\text{namemap : } (\text{EventRC} \times \text{Boolean}) \rightarrow \text{String}
\end{array} \right)
\]

\[
: \text{Int} \times \mathbb{P} \text{ Constant} \times \mathbb{P} \text{ Command} =
\]

\[
(\text{exitret.1} \cup \text{exitret.2}, \{\text{cmd1}, \text{cmd2}\} \cup \text{exitret.4})
\]

where

\[
\text{exitreq} = (\text{exit.name} = \text{Exit.ACT Parent}) \mid (\text{exit.name} = \text{Exit.ACT Trans})
\]

\[
\text{cmd1} = \left[ \begin{array}{c}
\text{cmd2} \exists \left( \begin{array}{c}
\text{andExprs}(\text{pcconstrs}) \& \text{exitreq} \rightarrow 1.0 : \text{exit.name} = \text{Exit.Sub.ACT};
\end{array} \right)
\end{array} \right]
\]

\[
\text{assigns} = (\text{exit.name}' = \text{Exit.EXITED}) \& (\text{scpcname}' = \text{id}(\text{cs}) \text{INACTIVE})
\]

\[
\text{exitret} = \left[ \begin{array}{c}
\text{getExitAction}(\text{cs}, 0, \text{stnumber}, \text{scpcname}, \text{null}, \text{assigns}, \text{ctrlopdefs}, \text{namemap}), 4'
\end{array} \right]
\]

\[
\text{cmd2} = \left[ \begin{array}{c}
\text{cmd1} \exists \left( \begin{array}{c}
\text{andExprs}(\text{pcconstrs}) \& \text{exit.name} = \text{Exit.Sub.EXITED}
\end{array} \right) \rightarrow
\end{array} \right] 1.0 : \text{if exitret.4} = 0 \text{ then exitret.3 else exitret.3} & (\text{exit.name}' = \text{Exit.NE})
\]

### Rule 123. Exit substates

\[
\text{exitSubstates} \left( \begin{array}{c}
\text{states} : \mathbb{P} \text{ State}, \text{exit} : \text{VarDeclP}, \text{scpcname} : \text{Name}, \text{pcconstrs} : \mathbb{P} \text{ BoolExprP}, \\
\text{stnumber} : \text{int}, \text{ctrlopdefs} : \mathbb{P} \text{ OperationDef}, \\
\text{namemap} : (\text{EventRC} \times \text{Boolean}) \rightarrow \text{String}
\end{array} \right)
\]

\[
: \text{Int} \times \mathbb{P} \text{ Constant} \times \mathbb{P} \text{ Command} =
\]

\[
\text{if states} = 0 \text{ then }
\]

\[
(\text{stnumber}, 0, 0)
\]

\[
\text{else}
\]

\[
(\text{othersret.1}, \text{sret.2} \cup \text{otherret.2}, \text{sret.3} \cup \text{otherret.3})
\]

where

\[
\text{s} \in \text{states}
\]

\[
\text{sret} = \text{exitSubstates}^1(\text{s}, \text{exit}, \text{scpcname}, \text{pcconstrs}, \text{stnumber}, \text{ctrlopdefs}, \text{namemap})
\]

\[
\text{othersret} = \text{exitSubstates}^2(\text{states} \setminus \{\text{s}\}, \text{exit}, \text{scpcname}, \text{pcconstrs}, \text{sret.1}, \text{ctrlopdefs}, \text{namemap})
\]

### Rule 124. Exit a substate

\[
\text{exitSubstate} \left( \begin{array}{c}
\text{s} : \text{State}, \text{exit} : \text{VarDeclP}, \text{scpcname} : \text{Name}, \text{pcconstrs} : \mathbb{P} \text{ BoolExprP}, \\
\text{stnumber} : \text{int}, \text{ctrlopdefs} : \mathbb{P} \text{ OperationDef}, \\
\text{namemap} : (\text{EventRC} \times \text{Boolean}) \rightarrow \text{String}
\end{array} \right)
\]

\[
: \text{Int} \times \mathbb{P} \text{ Constant} \times \mathbb{P} \text{ Command} =
\]

\[
\text{if IsComposite}^2(\text{s}) \text{ then }
\]

\[
\text{exitCompSubstate}^1(\text{s}, \text{exit}, \text{scpcname}, \text{pcconstrs}, \text{stnumber})
\]

\[
\text{else}
\]

\[
\text{exitSimpSubstate}^1(\text{s}, \text{exit}, \text{scpcname}, \text{pcconstrs}, \text{stnumber}, \text{ctrlopdefs}, \text{namemap})
\]
Rule 125. Exit a simple substate

\[
\text{exitSimpSubstate} \quad \begin{array}{c}
\text{s : State, exit : VarDeclPr, scpcname : Name, pcconstrs : } & \begin{array}{c}
P \text{boolExprPr, stnumber : int, ctrlopdefs : } P \text{ OperationDef, namemap : } (\text{EventSet} \times \text{Boolean}) \rightarrow \text{String}
\end{array} \\
\end{array} \\
\text{where}
\end{array}
\]

\[
\text{exitreq} = (\text{scpcname} = \text{id}(s)) \land (\text{exit} = \text{Exit\_Sub\_ACT})
\]

\[
\text{cmd1} = \{ \text{andExprs}(\text{pcconstrs}) \land \text{exitreq} \} \rightarrow 1.0 : (\text{exit.name}' = \text{Exit\_Sub\_ACT} \land (\text{id}(s).exit = \text{Exit\_EXITED}))
\]

\[
\text{exitedCheck} = (\text{scpcname} = \text{id}(s)) \land (\text{id}(s).exit = \text{Exit\_EXITED}) \land (\text{exit.name} = \text{Exit\_Sub\_Waiting})
\]

\[
\text{cmd2} = \{ \text{andExprs}(\text{pcconstrs}) \land \text{exitedCheck} \} \rightarrow 1.0 : (\text{exit.name}' = \text{Exit\_Sub\_EXITED} \land (\text{id}(s).exit = \text{Exit\_NONE}))
\]

Rule 126. Exit a composite substate

\[
\text{exitCompSubstate} \quad \begin{array}{c}
\text{s : State, exit : VarDeclPr, scpcname : Name, pcconstrs : } & \begin{array}{c}
P \text{boolExprPr, stnumber : int}
\end{array} \\
\end{array} \\
\text{where}
\end{array}
\]

\[
\text{exitreq} = (\text{scpcname} = \text{id}(s)) \land (\text{exit} = \text{Exit\_Sub\_ACT})
\]

\[
\text{cmd1} = \{ \text{andExprs}(\text{pcconstrs}) \land \text{exitreq} \} \rightarrow 1.0 : (\text{exit.name}' = \text{Exit\_Sub\_ACT} \land (\text{id}(s).exit = \text{Exit\_ACT}\_Parent))
\]

Rule 127. Enter substates (with entry actions)

\[
\text{enterSubstates} \quad \begin{array}{c}
\text{states : } P \text{ State, stm : StateMachineDef, scpcname : Name, pcconstrs : } & \begin{array}{c}
P \text{boolExprPr, stnumber : int, ctrlopdefs : } P \text{ OperationDef, namemap : } (\text{EventSet} \times \text{Boolean}) \rightarrow \text{String}
\end{array} \\
\end{array} \\
\text{where}
\end{array}
\]

\[
\text{if states} = \emptyset \text{ then}
\]

\[
(stnumber, \emptyset, \emptyset)
\]

\[
\text{else}
\]

\[
(othersret.1, sret.2 \cup otherret.2, sret.3 \cup otherret.3)
\]

where

\[
s \in \text{states}
\]

\[
\text{sret} = \text{enterSubstate}^1 (s, \text{stm}, \text{scpcname}, \text{pcconstrs}, \text{stnumber}, \text{ctrlopdefs}, \text{namemap})
\]

\[
\text{othersret} = \text{enterSubstates}^2 (\text{states} \setminus \{s\}, \text{stm}, \text{scpcname}, \text{pcconstrs}, \text{sret.1}, \text{ctrlopdefs}, \text{namemap})
\]
Chapter 5. Probabilistic Semantics

**Rule 128.** Enter a substate (with an entry action)

\[
\text{enterSubstate} \left( s: \text{State}, \text{stm}: \text{StateMachineDef}, \text{scpcname}: \text{Name}, \ \text{pcconstrs}: \text{List of BoolExpr}, \text{stnumber}: \text{int}, \text{ctrloDefs}: \text{List of OpDef}, \text{namemap}: (\text{EventRC} \times \text{Boolean}) \rightarrow \text{String} \right) : \text{int} \times \text{P Constant} \times \text{P Command} =
\]

\[
(\text{entryret}.1, \{\text{enteringconst}\} \cup \text{entryret}.2, \text{entryret}.4)
\]

where

\[
\text{enteringconst} = \text{const int id(s)}_\text{entering} = \text{stnumber};
\]

\[
\text{extraassign} = \left\{ \begin{array}{ll}
\text{id(s)}_\text{scpc} = \text{id(getInitial}(s)) & \text{if isComposite}^3(s) \\
\text{id(stm)}_{\text{lock}'} = \text{id(stm)}_{\text{LOCK_FREE}} & \text{else}
\end{array} \right.
\]

\[
\text{entryret} = \left[ \begin{array}{ll}
\text{getEntryAction}(s, \text{pcconstrs}, \text{stnumber} + 1, \text{scpcname}, \text{enteringconst}, \\
\{\text{scpcname}' = \text{id(s)}, \text{extraassign}\} , \text{ctrloDefs}, \text{namemap} \right) \right] A^3
\]

**Rule 129.** Constants representing states for named elements

\[
\text{constantsOfNamedElems} \left( \text{elems}: \text{List of NamedElement}, \text{stnumber}: \text{int} \right) : \text{int} \times \text{P Constant} =
\]

\[
\text{if} \ \text{elems} = \emptyset \ \text{then} \ (\text{stnumber}, \emptyset) \ \text{else} \ (\text{othersret}.1, \{\text{elconst}\} \cup \text{othersret}.2)
\]

where

\[
\text{el} \in \text{elems}
\]

\[
\text{elconst} = \text{const int id(el)} = \text{stnumber};
\]

\[
\text{othersret} = \text{constantsOfNamedElems}^2(\text{elems} \setminus \{\text{el}\}, \text{stnumber} + 1)
\]

**Rule 130.** Composite substates

\[
\left[ \begin{array}{ll}
\text{cstates}: \text{List of State}, \text{stm}: \text{StateMachineDef}, \text{scpcname}: \text{Name}, \\
\text{pcconstrs}: \text{List of BoolExpr}, \text{trnumber}: \text{int}, \text{ctrloDefs}: \text{List of OpDef}, \\
\text{namemap}: (\text{EventRC} \times \text{Boolean}) \rightarrow \text{String} \right) : \text{int} \times \text{P Constant} \times \text{P VarDecl} \times \text{P Command} =
\]

\[
\text{if} \ \text{cstates} = \emptyset \ \text{then} \ (\text{trnumber}, 0, 0, 0) \ \text{else} \ (\text{othersret}.1, \text{csret}.2 \cup \text{othersret}.2, \text{csret}.3 \cup \text{othersret}.3, \text{csret}.4 \cup \text{othersret}.4)
\]

where

\[
\text{cs} \in \text{cstates}
\]

\[
\text{csret} = [\text{cs}, \text{stm}, \text{pcconstrs} \cup \{\text{scpcname} = \text{id(cs)}\}, \text{trnumber}, \text{ctrloDefs}, \text{namemap}] \]

\[
\text{othersret} = [(\text{cstates} \setminus \{\text{cs}\}, \text{stm}, \text{scpcname}, \text{pcconstrs}, \text{csret}.1, \text{ctrloDefs}, \text{namemap}] \]
\]

**Transitions**
5.3 Translation to PRISM

**Rule 131. Nodes (transitions)**

\[
\begin{align*}
\text{nodes} & : \mathbb{P} \text{ Node, cs : NodeContainer, stm :StateMachineDef, exit : VarDeclPr,} \\
\text{scpcname} & : \text{Name, pcconstrs} : \mathbb{P} \text{ BoolExprPr, stnumber : int, trnumber : int,} \\
\text{ctrlopdefs} & : \mathbb{P} \text{ OperationDef, namemap} : (\text{Event}_{\text{rc}} \times \text{Boolean}) \rightarrow \text{String} \\
& : \text{int} \times \text{int} \times \mathbb{P} \text{ Constant} \times \mathbb{P} \text{ Command} =
\end{align*}
\]

\[
\text{if nodes} = \emptyset \text{ then} \\
\text{ (stnumber, trnumber, 0, 0)}
\]

\[
\text{else} \\
\text{ (othersret.1, othersret.2, nret.3 \cup othersret.3, nret.4 \cup othersret.4)}
\]

\[\text{where}\]

\[
n \in \text{ nodes} \\
nret = [[n, cs, stm, exit, scpcname, pcconstrs, stnumber, trnumber, ctrlopdefs, namemap]]
\]

\[
\text{othersret} = [[\text{nodes} \setminus \{n\}, cs, stm, exit, scpcname,} \\
\text{ pcconstrs, nret.1, nret.2, ctrlopdefs, namemap]]
\]

**Rule 132. Node (transitions)**

\[
\begin{align*}
\text{n} & : \text{Node, cs : NodeContainer, stm : StateMachineDef, exit : VarDeclPr,} \\
\text{scpcname} & : \text{Name, pcconstrs} : \mathbb{P} \text{ BoolExprPr, stnumber : int, trnumber : int,} \\
\text{ctrlopdefs} & : \mathbb{P} \text{ OperationDef, namemap} : (\text{Event}_{\text{rc}} \times \text{Boolean}) \rightarrow \text{String} \\
& : \text{int} \times \text{int} \times \mathbb{P} \text{ Constant} \times \mathbb{P} \text{ Command} =
\end{align*}
\]

\[
\text{if n} \in \text{ProbJunc} \text{ then} \\
\text{ [n, cs, stm, exit, scpcname, pcconstrs, stnumber, trnumber, ctrlopdefs, namemap]}
\]

\[
\text{else} \\
\text{ [n, cs, stm, exit, scpcname, pcconstrs, stnumber, trnumber, ctrlopdefs, namemap]}
\]

**Rule 133. Probabilistic junction (transitions)**

\[
\begin{align*}
\text{n} & : \text{ProbJunc, cs : NodeContainer, stm : StateMachineDef, exit : VarDeclPr,} \\
\text{scpcname} & : \text{Name, pcconstrs} : \mathbb{P} \text{ BoolExprPr, stnumber : int, trnumber : int,} \\
\text{ctrlopdefs} & : \mathbb{P} \text{ OperationDef, namemap} : (\text{Event}_{\text{rc}} \times \text{Boolean}) \rightarrow \text{String} \\
& : \text{int} \times \text{int} \times \mathbb{P} \text{ Constant} \times \mathbb{P} \text{ Command} =
\end{align*}
\]

\[
\text{(transret.1, transret.2, transret.3, \{cmd\} \cup transret.5)}
\]

\[\text{where}\]

\[
\text{trans} = \{ t : \text{cs.transitions} | t.\text{source} = n \} \\
\text{transret} = \{ \text{trans, n, stm, exit, scpcname, pcconstrs, stnumber, trnumber, ctrlopdefs, namemap} \}
\]

\[
\text{cmd} = \{ (\text{andExpr}^4(\text{pcconstrs}) \& (\text{scpcname} = \text{id}(n))) \rightarrow \text{transret.4} ;
\]

\[
\text{TNS}
\]

\[
\text{TN}^\prime
\]

\[
\text{TNprob'}
\]

\[
\text{TNother'}
\]
**Chapter 5. Probabilistic Semantics**

**Rule 134. Other nodes (initial, normal junction, and states) (transitions)**

\[
\begin{align*}
\text{n} & \colon \text{Node}, \text{cs} \colon \text{NodeContainer}, \text{stm} \colon \text{StateMachineDef}, \text{exit} \colon \text{VarDecl}_{\text{pr}}, \\
\text{scpcname} & \colon \text{Name}, \text{pcconstrs} \colon \mathbb{P} \text{~BoolExpr}_{\text{pr}}, \text{stnumber} \colon \text{int}, \text{trnumber} \colon \text{int}, \\
\text{ctrlopdefs} & \colon \text{IP OperationDef}, \text{namemap} : (\text{Event}_{\text{lo}} \times \text{Boolean}) \rightarrow \text{String} \\
& \quad \text{where} \\
& \quad \text{trans} = \{ \{ \text{cs}.\text{transitions} | \text{t.source} = \text{n} \} \} \\
& \quad \text{transret} = \left[ \begin{array}{c} \text{trans}, \text{stm}, \text{exit}, \text{scpcname}, \text{pcconstrs}, \\
\text{stnumber}, \text{trnumber}, \text{ctrlopdefs}, \text{namemap} \end{array} \right] \text{TS}^\prime
\end{align*}
\]

**Rule 135. Transitions from a node**

\[
\begin{align*}
\text{trans} & \colon \mathbb{P} \text{~Transition}, \text{n} \colon \text{Node}, \text{stm} \colon \text{StateMachineDef}, \text{exit} \colon \text{VarDecl}_{\text{pr}}, \\
\text{scpcname} & \colon \text{Name}, \text{pcconstrs} \colon \mathbb{P} \text{~BoolExpr}_{\text{pr}}, \text{stnumber} \colon \text{int}, \text{trnumber} \colon \text{int}, \\
\text{ctrlopdefs} & \colon \text{IP OperationDef}, \text{namemap} : (\text{Event}_{\text{lo}} \times \text{Boolean}) \rightarrow \text{String} \\
& \quad \text{where} \\
& \quad \text{if} \ \text{trans} = \emptyset \ \text{then} \\
& \quad \quad \{ \text{stnumber}, \text{trnumber}, 0, 0, 0 \} \\
& \quad \quad \text{else} \\
& \quad \quad \{ \text{othersret}, 1, \text{othersret}, 2, \text{tret}, 3 \cup \text{othersret}, 3, \text{tret}, 4 \cup \text{othersret}, 4, \text{tret}, 5 \cup \text{othersret}, 5 \} \\
& \quad \text{transret} = \left[ \begin{array}{c} \text{trans} \setminus \{ \{ \text{t}, \text{n}, \text{stm}, \text{exit}, \text{scpcname}, \text{pcconstrs}, \\
\text{stnumber}, \text{trnumber}, \text{ctrlopdefs}, \text{namemap} \} \end{array} \right] \text{TS}^\prime
\end{align*}
\]

**Rule 136. Action and target of a transition**

\[
\begin{align*}
\text{actionTargetOfTran} \left( \begin{array}{c} \text{t} \colon \text{Transition}, \text{stm} \colon \text{StateMachineDef}, \text{scpcname} \colon \text{Name}, \\
\text{pcconstrs} \colon \mathbb{P} \text{~BoolExpr}_{\text{pr}}, \text{stnumber} \colon \text{int}, \text{trnumber} \colon \text{int}, \\
\text{ctrlopdefs} & \colon \text{IP OperationDef}, \text{namemap} : (\text{Event}_{\text{lo}} \times \text{Boolean}) \rightarrow \text{String} \end{array} \right) \\
& \quad \text{where} \\
& \quad \text{target} = \left( \begin{array}{c} \text{if} \ \text{t.target} \in \text{State} \land \text{hasEntryAction}^\text{2}(\text{t.target}) \text{ then } \text{id}(\text{t.target}) \text{.entering} \\
\text{else } \text{id}(\text{t.target}) \end{array} \right) \\
& \quad \text{targetassigns} = \left( \begin{array}{c} \text{if} \ \text{t.target} \in \text{State} \land \neg \text{hasEntryAction}^\text{2}(\text{t.target}) \text{ then} \\
\text{if} \ \text{isComposite}(\text{t.target}) \\
\quad \text{then } \{ \text{id}(\text{t.target}) \text{.scpc} = \text{id}(\text{getInitial}^\text{5}(\text{t.target})) \} \\
\text{else } \{ \text{id}(\text{stm}) \text{.lock} = \text{id}(\text{stm})\text{.LOCK\_FREE} \} \\
\text{else } \emptyset \end{array} \right) \\
& \quad \text{tactionret} = \left[ \begin{array}{c} \text{taction}, \text{pcconstrs}, \text{stnumber}, \text{scpcname}, \text{null}, \\
\{ \text{scpcname} = \text{target} \} \cup \text{targetassigns}, \text{ctrlopdefs}, \text{namemap} \end{array} \right] \text{AST}^\prime
\end{align*}
\]
Rule 137. Transition from a node
\[
\begin{align*}
t &: \text{Transition}, \\
n &: \text{Node}, \\
stm &: \text{StateMachineDef}, \\
extit &: \text{VarDecl}_{\text{pr}}, \\
scpcname &: \text{Name}, \\
ppconstrs &: \text{P BooleanExpr}_{\text{pr}}, \\
\text{stnumber} &: \text{int}, \\
\text{trnumber} &: \text{int}, \\
\text{ctrlopdefs} &: \text{P OperationDef}, \\
\text{namemap} &: \text{Event}_{\text{rc}} \times \text{Boolean} \\
\text{update} &: \text{P Constant} \times \text{P Update} \times \text{P Command} =
\end{align*}
\]
\[
\begin{align*}
\text{if } n \in \text{Initial} & \text{ then} \\
[t,n,stm,exit,scpcname,ppconstrs,stnumber,trnumber,ctrlopdefs,namemap] \\
\text{else if } n \in \text{ProbJunc} & \text{ then} \\
[t,n,stm,exit,scpcname,ppconstrs,stnumber,trnumber,ctrlopdefs,namemap] \\
\text{else if } n \in \text{State} & \text{ then} \\
[t,n,stm,exit,scpcname,ppconstrs,stnumber,trnumber,ctrlopdefs,namemap] \\
\text{else} &
\end{align*}
\]

Rule 138. Transition from an initial junction
\[
\begin{align*}
t &: \text{Transition}, \\
n &: \text{Initial}, \\
stm &: \text{StateMachineDef}, \\
extit &: \text{VarDecl}_{\text{pr}}, \\
scpcname &: \text{Name}, \\
ppconstrs &: \text{P BooleanExpr}_{\text{pr}}, \\
\text{stnumber} &: \text{int}, \\
\text{trnumber} &: \text{int}, \\
\text{ctrlopdefs} &: \text{P OperationDef}, \\
\text{namemap} &: \text{Event}_{\text{rc}} \times \text{Boolean} \\
\text{update} &: \text{P Constant} \times \text{P Update} \times \text{P Command} =
\end{align*}
\]
\[
\begin{align*}
\text{if } n \in \text{Initial} & \text{ then} \\
[t,n,stm,exit,scpcname,ppconstrs,stnumber,trnumber,ctrlopdefs,namemap] \\
\text{else if } n \in \text{ProbJunc} & \text{ then} \\
[t,n,stm,exit,scpcname,ppconstrs,stnumber,trnumber,ctrlopdefs,namemap] \\
\text{else if } n \in \text{State} & \text{ then} \\
[t,n,stm,exit,scpcname,ppconstrs,stnumber,trnumber,ctrlopdefs,namemap] \\
\text{else} &
\end{align*}
\]

Rule 139. Transition from a probabilistic junction
\[
\begin{align*}
t &: \text{Transition}, \\
n &: \text{ProbJunc}, \\
stm &: \text{StateMachineDef}, \\
extit &: \text{VarDecl}_{\text{pr}}, \\
scpcname &: \text{Name}, \\
ppconstrs &: \text{P BooleanExpr}_{\text{pr}}, \\
\text{stnumber} &: \text{int}, \\
\text{trnumber} &: \text{int}, \\
\text{ctrlopdefs} &: \text{P OperationDef}, \\
\text{namemap} &: \text{Event}_{\text{rc}} \times \text{Boolean} \\
\text{update} &: \text{P Constant} \times \text{P Update} \times \text{P Command} =
\end{align*}
\]
\[
\begin{align*}
\text{if } n \in \text{ProbJunc} & \text{ then} \\
[t,n,stm,exit,scpcname,ppconstrs,stnumber,trnumber,ctrlopdefs,namemap] \\
\text{else if } n \in \text{State} & \text{ then} \\
[t,n,stm,exit,scpcname,ppconstrs,stnumber,trnumber,ctrlopdefs,namemap] \\
\text{else} &
\end{align*}
\]
Rule 140. Transition from a normal junction

\[ T_j : \text{Transition}, n : \text{Junction}, \text{stm} : \text{StateMachineDef}, \text{exit} : \text{VarDecl}_\text{pr}, \]
\[ \text{scpcname} : \text{Name}, \text{pcconst} : \text{P BoolExpr}_{\text{pr}}, \text{stnumber} : \text{int}, \text{trnumber} : \text{int}, \]
\[ \text{ctrlopdefs} : \text{P OperationDef}, \text{namemap} : (\text{Event}_{\text{loc}} \times \text{Boolean}) \rightarrow \text{String} \]
\[ : \text{int} \times \text{int} \times \text{P Constant} \times \text{P Update} \times \text{P Command} = \]
\[ (\text{tactret}.1, \text{trnumber}, \text{tactret}.2, 0, \text{tactret}.4 \cup \{\text{cmd1}\}) \]

where
\[ \text{tactret} = \text{actionTargetOfTran}^3 (t, \text{stm}, \text{scpcname}, \text{pcconst}, \text{stnumber}, \text{ctrlopdefs}, \text{namemap}) \]
\[ \text{scpcgrid} = \text{pcconst} \cup \{\text{scpcname} = \text{id}(n)\} \]
\[ \text{condgrid} = \text{if } t.\text{condition} \neq \text{null } \text{then } (\text{scpcgrid} \cup \{[t.\text{condition}]\}) \text{ else } \text{scpcgrid} \]
\[ \text{cmd1} = \{ \text{andExprs}^\text{p}(\text{condgrid}) \rightarrow 1.0 : \text{tactret}.3 ; \]
5.3 Translation to PRISM

**Rule 141. Transition from a state**

\[
\begin{align*}
\text{t}: & \rightarrow \text{Transition}, \text{n}: \rightarrow \text{State}, \text{stm}: \rightarrow \text{StateMachineDef}, \text{exit}: \rightarrow \text{VarDeclPr}, \\
\text{scpcname}: & \rightarrow \text{Name}, \text{pcconstrs}: \rightarrow \text{IP BoolExprPr}, \text{stnumber}: \rightarrow \text{int}, \text{ttnumber}: \rightarrow \text{int}, \\
\text{ctroldefs}: & \rightarrow \text{IP OperationDef}, \text{namemap}: \rightarrow (\text{EventIc} \times \text{Boolean}) \rightarrow \text{String}, \\
& \rightarrow \text{Int} \times \text{Int} \times \text{IP Constant} \times \text{IP Update} \times \text{IP Command} = \\
\end{align*}
\]

\[
(\text{trigret}, \text{ttnumber} + 1, \text{[locktconst | tactret2 | trigret2 | tactret4 | exitsrcret2 | trigret3]})
\]

where

\[
\begin{align*}
\text{locktfconst} & = \text{const int id(t)} = \text{ttnumber}; \\
\text{scpcgrd} & = \text{pcconstrs} \cup \{\text{scpcname = id(n)}\} \\
\text{condgrd} & = \text{if t.condition \neq null then \{scpcgrd \cup \{1, \text{condition}\}\}} \text{ else scpcgrd} \\
\text{lockfreegrd} & = \text{(id(stm).}\text{lock = id(stm).\text{LOCK FREE})} \\
\text{tactret} & = \text{actionTargetOfTran}^\text{d}(\text{t}, \text{stm}, \text{scpcname}, \text{pcconstrs}, \text{stnumber}, \text{ctroldefs}, \text{namemap}) \\
\text{locktgrd} & = \text{(id(stm).}\text{lock = lockconst.name)} \\
\text{exitsrcret} & = \text{if \text{isComposite}^\text{d}(\text{n}) then \text{exitCompSrcState}^\text{t} (\text{t}, \text{scpcgrd} \cup \{\text{locktgrd}\}, \text{tactret.3})} \text{ else \text{exitSimpSrcState}^\text{t} (\text{t}, \text{exit}, \text{scpcgrd}, \text{tactret.3})} \\
\text{trigvarassign} & = \text{if t.trigger \neq null \& t.trigger.type = \text{CommunicationType.INPUT}} \text{ then \{(id(t.trigger.parameter)' = \text{EVT}[\text{namemap}(t.trigger.event \rightarrow \text{false})]\} \text{ else } \emptyset \\
\text{locktassign} & = \text{id(stm).}\text{lock'} = \text{lockconst.name} \\
\text{lockassigns} & = \text{if t.target \neq \text{State}} \text{ then \{(locktassign)\} \text{ else } \emptyset} \\
\text{trigret} & = \text{if t.trigger.type = \text{INPUT then} \text{[t.trigger.\text{t.condition}, \text{pcconstrs}, \text{lockfreegrd}, id(n), \text{scpcname}, \text{tactret.1}, \text{locktassign}, \text{exitsrcret.1, namemap}]}} \\
& \text{ else if t.trigger.type = \text{OUTPUT} \lor t.trigger.type = \text{SYNC} then \text{[t.trigger.\text{t.condition}, \text{pcconstrs}, \text{lockfreegrd}, id(n), \text{scpcname}, \text{tactret.1}, \text{locktassigns} \cup \text{exitsrcret.1, false, namemap}]}} \\
& \text{ else if t.trigger.type = \text{SIMPLE then} \text{[t.condition, \text{pcconstrs}, \text{lockfreegrd}, id(n), \text{scpcname}, \text{tactret.1}, \text{locktassigns} \cup \text{exitsrcret.1, false}]}} \\
& \text{ else \text{[t.condition, \text{pcconstrs}, \text{lockfreegrd}, id(n), \text{scpcname}, \text{tactret.1}, \text{locktassigns} \cup \text{exitsrcret.1, false}]}}
\end{align*}
\]
Chapter 5. Probabilistic Semantics

**Rule 142. Exit composite source state**

\[
\text{exitCompSrcState}(t: \text{Transition}, \text{pcconstrs}: \text{BoolExpr}, \text{curassgn}: \text{P Assignment}) = \\
(\{ \text{id}(t.\text{source})_{\text{exit}} = \text{Exit\_ACT\_Trans} \}, \{ \text{exitcmd} \})
\]

where

\[
\text{exitcmd} = \{ \text{andExprs}^0(\text{pcconstrs}) \& (\text{id}(t.\text{source})_{\text{exit}} = \text{Exit\_EXITED}) \} \rightarrow 1.0: \text{curassgn};
\]

**Rule 143. Exit simple source state**

\[
\text{exitSimpSrcState}(t: \text{Transition}, \text{exit}: \text{VarDecl}, \text{pcconstrs}: \text{BoolExpr}, \text{curassgn}: \text{P Assignment}) = \\
(\text{P Assignment} \times \text{P Command}) = \\
\begin{cases}
\text{if} \neg \text{hasExitAction}(t.\text{source}) & \text{then} (\text{curassgns}, \emptyset) \\
\text{else} & (\{ \text{exit.name} = \text{Exit\_Sub\_ACT} \}, \{ \text{exitcmd} \})
\end{cases}
\]

where

\[
\text{exitcmd} = \{ \text{andExprs}^0(\text{pcconstrs}) \& (\text{exit.name} = \text{Exit\_Sub\_EXITED}) \} \rightarrow \\
1.0: \text{curassgns} & (\text{exit.name}' = \text{EXIT\_NONE});
\]

**Actions**

**Rule 144. Actions**

\[
\text{act} : \text{Action}, \text{pcconstrs} : \text{P BoolExpr}, \text{stnumber} : \text{Int}, \text{scpcname} : \text{Name}, \text{curstate} : \text{Constant}, \text{assigns} : \text{P Assignment}, \text{ctrlopdefs} : \text{P OperationDef}, \text{namemap} : (\text{Event} \times \text{Boolean}) \rightarrow \text{String}
\]

\[
A = \begin{cases}
\text{if} \; \text{act} = \text{null} & \text{then} (\text{stnumber}, \emptyset, \text{assigns}, \emptyset) \\
\text{else} & [\text{act}.\text{action}, \text{pcconstrs}, \text{stnumber}, \text{scpcname}, \text{curstate}, \text{assigns}, \text{ctrlopdefs}, \text{namemap}]_{\text{AST}}^{
\text{AST}}
\end{cases}
\]

The function \([\_]\text{AST}\) is the entry to translate a statement \text{stmt}, and the function \([\_]\text{ST}\) should not be called directly except inside this function \([\_]\text{AST}\).

**Rule 145. Statements**

\[
\text{stmt} : \text{Statement}, \text{pcconstrs} : \text{P BoolExpr}, \text{stnumber} : \text{Int}, \text{scpcname} : \text{Name}, \text{curstate} : \text{Constant}, \text{assigns} : \text{P Assignment}, \text{ctrlopdefs} : \text{P OperationDef}, \text{namemap} : (\text{Event} \times \text{Boolean}) \rightarrow \text{String}
\]

\[
\text{AST} = \begin{cases}
\text{if} \; \text{stmt} = \text{null} & \text{then} (\text{stnumber}, \emptyset, \text{assigns}, \emptyset) \\
\text{else} & [\text{stmt}, \text{pcconstrs}, \text{stnumber}, \text{scpcname}, \text{curstate}, \text{assigns}, \text{ctrlopdefs}, \text{namemap}]_{\text{ST}}^{
\text{ST}}
\end{cases}
\]
5.3 Translation to PRISM

Rule 146. Statement

\[
\begin{align*}
\text{stmt} &: \text{Statement, pcconstrs} : \mathbb{P} \text{BoolExpr}_{pr}, \text{stnumber} : \text{int}, \text{scpcname} : \text{Name}, \\
\text{curstate} &: \text{Constant}_{pr}, \text{assigns} : \mathbb{P} \text{Assignment}_{pr}, \text{ctrlopdefs} : \mathbb{P} \text{OperationDef}, \\
\text{namemap} &: (\text{Event}_{rc} \times \text{Boolean}) \rightarrow \text{String}
\end{align*}
\]

\[
\begin{align*}
: \text{int} \times \mathbb{P} \text{Constant} \times \mathbb{P} \text{Assignment} \times \mathbb{P} \text{Command} =
\end{align*}
\]

This rule is split in multiple rules from Rule 46 to Rule 52 according to the subtype of the statement.

Rule 147. Statement (Skip)

\[
\begin{align*}
\text{stmt} &: \text{Skip, pcconstrs} : \mathbb{P} \text{BoolExpr}_{pr}, \text{stnumber} : \text{int}, \text{scpcname} : \text{Name}, \\
\text{curstate} &: \text{Constant}_{pr}, \text{assigns} : \mathbb{P} \text{Assignment}_{pr}, \text{ctrlopdefs} : \mathbb{P} \text{OperationDef}, \\
\text{namemap} &: (\text{Event}_{rc} \times \text{Boolean}) \rightarrow \text{String}
\end{align*}
\]

\[
\begin{align*}
: \text{int} \times \mathbb{P} \text{Constant} \times \mathbb{P} \text{Assignment} \times \mathbb{P} \text{Command} =
\end{align*}
\]

\[
(\text{stnumber}, \emptyset, \text{assigns}, \emptyset)
\]

Rule 148. Statement (ParStmt)

\[
\begin{align*}
\text{stmt} &: \text{ParStmt, pcconstrs} : \mathbb{P} \text{BoolExpr}_{pr}, \text{stnumber} : \text{int}, \text{scpcname} : \text{Name}, \\
\text{curstate} &: \text{Constant}_{pr}, \text{assigns} : \mathbb{P} \text{Assignment}_{pr}, \text{ctrlopdefs} : \mathbb{P} \text{OperationDef}, \\
\text{namemap} &: (\text{Event}_{rc} \times \text{Boolean}) \rightarrow \text{String}
\end{align*}
\]

\[
\begin{align*}
: \text{int} \times \mathbb{P} \text{Constant} \times \mathbb{P} \text{Assignment} \times \mathbb{P} \text{Command} =
\end{align*}
\]

\[
[\text{stmt.stmt, pcconstrs, stnumber, scpcname, curstate, assigns, ctrlopdefs, namemap}]\]

\[
\text{AST}^3
\]

Rule 149. Statement (Assignment)

\[
\begin{align*}
\text{stmt} &: \text{Assignment, pcconstrs} : \mathbb{P} \text{BoolExpr}_{pr}, \text{stnumber} : \text{int}, \text{scpcname} : \text{Name}, \\
\text{curstate} &: \text{Constant}_{pr}, \text{assigns} : \mathbb{P} \text{Assignment}_{pr}, \text{ctrlopdefs} : \mathbb{P} \text{OperationDef}, \\
\text{namemap} &: (\text{Event}_{rc} \times \text{Boolean}) \rightarrow \text{String}
\end{align*}
\]

\[
\begin{align*}
: \text{int} \times \mathbb{P} \text{Constant} \times \mathbb{P} \text{Assignment} \times \mathbb{P} \text{Command} =
\end{align*}
\]

\[
\begin{align*}
\text{if curstate} \neq \text{null} & \text{ then stnumber else stnumber + 1,} \\
\text{if curstate} \neq \text{null} & \text{ then } \emptyset \text{ else } \{\text{const}\}, \\
\text{curassgns, } \text{cmd}
\end{align*}
\]

where

\[
\begin{align*}
\text{const} &= \text{if curstate} \neq \text{null then curstate else const int uname (stmt, stnumber) = stnumber;} \\
\text{curassgns} &= \{\text{scpcname'} = \text{const.name}\} \\
\text{cmd} &= (\emptyset | \text{andExprs}(\text{pcconstrs}) \& (\text{scpcname = const.name})) \\
& \rightarrow 1.0 : \text{assigns} \cup \{\text{id(stmt.left)'} = \text{[stmt.right]'c};
\end{align*}
\]

A CommunicationStmt does not allow an empty event and so the else branch in the definition of trigret should not be reached, which is guaranteed by the corresponding well-formedness condition.
Chapter 5. Probabilistic Semantics

Rule 150. Statement (CommunicationStmt)

\[
\text{stmt} : \text{CommunicationStmt}, \text{pcconstrs} : \text{P BoolExpr}, \text{stnumber} : \text{int}, \text{scpname} : \text{Name}, \\
\text{curstate} : \text{Constant}, \text{assigns} : \text{P Assignment}, \text{ctrlopdefs} : \text{P OperationDef}, \\
\text{namemap} : (\text{Event} \times \text{Boolean}) \rightarrow \text{String} : \text{int} \times \text{P Constant} \times \text{P Assignment} \times \text{P Command} = \\
\]

\[
\begin{align*}
\text{commret} &= 1.\text{if curstate} \neq \text{null then } 0 \text{else } \{\text{const} \cup \text{commret.2}; \{\text{curassgn}, \text{commret.3}\} \\
&\text{where } \\
\text{const} &= \text{if curstate} \neq \text{null then curstate else const int} \text{uname} (\text{stmt}, \text{stnumber}) = \text{stnumber}; \\
\text{stnumber} &= \text{if curstate} \neq \text{null then stnumber else stnumber} + 1 \\
\text{curassgn} &= \text{scpname}' = \text{const.name} \\
&\quad \text{if stmt.\text{communication}_\text{type} = \text{CommunicationType}.\text{INPUT} \text{ then} \\
&\quad \quad \text{stmt.\text{communication}, null, pcconstrs, 0, const.name,} \\
&\quad \quad \text{scpname, stnumber1, 0, assigns, namemap} \\
&\quad \quad \text{InputEvent'} \\
&\quad \text{else if} \\
&\quad \quad \text{stmt.\text{communication}_\text{type} = \text{CommunicationType}.\text{OUTPUT} \lor} \\
&\quad \quad \text{stmt.\text{communication}_\text{type} = \text{CommunicationType}.\text{SYNC} \text{ then} \\
&\quad \quad \text{stmt.\text{communication}, null, pcconstrs, 0, const.name,} \\
&\quad \quad \text{scpname, stnumber1, 0, assigns, namemap} \\
&\quad \quad \text{OutputEvent'} \\
&\quad \text{else if stmt.\text{communication}_\text{type} = \text{CommunicationType}.\text{SIMPLE} \text{ then} \\
&\quad \quad \text{stmt.\text{communication}, null, pcconstrs, 0, const.name,} \\
&\quad \quad \text{scpname, stnumber1, assigns, true, namemap} \\
&\quad \quad \text{SimpleEvent'} \\
&\quad \text{else} \\
\end{align*}
\]

Rule 151. Statement (If Statements)

\[
\text{stmt} : \text{IfStmt}, \text{pcconstrs} : \text{P BoolExpr}, \text{stnumber} : \text{int}, \text{scpname} : \text{Name}, \\
\text{curstate} : \text{Constant}, \text{assigns} : \text{P Assignment}, \text{ctrlopdefs} : \text{P OperationDef}, \\
\text{namemap} : (\text{Event} \times \text{Boolean}) \rightarrow \text{String} : \text{int} \times \text{P Constant} \times \text{P Assignment} \times \text{P Command} = \\
\]

\[
\begin{align*}
\text{elserset} &= 1.\text{if curstate} \neq \text{null then } 0 \text{else } \{\text{const}\} \cup \text{thenret.2} \cup \text{elserset.2}, \text{curassgn}, \\
&\quad \{\text{thencmd}, \text{elsecmd}\} \cup \text{thenret.4} \cup \text{elserset.4} \\
&\text{where } \\
\text{const} &= \text{if curstate} \neq \text{null then curstate else const int} \text{uname} (\text{stmt}, \text{stnumber}) = \text{stnumber}; \\
\text{curassgn} &= \{\text{scpname}' = \text{const.name}\} \\
\text{thenret} &= \text{stmt.then, pcconstrs, if curstate} \neq \text{null then stnumber else stnumber} + 1, \\
&\quad \text{scpname, null, assigns, ctrlopdefs, namemap} \\
&\text{thencmd} = \left(\text{andExpr}^1 (\text{pcconstrs}) \& \\
&\quad (\text{scpname} = \text{const.name})\& \\
&\quad [\text{stmt.expression}]\right) \rightarrow 1.0 : \text{thenret.3}; \\
\text{elsecmd} = \left(\text{andExpr}^1 (\text{pcconstrs}) \& \\
&\quad (\text{scpname} = \text{const.name})\& \\
&\quad [\text{stmt.expression}]\right) \rightarrow 1.0 : \text{elseret.3}; \\
\end{align*}
\]
Rule 152. Statement (Call)

\[
\begin{align*}
\text{stmt} &: \text{Call}, \\
\text{pcconstrs} &: \mathbb{P} \text{BoolExpr}, \\
\text{stnumber} &: \text{int}, \\
\text{scpcname} &: \text{Name}, \\
\text{curstate} &: \text{Constant}, \\
\text{curupdates} &: \mathbb{P} \text{Update}, \\
\text{assigns} &: \mathbb{P} \text{Assignment}, \\
\text{ctrlopdefs} &: \mathbb{P} \text{OperationDef}, \\
\text{namemap} &: (\text{Event} \times \text{Boolean}) \rightarrow \text{String}
\end{align*}
\]

\[
\begin{align*}
\text{ST} &= \text{int} \times \mathbb{P} \text{Constant} \times \mathbb{P} \text{Assignment} \times \mathbb{P} \text{Command} = \\
&= \begin{cases} \\
\text{if} \; \text{curstate} \neq \text{null} \; \text{then} \; \text{stnumber} \; \text{else} \; \text{stnumber} + 1, \\
\text{if} \; \text{curstate} \neq \text{null} \; \text{then} \; 0 \; \text{else} \; \{\text{const}\}, \\
\text{curassignments}, \text{cmds}
\end{cases}
\end{align*}
\]

where

\[
\begin{align*}
\text{const} &= \text{if} \; \text{curstate} \neq \text{null} \; \text{then} \; \text{curstate} \; \text{else} \; \text{const}, \\
\text{uname} &= \text{name}(\text{stmt}, \text{stnumber}) = \text{stnumber}; \\
\text{opvarassignments} &= \{ \text{scpname}' = \text{const.name} \}
\end{align*}
\]

\[
\begin{align*}
\text{opdef} &= \text{getOperationDef}(\text{stmt.operation}, \text{ctrlopdefs}) \\
\text{grd} &= \text{pcconstrs} \cup \{ \text{scpname} = \text{const.name} \}
\end{align*}
\]

\[
\begin{align*}
\text{cmds} &= \begin{cases} \\
\text{if} \; \text{opdef} \neq \text{null} \; \text{then} \\
\text{callOpdef}(& \text{opdef, grd, opvarassignments, assigns}) \\
\text{else} \\
\{ \; \{\text{id}(\text{stmt.operation})\}(\text{andExprs}(\text{grd}) \rightarrow 1.0 : \text{assigns} \cup \text{opvarassignments}; \}
\end{cases}
\end{align*}
\]

Rule 153. Statement (sequential composition)

\[
\begin{align*}
\text{stmt} &: \text{SeqStatement}, \\
\text{pcconstrs} &: \mathbb{P} \text{BoolExpr}, \\
\text{stnumber} &: \text{int}, \\
\text{scpcname} &: \text{Name}, \\
\text{curstate} &: \text{Constant}, \\
\text{assigns} &: \mathbb{P} \text{Assignment}, \\
\text{ctrlopdefs} &: \mathbb{P} \text{OperationDef}, \\
\text{namemap} &: (\text{Event} \times \text{Boolean}) \rightarrow \text{String}
\end{align*}
\]

\[
\begin{align*}
\text{ST} &= \text{int} \times \mathbb{P} \text{Constant} \times \mathbb{P} \text{Assignment} \times \mathbb{P} \text{Command} = \\
&= \text{stmt.statements} \cup \text{pcconstrs} \times \text{int} \times \text{scpcname} \times \text{curstate} \times \text{assigns} \times \text{ctrlopdefs} \times \text{namemap}
\end{align*}
\]
Rule 154. Statement (sequence of statements)

\[
\begin{align*}
\text{sts} & : \text{seq} \text{Statement}, \text{pcconstrs} : \mathbb{P} \text{BoolExpr}, \text{stnumber} : \text{int}, \text{scpclassname} : \text{Name}, \\
\text{curstate} & : \text{Constant}, \text{assigns} : \mathbb{P} \text{Assignment}, \text{ctrlodefs} : \mathbb{P} \text{OperationDef}, \\
\text{namemap} & : (\text{Event} \times \text{Boolean}) \rightarrow \text{String}
\end{align*}
\]

\[\text{sts} = \langle \rangle \]

\[
\begin{align*}
\text{if} \quad \text{sts} = \langle \rangle & \quad \text{then} \\
& \quad \text{(stnumber, } 0, \text{assigns, } 0) \\
\text{else if} \quad \#\text{sts} = 1 & \quad \text{then} \\
& \quad [\text{headsts}, \text{pcconstrs}, \text{stnumber}, \text{scpclassname}, \text{curstate}, \text{assigns}, \text{ctrlodefs}, \text{namemap}]^{\text{AST}} \\
\text{else} & \\
& \quad \text{let} \quad \text{lres} == [\text{laststs}, \text{pcconstrs}, \text{stnumber}, \text{scpclassname}, \text{null}, \text{assigns}, \text{ctrlodefs}, \text{namemap}]^{\text{AST}} \\
& \quad \text{fsres} == [\text{frontsts}, \text{pcconstrs}, \text{lres}.1, \text{scpclassname}, \text{curstate}, \text{lres}.3, \text{ctrlodefs}, \text{namemap}]^{\text{AST}} \\
& \quad \text{STs} = \text{lres}.2 \cup \text{fsres.2} \cup \text{fsres.2} \cup \text{fsres.4}
\end{align*}
\]

Connections

Rule 155. Asynchronous connections

\[
\text{syncConnectedEvents} (\text{parent} : \text{NamedElement}, \text{connections} : \mathbb{P} \text{Connection}, \\
\text{namemap} : (\text{Event} \times \text{Boolean}) \rightarrow \text{String}) : \mathbb{P} \text{Module} =
\]

\[
\begin{align*}
\text{c} : \text{connections} & \quad \text{if} \quad \text{isInternalAsyncConn}(c) & \quad \text{then} \\
& \quad \text{if} \quad \text{c.bidirect} & \quad \text{then} \\
& \quad \text{asyncConnectedEvent}^1 (\text{parent}, \text{c.from}, \text{c.to}, \\
& \quad \text{c.efrom}, \text{c.eto}, \text{namemap}) \\
& \quad \text{asyncConnectedEvent}^2 (\text{parent}, \text{c.to}, \text{c.from}, \\
& \quad \text{c.eto}, \text{c.efrom}, \text{namemap}) \\
& \quad \text{else} \quad \text{asyncConnectedEvent}^3 (\text{parent}, \text{c.from}, \text{c.to}, \\
& \quad \text{c.efrom}, \text{c.eto}, \text{namemap}) \\
& \quad \text{else} \quad \emptyset
\end{align*}
\]

For connections between a controller and its contained state machine. If it is from the controller to a state machine, its event should be regarded as INPUT for the state machine. Otherwise, it should be regarded as OUTPUT.
### Rule 156. Asynchronous connection

\[
\text{asyncConnectedEvent} \quad \begin{array}{l}
\text{parent} : \text{NamedElement},
\text{cfrom} : \text{ConnectionNode},
\text{cto} : \text{ConnectionNode},
\text{efrom} : \text{Event},
\text{eto} : \text{Event},
\text{namemap} : (\text{Event}_c \times \text{Boolean}) \to \text{String}
\end{array}
\] : \text{Module} =

\text{if} \ \text{efrom}.\text{type} \neq \text{null} \text{ then}
\begin{align*}
\text{buffer} & \left( \text{namemap}(\text{eout}), \text{namemap}(\text{ein}), \text{efrom}.\text{type} \right) \\
\text{else} & \ \text{simpleBuffer} \left( \text{namemap}(\text{eout}), \text{namemap}(\text{ein}) \right)
\end{align*}

where
\begin{align*}
\text{fromctrl} & = \text{parent} \in \text{Controller} \land \text{cfrom} = \text{parent} \\
\text{toctrl} & = \text{parent} \in \text{Controller} \land \text{cto} = \text{parent} \\
\text{eout} & = \text{if} \ \text{fromctrl} \ \text{then} \ (\text{efrom}, \text{false}) \ \text{else} \ (\text{efrom}, \text{true}) \\
\text{ein} & = \text{if} \ \text{toctrl} \ \text{then} \ (\text{eto}, \text{true}) \ \text{else} \ (\text{eto}, \text{false})
\end{align*}

A connection is called an internal asynchronous connection (\text{isInternalAsyncConn}) if the connection is asynchronous and not from or to a robotic platform. For the asynchronous connection between a controller and a platform, we do not need a buffer to connect them because the platform is the environment of the controllers.

### Rule 157. Asynchronous connection

\[
\text{isInternalAsyncConn} \quad \begin{array}{l}
c : \text{Connection}
\end{array} : \text{Boolean} =
\]

\[
\text{if} \ c.\text{async} \land c.\text{from} \notin \text{RoboticPlatform} \land c.\text{to} \notin \text{RoboticPlatform} \ \text{then} \ \text{true} \ \text{else} \ \text{false}
\]

In Rule 57, \text{namemap} is a function from an event and its direction (for input or output) to its name in PRISM. Here we use \text{true} to denote the event is used for output and \text{false} for input.

### Rule 158. Connections: events renaming

\[
\text{renameEventsConns} \quad \begin{array}{l}
\text{parent} : \text{NamedElement},
\text{connections} : \mathbb{P} \text{Connection},
\text{namemap} : (\text{Event}_c \times \text{Boolean}) \to \text{String}
\end{array}
\] : (\text{Event}_c \times \text{Boolean}) \to \text{String} =

\text{if} \ \text{connections} = \emptyset \ \text{then} \ \text{namemap} \ \text{else} \ \text{osnamemap}

where
\begin{align*}
\text{c} & \in \text{connections} \\
\text{cnamemap} & = \text{renameEventsConn}^1(\text{parent}, \text{c}, \text{namemap}) \\
\text{osnamemap} & = \text{renameEventsConns}^2(\text{parent}, \text{connections} \setminus \{c\}, \text{cnamemap})
\end{align*}
### Rule 159. Connection: events renaming

\[
\text{renameEventsConn}( \text{parent} : \text{NamedElement}, \text{c} : \text{Connection}, \text{namemap} : (\text{Event}_\text{IC} \times \text{Boolean}) \rightarrow \text{String} ) : (\text{Event}_\text{IC} \times \text{Boolean}) \rightarrow \text{String} = \\
\begin{align*}
\text{if } \text{isInternalAsyncConn}(\text{c}) \text{ then} \\
\quad \text{if } \text{c.bidirec} \text{ then} \\
\quad \quad \text{renameAsyncEvents}^1(\text{parent, c.from, c.to, c.efrom, c.eto, namemap}) \\
\quad \quad \oplus \\
\quad \quad \text{renameAsyncEvents}^2(\text{parent, c.to, c.from, c.efrom, c.eto, namemap}) \\
\quad \quad \text{else} \\
\quad \quad \text{renameAsyncEvents}^3(\text{parent, c.from, c.to, c.efrom, c.eto, namemap}) \\
\text{else} \\
\quad \text{if } \text{c.bidirec} \text{ then} \\
\quad \quad \text{renameSyncEvents}^1(\text{parent, c.from, c.to, c.efrom, c.eto, namemap}) \\
\quad \quad \oplus \\
\quad \quad \text{renameSyncEvents}^2(\text{c.to, c.from, c.efrom, c.eto, namemap}) \\
\quad \quad \text{else} \\
\quad \quad \text{renameSyncEvents}^3(\text{parent, c.from, c.to, c.efrom, c.eto, namemap})
\end{align*}
\]

If the connection is within a controller and between the controller and a state machine, the event direction considered will be different because the event on the controller acts as a relay and it is shared by two connections: one inside the controller and one outside the controller (inside a module). The event is used for opposite directions in both connections. We give names to events in connections of a module first, and then propagate to connections inside controllers. Therefore, for a connection that is inside a controller and between the controller and a state machine, its direction should be opposite. In Rule 59 and Rule 60, the definitions of \textit{eout} and \textit{ein} take this into account.
For an asynchronous connection between controllers or between state machines, we will add one buffer module and so the translated names for the two events in both ends of the connection are different.
Chapter 5. Probabilistic Semantics

Buffer

This buffer module simulates a buffer of size 1 for an asynchronous connection on an input event and an output event. The `fvar` denotes whether a buffer is full or not. The `vvar` is the element stored in the buffer. The `finvar` denotes whether a communication is finished or not because a communication takes two steps in PRISM: 1) `cmd1` synchronises and 2) `cmd2` updates the buffer.

```
Rule 162. Buffer
buffer(ein : String, eout : String, etype : Type) : Module =
   module
   where
   fvar = ein_f : bool init false;
   vvar = EVT_ein : [etype, false] t;
   finvar = FIN_ein : bool init true;
   cmd1 = (ein | (FIN_eout = true) & (finvar.name = true) -> 1.0 : (finvar.name' = false & vvar.name' = false));
   cmd2 = (l | (vvar.name = false) & (finvar.name = true) -> 1.0 : (finvar.name' = true & vvar.name' = EVT_OUT_BUF_ename));
   cmd3 = [eout] (vvar.name = true) -> 1.0 : (vvar.name' = false);
   module = [moduleBUF_ein vars--{fvar,vvar,finvar},commands--{cmd1,cmd2}]
endmodule
```

A simple buffer simulates an asynchronous connection on simple events.

```
Rule 163. Simple Buffer
simpleBuffer(ein : String, eout : String) : Module =
   module
   where
   fvar = ein_f : bool init false;
   cmd1 = [ein] (true) -> 1.0 : (fvar.name' = true);
   cmd2 = [eout] (vvar.name = true) -> 1.0 : (vvar.name' = false);
   module = [moduleBUF_ein vars--{fvar},commands--{cmd1,cmd2}]
endmodule
```

Events

The function `isStandaloneEvent` returns if an event used for input or output is a standalone event, that is, an event of a state machine that is not connected to the events of other state machines. The functions `isEventToBuffer` and `isEventToRP` are similar, and they return if an event for output is connected to an asynchronous connection or to a robotic platform respectively. These functions are implementation dependent and one possible solution is to use different name prefixing to distinguish
these events in PRISM.

**Rule 164. Input Events**

```
- trigger: Communication, condition: Expression, pcconstrs: P BoolExpr, 
- lockfreegrd: P BoolExpr, curstate: String, scpcname: Name, stnumber: int, 
- lockassign: P Assignment, assigns: P Assignment, 
- namemap: (Event × Boolean) → String 

: InputEvent 

InputEvent = (stnumber + 1, {stconst}, {cmd1, cmd2})

where

- ename = namemap(trigger.event → false)
- scpcgrd = pcconstrs ∪ {scpcname = curstate}
- condgrd = (if condition ≠ null

  \[
  \text{then substVarName}\left(\text{[condition]} \cdot \text{id(trigger, parameter)}, \text{EVT__ename}\right)
  \]

  \[
  \text{else true}
  \]
- stconst = \text{const int} uname(trigger.event, stnumber) = stnumber;
- notupdatinggrd = (if isStandaloneEvent(trigger.event, false) then true

  \[
  \text{else FIN__ename = false}
  \]
- scpcassign = scpcname' = stconst.name
- cmd1 = \text{[ename]} \text{andExprs} \rightarrow \text{lockfreegrd} \cup \text{scpcgrd} \cup 

  \[
  \text{condgrd, notupdatinggrd}
  \]
- scpcgrd2 = pcconstrs ∪ {scpcname = stconst.name}
- trigvarassign = id(trigger, parameter)' = \text{EVT__ename}
- finassign2 = FIN__ename' = true
- cmd2 = \text{[andExprs}} \rightarrow \text{assigns} \cup \{trigvarassign, finassign\} 

```
Chapter 5. Probabilistic Semantics

**Rule 165. Output Events**

\[
\text{OutputEvent} = \begin{cases} 
\text{if isEventToRP(trigger, event)} \text{ then } \\
(stnumber, \emptyset, \{\text{cmd}\}) \\
\text{else } (stnumber + 1, \{\text{stconst}\}, \{\text{cmd1}, \text{cmd2}\}) 
\end{cases}
\]

where

\[
\text{ename} = \text{namemap}((\text{trigger}.\text{event}) \mapsto \text{output}) \\
\text{scpcgrd} = \text{pcconstrs} \cup \{\text{scpcname} = \text{curstate}\} \\
\text{condgrd} = \text{if condition} \neq \text{null then } ||\text{condition}||_e, \text{else true} \\
\text{trigvarassign} = \text{EVT}._{\text{ename}}' = [\text{trigger.value}]_c
\]

**Rule 166. Simple Events**

\[
\text{SimpleEvent} = \begin{cases} 
\text{if isEventToRP(trigger, event)} \text{ then } \\
(stnumber, \emptyset, \{\text{cmd}\}) 
\end{cases}
\]

where

\[
\text{ename} = \text{namemap}((\text{trigger}.\text{event}) \mapsto \text{output}) \\
\text{scpcgrd} = \text{pcconstrs} \cup \{\text{scpcname} = \text{curstate}\} \\
\text{condgrd} = \text{if condition} \neq \text{null then } ||\text{condition}||_e, \text{else true} \\
\text{cmd} = [\text{ename}] (\text{andExprs}^{20} (\text{lockfreegrd} \cup \text{scpcgrd} \cup \{\text{condgrd}\}) \rightarrow 1.0 : \text{assigns})
\]
5.3 Translation to PRISM

**Rule 167. Empty Events**

\[
\text{EmptyEvent} = \begin{cases}
\text{condition}: \text{Expression}, \text{pcconstrs}: \mathbb{P} \text{BoolExpr} \\
\text{lockfreegrd}: \mathbb{P} \text{BoolExpr}, \text{curstate}: \text{String}, \text{scpcname}: \text{Name}, \text{stnumber}: \text{int}, \\
\text{assigns}: \mathbb{P} \text{Assignment} \\
\end{cases}
\]

where

\[
\begin{align*}
\text{scpcgrd} &= \text{pcconstrs} \cup \{ \text{scpcname} = \text{curstate} \} \\
\text{condgrd} &= \text{if condition} \neq \text{null} \text{ then } [\text{condition}] \text{ else true} \\
\text{cmd} &= [] \big( \text{andExprs} \big \{ \text{lockfreegrd} \cup \text{scpcgrd} \cup \{ \text{condgrd} \} \big \} \big) \rightarrow 1.0 \text{ : assigns}
\end{align*}
\]

**Operations**

In RoboChart, an operation can be introduced in several ways:

- **OP-1** provided by a robotic platform, and its reference is `OperationSig` in a model;
- **OP-2** defined fully (using a state machine, and so the number of nodes is larger than 0), in the model. The definition is of type `OperationDef`, inherited from `OperationSig`;
- **OP-3** defined partial (using a state machine but no detail is given, and so the number of nodes is 0), in the model. The definition is of type `OperationDef`.

The function `isFullyDefinedOperation` determines if an operation is `OP-2` or `OP-3`.

**Rule 168. Is an operation fully defined**

\[
isFullyDefinedOperation \text{ (opdef: OperationDef)} : \text{Boolean} =
\begin{cases}
\text{true} & \text{if } \#(\text{opdef.nodes}) > 0 \\
\text{false} & \text{else}
\end{cases}
\]

The function `getAllCalledOperations` returns all operations that are called in `cs`, a `StateMachineDef`, and provided by a robotic platform. If `cs` is

1. a `StateMachineDef`, recursively visit all required operations that are `OP-2` or `OP-3`, but exclude all operations that are `OP-1` because they might be not called in actions;
2. a `OperationDef` and `OP-3`, just all required operations in `cs` that are `OP-1`;
3. a `OperationDef` and `OP-2`, just all operations that are called in `cs` and provided by a robotic platform;
Rule 169. Get all called operations (that are provided by a robotic platform) in a StateMachineBody

\[
\text{getAllCalledOperations} \triangleright \text{reqallops : P OperationSig) : cs : StateMachineBody} \rightarrow \text{P OperationSig} = \\
\begin{align*}
\text{if } & \text{cs} \in \text{StateMachineDef} \text{ then} \\
& \bigcup \left( \text{getAllCalledOperations}^2 \triangleright \text{reqallops} \right) \cup \text{getCalledOperations}^1 \triangleright (cs, \text{reqallops}) \\
\text{where} \\
& \text{reqops} = \text{getRequiredOperations}^5 \triangleright (cs) \\
& \text{reqopdefs} = \{ \text{op : reqallops} | (\exists \text{rop : reqops} \cdot \text{rop.name} = \text{op.name}) \land \text{op} \in \text{OperationDef} \} \\
\text{else if } & \text{cs} \in \text{OperationDef} \land \neg \text{isFullyDefinedOperation}^2 \triangleright (cs) \text{ then} \\
& \{ \text{rop : reqops} \mid (\exists \text{op : reqallops} \cdot \text{rop.name} = \text{op.name} \land \text{op} \notin \text{OperationDef}) \} \\
\text{where} \\
& \text{reqops} = \text{getRequiredOperations}^5 \triangleright (cs) \\
\text{else if } & \text{cs} \in \text{OperationDef} \land \text{isFullyDefinedOperation}^3 \triangleright (cs) \text{ then} \\
& \text{getCalledOperations}^2 \triangleright (cs, \text{reqallops}) \\
\text{else} & 0
\end{align*}
\]

Rule 170. Get called operations (that are provided by a robotic platform) in a Node-Container

\[
\text{getCalledOperations} \triangleright \text{cs : NodeContainer, reqallops : P OperationSig) : P OperationSig} = \\
\begin{align*}
\text{calledops} \\
\text{where} \\
& \text{actions1} = \bigcup \{ n : cs.nodeselements | n \in \text{State} \cdot \{ \text{act : n.actions} | \text{act} \in \text{EntryAction} \lor \text{act} \in \text{ExitAction} \} \} \\
& \text{actions2} = \{ t : cs.transitions \mid t.action \neq \text{null} \cdot t.action \} \\
& \text{calledops} = \bigcup \left( \text{getCalledOperationsInStmt}^1 \triangleright \text{reqallops} \right) \\
& \{ \{ \text{act : actions1} \cup \text{actions2} \cdot \text{act.action} \} \}
\end{align*}
\]

Rule 171. Get called operations (that are provided by a robotic platform) in a statement

\[
\text{getCalledOperationsInStmt} \triangleright \text{reqallops : P OperationSig) : stmt : Statement} \rightarrow \text{P OperationSig} = \\
\begin{align*}
\text{if } & \text{stmt} \in \text{IfStmt} \text{ then} \\
& \text{thenops} \cup \text{elseops} \\
\text{where} \\
& \text{thenops} = \text{getCalledOperationsInStmt}^2 \triangleright \text{stmt.then, reqallops) \\
& \text{elseops} = \text{getCalledOperationsInStmt}^3 \triangleright \text{stmt.else, reqallops) \\
\text{else if } & \text{stmt} \in \text{SeqStatement} \text{ then} \\
& \bigcup \left( \text{getCalledOperationsInStmt}^4 \triangleright \text{reqallops} \right) \{ \text{stmt.statements} \} \\
\text{else if } & \text{stmt} \in \text{Call} \text{ then} \\
& \{ \text{op : reqallops} \mid \text{op.name} = \text{stmt.operation.name} \land \text{op} \notin \text{OperationDef} \} \\
\text{else} & 0
\end{align*}
\]
Rule 172. Operation definitions

\[
\text{if isFullyDefinedOperation}^{4}(opdef) \text{ then }
\]
\[
\text{if isFullyDefinedOperation}^{4}(opdef) \text{ then }
\]
\[
\text{if isFullyDefinedOperation}^{4}(opdef) \text{ then }
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\text{if isFullyDefinedOperation}^{4}(opdef) \text{ then }
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\text{if isFullyDefinedOperation}^{4}(opdef) \text{ then }
\]
\[
\text{if isFullyDefinedOperation}^{4}(opdef) \text{ then }
\]
Chapter 5. Probabilistic Semantics

**Rule 173. Partially defined operation definitions**

\[
\begin{align*}
\text{opdef} : \text{OperationDef}, & \quad \text{ctrolopdefs} : \text{OperationDef}, \\
\text{namemap} : (\text{Event}_\text{rc} \times \text{Boolean}) \to \text{String} & = \mathcal{OP}_{\text{par}} \\
\text{constvars} & = \bigcup \{ \text{getVariableLists}(\text{opdef}) \} \\
\text{bound} & = \text{if opdef.terminates then OP\_BOUND else 0} \\
\text{bounditer} & = \text{if opdef.terminates then Id(\text{opdef}).\_ITER : 0..bound} \text{ init 0; else null} \\
\text{const0} & = \text{const int Id(\text{opdef}).\_INACTIVE = 0} \\
\text{constterm} & = \text{const int Id(\text{opdef}).\_TERMINATED = 1} \\
\text{construnning} & = \text{const int Id(\text{opdef}).\_RUNNING = 2} \\
\text{conststop} & = \text{const int Id(\text{opdef}).\_STOP = 3} \\
\text{constnotcomp} & = \text{const int Id(\text{opdef}).\_NOTCOMPLETED = 4} \\
\text{scpc} & = \text{Id(\text{opdef}) \_scpc : [0..4] = const0.name} \\
\text{inactivegrd} & = \text{scpc.name} = \text{const0.name} \\
\text{inactiveassign} & = \text{scpc.name} = \text{const0.name} \\
\text{runninggrd0} & = \text{scpc.name} = \text{construnning.name} \\
\text{runningassign} & = \text{scpc.name} = \text{construnning.name} \\
\text{notcompgrd} & = \text{scpc.name} = \text{constnotcomp.name} \\
\text{notcompassign} & = \text{scpc.name} = \text{constnotcomp.name} \\
\text{stopassign} & = \text{scpc.name} = \text{conststop.name} \\
\text{termassign} & = \text{scpc.name} = \text{constterm.name} \\
\text{runninggrdbound} & = \begin{cases} \\
\text{if opdef.terminates then} & \text{runninggrd0} \& (\text{bounditer.name = bound}) \\
\text{else true} & \end{cases} \\
\text{runninggrd} & = \begin{cases} \\
\text{if opdef.terminates then} & \text{runninggrd0} \& (\text{bounditer.name < bound}) \\
\text{else runninggrd} & \end{cases} \\
\text{assigns} & = \begin{cases} \\
\text{if opdef.terminates then} & \{\text{bounditer.name} = \text{bounditer.name} + 1\} \text{ else } \emptyset \\
\text{else assigns} & \end{cases} \\
\text{varinscope} & = \{ \text{getVariableLists}(\text{opdef}) \cup \text{getRequiredVariableLists} \} \\
\text{varcmds} & = \begin{cases} \\
\text{v : varinscope |} & \text{isConstant}(v) \Rightarrow \\
\{ \text{val : enumValuesInType}(\text{[v.type].\_e}) \Rightarrow \\
\{ \text{\text{runninggrd} \rightarrow 1.0 : assigns \& (v.v' = \text{val})} \} \\
\} \end{cases} \\
\text{rops} & = \text{getRequiredOperations}(\text{opdef}) \\
\text{opcmds} & = \bigcup \{ \text{op: rops \_ callOpNondeter} \} \\
\text{events} & = \text{getEvents}(\text{opdef}) \\
\text{eventcmds} & = \bigcup \{ \text{e : event \_ occurEventNondeter} \} \\
\text{stopcmd} & = \{ \text{runninggrd} \rightarrow 1.0 : \text{assigns \_ stopassign} \} \\
\text{termcmd} & = \{ \text{runninggrd} \rightarrow 1.0 : \text{assigns \_ termassign} \} \\
\text{termcmds} & = \begin{cases} \\
\text{if opdef.terminates then} & \{ \text{runninggrdbound} \rightarrow 1.0 : \text{termassign} \} \text{ else } \emptyset \\
\end{cases}
\end{align*}
\]
Rule 174. Call Operations nondeterministically

\[
\text{callOpNondeter}(\text{rop} : \text{OperationSig}, \text{opdef} : \text{OperationDef}, \text{ctrlopdefs} : \text{P OperationDef}, \text{runninggrd} : \text{BoolExpr}_Pr, \text{runningassign} : \text{Assignment}_Pr, \text{notcompassign} : \text{Assignment}_Pr, \text{assigns} : \text{P Assignment}_Pr) : \text{P Command} =
\]

\[
\begin{align*}
\text{if } \text{ropdef} \neq \text{null} \text{ then} & \\
\text{if } \text{allopparassigns} = \emptyset \text{ then} & \\
\text{callOpdef}^2(\text{ropdef}, \text{runninggrd}, \{\text{notcompassign}\}, \text{assigns} \cup \{\text{runningassign}\}) & \\
\text{else} & \\
\bigcup \Big\{ \text{allopparassigns} : \text{allopparassigns} \cup \text{callOpdef}^3(\text{ropdef}, \text{runninggrd}, \{\text{notcompassign}\}, \text{assigns} \cup \{\text{runningassign}\}) \Big\} & \\
\text{else} & \\
\text{if } \text{allopparassigns} = \emptyset \text{ then} & \\
\{ \text{id}(\text{op}) \text{runninggrd} \rightarrow \text{if } \text{opdef.terminates then } 1.0 : \text{assigns} \text{else } \text{true} \} & \\
\text{else} & \\
\bigcup \Big\{ \text{allopparassigns} \cup \text{id}(\text{op}) \text{runninggrd} \rightarrow 1.0 : \text{assigns} \cup \text{allopparassigns} \Big\} & \\
\end{align*}
\]

where

\[
\text{ropdef} = \text{getOperationDef}^2(\text{rop}, \text{ctrlopdefs}) \\
\text{allopparassigns} = \text{permOPParameterAssigns}^1(\text{op}, \text{op.parameters})
\]

Rule 175. Get operation definition

\[
\text{getOperationDef}(\text{op} : \text{OperationSig}, \text{ctrlopdefs} : \text{P OperationDef}) : \text{OperationDef} =
\]

\[
\begin{align*}
\text{if } (\text{opdefs} = \emptyset) \text{ then} & \\
\text{null} & \\
\text{else} & \\
\mu \text{o} : \text{ctrlopdefs} \mid \text{o.name} = \text{op.name} & \\
\end{align*}
\]

where

\[
\text{opdefs} = \{ \text{o} : \text{ctrlopdefs} \mid \text{o.name} = \text{op.name} \}
\]

Rule 176. Call Operation definitions

\[
\text{callOpdef}(\text{opdef} : \text{OperationDef}, \text{pcconstrs} : \text{P BoolExpr}_Pr, \text{opvarassigns} : \text{P Assignment}_Pr, \text{assigns} : \text{P Assignment}_Pr) : \text{P Command} =
\]

\[
\begin{align*}
\text{cmd1} = \{ \text{andExprs}_22(\text{pcconstrs} \cup \{\text{opinactive}\}) \rightarrow 1.0 : \text{opvarassigns} \cup \{\text{ass1}\}; \\
\text{ass1} = \text{id(}\text{opdef}_\text{s} \text{scpc'} = \begin{cases} \\
\text{id(}\text{opdef}_\text{s} \text{getInitial}^4(\text{opdef}.\text{name}) & \text{ifFullyDefinedOperation}^5(\text{opdef}) \text{then} \\
\text{id(}\text{opdef}_\text{s} \text{RUNNING} & \text{else} \end{cases} \\
\text{opinactive} = \text{id(}\text{opdef}_\text{s} \text{scpc} = \text{id(}\text{opdef}_\text{s} \text{INACTIVE} \\
\text{cmd2} = \{ \text{andExprs}_23(\text{pcconstrs} \cup \{\text{opterminated}\}) \rightarrow 1.0 : \text{assigns} \cup \{\text{ass2}\}; \\
\text{ass2} = \text{id(}\text{opdef}_\text{s} \text{scpc'} = \text{id(}\text{opdef}_\text{s} \text{INACTIVE} \\
\text{opterminated} = \text{id(}\text{opdef}_\text{s} \text{scpc} = \text{id(}\text{opdef}_\text{s} \text{TERMINATED}
\end{align*}
\]
Rule 177. Events occur nondeterministically

\[
\text{occurEventNondeter} \quad \begin{cases} \text{event : Event, opdef : OperationDef, runninggrd : BoolExpr,} \\
\text{runningassign : Assignment, notcompassign : Assignment,} \\
\text{assigns : P Assignment, namemap : (Event \times Boolean) \rightarrow String} \end{cases} \\
: P \text{ Command =}
\]

\[
\text{inputcmds} \cup \text{outputcmds}
\]

where

\[
\text{forinput} = (\text{event, false}) \in \text{dom namemap} \\
\text{foroutput} = (\text{event, true}) \in \text{dom namemap} \\
\text{einame} = \text{namemap} (\text{event \rightarrow false}) \\
\text{eoname} = \text{namemap} (\text{event \rightarrow true})
\]

\[
\text{inputcmds} = \begin{cases} \text{if forinput then} \\
\{ \{\text{einame}\} \text{runninggrd} \\
\rightarrow \text{if opdef.terminates then 1.0 : assigns else true;} \\
\} \end{cases}
\]

\[
\text{outputcmds} = \begin{cases} \text{if foroutput \& event.type = null then} \\
\{ \{\text{einame}\} \text{runninggrd} \\
\rightarrow \text{if opdef.terminates then 1.0 : assigns else true;} \\
\} \end{cases}
\]

Auxiliary functions

The function \text{getVariableLists}, defined in Rule 77, returns a set of \text{VariableList} provided or defined in a \text{Context}.

Rule 178. Get variable lists

\[
\text{getVariableLists} (c : \text{Context}) : P \text{ VariableList =}
\]

\[
(c.\text{variableList} \cup \text{vl}_p \cup \text{vl}_d)
\]

where

\[
\text{vl}_p = \{ i : c.\text{plInterfaces} \cdot i.\text{variableList} \} \\
\text{vl}_d = \{ i : c.\text{interfaces} \cdot i.\text{variableList} \}
\]

Rule 179. Get required variable lists

\[
\text{getRequiredVariableLists} (c : \text{Context}) : P \text{ VariableList =}
\]

\[
\{ i : c.\text{rInterfaces} \cdot i.\text{variableList} \}
**Rule 180. Is a constant variable**

\[ \text{isConstant}(v : \text{Variable}) : \text{Boolean} = \]
\[ \text{if } (v.\text{modifier} = \text{CONST}) \text{ then true else false} \]

**Rule 181. Get events**

\[ \text{getEvents}(c : \text{Context}) : \mathbb{P} \text{ Event} = \]
\[ (c.\text{events} \cup \text{ev}_d) \]
\[ \text{where} \]
\[ \text{ev}_d = \bigcup \{ i : c.\text{interfaces} \cdot i.\text{events} \} \]

**Rule 182. Get required operations**

\[ \text{getRequiredOperations}(c : \text{Context}) : \mathbb{P} \text{ OperationSig} = \]
\[ \bigcup \{ i : c.r\text{interfaces} \cdot i.\text{operations} \} \]

**Rule 183. Get the exit action**

\[ \text{getExitAction}(s : \text{State}) : \text{Action} = \]
\[ \text{if } (\text{exitactions} = 0) \text{ then} \]
\[ \text{null} \]
\[ \text{else} \]
\[ \mu a : s.\text{actions} | a \in \text{ExitAction} \]
\[ \text{where} \]
\[ \text{exitactions} = \{ a : s.\text{actions} | a \in \text{ExitAction} \} \]

**Rule 184. Has the exit action**

\[ \text{hasExitAction}(s : \text{State}) : \text{Boolean} = \]
\[ \text{if } (\text{getExitAction}^n(s) = \text{null}) \text{ then} \]
\[ \text{false} \]
\[ \text{else} \]
\[ \text{true} \]
### Rule 185. Get the entry action

\[
\text{getEntryAction}(s : \text{State}) : \text{Action} = \\
\begin{align*}
\text{if } (\text{entryActions} = \emptyset) \text{ then} & \quad \text{null} \\
\text{else} & \quad \mu a : s.\text{actions} \mid a \in \text{EntryAction} \\
\text{where} & \quad \text{entryactions} = \{a : s.\text{actions} \mid a \in \text{EntryAction}\}
\end{align*}
\]

### Rule 186. Has the entry action

\[
\text{hasEntryAction}(s : \text{State}) : \text{Boolean} = \\
\begin{align*}
\text{if } (\text{getEntryAction}(s) = \text{null}) \text{ then} & \quad \text{false} \\
\text{else} & \quad \text{true}
\end{align*}
\]

### Rule 187. Conjunction of boolean expressions

\[
\text{andExprs}(\text{exprs} : \mathbb{P}\text{BoolExpr}) : \text{BoolExpr} = \\
\begin{align*}
\text{if } (\text{exprs} = \emptyset) \text{ then} & \quad \text{true} \\
\text{else} & \quad \text{expr} \& \text{andExprs}(\text{exprs} \setminus \{\text{expr}\}) \\
\text{where} & \quad \text{expr} \in \text{exprs}
\end{align*}
\]

### Rule 188. Is a state composite

\[
\text{isComposite}(s : \text{State}) : \text{boolean} = \\
\begin{align*}
\text{if } (s.\text{nodes} \neq \emptyset) \text{ then} & \quad \text{true} \quad \text{else} \quad \text{false}
\end{align*}
\]

### Rule 189. Get the initial junction of a node container

\[
\text{getInitial}(s : \text{NodeContainer}) : \text{Initial} = \\
(\mu n : s.\text{nodes} \mid n \in \text{Initial})
\]

### Rule 190. Get the final state of a node container

\[
\text{getFinal}(s : \text{NodeContainer}) : \text{Final} = \\
(\mu n : s.\text{nodes} \mid n \in \text{Final})
\]
The function `getParaArgPairs` in Rule 90 assembles a set of pairs from a sequence of parameters and a sequence of arguments, provided they have the same length.

**Rule 191. Get parameters and arguments pair**

```
getParaArgPairs (paras : seq Parameter, args : seq Expression) : Parameter ↔ Expression =
  if # paras = 0 then @Parameter × Expression
  else getParaArgPairs² (tail paras, tail args) ⊕ {head paras ↦ head args}
```

The function `enumValuesInType`, defined in Rule 91, lists all possible values of a PRISM type. In the rule, `vt. NAT_MIN, NAT_MAX, INT_MIN, INT_MAX, REAL_MIN, and REAL_MAX` are the parameters to the translation.

**Rule 192. Enumerate all values in a type**

```
enumValuesInType (vt : Type pr) : P Expr =
  if vt ∈ IntType pr then
    if vt.nat then {v : NAT_MIN .. NAT_MAX • ⌊value⇝v⌋ IntLitExpr}
    else {v : INT_MIN .. INT_MAX • ⌊value⇝v⌋ IntLitExpr}
  else if vt ∈ DoubleType pr then {v : REAL_MIN .. REAL_MAX • ⌊value⇝v⌋ IntLitExpr}
  else if vt ∈ RangeType pr then {v : vt.bottom .. vt.top • ⌊value⇝v⌋ IntLitExpr}
  else if vt ∈ BoolType pr then {value⇝true BoolLitExpr, value⇝false BoolLitExpr}
  else Error: Not yet supported!
```

**Rule 193. All possible combinations of assignments to parameters of an operation**

```
permOPParameterAssigns (op : OperationSig, paras : seq Parameter) : P (P Assignment) =
  if # paras = 0 then @
  else let tassigns == permParameterAssigns (op, tail paras);
        para == head paras;
        values == enumValuesInType³ ({para.type}):
        hassigns == {v : values • id(op, para)′ = v}:
        • {ta : tassigns; ha : hassigns • ta ∪ {ha}}
```

**Variables**

**Rule 194. Variable lists**

```
[vl : VariableList] ∀ v : P Constant × P VarDecl =
  (∪ retvars.1, ∪ retvars.2)
where
  retvars = {v : vl.vars • [v]}
```

The function `getParaArgPairs` in Rule 90 assembles a set of pairs from a sequence of parameters and a sequence of arguments, provided they have the same length.
Rule 195. Variables

\[
[v : \text{Variable}]_P : P \text{ Constant} \times P \text{ VarDecl} = \\
\begin{cases} 
\text{if } v.\text{modifier} = \text{"const"} & \begin{cases} 
\text{const } [v.\text{type}]_P, \text{id}(v) = [v.\text{initial}]_P; \end{cases}, \emptyset \\
\text{else if } v.\text{modifier} = \text{"var"} & \begin{cases} 
\emptyset, \{\text{id}(v) : [v.\text{type}]_P, [v.\text{initial}]_P; \end{cases}
\end{cases}
\]

Expressions

The translation of expressions (including types) is standard. We note, however, that the expression language of Z is much richer than that of PRISM. So, in some cases, we require user input to translate the expressions.
6  Assertion DSL Syntax  ...............  111
   6.1 Standard Assertions
   6.2 Probabilistic Properties

7  Assertions DSL Usage  ...............  123
   7.1 Standard Assertions
   7.2 Probabilistic Assertions

8  Checking core assertions  ............  129
6. Assertion DSL Syntax

The assertions DSL supports the specification of standard untimed and timed assertions suitable for verification with FDR (as well as CSP-M processes) and probabilistic assertions for verification with PRISM.

### 6.1 Standard Assertions

**Syntax — Assertions.**

```
Assertion ::= ('timed' | 'untimed')? 'assertion' N ':' SPEC
            ('in' 'the' MODEL)?
            ('with' ('constant'| 'constants') CONSTANTS)?
```

An assertion is named and marked as *timed*, *untimed* or both (no keyword). It contains a property specification (SPEC), and allows the specification of a model (e.g., traces model), and allows the specification of values for constants used in the specification.
Chapter 6. Assertion DSL Syntax

Syntax — Specification.

```
SPEC ::= N 'is' ('not'?)? PRED
   | N ('does' 'not' | 'terminates')
   | N 'is' ('not'?)? 'reachable' 'in' N
   | N REL N
   | 'clock' N 'is' ('not'?)? 'initialised'

PRED ::= 'deadlock-free'
   | 'divergence-free'
   | 'deterministic'
   | 'timelock-free'

REL ::= 'refines'
   | 'equals'
   | 'does' 'not' 'refine'
   | 'is' 'not' 'equal'
```

A specification can either be unary or binary. Unary assertions describe properties such as termination, state reachability, clock initialisation, deadlock freedom, divergence freedom, determinism and timelock freedom of specific RoboChart elements (i.e., state machines, controllers, and modules). Binary assertions compare two RoboChart elements via the refinement and equality relations.

Syntax — CSP Models.

```
MODEL ::= 'traces' 'model'
   | 'failures' 'model'
   | 'failures' 'divergence' 'model'
```

The currently supported CSP models are the standard traces, failures and failures divergences models.

Syntax — Constant Definitions.

```
CONSTANTS ::= (DEF (',' DEFs)*?)

DEF ::= N ('assigned' | 'set' 'to' | 'with' 'value') Expr
```

The value of constants used in the semantics of a RoboChart element, by default, defined by an initial value or through the instantiations.csp file. The constant definitions in an assertion can override such values using the syntax above.

Syntax — CSP specification.

```
CSP specification ::= ('timed' | untimed')? 'csp' N
   | 'csp-begin' CSPM 'csp-end'
```
A CSP specification can be identified as timed, untimed or both, its name must be used to define a CSP process, which is then exported for use in assertions. The definition of the process, as well as any auxiliary definitions, is written using CSP-M between the keywords `csp-begin` and `csp-end`.

### 6.2 Probabilistic Properties

**Syntax — Probabilistic Statements.**

<table>
<thead>
<tr>
<th>ProbStatements ::= ProbStatement*</th>
</tr>
</thead>
<tbody>
<tr>
<td>ProbStatement ::= Constant</td>
</tr>
<tr>
<td>Constants</td>
</tr>
<tr>
<td>Label</td>
</tr>
<tr>
<td>Formula</td>
</tr>
<tr>
<td>Rewards</td>
</tr>
<tr>
<td>Definitions</td>
</tr>
<tr>
<td>pModules</td>
</tr>
<tr>
<td>ProbProperty</td>
</tr>
</tbody>
</table>

The syntax of probabilistic properties consists of various probabilistic statements:

- constant declarations (`Constant` in Syntax 6.2.2),
- constant configurations (`Constants` in Syntax 6.2.2),
- labels (`Label` in Syntax 6.2.3),
- formulas (`Formula` in Syntax 6.2.3),
- rewards (`Rewards` in Syntax 6.2.4),
- function and operation definitions (`Definitions` in Syntax 6.2.5),
- probabilistic PRISM modules (`pModules` in Syntax 6.2.6),
- probabilistic properties (`ProbProperty` in Syntax 6.2.1).

### 6.2.1 Probability Properties

**Syntax — Probabilistic Properties.**

<table>
<thead>
<tr>
<th>ProbProperty ::= 'prob' 'property' N ':' pExpr</th>
</tr>
</thead>
<tbody>
<tr>
<td>('with' 'constants' (ConstConfig+</td>
</tr>
<tr>
<td>('with' 'definitions' ((pFunction</td>
</tr>
<tr>
<td>('with' 'modules' (pModule+</td>
</tr>
<tr>
<td>('with' 'cmdoptions' STRING)?</td>
</tr>
</tbody>
</table>

A probabilistic property starts with `prob`. And a name (`N` denotes the name category, actually it is `ID` in Syntax 6.2.11) is associated with the property. The body of the property is an expression (`pExpr` in Syntax 6.2.7) that denotes the property to be verified. This expression must be a boolean expression (see Section 6.2.7). In addition, a property optionally has constant configurations (given
Chapter 6. Assertion DSL Syntax

in ConstConfigs or a reference to a constants configuration name \( N \) in Syntax 6.2.2), function and operations definitions (given in pFunction or pOperation or a reference to definitions \( N \) in Syntax 6.2.5), PRISM modules (given in pModule or a reference to PRISM modules \( N \) in Syntax 6.2.6), and customised PRISM command line options. These options won’t be parsed and processed. They are just passed to the PRISM command line tool to provide a flexible way for users to specify command line options.

6.2.2 Constants

**Syntax — Constant Declaration.**

\[
\text{Constant} ::= \text{'const'} \ N \ '':' \ \text{Type}
\]

A constant variable declared with a type (Type is the RoboChart Type class, see Appendix B, but in probabilistic properties only primitive types \( \text{nat}, \text{int}, \text{bool}, \text{and real} \) are allowed, which is enforced in scoping and validation rules of RoboTool) will be used in probabilistic formulas.

**Syntax — Constants.**

\[
\text{Constants} ::= \text{'constants'} \ N \ '':' \ \text{ConstConfigs}
\]

\[
\text{ConstConfigs} ::= \text{ConstConfig} \ (','\ \text{ConstConfig})^* \ ((','\ ? 'and' \ \text{ConstConfig})?)
\]

Constants associates a name with configurations of various constants.

**Syntax — Constant Configuration.**

\[
\text{ConstConfig} ::= \text{QualifiedNameToElement}
\]

\[
(\text{"set" 'to' | 'assigned' | 'with' 'value'} \ \text{pExpr}
\]

\[
| \text{"from" 'set' \ pExpr})
\]

The configuration of each constant by ConstConfig can be a single value (pExpr) or a set of values (either a set extension or a set range expression in Syntax 6.2.7 and Section 6.2.7).

6.2.3 Labels and Formulas

**Syntax — Labels.**

\[
\text{Label} ::= \text{'label'} \ N \ ' '=' \ \text{pExpr}
\]

Labels provide a way to identify a set of states that are of particular interest. A label has its name associated with a boolean expression (see Section 6.2.7) and could be referred to later by ‘#’ \( N \) in properties (see Syntax 6.2.7).
6.2 Probabilistic Properties

**Syntax — Formulas.**

Formula ::= 'formula' N ' '=' pExpr

Formulas define expressions for reuse. The name given in a formula definition likes a shorthand to the defined expression. A formula can be referred to by `$` N in properties (see Syntax 6.2.7).

### 6.2.4 Rewards

**Syntax — Rewards.**

Rewards ::= 'rewards' N ' '=' Reward+ 'endrewards'

A collection of rewards can be assigned a name and this name will be used in RFormula in Syntax 6.2.7.

**Syntax — Reward.**

Reward ::= ('[' pEvent ']')? pExpr ' ':' pExpr ';

A reward composes an optional event (pEvent, in Syntax 6.2.8), a guard condition (a boolean expression, see Section 6.2.7), and a reward (a numeric expression, see Section 6.2.7).

### 6.2.5 Function and Operation Definitions

**Syntax — Function and Operation Definitions.**

Definitions ::= 'defs' N '::' (pFunction | pOperation)+
pFunction ::= 'pfunction' N '().' N* ')' ' '=' ' '{' 'return' pExpr '};
pOperation ::= 'poperation' N '().' N* ')' ' '='
          ' '{' pAssignment ('and' pAssignment)* '}'
pAssignment ::= '(' QualifiedNameToElement '=' pExpr ')

A Definitions identifies a set of function definitions (pFunction) and operation definitions (pOperation) by a name N. It can be referred to by its name in ProbProperty (see Syntax 6.2.1).

A pFunction defines a function with a name N, zero or more parameters (only their names N and no types), and a return expression pExpr. A pOperation, however, is defined as a collection of assignments pAssignment. A pAssignment assigns an expression to a RoboChart variable denoted by QualifiedNameToElement.
6.2.6 Probabilistic PRISM Modules

We can define PRISM modules `pModules` in properties. These modules will be added to the generated PRISM model, and used to specify properties for reactive systems that involve events. The need of these additional modules is due to the fact that the property language of PRISM is state-based. And so we cannot specify events directly.

**Syntax — PRISM Modules.**
```
pModules ::= 'pmodules' N ':' pModule+  
pModule ::= 'pmodule' N '{' pVariable* pCommand+ '}'  
pCommand ::= '[' pEvent? ']' pExpr '->'  
             ((pUpdate ('&' pUpdate)*) | 'skip') ';'
  pUpdate ::= '(' (pExpr ':'? @ N '=' pExpr ')'  
            (pUpdate ('&' pUpdate)*) | 'skip') ')';'
  pVariable ::= N ':' pType ('init' pExpr)? ';'
  pType ::= 'bool'  
           | '[' pExpr 'to' pExpr ']'  
```

With `pModules`, a name `N` gives one or more PRISM modules. A such module is given by `pModule` which includes zero or module variables `pVariable` and one or more commands `pComman`. A `pVariable` declaration has a name `N`, a type `pType`, and an optionally initial expression `pExpr`. A `pType` can be a boolean or an integer range. A `pCommand` has an optional event `pEvent`, a guard condition `pExpr`, and a set of updates or a skip. An update is composed of an optional probability value `pExpr`, a reference to a `pVariable` variable by its name `N`, and an expression assigned to the variable.

6.2.7 Expressions

Expressions used in probabilistic properties are different from those in RoboChart. On the one hand, expressions need to cover state and path formulas in temporal logic, but these formulas are not part of RoboChart. On the other hand, many expressions in RoboChart could not be in properties, such as set and sequence expressions. For this season, we cannot simply reuse RoboChart expressions. We, therefore, define expressions used in probabilistic properties here. In principle, if an expression has a counterpart in RoboChart, then we use the same syntax. For example, the syntax of conditional, logical, arithmetic, comparison, array, set extension, and set range expressions is the same as that of RoboChart.

Furthermore, expressions are categorised into boolean or non-boolean expressions, numeric or non-numeric expressions, and set or non-set expression. A boolean expression can be used in the place where a boolean expression is expected, such as `pExpr` in `ProbProperty` and `Label`. If a non-boolean is given in such a place, it results in a grammar error. Numeric and non-numeric expressions are similar.
Syntax — Expressions.

\[
pExpr ::= \begin{array}{ll}
\text{INT} & \text{— integer} \\
\text{FLOAT} & \text{— real number} \\
\text{BOOLEAN} & \text{— boolean} \\
\text{pExpr } 'iff' \text{ pExpr} & \text{— if and only if} \\
\text{pExpr } '=>' \text{ pExpr} & \text{— implication} \\
\text{pExpr } '\\/' \text{ pExpr} & \text{— disjunction} \\
\text{pExpr } '\\/' \text{ pExpr} & \text{— conjunction} \\
\text{'not' pExpr} & \text{— logical negation} \\
\text{pExpr } '==' \text{ pExpr} & \text{— equal} \\
\text{pExpr } '!=' \text{ pExpr} & \text{— inequal} \\
\text{pExpr } '>' \text{ pExpr} & \text{— larger than} \\
\text{pExpr } '>=' \text{ pExpr} & \text{— larger than or equal} \\
\text{pExpr } '<' \text{ pExpr} & \text{— less than} \\
\text{pExpr } '<=' \text{ pExpr} & \text{— less than or equal} \\
\text{pExpr } '+' \text{ pExpr} & \text{— addition} \\
\text{pExpr } '-' \text{ pExpr} & \text{— subtraction} \\
\text{pExpr } '*' \text{ pExpr} & \text{— multiplication} \\
\text{pExpr } '/' \text{ pExpr} & \text{— division} \\
\text{pExpr } '%' \text{ pExpr} & \text{— modulus} \\
\text{'-' pExpr} & \text{— negation} \\
\text{'if' pExpr 'then' pExpr} \quad \begin{array}{l}
\text{— conditional} \\
\text{'else' pExpr 'end'} \\
\text{pExpr } ']' \text{ pExpr} (',', \text{ pExpr}* ']' \text{— array} \\
\text{'{'} \text{ pExpr} (',', \text{ pExpr}* '}' \text{— set extension} \\
\text{'{'} \text{ pExpr } 'to' \text{ pExpr} \\
\text{('by' 'step' \text{ pExpr})? '}' \text{— set range} \\
\text{StateFormula} & \text{— state formula} \\
\text{PathFormula} & \text{— path formula} \\
\text{RPathFormula} & \text{— rewards path formula} \\
\text{QualifiedNameToElement} & \text{— refer to RoboChart elements} \\
\text{'@' N '::' N '::'} \text{ N} & \text{— refer to pModule variables} \\
\text{pEventVal} & \text{— refer to data on event} \\
\text{QualifiedNameToElement } 'is' 'in' \text{ QualifiedNameToElement} & \text{— current state of a composite state} \\
\text{'$' N} & \text{— refer to a Formula} \\
\text{LabelRef} & \text{— refer to a Label} \\
\text{'$$' N} & \text{— refer to a parameter of pFunction} \\
\text{'&' N '(', pExpr (',', pExpr)* ')'} & \text{— Call of a pFunction} \\
\text{ '(' pExpr ')} & \text{— parenthesised expression}
\end{array}
\end{array}
\]
Chapter 6. Assertion DSL Syntax

Boolean Expressions

Boolean expressions includes:

- **Boolean literals**: `true` or `false`;
- **Logical expressions**: `iff`, `=>`, `/\`, `\/`, `not`;
- **Comparison expressions**: `==`, `!=`, `>`, `>=`, `<`, `<=`;
- **Conditional**: `if ... then ... else ... end`, if the expressions of both `if` and `else` branches are boolean;
- **Array expressions**: `pExpr [ ... ]`, if the basic type of `pExpr` is boolean;
- **State formulas**: see Syntax 6.2.7 if a `Query` is not used;
- **Path formulas**;
- **Rewards path formulas**;
- **A reference to a variable in a RoboChart model**: `QualifiedNameToElement`, if the variable is boolean;
- **A reference to a variable in `pModule`**: `@`, if the variable is of the boolean type `bool`;
- **A reference to the data on an event**: `pEventVal`, if the event is of the boolean type;
- **Current state of a composite state**: `is in`;
- **A reference to a `Formula`**: `$`, if the expression of the formula (see Syntax 6.2.3) is boolean;
- **A reference to a `Label`**: `LabelRef`;
- **Call to a `pFunction`** if the result expression of the function definition is boolean.

Numeric Expressions

All boolean expressions are non-numeric. Numeric expressions includes:

- **Integer and real numbers**: `INT` and `FLOAT`;
- **Arithmetic expressions**: `+`, `-`, `*`, `/`, `%`, `-`;
- **Conditional**: `if ... then ... else ... end`, if the expressions of both `if` and `else` branches are numeric;
- **Array expressions**: `pExpr [ ... ]`, if the basic type of `pExpr` is numeric;
- **State formulas**: see Syntax 6.2.7 if a `Query` is used;
- **A reference to a variable in a RoboChart model**: `QualifiedNameToElement`, if the variable is numeric;
- **A reference to a variable in `pModule`**: `@`, if the variable is of the integer range type;
- **A reference to the data on an event**: `pEventVal`, if the event is of a numeric type;
- **A reference to a `Formula`**: `$`, if the expression of the formula (see Syntax 6.2.3) is numeric;
- **Call to a `pFunction`** if the result expression of the function definition is numeric.

Set Expressions

Set expressions includes:
6.2 Probabilistic Properties

- Set extension expressions;
- Set range expressions.

State Formulas

**Syntax — State Formulas.**

<table>
<thead>
<tr>
<th>StateFormula</th>
<th>::=</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFormula</td>
<td>::=</td>
</tr>
<tr>
<td>RFormula</td>
<td>::=</td>
</tr>
<tr>
<td>AFormula</td>
<td>::=</td>
</tr>
<tr>
<td>EFormula</td>
<td>::=</td>
</tr>
</tbody>
</table>

- A state formula could be one of the followings:
  - a probability formula (PFormula) starting with `Prob` and a bound (Bound) or a query (Query), followed by a boolean expression and an optional simulation method (UseMethod);
  - a reward formula (RFormula) starting with `Reward` and an optional rewards name, and a bound (Bound) or a query (Query), followed by a reward path formula (see Syntax 6.2.7) and an optional simulation method (UseMethod);
  - a non-probability property by a `Forall` operator followed by a boolean expression;
  - a non-probability property by an `Exists` operator followed by a boolean expression.

The syntax of Bound and Query is shown below.

**Syntax — Bound.**

```
Bound ::= (’>’ | ’>=' | ’<’ | ’<=’) pExpr
```

A bound is simply one of four comparison operators, followed by an expression to be compared.

**Syntax — Query.**

```
Query ::= ’?’ '='
        | ’min’ ’?’ '='
        | ’max’ ’?’ '='
```

A query has three formats: what is the probability, the minimum probability, and the maximum probability.

Path Formulas
Chapter 6. Assertion DSL Syntax

Syntax — Path Formulas.
PathFormula ::= 'Next' pExpr
| pExpr 'Until' (Bound)? pExpr
| 'Finally' (Bound)? pExpr
| 'Globally' (Bound)? pExpr
| 'Weak' 'Until' (Bound)? pExpr
| 'Release' (Bound)? pExpr

Path formulas could be constructed from one of six common CTL and LTL operators. Expressions in these formulas must be boolean and could be path formulas too.

Syntax — Rewards Path Formulas.
RPathFormula ::= 'Reachable' pExpr
| 'LTL' pExpr
| 'Cumul' pExpr
| 'Total'

Reward path formulas could specify reachability, cumulative, total and instantaneous rewards. Expressions in these formulas also must be boolean. In a reachability reward formula (Reachable), the expression should not include any path formulas. In a LTL reward formula (LTL), the expression is a path formula, but restricted to only Next, Finally, and Until operators\(^1\). In a cumulative formula, the expression must be numeric.

Label Reference

Syntax — Label Reference.
LabelRef ::= '#' N | 'deadlock' | 'init'

Defined labels (Label, see Syntax 6.2.3) can be referred to by its name with a prefix #. Two built-in labels deadlock and init can be specified directly without a prefix.

6.2.8 Events

An event on a state machine or robotic platform cannot be identified simply by its name because its role in a connection could be for input or for output. Its direction in the connection, therefore, should be taken into account.

\(^1\)In PRISM, it is called Co-Safe LTL reward properties. See [http://www.prismmodelchecker.org/manual/PropertySpecification/Reward-basedProperties](http://www.prismmodelchecker.org/manual/PropertySpecification/Reward-basedProperties) for more information.
6.2 Probabilistic Properties

We use `pEvent` to identify an event by its name (`QualifiedNameToElement`) and its role (`pEventDir`, either `in` or `out`) in a connection. For a typed event, we use `pEventVal` to refer to the data carried on the event.

6.2.9 Simulations

Statistic model checking which is based on simulation is another way to get an approximate result of properties in addition to precise model checking.

There are four simulation methods: `CI`, `ACI`, `APMC`, and `SPRT`. Each of them could have an optional path length in addition to their own parameters.

Both `CI` and `ACI` share the same parameters: width (`w`), confidence level (`alpha`), and the number of sampling (`n`). Here we use `&` to denote both sides could be present, but no more than once. The syntax of `CiMethod` ensures each parameter won’t appear more than once. Actually, the validation rules implemented in RoboTool enforce that users should supply exactly two parameters.
APMC also has three parameters: approximation ($\epsilon$), confidence level ($\delta$), and the number of sampling ($n$).

**Syntax — SPRT Simulation Method.**

```
SPRTMethod ::= (','?) 'alpha' '=' Expr)?
            & (','?) 'delta' '=' Expr)?
```

But SPRT only has two parameters: type I/II error ($\epsilon$), and indifference ($\delta$).

### 6.2.10 Qualified Names

**Syntax — Qualified Name To Element.**

```
QualifiedNameToElement ::= NamedElement ('::' NamedElement)*)
```

A fully qualified name annotated with :: provides a way to uniquely identify each instance of named elements (NamedElement) in RoboChart. Here instances for controllers and state machines denote every reference to them. For instance, there is a state machine definition (named $m$) in the RoboChart model and three state machine references to this definition: $r_1$, $r_2$, and $r_3$. In order to refer to every element $i$ of $m$, we use qualified names such as $...::r_1::i$. In particular, each qualified name shall start with a RoboChart module name, except that the constants declared in probabilistic properties by Constant (see Syntax 6.2.2).

### 6.2.11 Terminals

**Syntax — Terminal rules.**

```
ID ::= ('a'..'z'|'A'..'Z'| '_') ('a'..'z'|'A'..'Z'| '_'|'0'..'9')*
BOOLEAN ::= 'true' | 'false'
INT ::= ('0'..'9')+
FLOAT ::= INT'.'INT
STRING ::= '"' ('\' . | !('\'|"')}* "'
```
RoboTool also provides a simple text editor for an assertion DSL, which includes syntax highlighting, auto-completion, and error feedback.

### 7.1 Standard Assertions

The DSL helps you write simple assertions such as deadlock freedom and refinement without requiring knowledge of the naming conventions of our semantics. More complex properties can be specified in CSP within special environments, but this requires an understanding of the structure and naming conventions of the RoboChart semantics.

1. Create a new file by right-clicking the project, and selecting [New > File].
2. Name the file with the `.assertions` extension, and click OK.
3. (Optional) If RoboTool has not yet been configured to find the FDR executable, select the menu item [Window > Preferences].
4. (Optional) Select the RoboChart > Analysis item, and click Browse... to select the path to the installation directory of FDR.
5. (Optional) Click OK to apply the configuration.
6. In the `.assertions` file, write your custom assertions. Notice that it may be necessary to use the qualified name of RoboChart elements, such as, `MyController::MyStateMachine`.
7. In order to verify the assertions, right-click the `.assertions` file, and select the [RoboTool Analysis > Run FDR] item.
8. Provided there are no errors in the assertions or models, FDR checks the assertions in the
background, and RoboTool summarises the result in the form of a report, which is automatically
opened upon completion of the checks.

Alternatively, it is possible to run predefined standard assertions such as deadlock freedom and
nondeterminism. These assertions are generated automatically, and must be loaded into FDR
manually. The next chapter provides instructions for doing so.

7.2 Probabilistic Assertions

7.2.1 Instructions

1. Create a new file by right-clicking the project, and selecting [New > File].
2. Name the file with the .assertions extension, and click OK.
3. (Optional) If RoboTool has not yet been configure to find the PRISM executable, select the
   menu item [Window > Preferences].
4. (Optional) Select the RoboChart > PRISM item, and click Browse... to select the path to the
   installation directory of PRISM.
5. (Optional) Click OK to apply the configuration.
6. In the .assertions file, write your assertions according to the probabilistic syntax in Sec-
   tion 6.2.
7. (Optional) If the RoboChart model has not generated its PRISM model manually, right-click
   one .rct file, and select the [RoboTool > PRISM > Compile] item to generate the PRISM
   model.
8. In order to verify the assertions, right-click the .assertions file, and select the [RoboTool >
   PRISM > Run] item.
9. Provided there are no errors in the assertions or models, PRISM checks the assertions in the
   background, and RoboTool summarises the result in the form of a report, which is automatically
   opened upon completion of the checks.

7.2.2 Examples

This section provides several probabilistic assertion examples to show how to specify probabilistic
properties using our probabilistic assertion language.
Example 7.1 — Constants configuration. This example defines a constants configuration C1 that sets the constants batteryCapacity and chargeStep from the robotic platform reference rp_ref0 (that is from the module deliverMOD) to 20 and 4 respectively. Then the configuration C1 is referred in the property P_deadlock_free.

```plaintext
constants C1:
   deliverMOD::rp_ref0::batteryCapacity set to 20,
   and deliverMOD::rp_ref0::chargeStep set to 4
prob property P_deadlock_free:
   not Exists [Finally deadlock]
with constants C1
```

Example 7.2 — Constant declaration. A constant l of type nat is declared, then it is used in the property P_stuck_loc. In addition, l is configured in the constants configuration to have values from a set {0,2,4,6,8}. This property can be regarded as five properties that have l equal to each element in the set separately. This example also shows the usage of labels. A label l_stuck, associated with a boolean expression, is declared and used in the property.

```plaintext
const l : core::nat
constants C2:
   deliverMOD::rp_ref0::batteryCapacity set to 20,
   deliverMOD::rp_ref0::chargeStep set to 4,
   and l from set {0 to 8 by step 2}
label l_stuck =
   deliverMOD::ctrl_ref0::stm_ref0 is in
   deliverMOD::ctrl_ref0::stm_ref0::Stuck
prob property P_stuck_loc:
   Prob=? of [Finally deliverMOD::rp_ref0::p==l / \ #l_stuck]
with constant C2
```
Example 7.3 — Formula. A formula is just a shorthand of an expression and it is referred by putting a prefix $ in front of its name.

```plaintext
formula f_c = deliverMOD::rp_ref0::c
prob property P_stuck_loc1:
    Prob=? of [Finally deliverMOD::rp_ref0::p==1 /\ $f_c==0]
    with constant C1
```

Example 7.4 — Rewards. The reward nbmove assigns 1 to each synchronisation over the move event that is from the state machine reference stm_ref0 and used for input. Then a reward operator Reward uses this defined reward nbmove to check the average number of synchronisation over move when finally the robot gets stuck.

```plaintext
rewards nbmove =
    [deliverMOD::ctrl_ref0::stm_ref0::move.in] true : 1;
endrewards
prob property R_outofpower_moves:
    Reward {nbmove} =? of [ Reachable #l_stuck ]
    with constants C1
```

Example 7.5 — Forall. This assertion checks if the robot won’t always finally get stuck. A cmdoptions is also supplied to the PRISM tool to set its maximum CUDD memory to 32 gigabytes.

```plaintext
prob property A_stuck:
    not Forall [Finally #l_stuck]
    with constant C1
    with cmdoptions "-cuddmaxmem 32g"
```
Example 7.6 — Simulation. This example applies statistic model checking to verify the property using the CI method with supplied parameters.

\[
\text{prob property } P_{\text{stuck loc sim}}:
\begin{align*}
\text{Prob} = \text{? of } & \text{Finally deliverMOD::rp_ref0::p==1 } \lor \#\text{l_stuck} \\
& \text{using sim with CI at } \alpha=0.01, n=1000, \text{ and pathlen=100000} \\
& \text{with constant C1}
\end{align*}
\]
8. Checking core assertions

Along with the CSP semantics of a model, RoboTool automatically generates assertions to check standard properties such as deadlock freedom and determinism. These properties are specified in file with the suffix _coreassertions.csp, and can be checked by FDR.

1. The core assertions for the controller created in the previous chapter are contained in the file mycontroller_coreassertions.csp in the src-gen folder.

2. (Optional) In order to open the file in FDR directly from eclipse, select FDR as the default editor. Right-click the file, and select [Open With > Other...].

3. In the Editor Selection dialog, select External programs.

4. Check both “Use this editor for all FILENAME files” and “Use it for all ‘*.csp’ files”.

5. Click Browse... to select FDR as the editor.

6. Find the FDR4 executable, and click OK.

7. Make sure FDR4 is selected in the Editor Selection dialog, and click OK.

8. The last step opens the FDR4 windows with all assertions loaded and displayed on the right-hand side panel.

9. Click the Run All button at the top-right corner, and wait for the checks to finish. Alternatively, click each Check button to run each assertion separately.

10. If any of the (positive) assertions fail, a counter example is produced. It can be viewed by clicking the Debug button of the assertion.

A number of the core assertions of the model created in the previous chapter fail. In particular, all determinism and deadlock freedom checks fail. This is due to the underspecification of the operation move, which may or may not terminate. Next, we complete our model with information
about termination of the move operation.

1. Select the operation definition tool in the Architectural Constructs section of the palette, and click on the editor.
2. Input the operation signature and click OK.
3. Save the model, right-click the operation definition, and select [RoboChart > Toggle termination].
4. The operation definition label now indicates that the operation move terminates.
5. Reload the file mycontroller_coreassertions.csp on FDR and run the assertions.

The analysis of the updated model only fails in the verification of deadlock freedom of the move operations, which is expected as the operation terminates, and in FDR termination is not distinguished from deadlock.

In order to establish termination, we create two assertions. For example, in order to establish that the operation move terminates, we must show that the process $P_{move}$ is not deadlock free, and that the process $P_{move}$ followed by the process $\text{RUN}(r_{--})$ is deadlock free.
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Collections</td>
<td>133</td>
</tr>
<tr>
<td>9.1</td>
<td>Metamodel</td>
<td></td>
</tr>
<tr>
<td>9.2</td>
<td>Well-formedness Conditions</td>
<td></td>
</tr>
<tr>
<td>9.3</td>
<td>Semantics</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Conclusions</td>
<td>139</td>
</tr>
</tbody>
</table>
9. Collections

This chapter describes the RoboChart extensions designed to support modelling, analysis, and simulation of collections of robots. Section 9.1 describes the extensions of the metamodel of RoboChart, Section 9.2 describes the conditions that characterise well-formed RoboChart collections, and Section 9.3 specifies the semantics of collections based on the untimed and timed semantics in Section 4.

The contents of this chapter will be integrated into chapters 2, 3, and 4 when the extension is further validated through examples.

9.1 Metamodel

The metamodel of RoboChart is extended for collections in the following ways:

1. A new construct RCCollection is introduced to describe collections of robots modelled as Modules. Additional auxiliary construct, such as Instantiations, are also provided as part of RCCollection;
2. Events are extended to support the specification of broadcast events;
3. Triggers are extended to use broadcast events by recovering information about the source of the communication as well as by restricting the possible targets. This last feature introduces the possibility of one-to-one or one-to-many communications in a more restrictive form than broadcast (one-to-all);
4. Expressions are extended with two new types of expressions: ToExp and IdExp. They both characterise implicit parameters. The first applies only to state machines and allows the
restriction of communication patterns. The second applies to state machines, controllers and modules and provides a unique identifier for an instance of a module.

Figure 9.1 shows the part of the extensions of the metamodel. Collections are specified by RCCollections, which include:

- A `VariableList` specifies constant variables that can be used to instantiate the collection. For example, loose constants that bound the number of robots in the collection.
- An `Instantiation` describes how many instances (range) of a `Module` (modelling robots) are presents, and assigns the instances an index.
- A `ModuleRef` is a place holder for a `Module` and is used to specify how instances of the module can interact with instances of other modules (including instances of the same module).
- A `Connection` links two place holders and specifies the possible interactions between instances of the source and target place holders.
- An `InstantiationParameter` can include `InstantiationParameters` that are used to initialise constants of a module. `Events` are extended with a boolean attribute that is used to determine whether or not it a broadcast event.
Finally, triggers (shown in Figure 9.2) are extended with two new attributes:

- `from` is used to identify a variable in which to record the identifier of the source of the communication; and
- `predicate` is used to restrict the potential targets of communication. For example, an empty predicate is equivalent to `true`, and results on the message being sent to all possible targets (determined by the set of identifiers that characterise the target event), while a predicate such as `from = v` sends the message only to the target whose identifier is recorded in the variable `v`.

### 9.2 Well-formedness Conditions

#### 9.2.1 RCCollection

- **All variables in a collection must be constants.** At the level of collections, variables are only used to instantiate constants of the modules.
- **A collection can contain any number of placeholders, but at most two of the same module.** A placeholder corresponds to any instance of the module in a collection, and since we do not allow concrete identification of instances in the diagram, the can be at most two placeholders of the same type, identifying two different, but otherwise unspecified, instances.
- **Connections between placeholders of the same module must be bidirectional.** The semantics of connections `c` between placeholders of the same module `M` is summarised by "any two different instances of `M` can interact with each other via the connection `c`". This semantics essentially equate

#### 9.2.2 Instantiation

- **The range of an instantiation must be a bounded set.** While we do allow the use of loose constants in the specification of the range, for any value that the constants can take, the set of indices must be finite.

#### 9.2.3 Event

- **Events connected in a collection must be broadcast events.** Events connected in a collection model some form of communication, which in its most general form is a broadcast. Further restriction over the patterns of communication can be modelled internally using the `predicate` attribute of triggers.
- **Connections (at any level) involving a broadcast event in one end must link to another broadcast event.** The broadcast nature of the event is part of its type and affects the semantics of triggers, therefore the ends of the connection must be compatible.
9.2.4 Trigger

- A transition trigger must not record a value for _predicate_. In the context of broadcast communications, transition triggers are interpreted as input communications, in which restriction of the targets is meaningless.
- A send event statement trigger must not record a value for _from_. In the context of broadcast communications, send event statements are interpreted as output communications, in which case the source identifier obtained through the _from_ attribute is redundant, as it is the identifier of the machine that contains the send event statement.

9.3 Semantics

Rule 196. Semantics of Collections

\[
\begin{array}{l}
[c : RCCollection]_{\text{Lcl}} : \text{CSPProcess} = \\
\| \text{inst} : c.\text{instantiations} \bullet \| i : \text{inst.\text{range}} \bullet ![\text{inst.\text{module}}](i) \| \mapsto \\
(\| [e_1, e_2 | (e_1, e_2) \leftarrow \text{connectedEvents}(c)]\| \\
\| \text{conn} : c.\text{connections} \bullet ![\text{conn.\text{from}}](i, j : \text{inds}(c, \text{conn})) \\
\| \text{BBuffer}'(\text{eventId}(\text{conn.\text{from}}), i, \text{eventId}(\text{conn.\text{eto}}), j)) \\
\| \text{conn} : c.\text{connections} | \text{conn.\text{bidirec}} \land \text{heterogeneous} \bullet ![\text{conn.\text{eto}}](i, j : \text{inds}(c, \text{conn})) \\
\| \text{BBuffer}''(\text{eventId}(\text{conn.\text{eto}}), j, \text{eventId}(\text{conn.\text{from}}), i) \\
\end{array}
\]

where

\[
\text{connectedEvents}(c : \text{Collection}) : \text{P}(\text{Event} \times \text{Event}) = \\
\{ \text{conn} : c.\text{connections} \bullet (\text{eventId}(\text{conn.\text{from}}), \text{eventId}(\text{conn.\text{eto}})) \} \\
\cup \\
\{ \text{conn} : c.\text{connections} | \text{conn.\text{bidirec}} \bullet (\text{eventId}(\text{conn.\text{eto}}), \text{eventId}(\text{conn.\text{from}})) \}
\]

\[
\text{inds}(\text{conn}, \text{conn.\text{Collection}}, c : \text{Collection}) : \text{P}(\text{ID} \times \text{ID}) = \\
\text{if} \text{conn.\text{from}}.\text{ref} = \text{conn.\text{to}}.\text{ref} \text{then} \\
\text{range}(\text{conn.\text{to}}.\text{c}) \times \text{range}(\text{conn.\text{from}}.\text{c}) \setminus \{ i : \text{range}(\text{conn.\text{to}}.\text{c}) \bullet (i, i) \} \\
\text{else} \\
\text{range}(\text{conn.\text{to}}.\text{c}) \times \text{range}(\text{conn.\text{from}}.\text{c})
\]

\[
\text{range}(m : \text{Module}, c : \text{Collection}) : \text{P}\text{ID} = (i : c.\text{instantiations} | i.\text{module} = m).\text{range} \\
\text{heterogeneous} = (c.\text{from}.\text{ref} \neq c.\text{to}.\text{ref})
\]
Rule 197. Broadcast Buffer

\[
\text{BBuff}(e_{\text{in}}: \text{Event}, i: \text{ID}, e_{\text{out}}: \text{Event}, j: \text{ID}) : \text{CSPProcess} =
\]

\[
\text{let}
\]

\[
\text{BufferEmpty} = \text{prefixIn} \to \text{BufferFull}(x)
\]

\[
\text{BufferFull}(v) = \text{prefixIn} \to \text{BufferFull}(x) \Box \text{prefixOut} \to \text{BufferEmpty}
\]

\[
\text{within}
\]

\[
\text{BufferEmpty}
\]

\[
\text{where}
\]

\[
e_{\text{in}}: \text{broadcast}
\]

\[
\text{prefixIn} = \text{if } e_{\text{in}}.\text{type} \neq \text{null then eventId}(e_{\text{in}}) \text{?} x \text{ else eventId}(e_{\text{in}})
\]

\[
\text{prefixOut} = \text{if } e_{\text{out}}.\text{type} \neq \text{null then eventId}(e_{\text{out}}) \text{?} v \text{ else eventId}(e_{\text{out}})
\]

Rule 198. Semantics of triggers

\[
[t: \text{Trigger}]^{\text{id}}_{\text{Trigger}} : \text{CSPProcess} =
\]

\[
\text{if } t.\text{type} = \text{INPUT then}
\]

\[
\text{eventId}(t.\text{event}).\text{id}?! \text{id}? \text{?} x \to \text{set} \text{vid}(t.\text{from})!f \to \text{set} \text{vid}(t.\text{parameter})!x \to \text{Skip}
\]

\[
\text{else if } t.\text{type} = \text{SIMPLE then}
\]

\[
\text{eventId}(t.\text{event}).\text{id}?! \text{id} \to \text{set} \text{vid}(t.\text{from})!f \to \text{Skip}
\]

\[
\text{else These cases do not occur when the event is broadcast}
\]

\[
\text{where}
\]

\[
t.\text{event} . \text{broadcast}
\]

Rule 199. Semantics of send event statements

\[
[s: \text{SendEvent}]^{\text{id}}_{\text{Statement}} : \text{CSPProcess} =
\]

\[
\text{if } t.\text{type} = \text{OUTPUT} \lor t.\text{type} = \text{SYNC then}
\]

\[
\| i : \{ x : \text{ID} \mid [t.\text{predicate}]_{\text{EXPR}} \} \bullet \text{eventId}(t.\text{event})!\text{id}?!t.\text{value}!t.\text{value} \to \text{Skip}
\]

\[
\text{else if } t.\text{type} = \text{SIMPLE then}
\]

\[
\| i : \{ x : \text{ID} \mid [t.\text{predicate}]_{\text{EXPR}} \} \bullet \text{eventId}(t.\text{event})!\text{id}?!t \to \text{Skip}
\]

\[
\text{else These cases do not occur when the event is broadcast}
\]

\[
\text{where}
\]

\[
s.\text{trigger} . \text{broadcast}
\]
10. Conclusions

We have presented RoboChart, a diagrammatic notation for modelling of robotic systems. It is based on UML state machines, but includes the notions of robotic platform and controller, synchronous and asynchronous communications, an API of operations common to autonomous and mobile robots, a well defined action language, pre and postconditions, and time primitives. It also has a formal semantics suitable for verification. Examples of RoboChart models and their verification can be found at www.cs.york.ac.uk/circus/RoboCalc/.

We have described the semantics for the core constructs of RoboChart. It uses CSP, but we envisage its extension to use Circus [3], a process algebra that combines Z [16] and CSP, and includes time constructs [6]. Use of Circus and its UTP foundation will enable use of theorem proving as well as model checking.

An approach for writing object-oriented simulations of RoboChart diagrams has also been defined. Automatic generation of simulations is possible and part of our future work. Verification of correctness of simulations will use the object-oriented version of Circus [4], with a semantics given by the UTP theory in [12].

RoboChart itself misses support for modelling the environment and the robotic platforms in model detail. It is also in our plans to take inspiration from hybrid automata [30] to extend the notation, and from the UTP model of continuous variables [28] to define the semantics.
Appendices

A RoboChart diagrams - an informal overview ................. 143
   A.1 Time primitives

B Complete Metamodel .................. 153

C ✓-tock and share-CSP .................. 163
   C.1 ✓-tock
   C.2 share-CSP

D Mathematical Toolkit ................. 167

E OCL Well-formedness Conditions .... 173
To illustrate the concepts, we present the model of a robot for chemical detection based on that in [15] ¹. In our example, the robot employs a random walk and, upon detection of a chemical source, it turns on a light and drops a flag.

A robotic system is specified in RoboChart by a module, where a robotic platform is connected to one or more controllers. A robotic platform is characterised by variables, operations, and events representing its in-built facilities. For our example, the module ChemicalDetector is shown in Figure A.1, where we have a robotic platform named Vehicle and two controllers named MainController and MicroController.

Vehicle declares a number of events via named boxes on its border. The event flag is used to request an in-built flag holder to drop a flag. The events obstacle and odometer represent two sensors, one monitoring obstacles in front of the vehicle, and the other providing an estimation of the distance travelled. Finally, the event gas represents an array of in-built sensors that detect the type and intensity of gases.

An interface Operations groups operation declarations. The operation move(lv,α) takes a linear velocity lv and an angle α as parameters; it moves the vehicle forward at speed lv while turning by α degrees. The type of lv is real, and that of α is Angle, which is an enumerated type, including values left, right, front, and back for simplicity. In RoboChart, we can also define given types (uninterpreted sets), record types, and other structured types. The primitive types include numbers and strings. The operation randomWalk() carries out a random walk, and potentially does not terminate. The shortRandomWalk() operation, on the other hand, is a

¹http://tinyurl.com/hdaws7o
random walk that is guaranteed to terminate.

The operations \texttt{move(lv,a)} and \texttt{shortRandomWalk()} are defined separately, just to indicate that they terminate; \texttt{randomWalk()} is left undefined. Further elaboration of the model may include a definition for these operations via state machines, or via pre and postconditions. Such definitions would have the purpose to support reasoning, but since these are operations that we declare to be provided by the platform, they do not need to be implemented. The fact that \texttt{Vehicle} declares \texttt{Operations} as a provided (P) interface makes this clear.

The \texttt{Vehicle} behaviour is defined by the two controllers \texttt{MainController} and \texttt{MicroController} referenced in the module and defined in other diagrams. \texttt{MainController} uses \texttt{gas} to detect gases, and events \texttt{turn, stop and resume} to control the trajectory followed by the vehicle. The last three events are internal to the module and passed to \texttt{MicroController}, which implements the associated behaviours using the \texttt{move(lv,a)} operation, whilst avoiding obstacles.

\texttt{MicroController} implements obstacle avoidance using the events \texttt{obstacle} and \texttt{odometer}, implements the movement behaviors (\texttt{turn, stop and resume}) and drops a flag when a specific gas is found. The interactions between controllers and between a controller and the robotic platform are specified by arrows connecting the appropriate events. The directions of the arrows indicate the flow of information. For instance, when the \texttt{Vehicle} finds a chemical, it sends a sequence of \texttt{GasSensor} values through the \texttt{gas} event to \texttt{MainController}.

Communication with a robotic platform is always asynchronous, but communication between controllers can be synchronous or asynchronous. In our example, the communication between the controllers and the platform via the \texttt{gas, obstacle, flag, and odometer} events is asynchronous, as indicated by the label \texttt{async} on the arrows that represent the connections. That label is used on all connections with a robotic platform.
The connections between the controllers are all synchronous in this example. This is an abstraction, since typically controllers of a robot communicate asynchronously.

As mentioned, MainController and MicroController are defined in other diagrams, and referenced in the module ChemicalDetector. The diagrams are shown in Figures A.2 and A.3.

The behaviour of a controller is specified by one or more parallel state machines. They use variables, operations, and events that are either defined locally or required from the platform. Required interfaces identify the outer definitions that can be used. The micro-controller in Figure A.3, for instance, requires the operations provided by the platform to move the robot.

The events of a controller can be connected to those of the state machines that defines it. Communication between states machines is always synchronous, since parallelism at this level is used for convenience of modelling, rather than to indicate concrete designs.
MainController is defined by a single state machine GasAnalysis. It is referenced in the definition of MainController in Figure A.2, and defined in Figure A.4. The controller in this case just relays its events to and from the state machine.

GasAnalysis initially waits in state NoGas for an event gas communicating a value gs from the sensors. When it gets that value, it analyses it using a function call analysis(gs) to determine its nature. If there is no gas, the machine returns to the state NoGas sending a command (via an event) to the MicroController to resume the random walk. Otherwise, it moves to the state GasDetected, where it determines the intensity of the gas, using a function call intensity(gs).

If there is enough gas, indicated by an intensity greater than or equal to that of a threshold constant thr defined in the machine, it instructs the vehicle to stop using the event stop and terminates (entering the final state (F)). In this scenario, the robot found the gas. Otherwise, the machine calculates the direction of the detected gas (using the function call location(gs)) and instructs the vehicle to turn in that direction using the event turn before going to the state Reading. In that state, it reads a new value from the gas sensors for analysis.

The controller MicroController is also defined by a single state machine Movement. It also relays events to and from its state machine. It also defines an operation changeDirection(l) used by Movement when it finds an obstacle.

Movement avoids obstacles while receives events turn, resume and stop to control the movement of the vehicle. The avoidance mechanism uses the odometer event as well as a clock to detect situations where the vehicle becomes stuck. In this case, it takes special measures to leave the area before resuming its main behaviour of treating movement requests.

The strategy can be summarised as follows. When an obstacle is first detected, a clock is reset and
the distance travelled so far is recorded before the obstacle is avoided. If, after the avoidance action, another obstacle is detected, the machine checks whether enough time has elapsed since the first obstacle, but the vehicle has not moved enough, and in this case it takes measures to get out of the are. Otherwise, it resumes its normal activity.

In most states, except while actively avoiding an obstacle, the machine can respond to requests to turn. Additionally, it may receive requests to start a random walk (using the event resume) as well as to stop the vehicle, in which case it requests a flag to be dropped and terminates. In the next section we explain in more detail the time constructs used in Movement.

RoboChart state machines are standard, but restricted and with a well defined semantics. They can have composed states, junctions, and entry, during, exit, and transition actions defined using a well defined action language. Features of UML state machines [24] deemed not essential for robotics are not included, resulting in a streamlined semantics.

Definitions of a model can be organised in packages. Like in UML, they are just containers. They do not correspond to a concept or abstraction, and so do not have an interface. An imports mechanism controls scope of the definitions. All packages that do not have a package name conceptually compose the same package. Elements defined in the unnamed package are available in all other packages. Elements defined in a package with a name can only be used if they are explicitly imported. A model is identified by one module and all the other elements there. Figures A.6 and A.7 define two packages used in our example.
In Chemical, we specify a data model for handling the gas sensors. This involves a number of types, some of which are just named, like Chem, and a number of functions acting on those types. Functions are either left undefined, like greater, or defined by pre and postconditions, like intensity. To define these conditions, RoboChart provides a simple predicate language.

In the package Location, we define the operation changeDirection(l) used in the MicroController. An API can provide a collection of such definitions organised in packages.
A.1 Time primitives

RoboChart operations take zero time, and enabled transitions take place as soon as they can be triggered. Time constraints need to be explicitly defined. In Table 2.3 we summarize the syntax of all timed constructs that can be used in the definition of state machines.

The timed budget \( b \) for an action \( A \) can be specified by sequentially composing \( A \) with the action \( \text{wait}(b) \), which waits for \( b \) time units. In the machine Movement of the chemical detector (see Figure A.5), we compose the shortRandomWalk() and changeDirection(l) calls with \( \text{wait}(\text{outPeriod}) \) and \( \text{wait}(\text{evadeTime}) \), where \( \text{outPeriod} \) and \( \text{evadeTime} \) are constants.

In the case of changeDirection(l), the software operation is very simple (see Figure A.7). It involves a condition on the value of \( l \) and a call to the \( \text{move}([v,a]) \) operation, which is likely to involve just a simple assignment to actuator registers. So, the execution time of changeDirection(l) is negligible. The \( \text{wait}(\text{evadeTime}) \) action, in this case, represents the amount of time the software should wait for the effect of that change of direction to take place.

In the case of shortRandomWalk(), although this operation is not defined, we expect it to take some time to actually effect the walk. So, \( \text{wait}(\text{outPeriod}) \) records the amount of time we expect this operation to take. More realistically, we should give a range of time here, as it is very difficult to predict the exact amount of time an operation can take. This is possible in RoboChart by specifying a (closed or open) interval of time when using the \( \text{wait} \) action. In our example, we have a deterministic budget, for simplicity.

A deadline of \( d \) time units for an action \( A \) is specified by \( A < \{d\} \), while a deadline on an event \( e \) is specified by \( e < \{d\} \). Clocks allow transitions to be guarded by constraints relative to the occurrence of clock resets and the entering of a state. For that, we can use in guards the expressions \( \text{since}(C) \), which yields the elapsed time since the most recent reset \( \#C \) of clock \( C \), and \( \text{sinceEntry}(S) \), which yields the time elapsed since entering state \( S \).

Similarly to timed automata, expressions involving clocks are restricted to comparing single timed primitive with constant expressions. We, however, allow conjunctive as well as disjunctive expressions involving more than one clock.

To further illustrate the time primitives, we consider a robot that moves at constant speed in a square pattern while avoiding obstacles. The state machine is shown in Figure A.8. We omit the simple module and controller, and operation definitions that just specify termination.

When the robot is started, it transitions from the initial state, denoted by a black circle, to the state MovingForward, while resetting \( \#C \) a clock \( C \) and assigning 1 to a local variable segment. A RoboChart state machine is self-contained, in that it declares all the variables, events, and operations that it uses. In Figure A.8 two constants linear and angular are defined, to represent the linear
Chapter A. RoboChart diagrams - an informal overview

Figure A.8: Square-trajectory robot

...and angular speed, respectively. The local variable `segment` records how many sides of the square have been covered so far; the robot stops when it completes the square (`segment == 4`). This is achieved by sending an event `stop` to the platform and transitioning to the final state: a white circle. The event `stop` is given a deadline 0, indicating that it is expected that the robotic platform is always ready to accept this event immediately.

The state `MovingForward` is composite. In this state, the motion is linear, unless an obstacle is detected. Linear motion is activated by calling the operation `moveForward(linear)` in the entry action with a constant value `linear` passed as a parameter.

Before `MovingForward` is actually entered, its entry action executes, followed by that of its substate `Observing`, enabling the collision detection capability. Once a collision is detected, the event `collisionDetected` is raised by the robotic platform: the transition from `Observing` to the state `Collision` is then triggered, executing the exit action of `Observing` and subsequently the `avoid` operation that performs the actual collision avoidance. Here we do not specify this operation, but record its budget of 2 time units by sequentially composing it with the timed primitive `wait(2)`.

In RoboChart time elapses explicitly via budgets, unless a state has been entered and no transitions are enabled, or, every enabled transition is associated with an external event. Once the collision is resolved, a transition back to `Observing` is taken. Transitions are triggered once the guard is true.
and the associated event is raised, or, if there is no event or guard associated, immediately, as in this example.

The square motion pattern is achieved by limiting the linear motion to 5 time units before switching to angular motion for 2 time units, and then switching again to linear motion. Accordingly, we guard the transition from MovingForward to the state Turning with the expression since(C) == 5. Upon such a transition, the value of segment is incremented. Similarly, the angular motion is limited by guarding the transition from Turning to MovingForward using the timed primitive sinceEntry(Turning). Upon this transition, clock C is reset.

When entering the Turning state, the event stop is used to stop the robot before turning. This is an event, and so (may) require synchronisation to happen, and so, it may take time. The deadline 0, however, enforces that it must take place immediately. Since stop is actually an event of the platform (omitted here), this is simple to achieve, because the connection with the platform is asynchronous. In any case, the deadline makes the properties of the state machine independent of whether its stop event is in a synchronous or asynchronous connection.
This appendix contains the complete metamodel specified in Ecore and formatted by the tool OCLinEcore. The syntax of the representation used in this appendix is available [here](#).

A summary of the concepts of Ecore can be found [here](#), and a tutorial is available [here](#).

While this metamodel leaves the class of Expressions abstract, as this class is defined in the Z Standard [1], it includes the Expression subclasses: Application, as an illustration of the embedding of Z in the metamodel of RoboChart, and the timed expressions ClockExp and StateClockExp, which are unique to RoboChart. The definition of Application depends on the notion of Template, which represents (potentially infix) operators and is only partially described here (for the full description, see [1]).

```ecore

package robochart : robochart = 'http://www.robocalc.circus/RoboChart'
{
  class BasicPackage
  {
    attribute name : String[?];
    property imports : Import[*] { composes };
  }
  class RCPackage extends BasicPackage
  {
    property interfaces : Interface[*] { composes };
    property robots : RoboticPlatformDef[*] { composes };
    property types : TypeDecl[*] { composes };
    property machines :StateMachineDef[*] { composes };
  }
}
property controllers : ControllerDef[*] { composes };
property modules : RModule[*] { composes };
property operations : OperationDef[*] { composes };
property functions : Function[*] { composes };
}
class Import
{
    attribute importedNamespace : String[1];
}
abstract class NamedElement
{
    attribute name : String[1];
}

/*
 * Definition of type declarations
 */
abstract class TypeDecl extends NamedExpression;

/*
 * Primitive Types
 */
class PrimitiveType extends TypeDecl;

/*
 * Record Types
 */
class RecordType extends TypeDecl
{
    property fields : Field[*] { composes };
}
class Field extends Member,NamedExpression;
abstract class TypedNamedElement extends NamedElement
{
    property type : Expression[1] { composes };
}
abstract class Member extends TypedNamedElement;

/*
 * Enumeration Types
 */
class Enumeration extends TypeDecl
{
    property literals : Literal[*|1] { composes };
}
class Literal extends TypeDecl,NamedExpression
{
    property types : Expression[*] { composes };
}
```java
/*
 * Named Types
 */
class NamedType extends TypeDecl
{
    property type : Expression[1] { composes };
}

/*
 * Variables
 */
class VariableList
{
    attribute modifier : VariableModifier[1];
    property vars : Variable[*] { composes };
}
enum VariableModifier { serializable }
{
    literal VAR;
    literal CONST;
}
class Variable extends TypedNamedElement,Member,Mutable
{
    property initial : Expression[?] { composes };
    attribute modifier : VariableModifier[1] { derived transient volatile }
};

/*
 * Events
 */
class Event extends NamedElement
{
    property type : Expression[?] { composes };
    attribute broadcast : Boolean[1];
}

/*
 * Functions
 */
class Function extends TypedNamedElement,NamedExpression
{
    property parameters : Parameter[*] { ordered composes };
    property preconditions : Expression[*] { composes };
    property postconditions : Expression[*] { composes };
}
class Parameter extends Variable;

/*
 * Operations
 */
class OperationSig extends NamedElement
{
    attribute terminates : Boolean[1];
    property parameters : Parameter[*] { ordered composes };
    property preconditions : Expression[*] { composes };
    property postconditions : Expression[*] { composes };
}
abstract class Operation extends NamedElement, ConnectionNode;
class OperationDef extends Operation, OperationSig,StateMachineBody;

/*
 * The Reference class identifies reference constructs
 */
abstract class Reference;
class OperationRef extends Operation, Reference
{
    property ref : OperationDef[1];
}

/*
 * Interfaces
 */
class Interface extends NamedElement, BasicContext;
abstract class BasicContext
{
    property variableList : VariableList[*] { composes };
    property operations : OperationSig[*] { composes };
    property events : Event[*] { composes };
    property clocks : Clock[*] { composes };
}

/*
 * Robotic Platforms
 */
abstract class RoboticPlatform extends NamedElement, ConnectionNode;
class RoboticPlatformDef extends Context, RoboticPlatform;
abstract class Context extends BasicContext
{
    property pInterfaces : Interface[*] { !unique };
    property rInterfaces : Interface[*] { !unique };
    property interfaces : Interface[*] { !unique };
}
class RoboticPlatformRef extends RoboticPlatform, Reference
{
    property ref : RoboticPlatformDef[1];
}

/*
 * State Machines
abstract class StateMachine extends NamedElement, ConnectionNode;
class StateMachineDef extends StateMachineBody, StateMachine;
class StateMachineRef extends StateMachine, Reference {
    property ref : StateMachineDef[1];
}
class StateMachineBody extends Context, NodeContainer;
class Clock extends NamedElement;
abstract class NodeContainer {
    property nodes : Node[*] { composes };
    property transitions : Transition[*] { composes };
}
abstract class Node extends NamedElement;
class Junction extends Node;
class Initial extends Junction;
class State extends Node, NodeContainer {
    property actions : Action[*] { composes };
}
class Final extends State;
class ProbabilisticJunction extends Junction;
class Transition extends NamedElement {
    property source : Node[1];
    property target : Node[1];
    property trigger : Communication[*] { composes };
    property deadline : Expression[*] { composes };
    property condition : Expression[*] { composes };
    property action : Statement[*] { composes };
    property probability : Expression[*] { composes };
    property reset : ClockReset[*] { ordered composes };
}
class Communication {
    property event : Event[*];
    property _from : Variable[*];
    property _predicate : Expression[*] { composes };
    property parameter : Variable[*];
    property value : Expression[*] { composes };
    attribute _type : CommunicationType[1];
}
enum CommunicationType { serializable }
{
    literal SIMPLE;
    literal INPUT;
    literal OUTPUT;
    literal SYNC;
*/
* Actions
*/
abstract class Action
{
    property action : Statement[1] { composes };
}
class EntryAction extends Action;
class DuringAction extends Action;
class ExitAction extends Action;

/*/ 
* Controllers 
*/
abstract class Controller extends NamedElement, ConnectionNode;
class ControllerDef extends Context.Controller
{
    property machines : StateMachine[*] { composes };
    property lOperations : Operation[*] { composes };
    property connections : Connection[*] { composes };
}
class Connection
{
    property from : ConnectionNode[1];
    property to : ConnectionNode[1];
    property efrom : Event[1];
    property eto : Event[1];
    attribute async : Boolean[1];
    attribute bidirec : Boolean[1];
}
class ControllerRef extends Controller
{
    property ref : ControllerDef[1];
}

/*/ 
* Modules 
*/
class RCModule extends NamedElement
{
    property connections : Connection[*] { composes };
    property nodes : ConnectionNode[*] { composes };
}
 abstract class Statement;
class TimedStatement extends Statement {
    property stmt : Statement[1] { composes };
    property deadline : Expression[1] { composes };
} class Wait extends Statement {
    property duration : Expression[1] { composes };
} class Skip extends Statement;
class IfStmt extends Statement {
    property expression : Expression[1] { composes };
    property _'then' : Statement[1] { composes };
    property _'else' : Statement[?] { composes };
} class Assignment extends Statement {
    property left : Assignable[1] { composes };
    property right : Expression[1] { composes };
} class CommunicationStmt extends Statement {
    property communication : Communication[1] { composes };
} class SeqStatement extends Statement {
    property statements : Statement[2..*] { ordered composes };
} class ParStmt extends Statement {
    property stmt : Statement[1] { composes };
} class Call extends Statement {
    property operation : OperationSig[1];
    property args : Expression[*] { ordered composes };
} class ClockReset extends Statement {
    property clock : Clock[1];
}
abstract class Template;
class PrefixTemplate extends Template;
class PostfixTemplate extends Template;
class InfixTemplate extends Template;
class NofixTemplate extends Template;
abstract class OperatorTemplate;

/*
* Expression
*/
abstract class Expression;

/*
* Application includes the class of Relations of Z.
*/
abstract class Application extends Expression;
class PrefixApp extends Application
{
    property operator : PrefixTemplate[1];
    property arguments : Expression[+] { ordered composes };}
class PostfixApp extends Application
{
    property operator : PostfixTemplate[1];
    property arguments : Expression[+] { ordered composes };}
class InfixApp extends Application
{
    property operator : InfixTemplate[1];
    property arguments : Expression[+] { ordered composes };}
class NofixApp extends Application
{
    property operator : NofixTemplate[1];
    property arguments : Expression[+] { ordered composes };}

/*
* Timed Expression
*/
class ClockExp extends Expression
{
    property clock : Clock[1];
}
class StateClockExp extends Expression
{
    property state : State[1];
}
abstract class Assignable;
class VarSelection extends Assignable
{
    property receiver : Assignable[1] { composes };
    property member : Member[1];
}
class ArrayAssignable extends Assignable
{
    property value : Assignable[1] { composes };
    property parameters : Expression[+] { composes };
}
class VarRef extends Assignable
{
    property name : Mutable[1];
}
abstract class ConnectionNode;
abstract class NamedExpression;
class WaitingCondition extends NamedElement
{
    property expression : Expression[?];
    property transitions : Transition[*] { ordered };
}
class WaitingConditionRef extends Expression
{
    property ref : WaitingCondition[?];
}
class FieldDefinition
{
    property field : Field[1];
    property value : Expression[1] { composes };
}
abstract class Mutable extends NamedElement.NamedExpression;
In this chapter we describe additional operators for \(\sqrt{\text{-tock}}\)-CSP [9] that are used in the semantics of RoboChart, and the use of \textit{share} to model state in a distributed way, as required, for example, to give a compositional semantics to software operations.

\section{\(\sqrt{\text{-tock}}\)}

\subsection{Timeout operator}

The timeout operator can be defined in terms of core \(\sqrt{\text{-tock}}\) operators using: parallel composition, strict timed interrupt, external choice, and hiding.

\[
P_{>d} Q = (P \parallel \Sigma) \cdot (((\Box e : \Sigma \bullet e \rightarrow \text{Skip}) \trianglelefteq Stop); \text{RUN}(\Sigma)) \circ (\text{Wait}(d); Q)
\]

The process initially behaves as \(P\), and after exactly \(d\) time units, if no event of \(P\) is taken up by the environment, then the process behaves as \(Q\). The timed constraint on \(P\) is imposed by controlling the events that it can perform via the biased terminating parallel composition \((\parallel cs)\circ\) with a controller process that can perform any event \(e : \Sigma\) before \(d\) time units, followed by \(\text{RUN}(\Sigma)\), or if \(d\) time units pass before \(P\) engages in an event in \(\Sigma\), then the controller process deadlocks, effectively blocking \(P\) from performing any event. After \(d\) time units have passed \(Q\) is offered via the external choice if \(P\) has not engaged in any event.
### C.1.2 Biased terminating parallel composition

The following is a biased parallel composition operator where termination of the $P$ leads to the interruption of $Q$ and termination overall.

$$
P \left[ cs \right]_p Q = ((P; f \to Skip) \left[ cs \cup \{ f \} \right] (Q \triangle f \to Skip)) \setminus \{ f \}$$

It is defined by considering a fresh event $f$, where after termination of $P$ there is a prefixing on $f$. Upon synchronisation on $f$ this interrupts the behaviour of $Q$ leading to overall termination of the parallel composition. Finally the event $f$ is hidden.

### C.2 share-CSP

To define a compositional semantics with shared state, where assignments are encoded via set events, and reads via get events, we consider a special event \textit{share} to generically encode any changes in state. Processes that employ \textit{share} typically follow a synchronisation on \textit{share} by updating their copy of the shared state via synchronisation on get events. Processes offer to synchronise on \textit{share} events whenever there is the possibility for interference, that is, for other components to update a shared variable, while refusal of \textit{share} events can be used to ensure atomicity of state updates.

Two basic processes that allow \textit{share} events are $S\text{Stop}$ and $S\text{Skip}$, versions of $\text{Stop}$ and $\text{Skip}$, respectively.

**Definition C.2.1**

$$S\text{Stop} = \text{share} \to S\text{Stop}$$

$$S\text{Skip} = S\text{Stop} \triangle \text{Skip}$$

$S\text{Stop}$ always offers \textit{share}, while $S\text{Skip}$ offers, in addition, the possibility to terminate. Similarly to the \textit{tock-CSP} encoding of \textit{Skip} in FDR, for example, \textit{Skip} can nondeterministically terminate.

### C.2.1 Parallel composition

In order to enable processes to respond synchronously to updates to the shared state, below we introduce a meta alphabetised parallel operator, defined in terms of sets of NamedElements. This is the case, for example, in the semantics of composite states, where an assignment performed as part of the control flow of the state, or its during action, can directly influence the availability of its outgoing transitions.

The following meta operator enables the alphabetised parallel composition of processes $P$ and $Q$, synchronising on a set $cs$ of events, to be updated synchronously whenever a RoboChart ‘variable’ is updated. The set $p_{write}$ is the set of variables whose values may be changed by $P$, and $p_{read}$ is
the set of variables read by $P$. Similarly, for $Q$ there are two such sets $q_{\text{write}}$, $q_{\text{read}}$. Writes by $P$, via events $\text{set}_x$ to a variable $x$, which is in the intersection $p_{\text{write}} \cap q_{\text{read}}$ are propagated to $Q$, and writes by $Q$, to events in $q_{\text{write}} \cap p_{\text{read}}$ are similarly propagated to $P$.

**Definition C.2.2**

\[
P | p_{\text{read}} : p_{\text{write}} \mid cs \mid q_{\text{read}} : q_{\text{write}} | Q \]

\[
\begin{align*}
&= \left[ \begin{array}{l}
\text{share} \leftarrow \text{share}, \\
\forall v : p_{\text{read}} \cap q_{\text{write}} \quad \text{share} \leftarrow \text{setR}_1(v), \\
\forall v : p_{\text{write}} \cap q_{\text{read}} \quad \text{set}_1(v) \leftarrow \text{setL}_1(v)
\end{array} \right] \\
&\quad \cup \left[ \begin{array}{l}
\text{share} \leftarrow \text{share}, \\
\forall v : q_{\text{read}} \cap p_{\text{write}} \quad \text{share} \leftarrow \text{setL}_2(v), \\
\forall v : q_{\text{write}} \cap p_{\text{read}} \quad \text{set}_2(v) \leftarrow \text{setR}_2(v)
\end{array} \right] \\
&\quad \cup \left[ \begin{array}{l}
\forall v : p_{\text{read}} \cap q_{\text{write}} \quad \text{setR}_3(v) \leftarrow \text{set}_3(v), \\
\forall v : q_{\text{read}} \cap p_{\text{write}} \quad \text{setL}_3(v) \leftarrow \text{set}_4(v)
\end{array} \right] \\
&\quad \cup \{\text{share}\} \}
\]

The idea here is that $P$ or $Q$, can engage in $\text{share}$ events to participate in synchronous updates to state variables, subsequently refreshing the value of variables via $\text{get}$ events. If the $p_{\text{read}}$ and $p_{\text{write}}$ sets are the same, we omit the delimiter $:$ in $p_{\text{read}} : p_{\text{write}}$.

Because in RoboChart there is a need to take into account synchronous updates of other components, like reset of clocks, and entering of states, the operator is defined in terms of set of NamedElements, instead of Variables.

**Rule 200. Setter channel**

\[
\text{set}(n : \text{NamedElement}) : \text{CSPChannel} = \\
\] Split into several definitions according to the type of $n$.

**Rule 201. Setter channel**

\[
\text{set}(v : \text{Variable}) : \text{CSPChannel} = \\
\text{set}_{\text{id}}(v)
\]

**Rule 202. Setter channel**

\[
\text{set}(c : \text{Clock}) : \text{CSPChannel} = \\
\text{clockReset}_{\text{id}}(c)
\]
Chapter C. \textit{tock} and \textit{share}-CSP

Rule 203. Setter channels
\[
\text{setC}(\text{ns} : \text{Set}(\text{NamedElement})) : \text{CSPChannelSet} = \\
\{ \langle \text{n} : \text{ns} \cdot \text{set}^0(\text{n}) \rangle \}
\]

Rule 204. Left setter channel
\[
\text{setL}(v : \text{Variable}) : \text{CSPChannel} = \\
\text{setL}_{\text{id}}(v)
\]

Rule 205. Left setter channel
\[
\text{setL}(c : \text{Clock}) : \text{CSPChannel} = \\
\text{clockResetL}_{\text{id}}(c)
\]

Rule 206. Left setter channels
\[
\text{setLC}(\text{ns} : \text{Set}(\text{NamedElement})) : \text{CSPChannelSet} = \\
\{ \langle \text{n} : \text{ns} \cdot \text{set}^4(\text{n}) \rangle \}
\]

Rule 207. Right setter channel
\[
\text{setR}(v : \text{Variable}) : \text{CSPChannel} = \\
\text{setR}_{\text{id}}(v)
\]

Rule 208. Right setter channel
\[
\text{setR}(c : \text{Clock}) : \text{CSPChannel} = \\
\text{clockResetR}_{\text{id}}(c)
\]

Rule 209. Right setter channels
\[
\text{setRC}(\text{ns} : \text{Set}(\text{NamedElement})) : \text{CSPChannelSet} = \\
\{ \langle \text{n} : \text{ns} \cdot \text{set}^4(\text{n}) \rangle \}
This section presents the functions of the Z mathematical toolkit as modelled in RoboChart.

A package named \texttt{core} contains a number of primitive types and is imported by default in every RoboChart model. They are shown in Table 4.1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural numbers</td>
<td>nat</td>
</tr>
<tr>
<td>Integers</td>
<td>int</td>
</tr>
<tr>
<td>Strings</td>
<td>string</td>
</tr>
<tr>
<td>Booleans</td>
<td>boolean</td>
</tr>
<tr>
<td>Real numbers</td>
<td>real</td>
</tr>
</tbody>
</table>

\textbf{Table 4.1: Primitive types in \texttt{core} package.}

The functions are grouped in the set, relation, function, and sequence toolkits.
### Mathematical Toolkit

**package set_toolkit**

<table>
<thead>
<tr>
<th>Function</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>notin(m: ?X, s: Set(?X)): boolean</code></td>
<td>[\text{result} \Leftrightarrow \text{not } m \in s]</td>
</tr>
<tr>
<td><code>Union(A: Set(Set(?X))): Set(?X)</code></td>
<td>[\text{result} = { x: ?X</td>
</tr>
<tr>
<td><code>Inter(A: Set(Set(?X))): Set(?X)</code></td>
<td>[\text{result} = { x: ?X</td>
</tr>
<tr>
<td><code>diff(s1: Set(?X), s2: Set(?X)): Set(?X)</code></td>
<td>[\text{result} = { x: ?X \mid x \in s1 \setminus \text{not } x \in s2 }]</td>
</tr>
<tr>
<td><code>symetric_diff(s1: Set(?X), s2: Set(?X)): Set(?X)</code></td>
<td>[\text{result} = { x: ?X \mid \text{not } (x \in s1 \Leftrightarrow x \in s2) }]</td>
</tr>
<tr>
<td><code>subseteq(ss: Set(?X), s: Set(?X)): boolean</code></td>
<td>[\text{result} \Leftrightarrow (\text{forall } x: ?X \mid x \in s)]</td>
</tr>
<tr>
<td><code>subset(ss: Set(?X), s: Set(?X)): boolean</code></td>
<td>[\text{result} \Leftrightarrow \text{subseteq}(ss, s) \setminus ss! = s]</td>
</tr>
<tr>
<td><code>union(s1: Set(?X), s2: Set(?X)): Set(?X)</code></td>
<td>[\text{result} = { x: ?X \mid x \in s1 \setminus \text{in } s2 }]</td>
</tr>
<tr>
<td><code>inter(s1: Set(?X), s2: Set(?X)): Set(?X)</code></td>
<td>[\text{result} = { x: ?X \mid x \in s1 \setminus x \in s2 }]</td>
</tr>
<tr>
<td>Function</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>$f_x$ tr_closure(r: ?X&lt;&gt;=&gt;?X): ?X&lt;&gt;=&gt;?X</td>
<td>$\text{result} = \text{Inter}({ s: ?X&lt;&gt;=&gt;?X</td>
</tr>
<tr>
<td>$f_x$ dom(r: ?X&lt;&gt;=&gt;?Y): Set(?X)</td>
<td>$\text{result} = { p: ?X*?Y</td>
</tr>
<tr>
<td>$f_x$ dres(a: Set(?X), r: ?X&lt;&gt;=&gt;?Y): ?X&lt;&gt;=&gt;?Y</td>
<td>$\text{result} = { p: ?X*?Y</td>
</tr>
<tr>
<td>$f_x$ rimage(r: ?X&lt;&gt;=&gt;?Y, a: Set(?X)): Set(?Y)</td>
<td>$\text{result} = { p: ?X*?Y</td>
</tr>
<tr>
<td>$f_x$ override(r: ?X&lt;&gt;=&gt;?Y, s: ?X&lt;&gt;=&gt;?Y): ?X&lt;&gt;=&gt;?Y</td>
<td>$\text{result} = \text{union}(\text{dsup}(\text{dom}(s), r), s)$</td>
</tr>
<tr>
<td>$f_x$ first(p: ?X*:?Y): ?X</td>
<td>$\text{result} = p[1]$</td>
</tr>
<tr>
<td>$f_x$ rinv(r: ?X&lt;&gt;=&gt;?Y): ?Y&lt;&gt;=&gt;?X</td>
<td>$\text{result} = { p: ?X*?Y</td>
</tr>
<tr>
<td>$f_x$ refl_tr_closure(r: ?X&lt;&gt;=&gt;?X): ?X&lt;&gt;=&gt;?X</td>
<td>$\text{result} = \text{union}(\text{tr_closure}(r), \text{id}(0))$</td>
</tr>
<tr>
<td>$f_x$ second(p: ?X*:?Y): ?Y</td>
<td>$\text{result} = p[2]$</td>
</tr>
<tr>
<td>$f_x$ rres(r: ?X&lt;&gt;=&gt;?Y, b: Set(?Y)): ?X&lt;&gt;=&gt;?Y</td>
<td>$\text{result} = { p: ?X*?Y</td>
</tr>
<tr>
<td>$f_x$ dsub(a: Set(?X), r: ?X&lt;&gt;=&gt;?Y): ?X&lt;&gt;=&gt;?Y</td>
<td>$\text{result} = { p: ?X*?Y</td>
</tr>
<tr>
<td>$f_x$ maplet(x: ?X, y: ?Y): ?X*?Y</td>
<td>$\text{result} = (x, y)$</td>
</tr>
<tr>
<td>$f_x$ ran(r: ?X&lt;&gt;=&gt;?Y): Set(?Y)</td>
<td>$\text{result} = { p: ?X*?Y</td>
</tr>
<tr>
<td>$f_x$ id(): ?X&lt;&gt;=&gt;?X</td>
<td>$\text{result} = { x: ?X</td>
</tr>
<tr>
<td>$f_x$ rsub(r: ?X&lt;&gt;=&gt;?Y, b: Set(?Y)): ?X&lt;&gt;=&gt;?Y</td>
<td>$\text{result} = { p: ?X*?Y</td>
</tr>
<tr>
<td>Package</td>
<td>Function</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>sequence_toolkit</td>
<td><code>dconcat(s: Seq(Seq(T))): Seq(T)</code></td>
</tr>
<tr>
<td></td>
<td>`result::= if size(s)==0 then &lt;&gt; else the: Seq(T)</td>
</tr>
<tr>
<td></td>
<td><code>result::= if n==0 then id() else if n&gt;0 then reccomp(r, iter(n-1, n)) else iter(-n, rinv(r)) end end</code></td>
</tr>
<tr>
<td></td>
<td><code>size(a: Set(T)): nat</code></td>
</tr>
<tr>
<td></td>
<td><code>isFinite(a)</code></td>
</tr>
<tr>
<td></td>
<td>`result::= (the n: nat</td>
</tr>
<tr>
<td></td>
<td><code>squash(f: int-&gt;?X): Seq(?X)</code></td>
</tr>
<tr>
<td></td>
<td>`result::= (p: int*?X</td>
</tr>
<tr>
<td></td>
<td><code>concat(s: Seq(?X), t: Seq(?X)): Seq(?X)</code></td>
</tr>
<tr>
<td></td>
<td>`result::= union(s, n: int</td>
</tr>
<tr>
<td></td>
<td><code>infix(s: Seq(?X), t: Seq(?X)): boolean</code></td>
</tr>
<tr>
<td></td>
<td><code>result::= (exists u: Seq(?X), v: Seq(?X) @ concat(u, concat(s, v))==t)</code></td>
</tr>
<tr>
<td></td>
<td><code>hasMax(a: Set(int)): boolean</code></td>
</tr>
<tr>
<td></td>
<td>`result::= (exists m: int</td>
</tr>
<tr>
<td></td>
<td><code>hasMin(a: Set(int)): boolean</code></td>
</tr>
<tr>
<td></td>
<td>`result::= (exists m: int</td>
</tr>
<tr>
<td></td>
<td><code>tail(s: Seq(TX)): Seq(TX)</code></td>
</tr>
<tr>
<td></td>
<td>`result::= (lambda n: nat</td>
</tr>
<tr>
<td></td>
<td><code>min(a: Set(int)): int</code></td>
</tr>
<tr>
<td></td>
<td>`result::= a @ (forall n: int</td>
</tr>
<tr>
<td></td>
<td><code>head(s: Seq(?X)): ?X</code></td>
</tr>
<tr>
<td></td>
<td><code>result::= s[1]</code></td>
</tr>
<tr>
<td></td>
<td><code>last(s: Seq(?X)): ?X</code></td>
</tr>
<tr>
<td></td>
<td><code>result::= s[size(s)]</code></td>
</tr>
<tr>
<td></td>
<td><code>isInjectiveSequence(s: Seq(?X)): boolean</code></td>
</tr>
<tr>
<td></td>
<td><code>result::= isInjection(s)</code></td>
</tr>
</tbody>
</table>
import robochart : 'robochart.ecore'
import 'http://www.eclipse.org/emf/2002/Ecore'

package robochart

-- Robotic Platforms well-formedness conditions (RoboChart reference 3.1.1)
context RoboticPlatformDef
-- We note that variables and operations declared directly in the
   platform,
-- outside an interface, are considered as if declared in a provided
-- interface, for the reasons already explained above. Events declared
-- directly in the platform, on the other hand, are defined.
def: rpProvidedVars() : Bag(Variable) =
   self.pInterfaces.variableList.vars->union(self.variableList.vars)
def: rpProvidedOps() : Bag(OperationSig) = self.pInterfaces.operations->
   union(self.operations)
def: rpDefinedEvents() : Bag(Event) = self.interfaces.events->union(self.
   events)

-- RP1: Robotic platforms cannot require interfaces
inv RP1: self.interfaces->isEmpty()
-- RP2: Defined interfaces can only have events
inv RP2: self.interfaces->forall(i |
   i.variableList->isEmpty() and i.operations->isEmpty())

-- RP3: The names of variables, operations, and events are unique to the
   platform
inv RP3: self->collect(c | c.interfaces->union(c.rInterfaces)->union(c.
   pInterfaces))
Chapter E. OCL Well-formedness Conditions

\[
\text{variableList} \rightarrow \text{union}(\text{self. variableList}). \text{vars. name} \\
\rightarrow \text{union}(\text{self} \rightarrow \text{collect}(c \mid c. \text{interfaces} \rightarrow \text{union}(c. \text{pInterfaces})) \\
\rightarrow \text{union}(\text{self. operations}). \text{name} \\
\rightarrow \text{union}(\text{self. events}). \text{name}) \rightarrow \text{isUnique}(i \mid i)
\]

-- Interfaces well-formedness conditions (RoboChart reference 3.1.2)
context Interface

inv II: Context.allInstances() \rightarrow \text{collect}(c \mid c. \text{pInterfaces} \rightarrow \text{union}(c. \text{pInterfaces})) \rightarrow \text{includes}(\text{self}) \\
\text{implies self.events} \rightarrow \text{isEmpty}()

-- I2: Defined interfaces contain only variables and events
inv I2: Context.allInstances(). \text{interfaces} \rightarrow \text{includes}(\text{self}) \\
\text{implies self.operations} \rightarrow \text{isEmpty}()

-- I3: Names of variables, events and operations are unique
inv I3: self. variableList. \text{vars. name} \\
\rightarrow \text{union}(\text{self. operations} \rightarrow \text{asBag()}. \text{name}) \\
\rightarrow \text{union}(\text{self. events} \rightarrow \text{asBag()}. \text{name}) \rightarrow \text{isUnique}(i \mid i)

-- Modules well-formedness conditions (RoboChart reference 3.1.3)
context RModule

def: moduleControllers() : Set(\text{Controller}) = 
\text{self.nodes} \rightarrow \text{selectByKind}(\text{Controller})

def: moduleRP () : RoboticPlatform = 
\text{self.nodes} \rightarrow \text{selectByKind}(\text{RoboticPlatform}) \rightarrow \text{any}(true)

-- M1: A module must contain exactly one robotic platform, at least one controller, and not state machines
inv M1: self. nodes \rightarrow \text{selectByKind}(\text{RoboticPlatform}) \rightarrow \text{one}(true) \\
\text{and self.nodes} \rightarrow \text{selectByKind}(\text{Controller}) \rightarrow \text{exists}(true) \\
\text{and self.nodes} \rightarrow \text{selectByKind}(\text{StateMachine}) \rightarrow \text{isEmpty}()

-- M2: All variables and operations required by the module's controllers must be provided by the platform
inv M2: self. nodes \rightarrow \text{selectByKind}(\text{RoboticPlatform}) \rightarrow \text{exists}(true) \text{ implies} \\
(\text{self.moduleRP(). rpDef(). rpProvidedVars()}) \\
\rightarrow \text{includesAll}(\text{self.moduleControllers(). controllerDef(). controllerRequiredVars()})
\text{and self.moduleRP(). rpDef(). rpProvidedOps()}) \\
\rightarrow \text{includesAll}(\text{self.moduleControllers(). controllerDef(). controllerRequiredOps()})

-- M3: Each event on the robotic platform and controllers of a module must have at most one connection to or from it within the module
inv M3: self. nodes \rightarrow \text{selectByKind}(\text{RoboticPlatform}) \rightarrow \text{exists}(true) \text{ implies} \\
\text{self.moduleRP(). rpDef(). rpDefinedEvents()}

forAll(e | self.connections->select(c | c.efrom = e or c.etoo = e)->size() <= 1)
and self.moduleControllers().controllerDef().controllerDefinedEvents()
forAll(e | self.connections->select(c | c.efrom = e or c.etoo = e)->size() <= 1)

-- Connection well-formedness conditions (RoboChart reference 3.1.4)
context Connection
-- Cn1: Connections of a module must associate only events of the robotic platform and its controllers
inv Cn1: RCModule.allInstances()->select(m | m.connections->includes(self))
  ->forall(m | m.nodes->includes(self.from) and m.nodes->includes(self.to))
-- Cn2: Connections involving a robotic platform are always asynchronous
inv Cn2: (self.from.oclsIsKindOf(RoboticPlatform) or self.to.oclsIsKindOf(RoboticPlatform))
  implies self.async
-- Cn3: Connections of a controller must associate only its events and those of its state machines
inv Cn3: ControllerDef.allInstances()->select(c | c.connections->includes(self))
  ->forall(c | c.machines->including(c)->includes(self.from)
    and c.machines->including(c)->includes(self.to))
-- Cn4: Only events of the same type may be connected
-- NOTE: this requires and equality operator on RoboChart types
-- Cn5: Bidirectional connections of a module may only involve events of a controller which are connected by bidirectional connections within the controller
inv Cn5: (self.bidirec and RCModule.allInstances())->exists(m | m.connections->includes(self))
  implies (self.from.oclsIsKindOf(Controller)
    implies self.from.oclsAsType(Controller).controllerDef().connections
      ->select(c | (c.from = self.from and c.efrom = self.efrom)
        or (c.to = self.from and c.etoo = self.etoo))
      ->forall(c | c.bidirec))
and (self.to.oclsIsKindOf(Controller)
  implies self.to.oclsAsType(Controller).controllerDef().connections
    ->select(c | (c.from = self.to and c.efrom = self.etoo)
      or (c.to = self.to and c.etoo = self.etoo))
    ->forall(c | c.bidirec))
)-- Cn6: Non-bidirectional connections of a module may only connect to events of a controller which have a non-bidirectional connection from them within the controller
inv Cn6: (not self.bidirec
  and RCModule.allInstances())->exists(m | m.connections->includes(self))
Chapter E. OCL Well-formedness Conditions

and self.tooclIsKindOf(Controller)
) implies self.tooclAsType(Controller).controllerDef().connections
  ->select(c | (c.from = self.to and c.efrom = self.eto)
      or (c.to = self.to and c.eto = self.eto))
  ->forall(c | not c.bidirec and c.from = self.to)
-- Cn7: Non-bidirectional connections of a module may only connect from
-- events of a controller which have a non-bidirectional connection to
-- them within the controller
inv Cn7: (not self.bidirec
and RCModule.allInstances()->exists(m | m.connections->includes(self))
and self.fromoclIsKindOf(Controller)
) implies self.fromoclAsType(Controller).controllerDef().connections
  ->select(c | (c.from = self.from and c.efrom = self.efrom)
      or (c.to = self.from and c.eto = self.efrom))
  ->forall(c | not c.bidirec and c.to = self.from)
-- Cn8: Non-bidirectional connections of a controller must not connect to
-- events that a state machine uses as an output.
inv Cn8: (not self.bidirec
and ControllerDef.allInstances()->exists(c | c.connections->includes(self))
and self.tooclIsKindOf(StateMachine)
) implies self.tooclAsType(StateMachine).stmDef().ncOutputEvents() ->
excludes(self.eto)
-- Cn9: Non-bidirectional connections of a controller must not connect
-- from events that a state machine uses as an input
inv Cn9: (not self.bidirec
and ControllerDef.allInstances()->exists(c | c.connections->includes(self))
and self.fromoclIsKindOf(StateMachine)
) implies self.fromoclAsType(StateMachine).stmDef().ncInputEvents() ->
excludes(self.efrom)

-- Controllers well-formedness conditions (RoboChart reference 3.1.5)
context ControllerDef
-- Variables and events declared directly in the controller are
considered
-- as part of a defined interface.
def: controllerDefinedVars() : Bag(Variable) =
  self.interfaces.variableList.vars->union(self.variableList.vars)
def: controllerDefinedEvents() : Bag(Event) = self.interfaces.events->
  union(self.events)
def: controllerRequiredVars() : Bag(Variable) = self.rInterfaces.
  variableList.vars
def: controllerRequiredOps() : Bag(OperationSig) = self.rInterfaces.
  operations

-- C1: A controller must contain at least one state machine
inv C1: self.machines->exists(true)
-- C2: Controllers cannot provide variables or operations to other
controllers

inv C2: self.pInterfaces->collect(i | i.variableList.vars->union(i.operations))->isEmpty()
-- C3: all variables required by the controller's state-machines must be defined or required by the controller
inv C3: self.controllerRequiredVars()->union(self.controllerDefinedVars())
  -->includesAll(self.machines.stmDef().stmRequiredVars())
-- C4: all operations required by the controller's state-machines must be required or defined by the controller
inv C4: self.controllerRequiredOps()->union(self.1Operations)
  -->includesAll(self.machines.stmDef().stmRequiredOps())
-- C5: The names of variables, operations, and events are unique to the controller
-- operations declared directly in the controller are ruled out by C7
inv C6: self->collect(c | c.interfaces->union(c.rInterfaces)->union(c.pInterfaces))
  .variableList->union(self.variableList).vars.name
  ->union(self->collect(c | c.interfaces->union(c.rInterfaces)->union(c.pInterfaces))
  .operations->union(self.1Operations).name)
  ->union(self->collect(c | c.interfaces->union(c.rInterfaces)->union(c.pInterfaces))
  .events->union(self.events).name)->isUnique(i | i)
-- C6: Each event on state machines and boundary of a controller must have at most one connection to or from within the controller
inv C6: self.machines->forAll(m | m.stmDef().stmDefinedEvents())->forAll(e | self.connections
  -->select(c | (c.from = m and c.efrom = e) or (c.to = m and c.eto = e))
  -->size() <= 1)
  ) and self.controllerDefinedEvents()->forAll(e | self.connections
  -->select(c | (c.from = self and c.efrom = e) or (c.to = self and c.eto = e))->size() <= 1)
-- C7: Operations must not be declared directly in a controller, but may be defined in the controller
inv C7: self.operations->isEmpty()

-- State Machines well-formedness conditions (RoboChart reference 3.1.6)
context StateMachineDef
def: stmDefinedVars() : Bag(Variable) =
  self.interfaces.variableList.vars->union(self.variableList.vars)
def: stmDefinedEvents() : Bag(Event) = self.interfaces.events->union(self.events)
def: stmRequiredVars() : Bag(Variable) = self.rInterfaces.variableList.vars
def: stmRequiredOps() : Bag(OperationSig) = self.rInterfaces.operations

-- STM1: State machines cannot have provided interfaces
Chapter E. OCL Well-formedness Conditions

inv STM1: self.pInterfaces ->isEmpty()
-- STM2: Operations in state machines can only be required, not defined
-- i.e. operations must not be declared directly in the state machine (defined interfaces can’t have operations anyway by I2)
inv STM2: self.operations ->isEmpty()
-- STM3: Every state machine must have exactly one initial junction
inv STM3: self.nodes ->selectByKind(Initial) ->one(true)
-- STM4: State machines must contain at least one state
inv STM4: self.nodes ->selectByKind(State) ->exists(true)
-- STM5: The names of variables, operations, and events are unique to the machine
inv STM5: self ->collect(c | c.interfaces ->union(c.rInterfaces) ->union(c.pInterfaces))
  .variableList ->union(self.variableList).vars.name
  ->union(self ->collect(c | c.interfaces ->union(c.rInterfaces) ->union(c.pInterfaces))
  .operations .name)
  ->union(self ->collect(c | c.interfaces ->union(c.rInterfaces) ->union(c.pInterfaces))
  .events ->union(self.events).name) ->isUnique(i | i)
-- STM6: State machines must not have operations declared directly within them
inv STM6: self.operations ->isEmpty()

-- States well-formedness conditions (RoboChart reference 3.1.7)
context State
-- S1: If a state has a non-empty set of nodes, then conditions STM3 and STM4 apply
inv S1: self.nodes ->notEmpty() implies
  self.nodes ->selectByKind(Initial) ->one(true)
  and self.nodes ->selectByKind(State) ->exists(true)
-- S2: A state has at most one of each type of action: entry, during, and exit
inv S2: self.actions ->selectByKind(EntryAction) ->size() <= 1
  and self.actions ->selectByKind(DuringAction) ->size() <= 1
  and self.actions ->selectByKind(ExitAction) ->size() <= 1

-- Initial Junctions well-formedness conditions (RoboChart reference 3.1.8)
context Initial
-- IJ1: An initial junction does not have incoming transitions
inv IJ1: NodeContainer.allInstances() ->select(nc | nc.nodes ->includes(self)).transitions
  ->select(t | t.target = self) ->isEmpty()
-- IJ2: An initial junction must have exactly one outgoing transition
inv IJ2: NodeContainer.allInstances() ->select(nc | nc.nodes ->includes(self)).transitions
  ->one(t | t.source = self)
-- IJ3: All junction conditions apply
-- this is implicit since Initial inherits from Junction

-- Junction well-formedness conditions (RoboChart reference 3.1.9)
context Junction
   -- J1: A junction must contain at least one outgoing transition
   inv J1: NodeContainer.allInstances() -> select(nc | nc.nodes -> includes(self)) . transitions
     -> exists(t | t.source = self)
   -- J2: The guards of the transitions out of a junction must form a cover
   -- NOTE: cannot be checked in general, but does not prevent generation of semantics
   inv J2: NodeContainer.allInstances() -> select(nc | nc.nodes -> includes(self)) . transitions
     -> select(t | t.source = self) . condition
   -- J3: Transitions starting in junctions cannot have triggers
   inv J3: NodeContainer.allInstances() -> select(nc | nc.nodes -> includes(self)) . transitions
     -> select(t | t.source = self) -> forall(t | t.trigger = null or t.trigger._type = TriggerType::EMPTY)

-- Final states well-formedness conditions (RoboChart reference 3.1.10)
context Final
   -- FS1: Final states cannot be the source of transitions
   inv FS1: NodeContainer.allInstances() -> select(nc | nc.nodes -> includes(self)) . transitions
     -> select(t | t.source = self) -> isEmpty()

-- Triggers well-formedness conditions (RoboChart reference 3.1.11)
context Trigger
   -- Tg1: A trigger of type SIMPLE has neither the parameter attribute nor the value attribute set. This is a pure synchronisations and does not involve exchange of values
   inv Tg1: self._type = TriggerType::SIMPLE implies (self.parameter = null and self.value = null)
   -- Tg2: A trigger of type SIMPLE must use a typeless event. This is a pure synchronisations and does not involve exchange of values
   inv Tg2: self._type = TriggerType::SIMPLE implies (self.event <> null and self.event.type = null)
   -- Tg3: A trigger of type INPUT must have a parameter attribute and cannot have its value attribute set
   inv Tg3: self._type = TriggerType::INPUT implies (self.parameter <> null and self.value = null)
   -- Tg4: A trigger of type OUTPUT or SYNC must have a value attribute and cannot have its parameter attribute set
   inv Tg4: (self._type = TriggerType::OUTPUT or self._type = TriggerType::SYNC)
     implies (self.value <> null and self.parameter = null)
-- Tg5: A trigger of type empty must not have its attributes event, parameter and value set
inv Tg5: self._type = TriggerType::EMPTY
   implies (self.event = null and self.parameter = null and self.value = null)

-- Transitions well-formedness conditions (RoboChart reference 3.1.12)
context Transition
-- T1: The source and target of a transition must belong to the same container
inv T1: NodeContainer.allInstances()
   ->one(nc | nc.nodes->includes(self.source) and nc.nodes->includes(self.target))
-- T2: If a transition has a trigger, it must be of type INPUT or SIMPLE
inv T2: self.trigger <> null
   implies (self.trigger._type = TriggerType::INPUT
     or self.trigger._type = TriggerType::SIMPLE
     or self.trigger._type = TriggerType::EMPTY
   )

-- Operations well-formedness conditions (RoboChart reference 3.1.13)
context OperationDef
-- O1: All state-machine conditions apply to operation definitions
inv O1:
   -- STM1: State machines cannot have provided interfaces
   self.pInterfaces->isEmpty()
   -- STM2: Operations in state machines can only be required, not defined
   -- i.e. operations must not be declared directly in the state machine (defined interfaces can't have operations anyway by I2)
   and self.operations->isEmpty()
   -- STM3: Every state machine must have exactly one initial junction
   and self.nodes->selectByKind(Initial)->one(true)
   -- STM4: State machines must contain at least one state
   and self.nodes->selectByKind(State)->exists(true)
   -- STM5: The names of variables, operations, and events are unique to the machine
   and self->collect(c | c.interfaces->union(c.rInterfaces)->union(c.pInterfaces))
      .variableList->union(self.variableList).vars->isUnique(i | i)
   and self->collect(c | c.interfaces->union(c.rInterfaces)->union(c.pInterfaces))
      .operations->isUnique(i | i)
   and self->collect(c | c.interfaces->union(c.rInterfaces)->union(c.pInterfaces))
      .events->union(self.events)->isUnique(i | i)
   -- STM6: State machines must not have operations declared directly within them
   and self.operations->isEmpty()
Variables well-formedness conditions (RoboChart reference 3.1.14)

context Variable
-- V1: If the initial value of a required variable or constant of a state machine or controller is defined, it must be consistent with the initial value of any (complementing) variable provided or required by the contexts (controllers or modules) where the state machine or controller is used.
-- NOTE: This requires expression evaluation in order to be properly defined.

Expressions well-formedness conditions (RoboChart reference 3.1.15)
-- E1: The variables declared in a set comprehension must not have initial values
context SetComp
inv E1: self.variables ->forall(v | v.initial = null)
-- E2: Quantified variables in existential and universal quantifications must not have initial values
context QuantifierExpression
inv E2: self.variables ->forall(v | v.initial = null)
-- E3: The variables quantified in a lambda expression must not have initial values
context LambdaExp
inv E3: self.variables ->forall(v | v.initial = null)

Timed Expressions well-formedness conditions (RoboChart reference 3.2.1)
-- TE1: Expressions involving since(C) and sinceEntry(S) are only permitted in transition guards
-- corresponds to CE1 and SCE1 below
-- TE2: The clock C in an expression since(C) may only reference a clock declared within the expression's containing state-machine
-- corresponds to CE3 below
-- TE3: The state S in an expression sinceEntry(S) may only reference a state within the containing expression's state-machine. When the name S is ambiguous, because, for instance, there is a state and a substate with the same name in the state machine, the fully qualified name of the state S must be used.
-- corresponds to SCE3 below
-- TE4: The expressions since(C) or sinceEntry(S) may only occur in a comparison expression in which the other branch is a constant
-- corresponds to CE2 and SCE2 below

Clock expression well-formedness conditions
context ClockExp
-- CE1: An expression since(C) may only occur as part of a transition guard
inv CE1: self.parentIsTransition()
-- CE2: An expression since(C) may only occur in a branch of a comparison expression in which the other branch is an integer or float expression

inv CE2: Expression::ComparisonExpression() -> exists(comp | (comp.left = self
and (comp.rightoclIsKindOf(IntegerExp) or comp.rightoclIsKindOf(FloatExp))
or (comp.right = self
and (comp.leftoclIsKindOf(IntegerExp) or comp.leftoclIsKindOf(FloatExp))
))

-- CE3: The clock C in an expression since(C) may only reference a clock declared within the expression’s containing state-machine

inv CE3: self.parentIsTransition() implies self.parentTransition().containingStateMachine().clocks->includes(self.clock)

-- State Clock expression well-formedness conditions
context StateClockExp

-- SCE1: An expression sinceEntry(S) may only occur as part of a transition guard

inv SCE1: self.parentIsTransition()

-- SCE2: An expression sinceEntry(S) may only occur in a branch of a comparison expression in which the other branch is an integer or float expression

inv SCE2: ComparisonExpression() -> exists(comp | (comp.left = self
and (comp.rightoclIsKindOf(IntegerExp) or comp.rightoclIsKindOf(FloatExp))
or (comp.right = self
and (comp.leftoclIsKindOf(IntegerExp) or comp.leftoclIsKindOf(FloatExp))
))

-- SCE3: The state S in an expression sinceEntry(S) may only reference a state within the containing expression’s state-machine. When the name S is ambiguous, because, for instance, there is a state and a substate with the same name in the state machine, the fully qualified name of the state S must be used.

-- the state is referenced, not named in the metamodel, so the well-formedness conditions here are not concerned with resolving the ambiguity

inv SCE3: self.parentIsTransition() implies self.parentTransition().containingStateMachine().nestedStates() -> includes(self.state)

-- Timed Statements well-formedness conditions (RoboChart reference 3.2.2)
context ClockReset

-- TS1: A clock reset #C may only reference a clock declared within the action’s containing state-machine, or in the case of a trigger,
within the trigger's containing state-machine
inv TSI1: self.containingStateMachine().clocks->includes(self.clock)

-- Auxiliary definitions

-- function to extract RoboticPlatformDef from a RoboticPlatform (which may be a ref)
context RoboticPlatform
def: rpDef(): RoboticPlatformDef =
  if selfoclIsKindOf(RoboticPlatformDef) then
    selfoclAsType(RoboticPlatformDef)
  else
    selfoclAsType(RoboticPlatformRef).ref
  endif

-- function to extract ControllerDef from a Controller (which may be a ref)
context Controller
def: controllerDef() : ControllerDef =
  if selfoclIsKindOf(ControllerDef) then
    selfoclAsType(ControllerDef)
  else
    selfoclAsType(ControllerRef).ref
  endif

-- function to extract StateMachineDef from a StateMachine (which may be a ref)
context StateMachine
def: stmDef(): StateMachineDef =
  if selfoclIsKindOf(StateMachineDef) then
    selfoclAsType(StateMachineDef)
  else
    selfoclAsType(StateMachineRef).ref
  endif

-- functions to get input and output events of a node container
-- (An event is considered to be an output if it is used in an OUTPUT or SYN trigger.
-- or if it is used in an OUTPUT, SYN or SIMPLE send statement.)
-- (An event is considered to be an input if it is used in an INPUT or SIMPLE trigger.
-- or if it is used in an INPUT send statement.)
context NodeContainer
def: ncInputEvents(): Bag(Event) =
  self.transitions->select(t | t.trigger <> null and
    (t.trigger..type = TriggerType::INPUT or t.trigger..type = TriggerType::SIMPLE)
  ).trigger.event
  ->union(self.transitions->select(t | t.action <> null).action.
    statementInputEvents())
  ->union(self.nodes->selectByKind(NodeContainer).ncInputEvents())
  ->union(self.nodes->selectByKind(State).actions.action.
Chapter E. OCL Well-formedness Conditions

```plaintext
statementInputEvents()
def: ncOutputEvents() : Bag(Event) =
  self.transitions->select(t | t.trigger <> null and
    (t.trigger._type = TriggerType::OUTPUT or t.trigger._type =
      TriggerType::SYNC)
  ).trigger.event
->union(self.transitions->select(t | t.action <> null).action.
  statementOutputEvents())
->union(self.nodes->selectByKind(NodeContainer).ncOutputEvents())
->union(self.nodes->selectByKind(State).actions.action.
  statementOutputEvents())

context Statement
def: statementInputEvents() : Bag(Event) = Bag{}
def: statementOutputEvents() : Bag(Event) = Bag{}

context SendEvent
def: statementInputEvents() : Bag(Event) =
  Set{self.trigger}->select(t | t._type = TriggerType::INPUT).event
def: statementOutputEvents() : Bag(Event) =
  Set{self.trigger}->select(t | Set{TriggerType::OUTPUT, TriggerType::
    SYNC, TriggerType::SIMPLE}->includes(t._type)).event

context SeqStatement
def: statementInputEvents() : Bag(Event) =
  self.statements.statamentInputEvents() asBag()
def: statementOutputEvents() : Bag(Event) =
  self.statements.statamentOutputEvents() asBag()

context IfStmt
def: statementInputEvents() : Bag(Event) =
  self._'then'.statementInputEvents() ->union(self._'else'.
    statementInputEvents())
def: statementOutputEvents() : Bag(Event) =
  self._'then'.statementOutputEvents() ->union(self._'else'.
    statementOutputEvents())
```

```
-- functions on expressions to support timed expressions well-formedness
  conditions

context Expression
def: parentIsTransition() : Boolean =
  if selfoclContainer().oclIsKindOf(Expression) then
    selfoclContainer().oclAsType(Expression).parentIsTransition()
  else
    Transition.allInstances()->exists(t | t.condition = self)
  endif
def: parentTransition() : Transition =
  if selfoclContainer().oclIsKindOf(Expression) then
    selfoclContainer().oclAsType(Expression).parentTransition()
  else
    selfoclContainer().oclAsType(Transition)
  endif
def: ComparisonExpression() : Set(BinaryExpression) =
```
BinaryExpression.allInstances()->select(x |
  xoclIsKindOf(Equals) or xoclIsKindOf(Different)
  or xoclIsKindOf(GreaterThan) or xoclIsKindOf(LessThan)
  or xoclIsKindOf(GreaterOrEqual) or xoclIsKindOf(LessThanOrEqual)
)

-- function to obtain all states nested within a node container
context NodeContainer
def: nestedStates() : Bag(State) =
  self.nodes->selectByKind(State)->union(self.nodes->selectByKind(State).
    nestedStates())

-- functions to find the containing state machine for various
-- constructs.
-- particularly ClockReset to define the timed statement well-
-- formedness conditions
context NodeContainer
def: containingStateMachine() : StateMachineBody =
  if selfoclIsKindOf(StateMachineBody) then
    selfoclAsType(StateMachineBody)
  else
    selfoclContainer().oclAsType(NodeContainer).containingStateMachine()
  endif
def: containingStateMachine() : StateMachineBody =
  selfoclContainer().oclAsType(NodeContainer).containingStateMachine()
def: containingStateMachine() : StateMachineBody =
  selfoclContainer().oclAsType(State).containingStateMachine()
def: containingStateMachine() : StateMachineBody =
  if selfoclIsKindOf(Action) then
    selfoclContainer().oclAsType(Action).containingStateMachine()
  elseif selfoclIsKindOf(Transition) then
    selfoclContainer().oclAsType(Transition).containingStateMachine()
  else
    selfoclContainer().oclAsType(Statement).containingStateMachine()
  endif
def: containingStateMachine() : StateMachineBody =
  if selfoclIsKindOf(Transition) then
    selfoclContainer().oclAsType(Transition).containingStateMachine()
  else
    selfoclContainer().oclAsType(Statement).containingStateMachine()
  endif
def: containingStateMachine() : StateMachineBody =
  if selfoclIsKindOf(Trigger) then
    selfoclContainer().oclAsType(Trigger).containingStateMachine()
  else
    selfoclContainer().oclIsKindOf(Trigger) then

  endif
selfoclContainer().oclAsType(Trigger).containingStateMachine() else
    selfoclContainer().oclAsType(Statement).containingStateMachine() endif

depackage
**Credits**

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In this index you’ll find the list of semantic functions in alphabetic order, and page where they are defined. Timed versions of existig semantic rules are indexed by a timed item under the entry for the semantic function. Semantic functions exclusive to the timed model are identified by a timed annotation in parenthesis after the rule name. Rules whose names are abbreviation (e.g., S) are annotated with the full name in parenthesis.

A (Statement)
  prob prism, 88
Action, 56
actionTargetOfTran
  prob prism, 84
addLoopStateTrans
  prob norm, 74
allConstants, 37
allEvents, 36
allLocalConstants, 37
allLocalVariables, 37
allVariables, 37
andExprs
  prob prism, 106
AST (Statement)
  prob prism, 88
asyncConnectedEvent
  prob prism, 93
asyncConnectedEvents
  prob prism, 92
BBuffer (collection), 137
buffer, 39
  prob prism, 96
C (Controller), 40, 57
C (ControllerDef)
  prob prism, 77
callOpdef ()
  (prob prism), 103
callOpNondeter ()
  (prob prism), 103
Cl n (collection, collection), 136
clock(Clock), 62
clock(NamedElement), 62
INDEX OF SEMANTIC RULES

clock(State), 62
clockResets, 61
clocks(NamedElements)
  Timed, 62
combTransJunction
  probnorm, 75
combTransJunctions
  probnorm, 74
composeControllers, 38
composeMachines, 41
composeNodes, 50
composeTimedNodes, 59
Constant (Variable), 45
constantsOfNamedElems
  probprism, 82
cstInit, 38
cstMemory (Context), 44
CS (NodeContainer)
  probnorm, 73
ctrlMemory, 41

EmptyEvent ()
  probprism, 99
enterSubstate
  probprism, 82
enterSubstates
  probprism, 81
enumValuesInType
  probprism, 107
exitCompSrcState
  probprism, 88
exitCompState (State)
  probprism, 80
exitCompSubstate
  probprism, 81
exitSeqCtrlConsts
  probprism, 76
exitSimpSrcState
  probprism, 88
exitSimpSubstate
  probprism, 81
exitSubstate
  probprism, 80
exitSubstates
  probprism, 80
getAllCalledOperations
  probprism, 100
calledOperations
  probprism, 100
calledOperationsInStmt
  probprism, 100
callEntryAction
  probprism, 106
callExitAction
  probprism, 105
callFinal
  probprism, 106
callInitial
  probprism, 106
callParaArgPairs
  probprism, 103
callRequiredOperations
  probprism, 105
callRequiredVariableLists
  probprism, 104
callsetChannels, 43
callsetLocalChannels, 44
callVariableLists
  probprism, 104
hasEntryAction
  probprism, 106
hasExitAction
  probprism, 105
hiddenModuleChannels, 36

InputEvent ()
  probprism, 97
INDEX OF SEMANTIC RULES

inTransCombinableJuncs
  probnorm, 74
isCombinableTran
  probnorm, 74
isComposite
  probprism, 106
isConstant
  probprism, 105
isFullyDefinedOperation
  probprism, 99
isInternalAsyncConn
  probprism, 93

M (Module), 36
  probprism, 76
Memory (Variable), 45
memoryChannels, 36
modMemory, 38

N (Final), 52
N (Junction), 51
N (Node), 51
N (State)
  Composite State, 53
  Simple State, 52
NC, 46
NC (NodeContainer)(Timed), 58
ncBehaviour, 46, 47, 59
newState
  probrc, 75
newTransition
  probrc, 75
nodeD, 59

occurEventNondeter ()
  (probprism), 104
OP (OperationDef)
  probprism, 101
OPpar (OperationDef)
  probprism, 102
opToActionMaps (StateMachineDef)
  probprism, 77

OutputEvent ()
  probprism, 98
permOPParameterAssigns
  probprism, 107

R (RoboticPlaftorm)
  probprism, 76
readState, 62
readStateAtomic, 54, 63
renameAsyncEvents
  probprism, 95
renameEventsConn
  probprism, 94
renameEventsConns
  probprism, 93
renameSyncEvents
  probprism, 95
renameTriggerEvents, 47
renamingController, 39
renamingMachine, 42
renCtrlEvts, 39
renStmEvts, 42
requiredConstants, 37
requiredOperations, 37
requiredVariables, 37

S (NodeContainer)
  probprism, 79
S (State)
  probnorm, 73
set (NamedElement), 165, 165, 165
setC (NamedElement), 166
setL (NamedElement), 166, 166
setLC (NamedElement), 166
setR (NamedElement), 166, 166
sharedConstant (Variable), 46
sharedConstMemory (Context), 45
sharedMemory (Variable), 46
sharedVarMemory (Context), 45
SimpEvent ()
<table>
<thead>
<tr>
<th>Term</th>
<th>Page Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>probprism</td>
<td>98</td>
</tr>
<tr>
<td>simpleBuffer</td>
<td>96</td>
</tr>
<tr>
<td>singleBuffer</td>
<td>40</td>
</tr>
<tr>
<td>splitTran</td>
<td>75</td>
</tr>
<tr>
<td>SS</td>
<td>82</td>
</tr>
<tr>
<td>ST (Assignment)</td>
<td>89</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>ST (Call)</td>
<td>91</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>ST (CommunicationStmt)</td>
<td>90</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>ST (IfStmt)</td>
<td>90</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>ST (ParStmt)</td>
<td>89</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>ST (SeqStatement)</td>
<td>91</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>ST (Skip)</td>
<td>89</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>ST (Statement)</td>
<td>89</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>stateDeadlines</td>
<td>60</td>
</tr>
<tr>
<td>Stateful (State Machine)</td>
<td>44</td>
</tr>
<tr>
<td>Stateful (StateMachineBody)</td>
<td>58</td>
</tr>
<tr>
<td>Statement</td>
<td>53, 54, 55, 56, 63, 64, 64</td>
</tr>
<tr>
<td>timed</td>
<td>63, 63</td>
</tr>
<tr>
<td>ClockReset</td>
<td>64</td>
</tr>
<tr>
<td>Wait</td>
<td>63</td>
</tr>
<tr>
<td>Call Statement</td>
<td>55</td>
</tr>
<tr>
<td>CommunicationStmt</td>
<td>55</td>
</tr>
<tr>
<td>If Statement</td>
<td>55</td>
</tr>
<tr>
<td>Send Event</td>
<td>137</td>
</tr>
<tr>
<td>collection</td>
<td></td>
</tr>
<tr>
<td>Sequential Composition</td>
<td>56</td>
</tr>
<tr>
<td>Skip</td>
<td>56</td>
</tr>
<tr>
<td>StatementInContext</td>
<td>55</td>
</tr>
<tr>
<td>STB (StateMachineBody)</td>
<td>79</td>
</tr>
<tr>
<td>STM (OperationDef)</td>
<td>43, 43</td>
</tr>
<tr>
<td>STM (State Machine)</td>
<td>42</td>
</tr>
<tr>
<td>STM (StateMachineDef)</td>
<td>42</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>probnorm</td>
<td>73</td>
</tr>
<tr>
<td>probprism</td>
<td>78</td>
</tr>
<tr>
<td>M Statement</td>
<td>(probprism), 92</td>
</tr>
<tr>
<td>T (Node)</td>
<td>85</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>T (Transition)</td>
<td>50, 61</td>
</tr>
<tr>
<td>tevent(Transition)</td>
<td>47</td>
</tr>
<tr>
<td>Ti (Initial)</td>
<td>85</td>
</tr>
<tr>
<td>Tj (Junction)</td>
<td>86</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>TN (Node)</td>
<td>83</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>TOther (Node)</td>
<td>84</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>TNprob (ProbJunc)</td>
<td>83</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>TNS</td>
<td>83</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>Tp (ProbJunc)</td>
<td>85</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>transitionDeadline</td>
<td>60</td>
</tr>
<tr>
<td>Transitions</td>
<td>50, 61</td>
</tr>
<tr>
<td>transitionsOf</td>
<td></td>
</tr>
<tr>
<td>probnorm</td>
<td>74</td>
</tr>
<tr>
<td>Trigger</td>
<td></td>
</tr>
<tr>
<td>collection</td>
<td>137</td>
</tr>
<tr>
<td>triggerForMemory</td>
<td>51</td>
</tr>
<tr>
<td>TS (Node)</td>
<td>84</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>Ts (State)</td>
<td>87</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>usedVariables</td>
<td>48, 48</td>
</tr>
<tr>
<td>V (Variable)</td>
<td>108</td>
</tr>
<tr>
<td>(probprism)</td>
<td></td>
</tr>
<tr>
<td>varMemory (Context), 44</td>
<td>VL (VariableList)</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>vars, 48, 48, 49, 49</td>
<td>prob prism, 107</td>
</tr>
<tr>
<td>SeqStatement, 49</td>
<td>Wait, 63, 64, 64</td>
</tr>
</tbody>
</table>

**INDEX OF SEMANTIC RULES**
In this index you'll find the location of call to the semantic rules. For each call of a semantic function, the page number superscripted with the usage index is provided. The index of the call is unique with respect to the semantic function, and also shown superscripted in the call location.

A (Actions,probrism) , 80\textsuperscript{1}, 81\textsuperscript{2}, 82\textsuperscript{3}
Action , 52\textsuperscript{1}, 52\textsuperscript{2}, 52\textsuperscript{3}, 53\textsuperscript{4}, 53\textsuperscript{5}, 53\textsuperscript{6}
actionTargetOfTran (.probrism) , 85\textsuperscript{1}, 85\textsuperscript{2}, 86\textsuperscript{3}, 87\textsuperscript{4}
addLoopStateTrans (probnorm) , 73\textsuperscript{1}
allConstants , 38\textsuperscript{1}, 43\textsuperscript{2}, 43\textsuperscript{3}
allEvents , 43\textsuperscript{1}
allLocalConstants , 36\textsuperscript{1}, 40\textsuperscript{2}, 44\textsuperscript{3}, 44\textsuperscript{4}, 44\textsuperscript{5}, 57\textsuperscript{6}
allLocalVariables , 36\textsuperscript{1}, 38\textsuperscript{2}, 40\textsuperscript{3}, 41\textsuperscript{4}, 44\textsuperscript{5}, 44\textsuperscript{6}, 44\textsuperscript{7}, 57\textsuperscript{8}
allVariables , 43\textsuperscript{1}, 43\textsuperscript{2}, 43\textsuperscript{3}
andExprs (probrism) , 80\textsuperscript{1}, 80\textsuperscript{2}, 81\textsuperscript{3}, 81\textsuperscript{4}, 81\textsuperscript{5}, 83\textsuperscript{6}, 85\textsuperscript{7}, 86\textsuperscript{8}, 88\textsuperscript{10}, 88\textsuperscript{9}, 89\textsuperscript{11}, 90\textsuperscript{12}, 90\textsuperscript{13}, 91\textsuperscript{14}, 97\textsuperscript{15}, 97\textsuperscript{16}, 98\textsuperscript{17}, 98\textsuperscript{18}, 98\textsuperscript{19}, 98\textsuperscript{20}, 99\textsuperscript{21}, 103\textsuperscript{22}, 103\textsuperscript{23}, 106\textsuperscript{24}
AST (Actions,probrism) , 84\textsuperscript{1}, 88\textsuperscript{2}, 89\textsuperscript{3}, 90\textsuperscript{4}, 90\textsuperscript{5}, 92\textsuperscript{6}, 92\textsuperscript{7}
asyncConnectedEvent
(Connection,probrism) , 92\textsuperscript{1}, 92\textsuperscript{2}, 92\textsuperscript{3}
asyncConnectedEvents
(Connections,probrism) , 76\textsuperscript{1}, 77\textsuperscript{2}
BBuffer , 136\textsuperscript{1}, 136\textsuperscript{2}
buffer , 36\textsuperscript{1}
buffer (.probrism) , 93\textsuperscript{1}
C (Controller) , 39\textsuperscript{1}
C (Controller,.probrism) , 76\textsuperscript{1}
callOpdef (.probrism) , 91\textsuperscript{1}, 103\textsuperscript{2}, 103\textsuperscript{3}
callOpNondeter (.probrism) , 102\textsuperscript{1}
clock (timed) , 62\textsuperscript{1}
clock Resets (timed) , 61\textsuperscript{1}, 61\textsuperscript{2}
clocks (timed) , 57\textsuperscript{1}, 58\textsuperscript{2}, 58\textsuperscript{3}
combTransJunction (probnorm) , 74\textsuperscript{1}
combTransJunctions (probnorm) , 73\textsuperscript{1}, 74\textsuperscript{2}
composeControllers , 36\textsuperscript{1}, 38\textsuperscript{2}
composeMachines, 40\textsuperscript{1}, 41\textsuperscript{2}, 57\textsuperscript{3}
composeNodes, 47\textsuperscript{1}
composeTimedNodes, 59\textsuperscript{1}
Constant, 44\textsuperscript{1}
constantsOfNamedElems (.probprism), 79\textsuperscript{1}, 82\textsuperscript{2}
constInit, 38\textsuperscript{1}, 41\textsuperscript{2}
constMemory, 44\textsuperscript{1}, 57\textsuperscript{2}, 58\textsuperscript{3}
CS (NodeContainer,probnorm), 73\textsuperscript{1}, 73\textsuperscript{2}
ctrlMemory, 40\textsuperscript{1}, 57\textsuperscript{2}

EmptyEvent (.probprism), 87\textsuperscript{1}
enterSubstate (.probprism), 81\textsuperscript{1}
enterSubstates (.probprism), 79\textsuperscript{1}, 81\textsuperscript{2}
enumValuesInType (probprism), 102\textsuperscript{1}, 104\textsuperscript{2}, 107\textsuperscript{3}
exitCompSrcState (.probprism), 87\textsuperscript{1}
exitCompState (.probprism), 79\textsuperscript{1}
exitCompSubstate (.probprism), 80\textsuperscript{1}
exitSeqCtrlConsts (.probprism), 76\textsuperscript{1}
exitSimpSrcState (.probprism), 76\textsuperscript{1}
exitSimpSubstate (.probprism), 80\textsuperscript{1}
exitSubstate (.probprism), 80\textsuperscript{1}
exitSubstates (.probprism), 79\textsuperscript{1}, 80\textsuperscript{2}

getAll Called Operations (.probprism), 78\textsuperscript{1}, 100\textsuperscript{2}
get Called Operations (.probprism), 100\textsuperscript{1}, 100\textsuperscript{2}
getCalledOperationsInStmt (.probprism), 100\textsuperscript{1}, 100\textsuperscript{2}, 100\textsuperscript{3}, 100\textsuperscript{4}
getEntryAction (probprism), 82\textsuperscript{1}, 106\textsuperscript{2}
getEvents (Events,probprism), 76\textsuperscript{1}, 102\textsuperscript{2}
getExitAction (probprism), 80\textsuperscript{1}, 81\textsuperscript{2}, 105\textsuperscript{3}
getFinal (probprism), 79\textsuperscript{1}
getInitial (probprism), 79\textsuperscript{1}, 82\textsuperscript{2}, 84\textsuperscript{3}, 103\textsuperscript{4}
getOperationDef (.probprism), 91\textsuperscript{1}, 103\textsuperscript{2}
getParaArgPairs (.probprism), 91\textsuperscript{1}, 107\textsuperscript{2}
getRequiredOperations
(Operations,probprism), 77\textsuperscript{1}, 77\textsuperscript{2}, 78\textsuperscript{3}, 78\textsuperscript{4}, 100\textsuperscript{5}, 100\textsuperscript{6}, 102\textsuperscript{7}

getRequiredVariableLists
(VariableList,probprism), 102\textsuperscript{1}
getsetLocalChannels, 44\textsuperscript{1}, 44\textsuperscript{2}, 58\textsuperscript{3}, 58\textsuperscript{4}
getVariableLists (VariableList,probprism), 76\textsuperscript{1}, 77\textsuperscript{2}, 78\textsuperscript{3}, 79\textsuperscript{4}, 102\textsuperscript{5}, 102\textsuperscript{6}
hasEntryAction (probprism), 79\textsuperscript{1}, 84\textsuperscript{2}, 84\textsuperscript{3}
hasExitAction (probprism), 88\textsuperscript{1}
hiddenModuleChannels, 36\textsuperscript{1}
InputEvent (.probprism), 87\textsuperscript{1}, 90\textsuperscript{2}
inTransCombinableJuncs (probnorm), 73\textsuperscript{1}, 73\textsuperscript{2}
isCombinableTran (probnorm), 74\textsuperscript{1}, 75\textsuperscript{2}
isComposite (probprism), 79\textsuperscript{1}, 80\textsuperscript{2}, 82\textsuperscript{3}, 87\textsuperscript{4}
isConstant (Variable,probprism), 102\textsuperscript{1}
isFullyDefinedOperation (.probprism), 99\textsuperscript{1}, 100\textsuperscript{2}, 100\textsuperscript{3}, 101\textsuperscript{4}, 103\textsuperscript{5}
isInternalAsyncConn
(Connection,probprism), 92\textsuperscript{1}, 93\textsuperscript{2}, 94\textsuperscript{3}
M (Module), 136\textsuperscript{1}
Memory, 44\textsuperscript{1}
memoryChannels, 36\textsuperscript{1}, 36\textsuperscript{2}
modMemory, 36\textsuperscript{1}
N, 50\textsuperscript{1}, 59\textsuperscript{2}, 59\textsuperscript{3}
NC, 44\textsuperscript{1}, 52\textsuperscript{2}, 53\textsuperscript{3}
NC (timed), 58\textsuperscript{1}
ncBehaviour, 46\textsuperscript{1}, 58\textsuperscript{2}
ncCoreBehaviour, 46\textsuperscript{1}
newState (.probrc), 74\textsuperscript{1}
newTransition (.probrc), 74\textsuperscript{1}, 74\textsuperscript{2}
odeD, 59\textsuperscript{1}

occurEventNondeter (.probprism), 102\textsuperscript{1}
OP (OperationDef,probprism), 78\textsuperscript{1}
OPpar (OperationDef,probprism), 101\textsuperscript{1}
opToActionMaps (State machine,probprism), 77\textsuperscript{1}
OutputEvent (.probprism), 87\textsuperscript{1}, 90\textsuperscript{2}
INDEX OF CALLS TO SEMANTIC RULES

permOPParameterAssigns (probprism) , 103
R (RoboticPlatform,probprism) , 76
readState , 54, 54, 55
readState (timed) , 60, 62, 64
readStateA , 50, 61
readStateA (timed) , 60, 60
readStateAtomic , 54, 54, 54, 54
readStateAtomic (timed) , 63, 63
renameAsyncEvents (.probprism) , 94, 94, 94
renameEventsConn (.probprism) , 93
renameEventsConns (.probprism) , 76, 77, 93
renameSyncEvents (.probprism) , 94, 94, 94
renameTriggerEvents , 46
renamingController , 38, 38
renamingMachine , 41, 41
renCtrlEvts , 38, 38
renStmEvts , 41, 41
requiredConstants , 39, 39, 40, 42, 42, 42
requiredOperations , 40, 40, 57, 57
requiredVariables , 36, 38, 40, 41, 41
requiredVariables Atomic , 42, 42, 42, 45
requiredVariables Atomic (timed) , 45, 57
S (NodeContainer,probprism) , 79, 82
S (States,probnorm) , 73
set , 165, 165, 165, 165, 166
setL , 165, 165, 165, 166
setLC , 165
setR , 165, 165, 165, 166
setRC , 165
sharedConstant , 45
sharedConstMemory , 42
sharedMemory , 45
sharedVarMemory , 42
SimpEvent (.probprism) , 87, 90
simpleBuffer (.probprism) , 93
splitTran (probnorm) , 73
SS (NodeContainer,probprism) , 79, 82
ST (Statement,probprism) , 88
stateDeadlines , 59
stateful , 42, 43
Statement , 55, 63, 64
StatementInContext , 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50
STM (State machine) , 40, 40, 40, 57
STM (State machine,probprism) , 77
STS (Action,probprism) , 91, 92
T (Transition) , 50
T (Transition, timed) , 61
T (Transitions,probprism) , 84
tevent , 47, 47, 50, 50, 50, 50, 50
Tj (Transitions,probprism) , 85
TN (.probprism) , 83
TNother (.probprism) , 83
TNprob (.probprism) , 83
TNS (.probprism) , 79, 83
Tp (Transitions,probprism) , 85
transitionDeadline , 60
transitions , 47, 57, 59, 60
transitionsOf (probnorm) , 73, 74, 74
trigger , 50, 50, 61, 61
TS (.probprism) , 83, 84, 84
Ts (Transitions,probprism) , 85
usedVariables , 47, 48, 48, 48, 48, 48
usedVariables Atomic , 48, 48, 48, 48, 48, 48
usedVariables Atomic (timed) , 49, 49, 49, 49, 49, 49
usedVariables Atomic (timed 2) , 49, 49, 49, 49, 49, 49
V (Variable,probprism) , 107
varMemory , 44, 57, 58
vars , 47, 48, 48, 48, 48, 48, 48, 49, 49
varMem , 47, 47, 47, 47, 47, 47, 47

49\textsuperscript{16}, 49\textsuperscript{17}, 49\textsuperscript{7}, 49\textsuperscript{8}, 49\textsuperscript{9}, 53\textsuperscript{18}, 53\textsuperscript{19}, 59\textsuperscript{20}, 79\textsuperscript{4}, 102\textsuperscript{5}

VL (VariableList,prob prism), 76\textsuperscript{1}, 77\textsuperscript{2}, 78\textsuperscript{3}, Wait, 63\textsuperscript{1}
Connection
  async, 18
  bidirec, 18
  Description, 18
  efrom, 18
  eto, 18
  from, 18
  to, 18
ConnectionNode
  Description, 17, 18
Event

Expression, 18

Module
  Description, 18

RCPackage
  Description, 17
Robotic Platform
  Description, 18
  RoboticPlatformDef, 18
  RoboticPlatformRef, 18
  Well Formedness, 27