Budapest University of Technology and Economics
Faculty of Electrical Engineering and Informatics
Department of Measurement and Information Systems

Formal Modeling and Verification of Process Models in Component-based Reactive Systems

Scientific Students' Association Report

Author:

Ármin Zavada

Advisor:

dr. Vince Molnár
Bence Graics

Contents

Kivonat **i**

Abstract **ii**

1 Introduction **1**

2 Background **3**

2.1 Model-based Systems Engineering 3

2.1.1 Systems Modeling Language 4

2.2 Formal Verification 6

2.2.1 Model Checking 6

2.2.2 Petri Nets 7

2.2.3 Activities as Petri Nets 8

2.3 Gamma Statechart Composition Framework 9

2.3.1 Example Statechart 10

2.4 Extended Symbolic Transition System 12

2.4.1 Formal Definition 12

2.4.2 Traffic Light Controller Example 13

2.5 Related Work 15

3 Gamma Activity Language **16**

3.1 Language Design 16

3.1.1 Supported SysML Feature Subset 16

3.2 Formal Definition 17

3.2.1 Formal Behaviour 18

3.3 Language Gramar 24

3.3.1 Metamodel 24

3.3.2 Concrete Syntax 29

4 Integrating the Activity Language Into Gamma **31**

4.1 Activities Alongside Statecharts . . . 31
4.1.1 Calling Activities . . . 31
4.1.2 Activities Defining Components . . . 32
4.2 Integration Semantics . . . 33
4.2.1 Preprocess Components . . . 33
4.2.2 Transform Components and Activities . . . 33
4.3 Implementation Remarks . . . 34

5 Evaluation **36**
5.1 Case Study - Compilation . . . 36
5.1.1 Modeling . . . 36
5.1.2 Results and Conclusion . . . 37
5.2 Case Study - Simple Space Mission . . . 37
5.2.1 System Modeling . . . 38
5.2.2 Results and Conclusion . . . 40

6 Conclusion **42**

Acknowledgements **43**

Bibliography **44**

Appendix **47**
A.1 XSTS Language . . . 47
A.2 Gamma Activity Language . . . 49
A.3 Spacecraft Model . . . 52

Kivonat

A biztonságkritikus rendszerek komplexitása folyamatosan növekedett az elmúlt években. A komplexitás csökkentése érdekében a modellalapú paradigma vált a meghatározó módszerré ilyen rendszerek tervezéshez. Modellalapú rendszertervezés során a komponensek viselkedését általában állapotalapú, vagy folyamatorientált modellek segítségével írjuk le. Az előbbi formalizmusa azt írja le, hogy a komponens milyen állapotokban lehet, míg az utóbbié azt, hogy milyen lépéseket hajthat végre, valamint milyen sorrendben. Gyakran ezen modellek valamilyen kombinálása a legjobb módja egy komplex komponens viselkedésének leírásához.

Formális szemantikával rendelkező modellezési nyelvek lehetővé teszik a leírt viselkedés (kimerítő) verifikációját. Formális verifikáció használatával már a fejlesztés korai fázisaiban felfedezhetőek a hibák: a módszer ellenőrzi, hogy a rendszer egy adott (hibás) állapota elérhető-e, és amennyiben elérhető, ad hozzá egy elérési útvonalat. A formális verifikációs eszközök emiatt gyakran csak alacsony szintű, állapotalapú modelleken működnek, melyek messze vannak az emberek által könnyen érthető nyelvektől. Ezért, hogy magas szintű viselkedési modelleket tudjunk verifikálni, implementálnunk kell egy olyan modell transzformációt, mely megtartja a folyamat- és állapotalapú modellek szemantikáját azok kombinációja után is.

Ebben a dolgozatban megvizsgálom a folyamatalapú modellek szemantikáját, valamint a kapcsolatukat egyéb hagyományos állapotalapú modellekkel. Emellett megoldásokat vetek fel a potenciális konfliktusokra a kombinált alacsonyszintű modellben. Munkám során a Gamma állapotgép kompozíciós keretrendszerre építek, mellyel komponensalapú reaktív rendszereket modellezhetünk és verifikálhatunk. Mivel a Gamma még nem támogatja az aktivitásokat, bevezetek egy új aktivitás nyelvet, melyhez a SysMLv2 szolgál inspirációként. Ezzel együtt implementálom hozzá a szükséges transzformációkat a Gamma alacsony szintű analízis formalizmusára. Végezetül pedig kiértékelem a koncepcionális és gyakorlati eredményeket esettanulmányokon és méréseken keresztül, valamint felvetek lehetséges fejlesztéseket és alkalmazásokat.

Abstract

The complexity of safety-critical systems has been increasing rapidly in recent years. To mitigate said complexity, the model-based paradigm has become the decisive way to design such systems. In model-based systems engineering, we usually define the behaviour of system components using state-based or process-oriented models. The former formalism describes what states the component can be in, while the latter describes what steps it can perform and in what order. Oftentimes, the best way to model the behaviour of a complex component is to combine these models in some way.

Modelling languages with formal semantics enable the (exhaustive) verification of the described behaviour. Formal verification may be used to detect errors early during development by checking if a given (erroneous) state of the system can be reached, and if so, providing a way to reach it. Formal verification tools often require low-level state-based mathematical models, which are far from human-understandable languages. Thus, to enable the verification of high-level behavioural models, a model transformation must be implemented that preserves the semantics of both process-oriented and state-based models, even when combined.

In this report, I analyse the semantics of process-oriented models, as well as their relation to traditional state-based models, and propose solutions for the possible conflicts in a combined low-level model. In my work, I build on the Gamma Statechart Composition Framework, which is a tool for modelling and verifying component-based reactive systems based on statecharts. Since Gamma does not support activities yet, I introduce a new activity language inspired by SysMLv2 and implement the necessary transformations to Gamma's low-level analysis formalism. Finally, I evaluate the conceptual and practical results through case studies and measurements then propose potential improvements and applications.

Chapter 1

Introduction

Reactive systems, such as embedded control systems in the railway, automotive and aerospace industries, are getting more and more complex as user requirements proliferate. As a result, such systems are generally not centralized; they consist of heterogeneous components distributed among several computing nodes, which constantly interact with each other and external resources (e.g., cloud computing via the Internet) while carrying out critical tasks.

In order to tackle the increasing development complexity, new approaches and tools have been introduced to supervise the design, verification and implementation of reactive systems. Component-based systems engineering (CBSE) and model-based systems engineering (MBSE) aim to support the development process based on the integration of reusable components defined in high-level modeling languages, preferably with automatically derivable implementation and verifiable design.

UML and SysML, the de facto language standards in CBSE and MBSE methodologies, offer the State Machine Diagram and the Activity Diagram to describe reactive component behaviour. These diagram types are often combined: state machines describe changes in component states, whereas activities can define continuous and batch process behaviour in active states and during transitions. Unfortunately, UML and SysML do not provide formal execution semantics for state machines and activities, hindering the verification of the design models. In turn, modeling languages with formal semantics with the necessary tooling can support the verification of component behaviour early during the development process – an essential facility in the context of critical systems.

This work focuses on process-based (activity) behavioural models and their usability in traditional state-based descriptions, and aims to propose solutions for the formal verification of the combined models. I build on and integrate my work into the Gamma Statechart Composition Framework, a modeling tool for the design and analysis of component-based reactive systems. Gamma supports the semantically sound composition of state-based components and provides system-level formal verification and validation (V&V) by mapping composite models into analysis formalisms of integrated model checker back-ends. The framework facilitates the implementation process with automated code generators. So far, Gamma has lacked support for activities.

As a novelty, I introduce the following contributions to aid the formal modeling and verification of process models in component-based reactive systems.

- I introduce an activity language with formal semantics inspired by SysMLv2 and integrate it into the modeling language family of the Gamma framework, allowing for the combination of state-based and process-oriented behaviour.
- I define and implement a model transformation that maps activity descriptions into the analysis formalism of Gamma (eXtended Symbolic Transitions Systems - XSTS), enabling the formal verification of combined state-based and process-based behaviour with integrated model checker back-ends.
- Finally, I evaluate the theoretical and practical results of my work on case studies from the aerospace domain and identify improvement possibilities and potential applications.

The rest of the work is structured as follows. Chapter 2 introduces the background necessary to understand the rest of the work. Chapter 3 presents the Gamma Activity Language including its metamodel, textual syntax and the formal semantics of the model elements. In Chapter 4, I introduce questions regarding the interplay of state machines and activities, propose solutions for them and I integrate the Gamma Activity Language into Gamma. Chapter 5 presents three case studies showcasing the capabilities and correctness of the modeling language and its integration into the Gamma framework. Lastly, in Chapter 6, I draw the conclusions of the work, and lay down possible future enhancements.

Chapter 2

Background

In this chapter, I present the theoretical foundations of my contribution. In Section 2.1, I introduce the concept of model-based systems engineering, which is a well-known approach for complex system design. This section also goes into detail about SysML (Section 2.1.1), which is a general-purpose modeling language for system design. Next, I talk about the concept of formal verification in Section 2.2, and introduce Petri nets (Section 2.2.2) and a mapping between UML/SysML Activity Diagrams and Petri nets (Section 2.2.3). Lastly, I introduce the Gamma Statechart Composition Framework, which is a tool for modeling and verifying component-based reactive systems based on statecharts (Section 2.3), and a low-level formalism called XSTS (Section 2.4) used as an intermediary language for model checking by Gamma.

2.1 Model-based Systems Engineering

The INCOSE SE Vision 2020 defines model-based systems engineering (MBSE) as:

> "The formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. MBSE is part of a long-term trend toward model-centric approaches adopted by other engineering disciplines, including mechanical, electrical and software. In particular, MBSE is expected to replace the document-centric approach that has been practiced by systems engineers in the past and to influence the future practice of systems engineering by being fully integrated into the definition of systems engineering processes." [1]

Applying MBSE is expected to provide significant benefits over document-centric approaches by enhancing productivity and quality, reducing risk, and providing improved communications among the system development team [2].

In MBSE, one of the most important concepts is the term "model" itself. Literature gives various definitions for models:

1. A physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process [**?**].
2. A representation of one or more concepts that may be realized in the physical world [10].

3. A simplified representation of a system at some particular point in time or space intended to promote understanding of the real system [5].

4. An abstraction of a system, aimed at understanding, communicating, explaining, or designing aspects of interest of that system [8].

5. A selective representation of some system whose form and content are chosen based on a specific set of concerns. The model is related to the system by an explicit or implicit mapping [14].

2.1.1 Systems Modeling Language

Systems Modeling Language (OMG SysML [12]) is a general-purpose modeling language that supports the specification, design, analysis, and verification of systems that may include hardware and equipment, software, data, personnel, procedures, and facilities. SysML is a graphical modeling language with a semantic foundation for representing requirements, behaviour, structure, and properties of the system and its components [10].

This work focuses only on the *behavioural* modeling facilities SysML provides. In the following section, I present two of the most used diagram types in SysML: State Machine Diagrams and Activity Diagrams.

State Machine Diagram

Reactive systems are all around us in our daily lives: in smartphones, avionics systems or even our calculators. Oftentimes, reactive systems appear in areas, where safety-critical operation is crucial, as even the slightest error can have catastrophic consequences.

The defining characteristic of reactive systems is their event-driven nature, which means that they continuously receive external stimuli (*events*), based on which they change their internal *state* and possibly react with some output [16]. Statecharts [17] are a popular and intuitive language to capture the behaviour of reactive systems [18, 29].

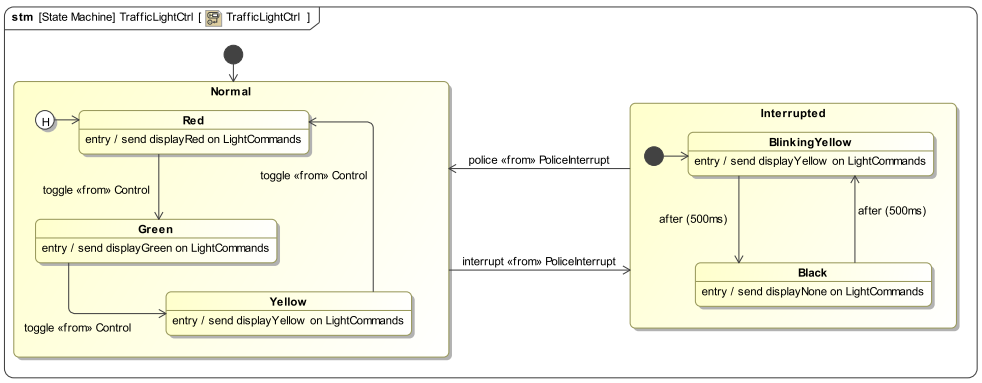


Figure 2.1: SysML State Machine describing the behaviour of a traffic light controller.

SysML State Machines extend the concept of automata with hierarchical state-refinement, orthogonal regions, action-effect behaviour and state machine composition. These advanced abstraction constructs support the concise modeling of state machines for engineers, making their formal verification harder. This abstraction gap can be bridged using a transformation tool, such as Gamma (see Section 2.3) that maps these high-level constructs into low-level analysis formalisms.

Figure 2.1 shows a state machine modeling the behaviour of a traffic light controller. The *TrafficLightCtrl* component has three ports, two inputs (*Control* and *PoliceInterrupt*) for user input, and one output (*LightCommands*) for controlling (turning on and off) the specific light it is connected to. The state machine changes between the *red-green-yellow* lights, upon a *toggle* command (Normal state - main cycle). However, if a *police* signal is received, it starts turning on and off the yellow light every 500ms (Interrupted state - blinking cycle).

Activity Diagram

Using State Machines, it is harder to describe the complicated semantics of distributed systems with concurrent, parallel behaviour, where the *interesting* thing is what the system *does* step-by-step (e.g., batch processing). SysML Activity Diagrams are a primary representation for modeling process based behaviour [12] for distributed, concurrent systems. Figure 2.2 shows the set of modeling elements related to this work. In the following, I introduce the different modeling elements of SysML activities and show an example of a SysML activity diagram.

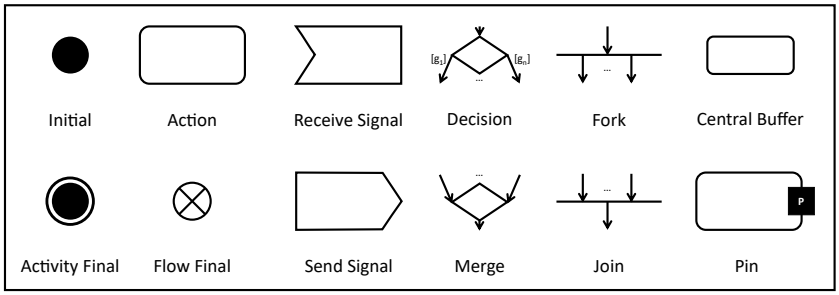


Figure 2.2: Artifacts of SysML activity diagrams.

SysML Activity Diagram is a graph-based model, where the nodes are connected via flows. The dynamic behaviour of activity diagrams comes from *tokens* travelling from node to node; based on the given node's semantics, a connected flow removes tokens from the source node and transfers them onto the target node. Flows can also have *guards*, which are expressions specifying when the given flow is *enabled* or not; only enabled flows can transfer tokens.

Tokens are a way of controlling which node can run, and which cannot; a given node is considered *running*, only when it contains a token from all of its input flows. Tokens *flow* between nodes, carrying with them a given value - this value can also be of type *void*, which makes it a *control* token.

The different nodes represent the different semantic "tools" at our disposal; they can represent different actions, or introduce interesting token flow semantics. Simple *actions* represent a single step of behaviour that convert a set of inputs to a set of outputs. Both inputs and outputs are specified as *pins*, which get their data from connected flows - making that flow a *data flow*. Execution starts from the initial node and ends with a *Flow Final* or *Activity Final* node. *Fork* nodes generate tokens on all of their output flows, and *Join* nodes forward the tokens, only when all input flows contain one - thus, the two nodes complement each other. On the other hand, *Merge* nodes do not wait for all flows, they forward any token they receive instantly, complimenting *Decision* nodes, which take one token from its input flows, and send it out on its single enabled output flow.

The detailed specification for SysML Activity Diagrams can be found in the OMG specification [12].

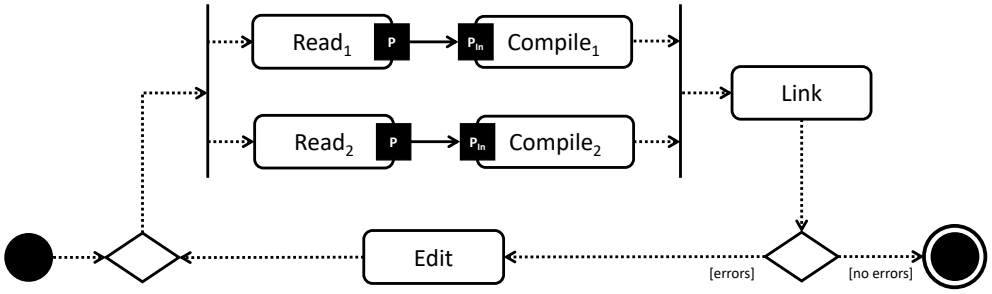


Figure 2.3: The activity of editing, compiling and linking two files.

Figure 2.3 shows an example activity diagram, modeling the process of editing, compiling and linking two files. First, the files have to be *read*, after which they are *transferred* to the *compilers*. We want to compile the two different files in *parallel*, thus we split the control flow using a *fork* node. Once the files are compiled, we *link* them - since linking requires both files, it is preceded by a *join* node. Finally, if the resulting code contains errors, we *edit* the source files and start over - otherwise we are done.

2.2 Formal Verification

In order to ensure the reliability of system models, various analysis techniques are used to verify their correctness. Among these techniques are *unit tests*, *module tests*, *system tests* and *acceptance tests*. However, no matter how many kinds of tests we use, the test cases can not cover the entire system. Formal verification tools are meant to extend these analysis techniques by not specifying a given *sequence* of events, but rather specifying the undesirable state of the system [6]. Formal verification methods are primarily based on theoretical computer science fundamentals like logic calculi, automata theory and strongly typed systems [**?**]. The main principle behind formal analysis of a system is to construct a computer-based mathematical model of the given system and formally verify, within a computer, that this model meets rigorous specifications of the intended behaviour. Due to the mathematical nature of the analysis, very high accuracy can be guaranteed.

2.2.1 Model Checking

Model checking is a formal verification method to verify properties of finite systems, i.e., to decide whether a given formal model M satisfies a given requirement γ or not. The name comes from formal logic, where a logical formula may have zero or more models, which define the interpretation of the symbols used in the formula and the base set such that the formula is true. In this sense, the question is whether the formal model is indeed a model of the formal requirement: $M \models \gamma$?

Model checker algorithms (see Figure 2.4), such as the ones used in UPPAAL[1] [4] or Theta[2] [30] can answer this question, and can even return a *proof* (i.e., a diagnostic trace of the model) that M indeed does satisfy said requirement[3].

[1] https://uppaal.org/
[2] https://inf.mit.bme.hu/en/theta
[3] These proofs usually come in the form of an execution trace

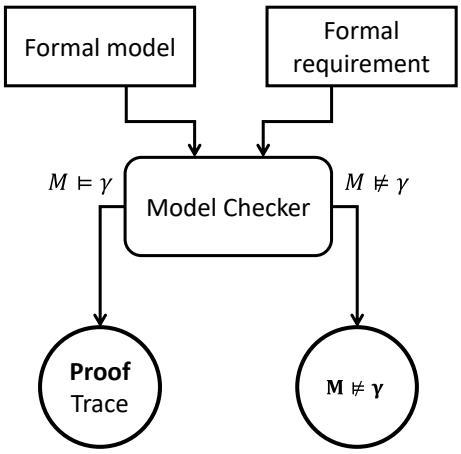


Figure 2.4: An illustration of model checking.

2.2.2 Petri Nets

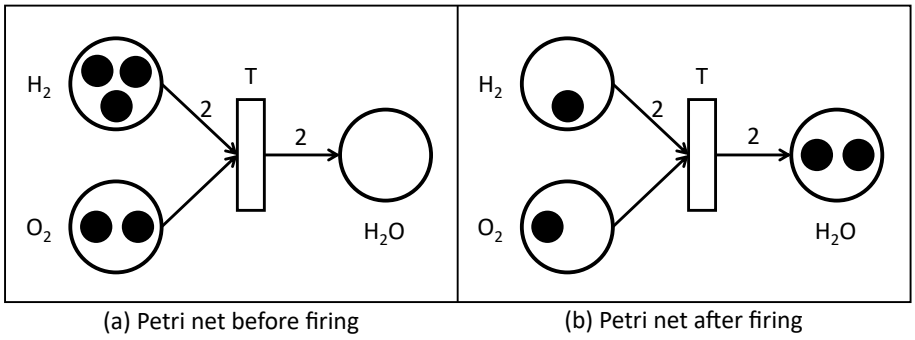


Figure 2.5: An example Petri net modeling the process of H_2O molecule creation.

Petri nets are an example of formal models, and thus can be formally verified. Petri nets are a widely used formalism to model concurrent, asynchronous systems [24]. The formal definition of a Petri net [3] is as follows (see Figure 2.5 for an illustration of the notations).

Definition 1 (Petri net). A Petri net is a tuple $PN = (P, T, W, M_0)$

- P is the set of *places* (defining state variables);
- T is the set of *transitions* (defining behaviour), such that $P \bigcap T = \emptyset$;
- $W \subseteq W^+ \bigcup W^-$ is a set of two types of arcs, where $W^+ : T \times P \to \mathbb{N}$ and $W^- : P \times T \to \mathbb{N}$ are the set of input arcs and output arcs, respectively ($\mathbb{N}$ is the set of all natural numbers). The number returned is an arc's *weight*;
- $M_0 : P \to \mathbb{N}$ is the *initial marking*, i.e., the number of *tokens* on each place. ▪

The state of a Petri net is defined by the current marking $M : P \to \mathbb{N}$. The behaviour of the systems is described as follows. A transition t is enabled if $\forall p \in P : M(p) \geq W(p, t)$. Any enabled transition t may fire nondeterministically, creating the new marking M' of the Petri as follows: $\forall p \in P : M'(p) = M(p) - W^-(p, t) + W^+(t, p)$.

In words: W describes the *weight* of each arc from a transition to a place, or from a place to a transition. Firing a transition t in a marking M consumes $W^-(p_i, t)$ tokens from

each of its input places p_i, and produces $W(t, p_o)$ tokens in each of its output places p_o. One such transition t is *enabled* (it may *fire*) in M if there are enough tokens in its input places for the consumptions to be possible.

2.2.3 Activities as Petri Nets

Formal verification requires models to be specified using *mathematical* precision, i.e., the modeling language must have a formal syntax and semantics. However UML/SysML does not have precise semantics [23, 25, 20]. Huang et al. in [19] propose a way to *partially* map SysML Activity Diagrams to Petri nets, giving a denotational semantics to the subset of SysML Activity Diagrams. In the following, I will summarise their work, as my main contributions (see Chapter 3) build on it.

Constrained Subset of SysML

Since UML/SysML Activity Diagrams do not have precise execution semantics, the Petri net mapping can be defined only for a limited subset of the modeling elements: *actions*, *initial nodes*, *final nodes*, *join nodes*, *fork nodes*, *merge nodes*, *decision nodes*, *pins* and *object/control flows*, which have precise execution semantics as defined in the Foundational Subset for Executable UML Models [15].

The paper also assumes the following constrains:

1. The value of tokens is not considered.
2. Control flows with multiple tokens at a time are not considered.
3. Optional object/control flows are not considered, i.e., multiplicity lower bounds are strictly positive.

These constraints allow the mapping between activities and Petri nets, however, the constructed Petri net will not be semantically equivalent - data cannot flow between nodes. This fact is the motivation behind formalising a more-complete mapping (see Chapter 3).

Mapping Rules

Activity elements can be grouped into two sets: *load-and-send* (LAS) and *immediate-repeat* (IR).

LAS nodes are fired when all their inputs have tokens. When an *LAS* node fires, the number of tokens associated with the input flows/pin is consumed and the number of tokens associated with an output flows/pin is added. In SysML activity diagrams, the execution semantics of all nodes - except *decision* and *merge* nodes - are LAS, because these nodes are fired when all their input nodes have at least one token. As a result, these nodes can be mapped to *transitions* in the resulting Petri net.

In contrast, as soon as an *IR* node receives a token from any input, it immediately adds a token to its output nodes. For SysML activity diagrams, merge nodes, decision nodes are IR nodes, because they are fired immediately when any token is received. As a result, these nodes can be mapped to *places* in the resulting Petri net.

Given the set of assumptions in Section 2.2.3, control flows and object flows in an activity diagram can be mapped to arcs in a Petri net.

Finally, after mapping the elements, the resulting Petri net may contain transition-transition and place-place arcs, which are not valid; as the final step, these arcs must be split in two by inserting a transition or a place in the middle (with a weight of 1), making the model conform to the formalism.

Example Mapping

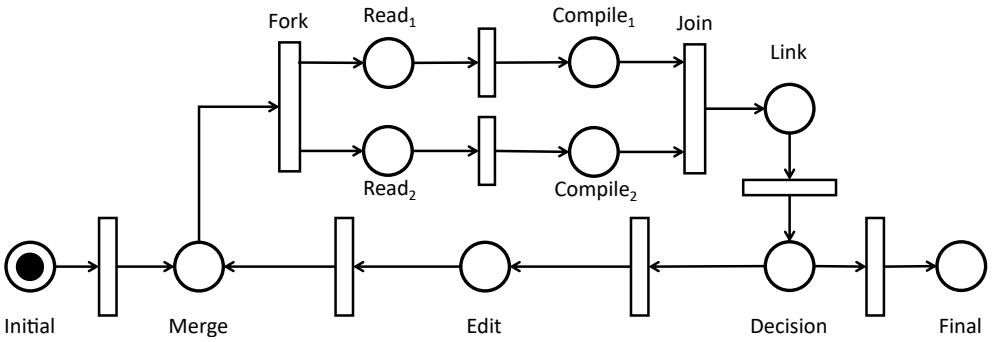


Figure 2.6: Example mapping from activity diagram to Petri net.

Figure 2.6 shows an example mapping from the activity Figure 2.3. The resulting elements are annotated with the names of their counter parts in the activity diagram.

For more about the Petri net mapping, please refer to [19].

2.3 Gamma Statechart Composition Framework

The Gamma Statechart Composition Framework[4] [11] is an integrated tool to support the design, verification and validation of, as well as code generation for component-based reactive systems. The behaviour of each component is captured by a statechart, while assembling the system from components is driven by a domain-specific composition language[5]. Gamma supports the formal verification of the assembled system by mapping composite statecharts to a back-end model checker. Execution traces obtained as witnesses during verification are back-annotated as test cases to replay an error trace or to validate external code generators [21].

The workflow of Gamma builds on a model transformation chain depicted in Figure 2.7, which illustrates the input and output models of these model transformations as well as the languages in which they are defined, and the relations between them. The modeling languages are as follows.

- The **Gamma Expression Language (GEL)** is a lightweight expression language, created to describe value expression (addition, subtraction, etc.) in actions.
- The **Gamma Action Language (GAL)** is a lightweight action language, created to describe actions on statechart transitions.
- The **Gamma Statechart Language (GSL)** is a UML/SysML-based statechart language supporting different semantic variants of statecharts.

[4]https://inf.mit.bme.hu/en/gamma

[5]The composition language bears close similarities to the *ibd* language in SysML

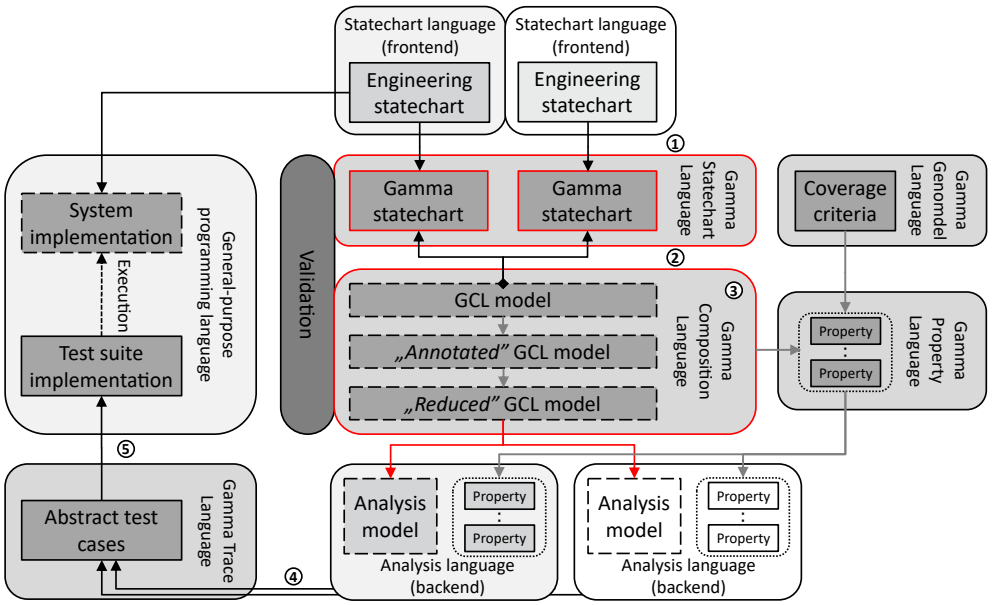


Figure 2.7: The overview of model transformation chains and modeling languages of the Gamma framework [11]. The parts relevant to this work have been marked with red outline.

- The **Gamma Composition Language (GCL)** is a composition language for the formal hierarchical composition of state-based components according to multiple execution and interaction semantics.
- The **Gamma Genmodel Language (GGL)** is a configuration language for configuring model transformations.
- The **Gamma Property Language (GPL)** is a property language supporting the definition (CTL*) properties and thus, the formal specification of requirements regarding (composite) component behavior.
- The **Gamma Trace Language (GTL)** is a high-level specification language for execution traces of (composite) components.

The component integration and verification workflow in Gamma is as follows. Optionally, statechart models defined in supported modeling tools (front-ends) can be imported into Gamma (Step 1), which can be integrated according to well-defined execution and interaction semantics (Step 2). The resulting composite model is processed and transformed into the input formalisms of integrated model checker back-ends (Step 3). The model checker back-ends provide witnesses (diagnostic traces) based on specified properties, which are back-annotated, resulting in abstract traces (Step 4). Finally, the abstract traces are mapped into concrete (executable) traces tailored to the targeted execution environment (Step 5). For a more detailed description, see [11].

2.3.1 Example Statechart

Listing 2.1 shows the Gamma Statechart representation of the SysML State Machine introduced in Figure 2.1. The Gamma Statechart Language is highly expressive language, capable of defining composite statecharts with *ports*, *timeout triggers* and composite actions. My work builds the activity language on top of this formalism.

```
package TrafficLightCtrl
import "Interfaces"
statechart TrafficLightCtrl [
    port Control : requires Control
    port PoliceInterrupt : requires PoliceInterrupt
    port LightCommands : provides LightCommands
] {
    timeout BlinkingYellowTimeout3
    timeout BlackTimeout4
    region main_region {
        state Normal {
            region normal {
                shallow history Entry2
                state Green {
                    entry / raise LightCommands.displayGreen;
                }
                state Red {
                    entry / raise LightCommands.displayRed;
                }
                state Yellow {
                    entry / raise LightCommands.displayYellow;
                }
            }
        }
        state Interrupted {
            region interrupted {
                initial Entry1
                state Black {
                    entry / set BlackTimeout4 := 500 ms;
                        raise LightCommands.displayNone;
                }
                state BlinkingYellow {
                    entry / set BlinkingYellowTimeout3 := 500 ms;
                        raise LightCommands.displayYellow;
                }
            }
        }
        initial Entry0
    }
    transition from Yellow to Red when Control.toggle
    transition from Normal to Interrupted when PoliceInterrupt.police
    // ...
    transition from BlinkingYellow to Black when timeout BlinkingYellowTimeout3
    transition from Black to BlinkingYellow when timeout BlackTimeout4
}
```

Listing 2.1: The traffic light controller state machine in the textual representation of the Gamma Statechart Language.

2.4 Extended Symbolic Transition System

In this section, I introduce the Extended Symbolic Transition System [22] language, which is a low-level modeling formalism designed to bridge the abstraction gap between engineering models and formal methods.

2.4.1 Formal Definition

Definition 2 (Extended symbolic transition system). An *Extended symbolic transition system* is a tuple $XSTS = (D, V, V_C, IV, Tr, In, En)$, where:

- $D = \{d_{v_1}, d_{v_2}, \ldots, d_{v_n}\}$ is a set of value domains;
- $V = \{v_1, v_2, \ldots, v_n\}$ is a set of variables with domains $\{d_{v_1}, d_{v_2}, \ldots, d_{v_n}\}$;
- $V_C \subseteq V$ is a set of variables marked as *control variables*;
- $IV \in d_{v_1} \times d_{v_2} \times \cdots \times d_{v_n}$ is the *initial value function* used to describe the initial state. The initial value function IV assigns an initial value $IV(v) \in d_v$ to variables $v \in V$ of their domain d_v;
- $Tr \subseteq Ops$ is a set of operations, representing the *internal transition relation*; it describes the internal behaviour of the system;
- $In \subseteq Ops$ is a set of operations, representing the *initialisation transition relation*; it is used to describe more complex initialisation, and is executed once and only once, at the very beginning;
- $En \subseteq Ops$ is a set of operations, representing the *environmental transition relation*; it is used to model the system's interactions with its environment. ▪

In any state of the system, a single operation is selected from the sets introduced above (Tr, In and En). The set from where the operation can be selected depends on the current state: In the initial state - which is described by the initialization vector IV - operations only from the In set can be executed. Operations from the In set can fire only in the initial state and nowhere else. After that, operations from En and Tr are selected in an alternating manner.

Operations $op \in Ops$ describe the transitions between states of the system, where Ops is the set of all possible transitions. All operations are atomic in the sense that they are either executed in their entirety or none at all. XSTS defines the following basic and composite operations.

Basic operations Basic operations contain no inner (nested) operations.

- *Assignments* assign a given value v from domain d_n to variable V_n.
- *Havocs* behave likewise, except the value is not predetermined, giving a way to assign a nondeterministic value to a variable.
- Lastly, *assume* operations check a condition, and can be executed only if their condition evaluates to *true*.

Composite operations Composite operations contain other operations, and can be used to describe complex control stuctures.

- *Sequences* are essentially multiple operations executed one after the other.
- *Parallels* are execute all operations in parallel.
- And lastly, *choices* model non-deterministic choices between multiple operations; one and only one branch of the choice operation is selected for execution.

Note that while these are composite operations, their execution is still atomic; i.e., a potential false evaluation of a containing assume operation prevents the execution of all operations in that particular branch. E.g., if a sequence's second operation is an assume operation, which cannot execute, then the whole sequence operation will be prevented from execution.

2.4.2 Traffic Light Controller Example

Listing 2.2 shows the example traffic light controller statechart (Figure 2.1) transformed into the textual representation of XSTS, using the Gamma framework. It shows how the different states and regions are modeled, and clearly showcases the structure of XSTS. For a more exact presentation see Section A.1.

```
type ActivityNodeState : { __Idle__, __Running__, __Done__ }
// ...
type Operating_Controller : {
    __Inactive__, Priority, Init,
    PriorityPrepares, Secondary, SecondaryPrepares
}
var PoliceInterrupt_police_In_Controller : boolean = false
// ...
ctrl var main_region_Controller : Main_region_Controller = __Inactive__
ctrl var operating_Controller : Operating_Controller = __Inactive__
var SecondaryTimeout2_Controller : integer = 0

trans {
    // ...
    choice {
        assume (main_region_Controller == Interrupted);
        // ...
    } or {
        assume (main_region_Controller == Normal);
        // ...
    }
    PoliceInterrupt_police_In_Controller := false;
}
init {
    SecondaryTimeout2_Controller := 2 * 1000;
    // ...
    PriorityPolice_police_Out_Controller := false;
    choice {
        assume (operating_Controller == __Inactive__);
        operating_Controller := Init;
    } or {
        assume !(operating_Controller == __Inactive__);
    }
    // ...
}
env {
    havoc PoliceInterrupt_police_In_Controller;
    // ...
    SecondaryPolice_police_Out_Controller := false;
}
```

Listing 2.2: Gamma XSTS Language representing the traffic light controller statechart.

2.5 Related Work

In this section, I showcase various works in the area of process-based model formal verification.

Rik Eshuis [9] translates activity diagrams to NuSMV code. The mapping is based on a state machine, and follows the following steps: (1) Inserting a WAIT node for each edge entering a join, (2) Inserting a WAIT node between a join and a fork, (3) Replacing object nodes and flows by wait nodes and control flows, (4) Eliminating pseudo-nodes and define hyperedges. The resulting NuSMV can be checked with LTL temporal logic.

Samir Ouchani et al. in [26] introduce an abstraction approach for SysML Activity Diagrams that helps mitigate the state-explosion problem. They defined two algorithms for this, the first one eliminates the parts of the model which are irrelevant to the formal requirement, while the second merges nodes, thus abstracting the model.

Samir Ouchani et al. in [27] propose a mapping from SysML Activity Diagrams to probabilistic automata written in PRISM language. They have done this by first defining a mapping from the model elements to NuAC terms, which are then mapped to PrismCode using a simple algorithm traversing the activity model. This mapping then was checked by comparing the semantics of the Activity Diagram with the resulting PA.

Huang et al. in [19] propose a partial mapping algorithm from SysML Activity Diagrams to Petri nets, using a constrained subset of SysML. More about this work in Section 2.2.3.

Jan Czopik et al. in [7] introduce a mapping from SysML Activity Diagrams to Coloured Petri Nets. Coloured Petri Nets is a formalism that extends the semantics of Petri nets with distinguishable tokens. The highlight of this work is the incorporation of data tokens into the resulting formal model.

Messaoud Rahim et al. in [28] introduces a modular and distributed verification process for composite SysML Activity Diagrams mapped to Petri nets. They achieve minimal state-space for the underlying model checker algorithm, by separating the resulting Petri nets into modules, and only explore the state-space of other activities, if the corresponding SysML Activity Diagram called, or is called by the other module. Thus, the resulting state space is significantly reduced.

These works mainly focus on the verification of sole activities, without incorporating state machines; to the best of my knowledge, there is no work in the literature focusing on the formal verification of combined high-level state-based and process-based behaviour descriptions.

Chapter 3

Gamma Activity Language

The high-level nature of SysML activities means they are easy to use for modeling complicated behaviours of distributed systems, but their complexity encumbers formal verification. As discussed in Section 2.2.3, we can define a semantic-preserving mapping between activities and Petri nets (which have a formal semantic), however, that mapping is not complete as it disregards (among many things) the data contained in tokens.

The Gamma Statechart Composition Framework (Section 2.3) implements a model transformation pipeline (see Figure 2.7) for the formal verification of collaborating statecharts, however, it does not include activity diagrams. In order to support the definition and verification of activities in the Gamma framework, I propose the Gamma Activity Language (GATL) (Chapter 3) and integrate it (Chapter 4) into the transformation pipeline.

3.1 Language Design

The purpose of GATL is twofold: it should support as many features from SysML activity diagrams as possible, while also having formal semantics. In order to make the transformation easier, the language supports only a constrained subset of the SysML feature set.

3.1.1 Supported SysML Feature Subset

Compared to SysML activity diagrams, GATL supports the following language constructs:

- *control* and *data* flows;
- *Initial* and *activity final* nodes;
- *Decision* and *merge* nodes - without probability;
- *Fork* and *join* nodes;
- *Action nodes* – which can contain inner activities (Call behaviour in SysML) or specific internal actions[1] that can calculate values, and send signals through specific ports.
- *Pins* on action nodes.

[1] Written in the Gamma Action Language

3.2 Formal Definition

In order to offer mathematical precision, formal verification methods require formally defined models with clear semantics. In this section I present the formal definition of the GATL formalism.

Definition 3 (Gamma Activity Language). A Gamma Activity is a tuple of $GATL = (D, V, N, P, F, G, F_{Action})$, where:

- $D = \{d_1, d_2, \ldots, d_n\}$ is a set of value domains;
- $V = \{v_1, v_2, \ldots, v_n\}$ is a set of variables with domains $\{d_{v_1}, d_{v_2}, \ldots, d_{v_n}\}$;
- $N = N_{IR} \bigcup N_{LAS}$ is a set of *Nodes*, where N_{IR} contains the *immediate-repeat* nodes and N_{LAS} contains the *load-and-send* nodes (see Section 2.2.3). $N_{Action} \in N_{LAS}$ is a special set of nodes, which are the *Action* nodes;
- $P \subseteq P_{In} \bigcup P_{Out}$ is a set of two types of pins, where $P_{In} : N_{Action} \to \{p_1^-, \ldots, p_n^-\}$ and $P_{Out} : N_{Action} \to \{p_1^+, \ldots, p_m^+\}$ are the set of *InputPins* and *OutputPins*, respectively, with domains $\{d_1, \ldots, d_n\} \subseteq D$;
- $F \subseteq F_C \bigcup F_D$, where $F_C = \{f_{C_1}, \ldots, f_{C_n}\}$ and $F_D = \{f_{D_1}, \ldots, f_{D_n}\}$ are the control and data flows, respectively. Let us denote the input/output flows of node n as $\delta(n)$ and $\Delta(n)$, and the source/target pins of flow f as $\phi(f)$ and $\Phi(f)$. For any given node n, $\delta(n) \neq \Delta(n)$ and for any given action node n_a, $\forall f \in F_D \bigcap \delta(n_a) : \Phi(f) \in P_{In}(n_a)$ and $\forall f \in F_D \bigcap \Delta(n_a) : \phi(f) \in P_{Out}(n_a)$ shall always hold. This means, that a flow cannot be input and output to the same node at the same time, and for a given action node, all input/output flows shall be associated with an input/output port, respectively;
- $G : F \subseteq g_1 \times g_2 \times \cdots \times g_n$ is a function mapping an *expression* to each flow.;
- $F_{Action} \subseteq a_1 \times a_2 \times \cdots \times a_n$ is a function mapping an *action* to each node. ▪

Informally, Gamma Activities are composed of *nodes* and flows in between them. A given *Action* node may have any number of *pins* with domain $d \in D$, for which there must be one and only one flow connected to the node.

A node $n \in N_{Action}$ may define the composition of activities when its effect is to call a specific subset of nodes. The subset is denoted as $GATL_n$.

N_{IR} contains the nodes *decision/merge*, while N_{LAS} contains the nodes *fork/join*, *initial/final* and *action* nodes. For the most part, these elements have similar behaviour as their SysML counterparts; however, there is a crucial difference regarding how a flow transmits a token. Figure 3.1 shows a simple data flow between two nodes, connected via their pins. Upon token transfer, the data inside the pins are transferred instantly, without any intermediate state in between.

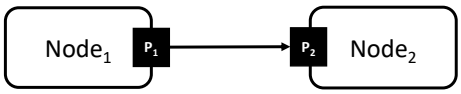


Figure 3.1: An example SysML data flow.

Contrarily, in GATL, the equivalent data flow does indeed contain the given token, creating an intermediate state, where the token is in neither of the nodes. This behaviour could

be modeled using a *Central Buffer* in SysML (Figure 3.2). The reason for this solution is simplicity; by creating this intermediate state (and others), it is easier to define the set of transitions necessary to formally define the semantics of the language.

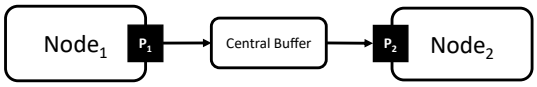


Figure 3.2: An example SysML data flow with a central buffer node.

3.2.1 Formal Behaviour

The behaviour of GATL is defined using the XSTS (Section 2.4) formalism:

Definition 4 (Gamma Activity Behaviour). In the context of XSTS, the defined set D becomes an XSTS domain set, the set V becomes an XSTS variable set. On a similar line, the functions G and F_{Action} return an *assume* and a *sequence* operation, respectively.

The XSTS describing the behaviour of GATL is the following: $XSTS_{GATL} = (D, V, V_C, IV, Tr, In, En)$, where:

- $D = GATL\rangle D \bigcup d_{NodeState} \bigcup d_{FlowState}$, where $GATL\rangle D$ is the domain in $GATL$, $d_{NodeState} = \{Idle, Running, Done\}$ and $d_{FlowState} = \{Empty, Full\}$ are the node and flow state domains representing their internal state. Node state *Idle* means a node is ready for a token, *Running* means it is currently executing and *Done* means it is done (but still contains a token). Flow states *Empty* and *Full* represent whether the flow contains a token;
- $V = GATL\rangle V \bigcup V_{NS} \bigcup V_{FS} \bigcup V_{NV} \bigcup V_{FV} \bigcup V_{PV}$, where $GATL\rangle V$ is the variables in $GATL$, $V_{NS} = \{v_{NS_1}, v_{NS_2}, \ldots, v_{NS_n}\}$ is the variable representing the *state* of the nodes with domain $d_{NodeState}$, $V_{FS} = \{v_{FS_1}, v_{FS_2}, \ldots, v_{FS_m}\}$ is the variable representing the *state* of the flows with domain $d_{FlowState}$ and V_{NV}, V_{FV}, V_{PV} are the variables representing the values contained inside *flows*, *nodes* and *pins* respectively;
- IV sets all variables to their default value;
- $V_C = V_{NS} \bigcup V_{FS}$ are the *control variables*;
- $Tr = T$, where T is single transition (defined at the end of the section);
- In sets all values of variables associated with *InitialNodes* to *Running*;
- $En = \emptyset$ is the empty environment transition, as simple activities do not have environments. ▪

We also define the following helper functions:

- $S_N : N \to V_{NS}$ is a function that returns the *state variable* of a node;
- $S_F : N \to V_{FS}$ is a function that returns the *state variable* of a flow;
- $V_{N_{In}} : N \times F \to V_{NV}$ is a function that returns the *input value variable* of a node regarding a specific connected flow;

- $V_N : N \to V_{NV}$ is a function that returns the *value variable* of a node;
- $V_F : F \to V_{FV}$ is a function that returns the *value variable* of a flow;
- $PV_N : N \times P \to V_{PV}$ is a function returning the *value variable* of a pin inside a node.

Informally, the behaviour of Gamma Activities is determined by the nodes' *state* (*Idle*, *Running*, *Done*), the nodes' and their pins' values, the flows' *state* (*Empty*, *Full*) and their values. For example, given an action node n and one of its pins p_1, $PV_N(n, p_1)$ would give us the exact value that p_1 contains in this instance. This gives us the power – contrary to the Activity-PN mapping introduced in Section 2.2.3 – to formally define the values contained in tokens.

Each flow and node may only contain one flow at a time; creating and destroying them on each transfer. The flow of tokens is modeled by changing the value of the state variables in such a way, that keeps the defined semantics. In the following, I incrementally build up these change operations and then construct the resulting XSTS.

Let us define a shorthand function for finding a node's input variable associated with a given flow:

$$V_{N_{In}}(n, f) = \begin{cases} PV_N(n, \Phi(f)) & \text{if } n \in N_{Action} \\ V_N(n), & \text{otherwise} \end{cases}$$

And a shorthand function for finding a node's output variable associated with a given flow:

$$V_{N_{Out}}(n, f) = \begin{cases} PV_N(n, \phi(f)) & \text{if } n \in N_{Action} \\ V_N(n), & \text{otherwise} \end{cases}$$

Next, I define various functions that return operations, which will be used to construct the transition T. In the next section, I use the following notations for XSTS operations:

- *sequences* are represented as operations after one another, or *sequence*(*op*), where *op* is a set of operations;
- *parallels* are represented as *parallel*(*op*), where *op* is a set of operations;
- *choices* are represented as *choice*(*op*), where *op* is a set of operations;
- *assumptions* are represented as *assume*(e), where e is an expression;
- *assignments* are represented as *assign*(v, *value*), where v and *value* are a *variable* and a *value*, respectively, with the same *domain*.

Definition 5 (Flow Transition Operations). Let us denote the source/target node of flow f as $\theta(f)$ and $\Theta(f)$ respectively. $O_{FlowIn}(f)$ is a function returning a *sequential* operation, which takes a token from a flow to a node:

$$
\begin{aligned}
&assume(S_F(f) = Full)\\
&assume(S_N(\Theta(f)) = Idle)\\
&assign(S_F(f), Empty)\\
&assign(S_N(\Theta(f)), Running)\\
&assign(V_{N_{In}}(\Theta(f), f), V_F(f))
\end{aligned}
$$

Informally, the returned operation checks that the flow's target node is in *Idle* state and the flow is in *Full* state. In which case it transfers the token by changing the state of the target node to *Running*, and its state to *Empty*. It also transfers its value to the correct value variable of the node. Let $O_{FlowOut}(f)$ be the function returning a *sequential* operation, which transfers a token from a node to a flow:

$$
\begin{aligned}
&G(f)\\
&assume(S_F(f) = Empty)\\
&assume(S_N(\theta(f)) = Done)\\
&assign(S_F(f), Full)\\
&assign(S_N(\theta(f)), Idle)\\
&assign(V_F(f), V_{N_{Out}}(\theta(f), f))
\end{aligned}
$$

The returned operation checks that the node is *Done* and the flow is *Empty* and *enabled*, in which case it transfers the token by changing their states. Note, that it also calls the function G, which returns an assume operation for the given flow. ▪

Definition 6 (Node Token In/Out Operations). Given the different behaviours of *IR* and *LAS* nodes, we must construct different operations for their in and out transitions. $O_{IRNodeIn}(n)$ is the function returning a *choice* operation that represents the "token intake" of an *IR* node:

$$
O_{IRNodeIn}(n) = choice\left(\bigcup_{f \in \delta(n)} O_{FlowIn}(f)\right)
$$

And $O_{IRNodeOut}(n)$ is the function returning a *choice* operation that represents the "token output" of an *IR* node:

$$
O_{IRNodeOut}(n) = choice\left(\bigcup_{f \in \Delta(n)} O_{FlowOut}(f)\right)
$$

On a similar note, the functions constructing the *LAS* node "token intake" and „token output" operations are the following:

$$O_{LASNodeIn}(n) = parallel\left(\bigcup_{f \in \delta(n)} O_{FlowIn}(f)\right)$$
$$O_{LASNodeOut}(n) = parallel\left(\bigcup_{f \in \Delta(n)} O_{FlowOut}(f)\right)$$

For the sake of simplicity, I define the following functions to merge all the node in/out operations:

$$O_{LASNodeIO}(n) = choice\left(O_{LASNodeIn}(n) \bigcup O_{LASNodeOut}(n)\right)$$
$$O_{IRNodeIO}(n) = choice\left(O_{IRNodeIn}(n) \bigcup O_{IRNodeOut}(n)\right)$$
$$O_{NodeIO}(n) = \begin{cases} O_{IRNodeIO}(n) & \text{if } n \in N_{IR} \\ O_{LASNodeIO}(n), & \text{otherwise} \end{cases} .$$

In which case, $O_{NodeIO}(n)$ returns an operation that can transfer the tokens in/out of the specified node.

Informally, these operations realise the semantics of the *LAS* and *IR* nodes, by either putting the *flow in* and *flow out* operations inside a *parallel* or a *choice*, respectively.

Definition 7 (Node Run Operations). Node transition operations take the given node from *Running* state to *Done* state, while also executing the underlying operation. Generally, $O_{NodeRun}(n)$ function is defined as:

$$assume(S_N(n), Running)$$
$$assign(S_N(n), Done)$$

However, some nodes have special behaviours. If the node is an *Action* node, it can contain either a *Gamma Action* expression, or a composite *Activity*.

- If the node contains *Gamma Action*, the contained action is mapped to an operation $O_{Action}(n)$, and added to $O_{NodeRun}(n)$. Let us call this function $O'_{NodeRun}(n)$
- If the node contains an *Activity*, the contained activity first has to be started, and the state of the node can change only when the contained activity is done. Let us call this function as $O''_{NodeRun}(n)$.

$O'_{Run}(n)$ function is defined as:

$$\begin{aligned} &assume(S_N(n), Running) \\ &O_{Action}(n) \\ &assign(S_N(n), Done) \end{aligned}$$

In contrast, $O''_{NodeRun}(n)$ has to be defined to start and wait for the contained activity. Let $In(n)$ and $Fin(n)$ be the sets of *initial* and *final* nodes in $GATL_n$.

$$O_{Start}(n) = sequence\left(\bigcup_{n_{In} \in In(n)} \Big(assume(S_N(n_{In}) = Idle) \bigcup assign(S_N(n_{In}), Running)\Big)\right)$$

$$O_{Finish}(n) = sequence\left(\left(\bigcup_{n_{Fin} \in Fin(n)} assume(S_N(n_{Fin}) = Done)\right) \bigcup assign(S_N(n), Done)\right)$$

$$O_{ActivityRun}(n) = choice\Big(O_{Start}(n) \bigcup O_{Finish}(n)\Big)$$

$$O''_{NodeRun}(n) = sequence\Big(assume(S_N(n), Running) \bigcup O_{ActivityRun}(n)\Big) \quad .$$

Informally, the returned operation checks if the node is in state *Running*, and then chooses: it either sets the contained activity's initial nodes *Running* if they are currently *Idle*, or sets the node's state *Done* if the contained activity's final nodes are *Done*. Thus, the node is considered *Done* only when the contained activity is also done.

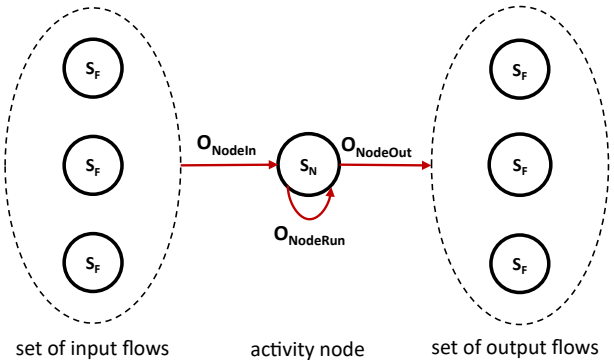
Definition 8 (Composite Node Operation). Putting all of the work together, we can define a function returning the operation representing all behaviour of a given node:

$$O_{Node}(n) = choice\Big(O_{NodeIO}(n) \bigcup O_{NodeRun}(n)\Big) \quad .$$

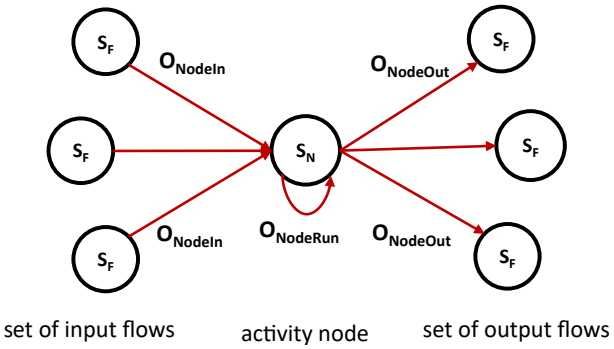
Informally, $O_{Node}(n)$ returns a choice operation, that either moves the tokens in/out, or executes the internal action of the node. The various operations defined in the previous sections can be seen in Figure 3.3.

As the final step, the transition T is constructed by applying the $O_{Node}(n)$ function on each node, and wrapping them with a *parallel* operation:

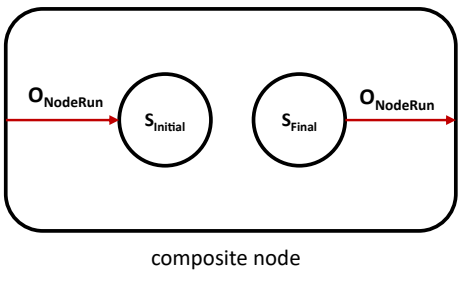
$$T = parallel\left(\bigcup_{n \in N} O_{Node}(n)\right)$$



(a) O_{Node} operations for a LAS node.



(b) O_{Node} operations for an IR node.



(c) $O_{NodeRun}$ operations for a *composite* action node.

Figure 3.3: An illustration of the state change operations.

3.3 Language Gramar

Similarly to the Gamma Statechart Language, the Gamma Activity Language is intended to be a first-class citizen in the Gamma Framework, thus it must have a grammar to support the representation of models in a textual way. This grammar definition incorporates elements from the SysMLv2 [13] language design, while also fitting into the already existing language family of Gamma (Section 2.3). In the following, I define the *metamodel* and the *grammar* created to realise the formalism specified in Section 3.2.

3.3.1 Metamodel

Due to the complexity of the final metamodel of the language, I have split it into multiple parts for easier understanding: Pins, Flows, Activity Nodes, Structure, Composite Activities and Data-, Pin-reference.

Pins

Pins are categorised into two sets, *InputPins* and *OutputPins*. All pins have a *Type*[2] associated with them, which define their domain. Figure 3.4 shows this section of the metamodel.

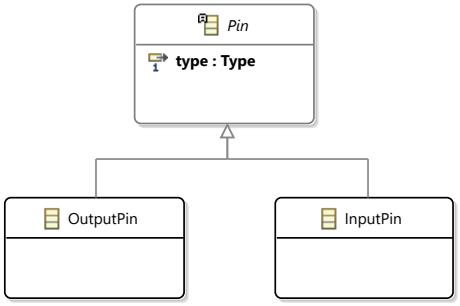


Figure 3.4: The pin metamodel diagram

Flows

Flows have two kinds, *ControlFlows* and *DataFlows*. All flows have a guard of type *Expression*[3], which can evaluate to a *boolean* value; if it evaluates to *True*, the flow is considered *enabled*. Figure 3.5 depicts the relation of flows in the metamodel.

Control Flow *ControlFlows* have a reference to their source and target nodes.

Data Flow *DataFlows* contain a *DataSourceReference* and a *DataTargetReference*, which can either be a *Pin*, or a *DataNode*. A data token may contain a value of any kind, but that token can travel only to and from data *sources* and *targets*. This will be explained in more detail below.

[2]Types come from the Gamma Expression Language
[3]Written in the Gamma Expression Language

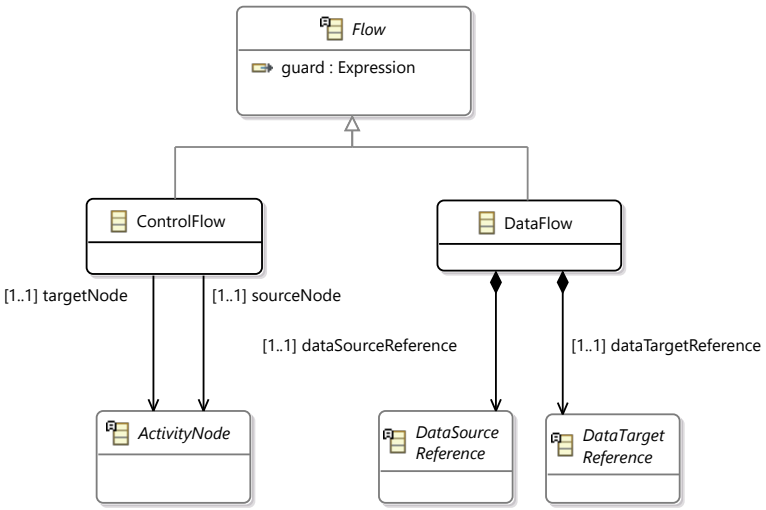


Figure 3.5: The Flows structure.

Activity Nodes

In the following, I will talk about the different kinds of *ActivityNodes* and their special meanings. The metamodel described in this section can be seen in Figure 3.6.

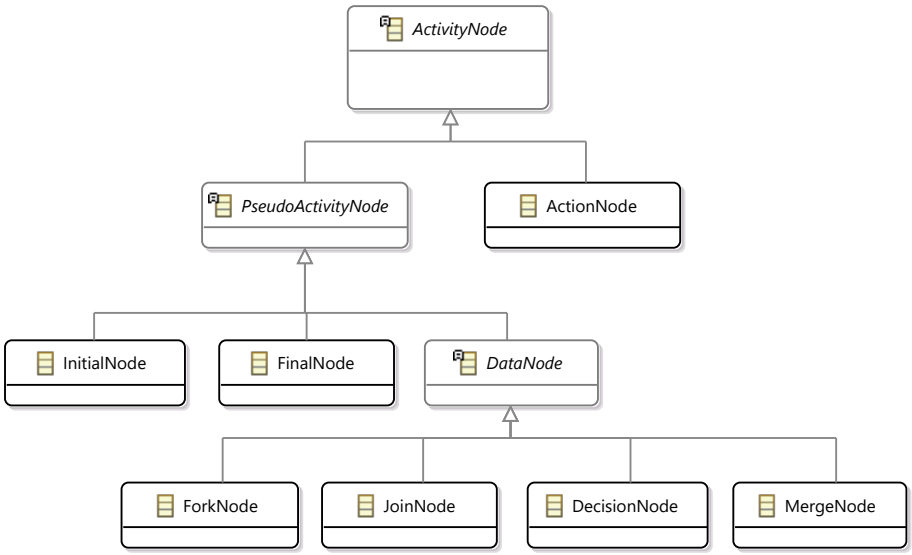


Figure 3.6: The Activity Node structure.

Action Node *ActionNodes* represent a specific action the activity may execute. This action can be defined in multiple ways.

Pseudo Activity Node *PseudoActivityNodes* are nodes that do not represent a specific action, however are needed to convey specific meanings, e.g., the initial active node, or a decision between flows.

Initial Node *InitialNodes* represent the entry point of the activity.

Final Node A node representing the final node of the activity.

Data Node *DataNodes* encapsulate the meaning of *data* inside activities.

Fork Node *ForkNodes* are used to model parallelism by creating one token on each of its output flows when executed.

Join Node *JoinNodes* are the complementary elements of fork nodes; the additional created tokens are swallowed by this node by transfering out one token, regardless of the number of input flows.

Decision Node *DecisionNodes* create branches across multiple output flows. An input flow's token is removed, and transfered out to a single output flow – depending on which of the output flows are *enabled*[4].

Merge Node *MergeNodes* forward all incoming tokens as soon as they arrive, one by one. They are used to *merge* different flow paths (created using *decisions*).

Root Structure

The root structure defines where the elements of the activity reside in the model. The metamodel described in this section is depicted in Figure 3.7.

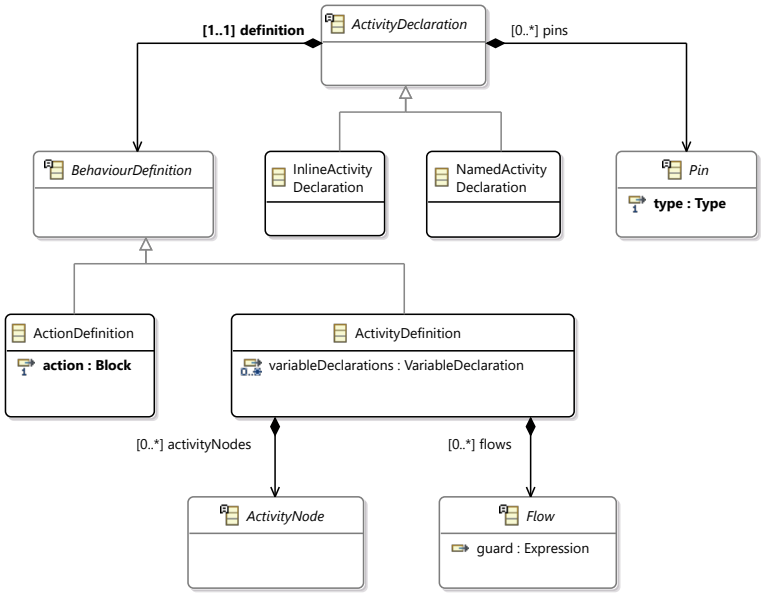


Figure 3.7: The root structure of the language.

Activity Declaration All elements inside an activity are contained in a root *Activity-Declaration* element. It contains *Pins* needed for value passing and a *BehaviourDefinition*. Declarations can be *InlineActivityDeclarations*, which means they are declared in an other

[4]In the case when multiple flows are enabled one is chosen nondeterministically

declaration, or *NamedActivityDeclaration*, which is a standalone activity declaration – *NamedActivityDeclaration* can be referenced from other parts of the model, while *Inline-ActivityDeclaration* cannot.

Behaviour Definition *BehaviourDefinitions* define how the activity is described; using activity nodes, or by the Gamma Action Language. *ActionDefinition* contains a single *Block*[5], which is executed as is when the activity is executed[6]. *ActivityDefinitions* contain *ActivityNodes* and *Flows*, and are used to *compose* activities.

Composing Activities

ActionNodes may contain a single *ActivityDeclarationReference* to an *ActivityDeclaration*[7], in which case the execution of said node will also include the execution of the underlying *ActivityDeclaration*. This construction gives us the power to pre-declare, or inline specific activities in the model; and use any behaviour definition defined above (Section 3.3.1) for them. Figure 3.8 shows this part of the metamodel.

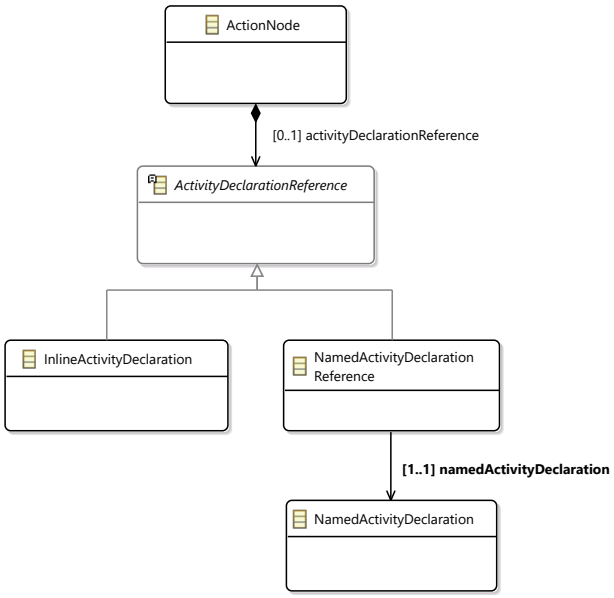


Figure 3.8: The action node containment hierarchy.

Data Source Reference and Data Target Reference

In order to correctly set a data flow's data source and data target, the model has to store where the pins are referenced. A given *InputPin* can be considered a *DataTarget* from outside of the associated *Activity*, however, it is a *DataSource* from inside the *Defintion*. *DataNodes* can be considered both data sources and data targets. See Figure 3.9 for the corresponding metamodel part.

[5] A *Block* contains multiple *Actions* which are executed one after the other

[6] This means, that upon execution the given activity is executed atomically; it will not be interlaced with other XSTS transitions. See Section 4.1.1.

[7] If the node does not have any, it is considered a *simple* node, without any implementation

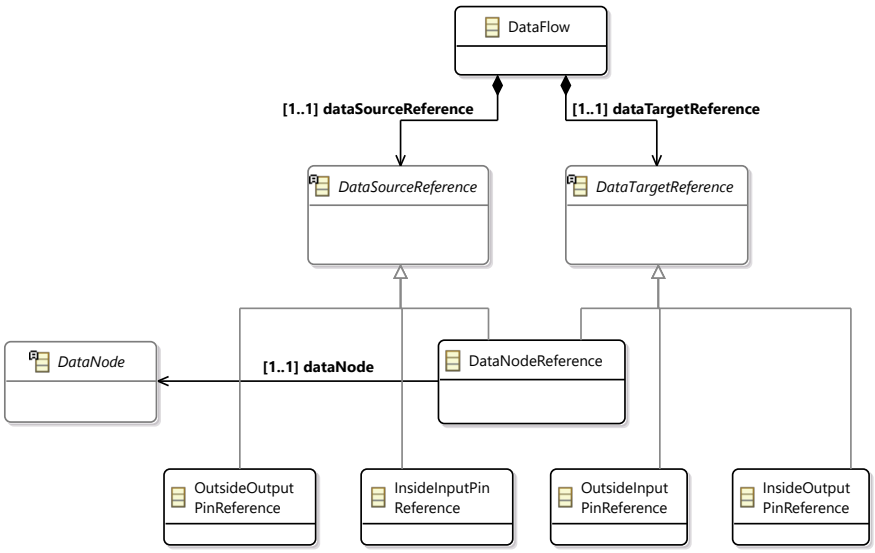


Figure 3.9: The Data Source-Target reference structure.

Example of inside-input/outside-output pin Figure 3.10 shows an example for the multidirectional effect of pins. From the perspective of the flow $P_1 \rightarrow P_2$ the pin P_1 is a *DataSource* and the pin P_2 is a *DataTarget*. However, from the perspective of the flow $P_2 \rightarrow P_3$, the pin P_2 is a *DataSource* – because the latter flow is inside the composite activity.

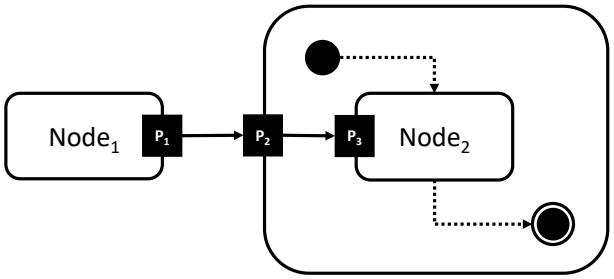


Figure 3.10: The Data node reference structure.

Pin Reference

Pin references are used to define a rigid pin-reference structure in the model. *InputPin-References* have a reference to a specific *InputPin*, *OutputPinReferences* have a reference to a specific *OutputPin*. *InsidePinReferences* and *OutsidePinReferences* are used to define the direction in which the reference sees the given pin; inside references see it from the inside, outside references see it from the outside. The *OutsidePinReference* must also have a reference to the specific *ActionNode* the pin is associated with[8]. See Figure 3.11 for the corresponding metamodel part.

[8]Note that the inside pin reference does not have a node reference, because the node must be the activity that contains the pin

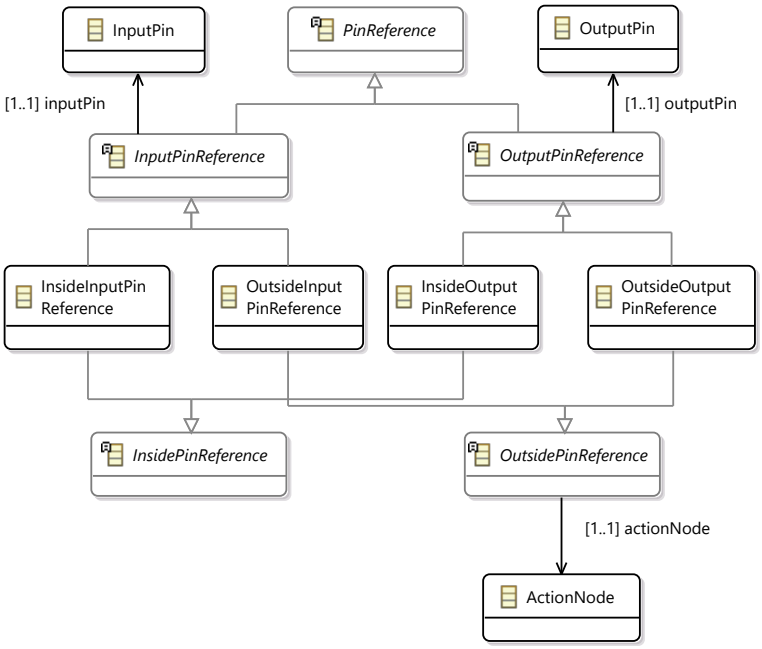


Figure 3.11: The Pin reference structure.

3.3.2 Concrete Syntax

In order to make it easier to test and visualise activities, I defined a grammar for the metamodel in Xtext. The SysMLv2 language served as the main inspiration for the language, however, much of the *syntactic sugars* have been omitted for the sake of simplicity. Listing 3.1 is the activity Figure 2.3 example written in GATL. For the exact grammar definition, please see Section A.2.

```
activity CompilationProcess {
    var errors : boolean := false

    initial Initial
    merge Merge
    fork Fork

    action Read1 : activity (out pr1 : integer)
    action Compile1 : activity (in pc1 : integer)
    action Read2 : activity (out pr2 : integer)
    action Compile2 : activity (in pc2 : integer)

    join Join
    action Link
    decision Decision
    action Edit
    final Final

    control flow from Initial to Merge
    control flow from Merge to Fork
    control flow from Fork to Read1
    control flow from Fork to Read2

    data flow from Read1.pr1 to Compile1.pc1
    data flow from Read2.pr2 to Compile2.pc2

    control flow from Read1 to Join
    control flow from Read2 to Join
    control flow from Join to Link
    control flow from Link to Decision
    control flow from Decision to Edit [errors]
    control flow from Edit to Merge
    control flow from Decision to Final [!errors]
}
```

Listing 3.1: Gamma Activity Language representation of the compilation activity.

Chapter 4

Integrating the Activity Language Into Gamma

In the previous chapter, I introduced the Gamma Activity Language – the important parts of its metamodel along with the semantics of the model elements and their textual syntax. However, in order to formally verify activity models, the language has to be integrated into the Gamma transformation pipeline (see Figure 2.7). I present the important aspects of this integration, I start by defining the semantics of activities alongside statecharts in Section 4.1, after which I define the integration semantics in Section 4.2. Finally, I overview the implementation details in Section 4.3.

4.1 Activities Alongside Statecharts

In this section, I present the various questions that arose when I integrated GATL into the statechart language of Gamma, and present my solutions and reasoning for them.

4.1.1 Calling Activities

In order to create a connection between statecharts and activities, the user needs an interface to do so. In SysML, there are many ways to call activities from statecharts. In the following I summarize them, and chose one for the language.

Transition Actions One possible solution is calling activities from transition actions. At first glance, this makes the most sense, however transitions have to be executed in a single step, meaning they can not contain loops and recursions. As activities are inherently parallel in nature, the resulting implementation would have to *flatten* the activity model. Because of time constraints, this solution was implemented.

Do Behaviours In SysML, states may have *do behaviours*. This means, that the *behaviour* (activity in our case) is *under execution* while the state machine is inside the given state, and *halted* when the state is left. However, there are many questions:

How does an activity know to halt?

- The state *signals* the activity that it should end, and waits until it halts – in this case a synchronisation step is created;

- The activity checks if it should run, that is, whether the state machine is in the given state. However, this adds an extra assume operation per each node and flow.

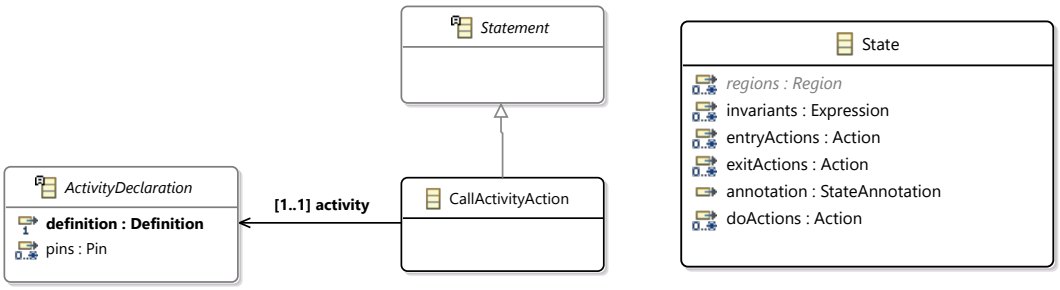
What happens, when a state has a transition into itself, while also having a do behaviour action?

- Either a new activity is created each time the state is entered;
- Or the same activity is used after reset.

For the sake of simplicity, I choose the last option of each for do behaviours:

- The activity should check if its state is active before each operation;
- The entry action of the transition resets the activity.

Note that these questions have a critical impact on the semantics of composing state machines and activities, and unfortunately, SysML does not give an exact answer. Figure 4.1 shows the added elements to the Gamma metamodel.



(a) Call activity action

(b) Do action on states

Figure 4.1: Extensions to the Gamma metamodel

4.1.2 Activities Defining Components

In SysML, components' behaviour may be defined directly by activities. However, in Gamma, all components use reactive semantics, which would have been difficult to implement, in the context of activities. Thus, SysML components that use Activity Diagrams as their behaviour must be mapped wrapper statechart calling the activity.

Although this constrains us to only use statecharts directly, we can still utilise the reactive nature of components, by adding a special activity node, that listens for such events.

TriggerNodes extend the activity semantics, by adding an additional assumption operation inside the $O_{NodeRun}$ operation function, checking if the given event has been received. The example in Listing 4.1 shows a trigger node, which is only executed when it has a token from the initial node, and the *start* event is received from the *Control* port.

```
statechart Statechart [
    port connection : requires Control
] {
    // definitions ...

    activity DoActivity {
        initial Initial
        trigger AcceptEvent when connection.start
        final Final

        control flow from Initial to AcceptEvent
        control flow from AcceptEvent to Final
    }
}
```

Listing 4.1: An example trigger node accepting a start signal.

4.2 Integration Semantics

As presented in the transformation pipeline (Figure 2.7), Gamma transforms the *statecharts* and *components* into an XSTS model instance. In the following, I show how to merge XSTS created from *components* with the XSTS created from activities.

The unified transformation is carried out in three steps. Section 4.2.1 presents how we preprocess the composite model by creating activity *instances* and adding the initialisation action to the calling states. Next, in Section 4.2.2 we transform the components using the Gamma transformation pipeline and then transform the called (now unique) activities. The resulting XSTS models are merged, resulting in the final XSTS. This XSTS model then can be forwarded to the model checkers.

4.2.1 Preprocess Components

As the first step, we find all states that contain a *call activity* do action – denoted as S. For each $s \in S$, we construct a new *ActivityInstance* for the called activity S_{Act}, and add an *InitialiseActivityAction* to its entry actions. This step ensures that two states calling the same activity will not have conflicting variables in the resulting XSTS[1], and the called activity is initialised correctly before it is started. Figure 4.2 shows the extensions added to the Gamma metamodel.

4.2.2 Transform Components and Activities

As the next step, we transform the Gamma components, denoting the resulting model as $XSTS_{Comp}$, and the activity instances, denoted as $XSTS_{S_{Act}}$. In order to prevent the activity from running when the state is not active, an additional *assume* operation is added to the $O_{Node}(n)$ function, checking whether the associated state is active or not. Finally, the resulting XSTS models are merged.

$$XSTS = XSTS_{Comp} \bigcup \left(\bigcup_{s_{Act} \in S} XSTS_{s_{Act}} \right)$$

[1] In XSTS all variables are defined the a global scope, thus they must have unique name

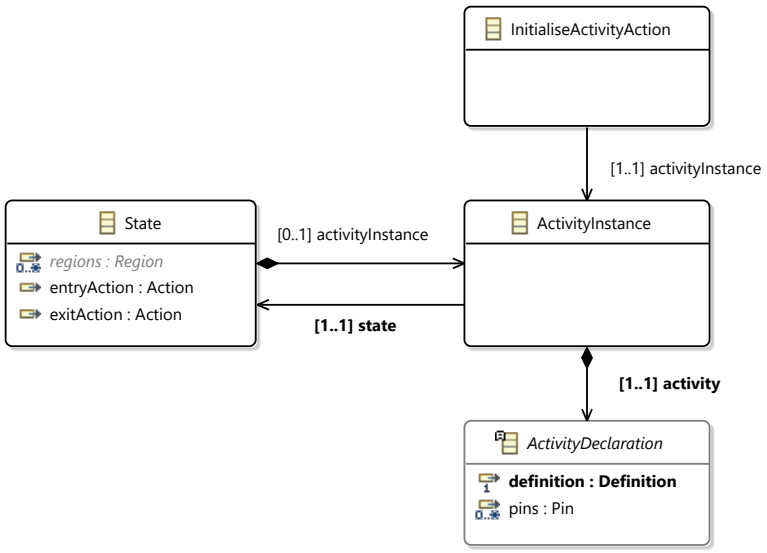


Figure 4.2: Activity instance and initialise activity extensions for the Gamma metamodel.

4.3 Implementation Remarks

I used multiple technologies during the implementation of GATL. Gamma is implemented as an Eclipse plugin[2], and uses multiple frameworks: Ecore Modeling Framework[3] (EMF) to create the metamodels, Xtext[4] to define the language grammars, and Viatra[5] to transform the models.

During the implementation, I added a new *EMF* project and a new *Xtext* project. I then had to extend the preexisting Gamma Statechart Language, and the transformation pipeline.

The contributions include (at the time of writing) 12,601 line additions, 2,235 line deletions in 42 commits. There is currently an open pull request to the main GitHub repository[6].

These changes implemented are visualised in Figure 4.3: added parts are outlined with green, while edited parts are outlined with orange.

[2]https://www.eclipse.org/downloads/
[3]https://www.eclipse.org/modeling/emf/
[4]https://www.eclipse.org/Xtext/
[5]https://www.eclipse.org/viatra/
[6]https://github.com/ftsrg/gamma

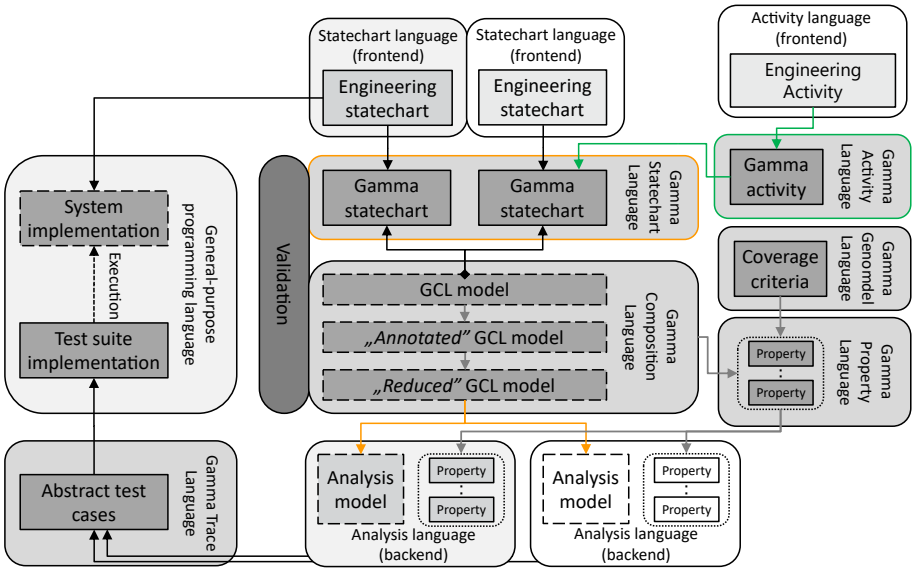


Figure 4.3: Overview of my modification to the Gamma transformation pipeline.

Chapter 5

Evaluation

In this chapter, I present two case studies to showcase the usability and verifiability of the Gamma Activity Language, using a handcrafted simple model and an industry example model.

5.1 Case Study - Compilation

The first case study is about the running example introduced in Figure 2.3. The goal of this experiment is to evaluate the formal verification capabilities of the language using a toy model.

5.1.1 Modeling

The GATL representation of the model has already been presented in Listing 3.1, however, some modifications have to be implemented in order to run the verification. As activities can not be verified directly, they must be wrapped within a statechart. Also, because GPL properties can not reference activity model elements, an additional flag (variable declaration of type boolean) must be added, to enable the construction of a reachability property specifying the end of the activity. The modifications can be seen in Listing 5.1.

```
1  statechart CompilationWrapper {
2      var activityDone : boolean := false
3      region Main {
4          initial MainEntry
5          state Wrapper {
6              do / call CompilationProcess;
7          }
8      }
9      transition from MainEntry to Wrapper
10     activity CompilationProcess {
11         // ...
12         action Done : activity [language=action] {
13             activityDone := true;
14         }
15         final Final
16         // ...
17         control flow from Decision to Done [!errors]
18         control flow from Done to Final
19     }
20 }
```

Listing 5.1: The textual representation of the modified compilation example.

The next step was to wrap the statechart in a *cascade* component, and define the reachability property of the variable *activityDone* being true:

```
cascade Compilation {
    component CompilationWrapper : CompilationWrapper
}
```

```
component Compilation

// Can the variable activityDone ever be true?
E F [ { variable CompilationWrapper.activityDone } ]
```

Finally, I ran the verification using the Theta and the UPPAAL model checkers.

5.1.2 Results and Conclusion

Table 5.1 contains the execution time of the two model checkers. Interestingly, Theta took – on average – one order of magnitude more time, then UPPAAL.

The trace Listing 5.2 shows the steps the model checkers took to reach the state described by the property ($activityDone = true$). The first step shows the initial values of the system, while the following steps show how the values change after the component is scheduled. As can be seen, the second step is repeated 17 times before the variable becomes true. As there are no transitions in the XSTS model from the statechart, the only transitions that can be fired come from the activity. The token in the activity goes through eight[1] nodes and eight flows to reach node *Done*, after which an additional step is needed to execute its action: thus resulting in a total of $8 + 8 + 1 = 17$ steps.

Model Checker	Successful Verification	Execution Time
Theta	*Yes*	1332 ms
UPPAAL	*Yes*	162 ms

Table 5.1: The execution times for the compilation example.

The reason for the repetition is the lack of trace information regarding the activity model; the XSTS transitions are executed as expected, however, the trace mechanism of Gamma can not display these changes.

This case study showed that the Gamma Activity Language formalism does indeed work for simple examples. However, there is still more work to be done, to let the user choose activity nodes as reachability properties, and to show activity variables in the resulting trace (see Chapter 6).

5.2 Case Study - Simple Space Mission

This section introduces an example model from the aerospace domain which we use as a case study to demonstrate the capability of the Gamma Activity Language to model complex SysML behavioural models. The example model was proposed by NASA in the context of the OpenMBEE[2] framework. The goal of OpenMBEE is to create a common model repository to facilitate tool integration, so the ability to handle models in the scope of this project can raise the relevance of any model analysis tool.

[1] Merge, Fork, Read(1,2), Compile(1,2), Join, Link, Decision, Edit, Done
[2] https://www.openmbee.org/

```
step {
    act {
        reset
    }
    assert {
        CompilationWrapper.Wrapper
        CompilationWrapper.activityDone = false
    }
}
step {
    act {
        schedule component
    }
    assert {
        CompilationWrapper.Wrapper
        CompilationWrapper.activityDone = false
    }
}
// 16 more
step {
    act {
        schedule component
    }
    assert {
        CompilationWrapper.Wrapper
        CompilationWrapper.activityDone = true
    }
}
```

Listing 5.2: The trace of the run formal verification.

The Gamma models used in this section are a modification of a previous case study [11], in which the activities were mapped to parallel regions and composite states. For this case study, I modified the models to use GATL to represent the activities.

5.2.1 System Modeling

The Simple Space Mission SysML model describes how a satellite with limited battery charge communicates with a ground station, where data transfer results in large power losses. The state-based behaviour of the system can be seen in Figures 5.1 and 5.2, while the more complex activities are depicted in Figures 5.3 and 5.4.

The challenge of the mapping is posed by the elements that are not supported in GATL. The SysML activities use *duration constraints* to model how much time a given action takes to execute, along with *interrupting edges* and *internal signals* to simplify the models. The GATL language does not support these elements, however, they can be substituted with other modeling constructs. Duration constraints can be modeled using *timeouts* and *trigger nodes* to insert waiting before the given action can be executed – although the time waited will be deterministic, unlike the SysML specification. The behaviour defined with the interrupting edge and internal signals can be substituted with additional boolean variables that signal when the execution of the activity should be halted. The easiest way to halt the activity is to leave its state. To detect the changes in the flags, I added a timeout that tests for the flags every second. The created Gamma models can be found in Section A.3

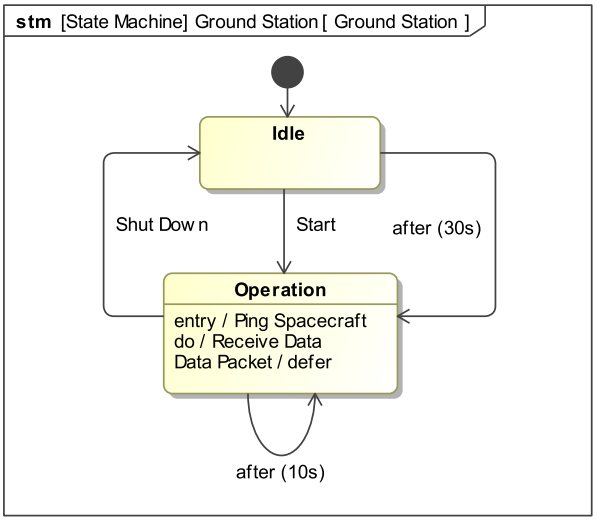


Figure 5.1: The state machine describing the behaviour of the ground station component.

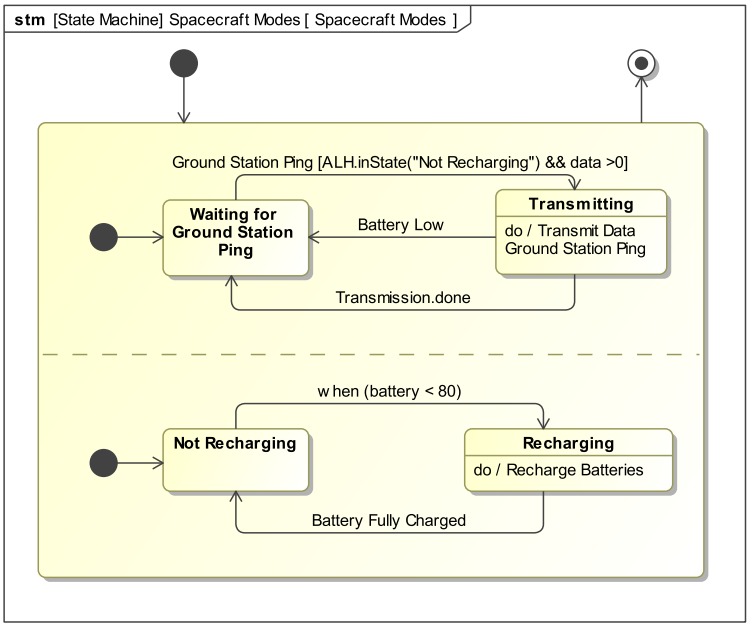


Figure 5.2: The state machine describing the behaviour of the spacecraft component.

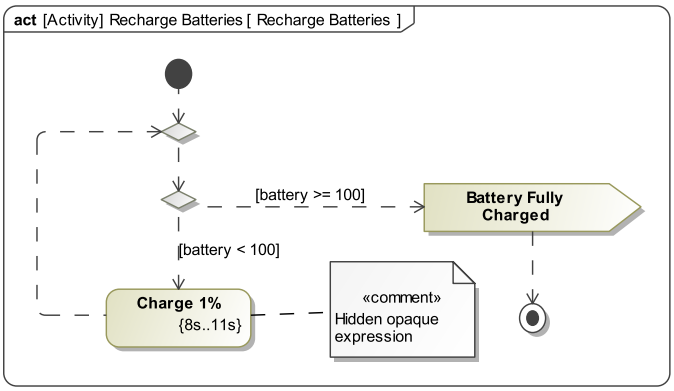


Figure 5.3: The activity diagram describing the battery recharge process of the spacecraft component.

5.2.2 Results and Conclusion

To check the conformance of the Gamma model with the original SysML model, I generated a state covering test set using the test generation functionality of Gamma, which produces reachability properties for all states in the system. Table 5.2 shows the execution times of the UPPAAL model checker. The table clearly shows how the state space of the low-level formalism "exploded" when checking for the *Satellite.Battery.Recharging* state, hence the high duration.

State	Successful Verification	Execution Time
Station.Main.Idle	Yes	239 ms
Station.Main.Operation	Yes	222 ms
Satellite.Communication.WaitingPing	Yes	179 ms
Satellite.Communication.Transmitting	Yes	220 ms
Satellite.Battery.NotRecharging	Yes	171 ms
Satellite.Battery.Recharging	Yes	35,998 ms

Table 5.2: The execution times for the Simple Space Mission system using UPPAAL.

In contrast, Table 5.3 shows the execution times of the Theta model checker. Every property took significantly more time to run on Theta, moreover, the previous state space explosion caused Theta to run out of memory.

State	Successful Verification	Execution Time
Station.Main.Idle	Yes	960 ms
Station.Main.Operation	Yes	1450 ms
Satellite.Communication.WaitingPing	Yes	890 ms
Satellite.Communication.Transmitting	Yes	1172 ms
Satellite.Battery.NotRecharging	Yes	947 ms
Satellite.Battery.Recharging	–	*out of memory*

Table 5.3: The execution times for the Simple Space Mission system using Theta.

This case study showed, that real world SysML models can be mapped to the Gamma Activity Language, although, some SysML elements may have to be transformed into a series of GATL elements manually. However, the model verification takes exponentially more time as we increase the model elements.

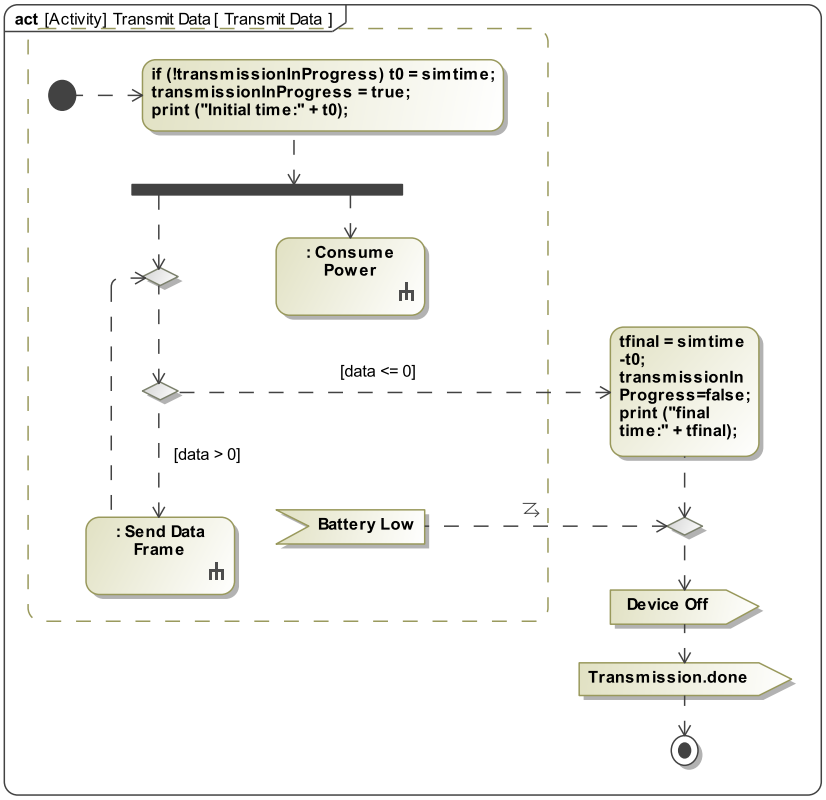


Figure 5.4: The activity diagram describing the data transmission process of the spacecraft component.

Chapter 6

Conclusion

In this work, I have proposed and implemented the Gamma Activity Language that extends the Gamma Statechart Composition Framework with support for *do actions* in states describing activities. I have shown the theoretical background of state-based and process-based behavioural modelling and motivated the need for formal verification of such models. After examining the related work, which mainly focuses on verifying activities alone, I have formalized the precise semantics of the new activity language by providing a mapping to Gamma's XSTS language. Combining state machines and activities in Gamma is now possible with the usage of *do actions*, which are activities performed while the component is in a certain state. Finally, I have demonstrated through the simple case study model used throughout the report as well as a more complex example coming from the space domain that the proposed approach indeed works. This work will provide the foundations to more closely examine the possible interactions between state machines and activities, and create solid foundations to improve upon all the shortcomings of this initial prototype.

Future Work As direct next steps, I plan to:

- Extend the Gamma Property Language and Gamma Trace Language to integrate with activity models.
- Implement a broader subset of the SysML formalism to take the language closer to the user level.
- Extend the semantics of Gamma Activity models with a queueing system for multiple tokens flowing on the same flow.
- Enable the definition of Gamma components directly with activities - as this would allow more flexibility in the design of heterogeneous systems.
- Find a way to use activities as transition effects, entry or exit behaviours, which would require a different mapping of activities to XSTS models.
- Explore alternatives in the XSTS mapping to improve verification performance.

Acknowledgements

I would like to express my gratitude to my supervisors, Vince Molnár and Bence Graics, who have continuously guided me during this work, providing me valuable insights and feedback anytime I needed it. I would also like to thank András Vörös for starting me down the path of MBSE and formal verification all those years ago, and giving me the courage to write this report. And last, but not least, I would like to thank all my friends for their extreme patience and understanding during the last weeks.

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Appendix

A.1 XSTS Language

In this appendix I introduce the exact language constructs for the XSTS language

Types

XSTS contains two default variable types, logical variables (*boolean*) and mathematical integers (*integer*). XSTS also allows the user to define *custom types*, similarly to enum types in common programming languages.

A custom type can be declared the following way:

```
type <name> : { <literal_1>, . . . , <literal_n> }

type Color : { RED, GREEN, BLUE }
```

Variables

Variables can be declared the following way, where `<value>` denotes the value that will be assigned to the variable in the initialization vector:

```
var <name> : <type> = <value>
```

The variable can only take a value of the specified type.

If the user wishes to declare a variable without an initial value, this is possible as well:

```
var <name> : <type>
```

A variable can be tagged as a control variable with the keyword `ctrl`:

```
ctrl var <name> : <type>
```

In which case the variable v will also be added to V_C (the set of control variables).

Examples:

```
var a : integer
ctrl var b : boolean = false
var c : Color = RED
```

Operations

The behaviour of XSTS can be described using basic and composite operations. Basic operations include assignments, assumptions and havocs. In the following, you can see an example for each, where `<expr>` is an expression returning a value, and `<varname>` is the name of a variable.

```
assume <expr>

<varname> := <expr>

havoc <varname>
```

Composite operations are either non-deterministic choices, sequences or parallels. Nondeterministic choices have the following syntax, where `<operation>` are arbitrary basic or composite operations:

```
choice {
    <operation>
} or {
    <operation>
}
```

Sequences have the following syntax:

```
<operation>
<operation>
<operation>
```

And parallels have the following syntax:

```
parallel {
    <operation>
    <operation>
}
```

Transitions

Each transition is a single operation (basic or composite). We distinguish between three sets of transitions, *Tran*, *Init* and *Env*. Transitions are described with the following syntax, where `<transition-set>` is either `tran`, `env` or `init`:

```
<transition-set> {
    <operation>
} or {
    <operation>
} or
//...
or {
    <operation>
}
```

A.2 Gamma Activity Language

The following section gives high level introduction into the syntax of the Gamma Activity Language.

Pins

Pins can be declared the following way, where `<direction>` can be either `in` or `out`, and `type` a valid Gamma Expression type.

```
<direction> <name> : <type>
```

For example:

```
in examplePin : integer
```

where the direction is `in`, the name is `examplePin` and the type is `integer`.

Nodes

Nodes can be declared by stating the `type` of the node and then it's name. The type determines the underlying meta element.

The available node types:

```
initial InitialNode
decision DecisionNode
merge MergeNode
fork ForkNode
join JoinNode
final FinalNode
action ActionNode
```

Flows

The behaviour of the Activity can be described by stating `data` or `control` flows between two nodes. Flows may have `guards` on them, which limits when the flow can fire. Activities may only be from the current activity definition's children. Pins can be accessed using the `.` accessor operator, the activity on the left hand side, and the pin's name on the right. The enclosing activity's name is `self`.

Flows can be declared the following way, where `<kind>` is the kind of flow, `<source>` and `<target>` is the source/target node or pin, and `<guard>` is a Gamma Expression returning boolean:

```
<kind> flow from <source> to <target> [<guard>]

control flow from activity1 to activity2
control flow from activity1 to activity2 [x == 10]
data flow from activity1.pin1 to activity2.pin2
data flow from self.pin to activity3.pin2
```

Declarations

Activity declarations state the *name* of the activity, as well as its *pins* A.2.

```
activity Example (
    //..pins..
) {
    //..body..
}
```

You can also declare activities inline by using the : operator:

```
activity Example {
    action InlineActivityExample : activity
}
```

Definitions

Activities also have definitions, which give them bodies. The body language can be either `activity` or `action` depending on the language metadata set. Using the `action` language let's you use any Gamma Action expression, including timeout resetting, raising events through component ports, or simple arithmetic operations.

An example activity defined by an action body:

```
activity Example (
    in x : integer,
    out y : integer
) [language=action] {
    self.y := self.x * 2;
}
```

Inline activities may also have pins and be defined using action language:

```
activity Example {
    action InlineActivityExample : activity (
        in input : integer,
        out output : integer
    ) [language=action] {
        self.output := self.input;
    }
}
```

A composite activity can be easily created using inline activity definition:

```
activity Example {
    initial Init1
    final Final1

    action InlineActivityExample : activity {
        initial Init2
        final Final2

        control flow from Init2 to Final2
    }

    control flow from Init1 to InlineActivityExample
    control flow from InlineActivityExample to Final1
}
```

```
activity Adder(
    in x : integer,
    in y : integer,
    out o : integer
) [language=action]  {
    self.o := self.x + self.y;
}

activity Example {
    initial Initial

    action ReadSelf1 : activity (
        out x : integer
    )
    action ReadSelf2 : activity (
        out x : integer
    )
    action Add : Adder
    action Log : activity (
        in x : integer
    )

    final Final

    control flow from Initial to ReadSelf1
    control flow from Initial to ReadSelf2
    control flow from Initial to Add
    data flow from ReadSelf1.x to Add.x
    data flow from ReadSelf2.x to Add.y
    data flow from Add.o to Log.x
    control flow from Log to Final
}
```

Listing A.2.1: Basic adder example.

Example

A simple example activity can be seen in Listing A.2.1. This example shows two read actions, that return a random value, which are added together and logged to the console. The addition is defined using a *NamedActivitDeclaraionReference*.

A.3 Spacecraft Model

```
package mission

import "Interface/Interfaces"
import "Groundstation/GroundStation"
import "Spacecraft/Spacecraft"

sync Mission [
    port _control : requires StationControl
] {
    component station : GroundStation
    component satellite : Spacecraft
    bind _control -> station._control
    channel [ satellite.connection ] -o)- [ station.connection ]
}
```

Listing A.3.1: The wrapper synchronous component.

```
import "/hu.bme.mit.jpl.spacemission.casestudy/model/.Mission.gsm"
component Mission
@ ("station.Main.Idle")
E F [ { state station.Main.Idle } ]
@ ("station.Main.Operation")
E F [ { state station.Main.Operation } ]
@ ("satellite.Communication.Transmitting")
E F [ { state satellite.Communication.Transmitting } ]
@ ("satellite.Battery.Recharging")
E F [ { state satellite.Battery.Recharging } ]
@ ("satellite.Communication.WaitingPing")
E F [ { state satellite.Communication.WaitingPing } ]
@ ("satellite.Check.CheckTimeout")
E F [ { state satellite.Check.CheckTimeout } ]
@ ("satellite.Battery.NotRecharging")
E F [ { state satellite.Battery.NotRecharging } ]
```

Listing A.3.2: The reachability properties generated by Gamma.

```
import "Interface/Interfaces.gcd"
import "Mission.gcd"

analysis {
    component : Mission
    language : XSTS-UPPAAL
    state-coverage
    constraint : {
        minimum-orchestrating-period : SCHEDULE_CONSTRAINT ms
        maximum-orchestrating-period : SCHEDULE_CONSTRAINT ms
    }
}

verification {
    language : XSTS-UPPAAL
    file : "Mission.xml"
    property-file : ".Mission.gpd"
}
```

Listing A.3.3: The definition of the run analysis and verification tasks.

```
package interfaces

interface DataSource {
    out event _data
    in event ping
}

interface StationControl {
    out event start
    out event shutdown
}

const SCHEDULE_CONSTRAINT : integer := 1501
```

Listing A.3.4: The interface model specifying the signals between the two components.

```
activity ReceiveData {
    initial Initial

    merge Merge

    trigger DataPacket when connection._data

    action ProcessData

    control flow from Initial to Merge
    control flow from Merge to DataPacket
    control flow from DataPacket to ProcessData
    control flow from ProcessData to Merge
}
```

Listing A.3.5: The Gamma implementation of the ReceiveData activity.

```
package groundstation

import "Interface/Interfaces.gcd"

statechart GroundStation [
    port connection : requires DataSource
    port _control : requires StationControl
] {
    timeout pingTimeout
    timeout autoStart

    region Main {
        initial Entry
        state Idle {
            entry / set autoStart := 30s;
        }
        state Operation {
            do / call ReceiveData;
            entry / raise connection.ping; set pingTimeout := 10s;
        }
    }

    transition from Entry to Idle
    transition from Idle to Operation when _control.start
    transition from Idle to Operation when timeout autoStart
    transition from Operation to Operation when timeout pingTimeout
    transition from Operation to Idle when _control.shutdown

    activity ReceiveData {
        // ...
    }
}
```

Listing A.3.6: The Gamma implementation of the Ground Station component.

```
activity RechargeBatteries {
    initial Initial

    merge Merge
    decision Decision
    action SetWait : activity [language=action] {
        set rechargeTimeout := 10s;
    }
    trigger Wait when timeout rechargeTimeout
    action Charge : activity [language=action] {
        batteryVariable := batteryVariable + 1;
    }
    action Full : activity [language=action] {
        batteryFullyCharged := true;
    }
    final Final

    control flow from Initial to Merge
    control flow from Merge to Decision
    control flow from Decision to SetWait [batteryVariable < 100]
    control flow from SetWait to Wait
    control flow from Wait to Charge
    control flow from Charge to Merge
    control flow from Decision to Full [batteryVariable >= 100]
    control flow from Full to Final
}
```

Listing A.3.7: The Gamma implementation of the Recharge Batteries activity.

```
activity TransmitData {
    initial Initial

    fork Fork

    merge TransmitMerge
    decision TransmitDecision
    action SetTransmitWait : activity [language=action] {
        set transmitTimeout := 1s;
    }
    trigger TransmitWait when timeout transmitTimeout
    action TransmitData : activity [language=action] {
        _data := _data - 1;
        raise connection._data;
    }

    merge ConsumeMerge
    action SetConsumeWait : activity [language=action] {
        set consumeTimeout := 1s;
    }
    trigger ConsumeWait when timeout consumeTimeout
    action ConsumeEnergy : activity [language=action] {
        batteryVariable := batteryVariable - 1;
    }
    decision ConsumeDecision

    merge Merge

    action SetDone : activity [language=action] {
        transmitionDone := true;
    }

    final Final

    control flow from Initial to Fork

    control flow from Fork to TransmitMerge
    control flow from TransmitMerge to TransmitDecision
    control flow from TransmitDecision to SetTransmitWait [_data > 0]
    control flow from SetTransmitWait to TransmitWait
    control flow from TransmitWait to TransmitData
    control flow from TransmitData to TransmitMerge
    control flow from TransmitDecision to Merge [_data <= 0]

    control flow from Fork to ConsumeMerge
    control flow from ConsumeMerge to SetConsumeWait
    control flow from SetConsumeWait to ConsumeWait
    control flow from ConsumeWait to ConsumeEnergy
    control flow from ConsumeEnergy to ConsumeDecision
    control flow from ConsumeDecision to ConsumeMerge [batteryVariable >= 40]
    control flow from ConsumeDecision to Merge [batteryVariable < 40]

    control flow from Merge to SetDone
    control flow from SetDone to Final
}
```

Listing A.3.8: The Gamma implementation of the Transmit Data activity.

```
package spacecraft
import "Interface/Interfaces.gcd"
@RegionSchedule = bottom-up
statechart Spacecraft [
port connection : provides DataSource
] {
    var batteryVariable : integer := 100
    var _data : integer := 100

    var batteryRecharging : boolean := false
    var batteryFullyCharged : boolean := false
    var transmitionDone : boolean := false

    timeout rechargeTimeout
    timeout consumeTimeout
    timeout transmitTimeout

    timeout checkTimeout

    region Communication {
        initial CommunicationEntry
        state WaitingPing
        state Transmitting {
            do / call TransmitData;
        }
    }
    region Battery {
        initial BatteryEntry
        state NotRecharging {
            entry / batteryRecharging := false;
        }
        state Recharging {
            do / call RechargeBatteries;
            entry / batteryRecharging := true;
        }
    }

    region Check {
        initial CheckEntry
        state CheckTimeout {
            entry / set checkTimeout := 500ms;
        }
    }

    transition from CheckEntry to CheckTimeout
    transition from CheckTimeout to CheckTimeout when timeout checkTimeout

    transition from CommunicationEntry to WaitingPing
    transition from WaitingPing to Transmitting
        when connection.ping [!batteryRecharging and _data > 0]
    transition from Transmitting to WaitingPing when timeout checkTimeout [transmitionDone]
        / transmitionDone := false;

    transition from BatteryEntry to NotRecharging
    transition from NotRecharging to Recharging when timeout checkTimeout [batteryVariable < 80]
    transition from Recharging to NotRecharging when timeout checkTimeout [batteryFullyCharged]
        / batteryFullyCharged := false;

    activity TransmitData {
        // ...
    }

    activity RechargeBatteries {
        // ...
    }

}
```

Listing A.3.9: The Gamma implementation of the Spacecraft component.