TEACHING PROGRAMMING WITH FORMAL MODELS IN GREENFOOT

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Abstract: Formal methods for software development are subject to teaching in computer science as a matter of course. However, it is difficult to relate the theories to the practical matter of program code creation. The reason for this is the complexity of model-driven software development approaches which would be needed to derive executable applications from formal models, but are usually not in the focus of the courses. We propose to teach formal methods by using "embedded models", i.e. program code patterns that represent the semantics of formal methods inside arbitrary object-oriented programs. The approach is realized within the Greenfoot graphical simulation enginge. With this approach the technical barrier to the practical use of formal methods is lowered, so that students can easily experiment with such models in a game-oriented environment.

1 INTRODUCTION

Teaching formal methods for software development is important (Mili, 1983), but a difficult task. Not only are the formal methods themselves complicated and require abstract thinking by students. More important, they are hard to connect to practical software development and the every-day programming tasks. That leads to two observations: (1) The examples being used are usually very simple, like an elevator control or a traffic light; (2) the examples are usually realized in modelling tools only and not as program code. This leads to the situation that teaching of formal methods and of programming are in most cases completely separated, making it hard for students to grasp the benefits of formal methods for software development.

Existing tools that are appropriate for teaching purposes usually target either teaching of programming *or* formal methods. For teaching programming, a good example is the graphical simulation environment Greenfoot (Henriksen and Klling, 2004), which allows with little effort to create worlds and interacting entities therein, which are graphically represented on the screen. Formal methods can be illustrated with appropriate models like state machines, whose states and transitions intuitively explain the purpose of systems developed based on such models. Tools like UPPAAL (Larsen et al., 1997) can be used in this context that allow for graphical design, simulation and verification of state machines.

However, a direct connection between models and program code is hard to teach, because both abstraction levels are usually separated and hard to bridge. This is a problem widely acknowledged in numerous approaches of model-driven software development (MDSD). In this context, the concept of *embedded models* (Balz et al., 2008; Goedicke et al., 2009) was proposed that connects models and programming languages by representing the model syntax in static program code structures. We now want to use this approach for teaching purposes, too. In this contribution we present our approach to integrate programming with state machine models inside Greenfoot. An appropriate embedded model allows to represent interacting entities in Greenfoot as communicating state machines which can be verified graphically in UPPAAL.

In order to do this, this contribution is structured as follows: In section 2 we consider related work regarding MDSD and formal methods teaching. The concept of embedded state machine models is briefly introduced in section 3 and then adapted to Greenfoot simulations in section 4. Based upon this, we show how verification of this simulation is possible with the state machine tool UPPAAL in section 5 to demonstrate the usefulness of our approach for teaching formal methods. Finally, we give a conclusion and a short outlook to future work, especially regarding tools, in section 7.

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2 RELATED WORK

We consider approaches to be related to our contribution that aim at bridging the gap between the different abstraction levels of formal models and program code. This concerns software development approaches as well as formal method teaching approaches.

MDSD approaches have the objective of developing high-level models and derive software from them (Hailpern and Tarr, 2006). This could be of interest for our purpose because it embraces different abstraction levels. Usually, *code generation* (Brown et al., 2006) is used that derives program code automatically from a model. This raises difficulties when the generated code is to be integrated in non-generated program code, for example in special environments like Greenfoot. In addition, high-quality program code is required for teaching purposes, but the quality of generated code varies depending on the generator tool. *Model round-trip engineering* (Sendall and Kster, 2004) concepts relate generated program code to high-level models, but are based on heuristics and not unambiguous and therefore inappropriate for our purpose. *Executable models* (Luz and da Silva, 2004; Hen-Tov et al., 2008) interpret model descriptions independent from programming languages. While this is a clean single-source approach and also suited to demonstrate software execution based on high-level models, it is difficult to express all business logic of a program in high-level models. For teaching purposes, this is also not helping to demonstrate the interconnections between formal models and programming.

Approaches for teaching formal methods usually work at higher levels of abstraction and without comprising program code, as stated in the introduction. When program code is considered, the objective is usually to verify its correctness by means of formal methods, but at a low level of abstraction. Examples for this are the formal specification of algorithms (McLoughlin and Hely, 1996; Bubel and Hhnle, 2008) and specification of protocols (Brakman et al., 2006). Similar, model checking of program code (Roychoudhury, 2006) is related to the low-level semantics of the programming language and thus not appropriate for teaching the interconnections to high-level models.

In summary, there is a lack of approaches that work on multiple levels of abstractions at the same time and illustrate the relations. This is especially true with respect to tools appropriate for teaching purposes: MDSD approaches and techniques make assumptions about program code structures and are thus hard to integrate in special frameworks like Greenfoot that make conflicting assumptions.

3 EMBEDDED STATE MACHINES

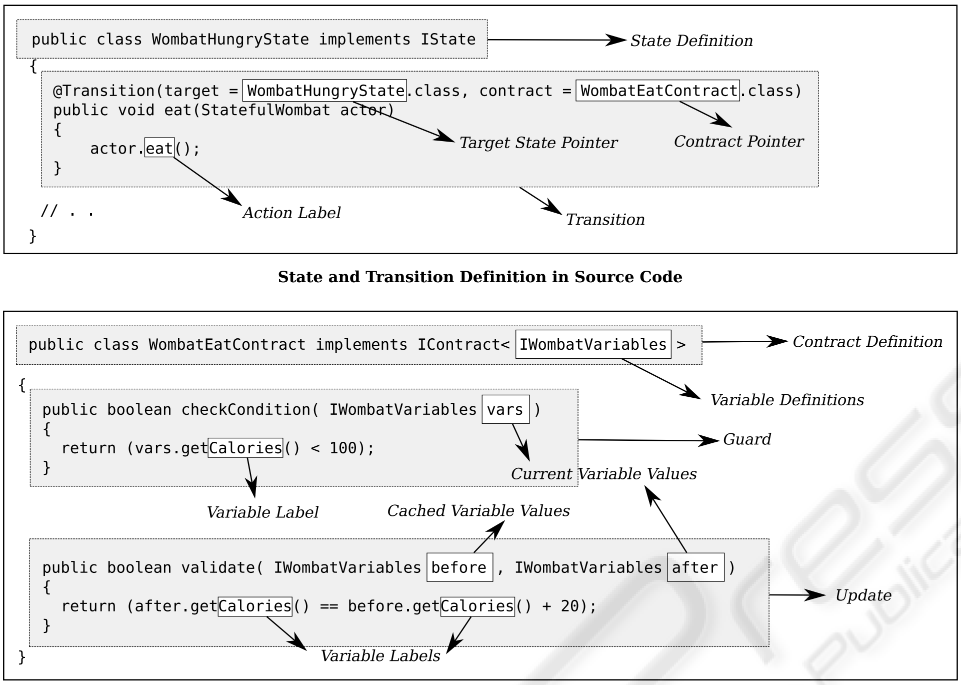
In the last years, approaches were developed that consider program code not only with respect to the semantics of the programming language, but also with respect to higher-level semantics that can be influenced by the developer. This applies to so-called *internal DSLs* (Fowler, 2006), i.e. domain-specific languages that are embedded in general-purpose languages (host languages) and provide semantics of DSLs there. Furthermore, *attribute-enabled programming* (Schwarz, 2004) uses the capability of modern programming language versions to incorporate type-safe, compiled meta data to annotate source code fragments.

Embedded models (Balz et al., 2008; Balz et al., 2009) build on these concepts to relate program code fragments to abstract models like state machines. When an appropriate program code pattern is defined, different abstraction levels are maintained in the same program code. Access to the fragments is not only possible at development time, but also at run time by means of structural reflection (Demers and Malenfant, 1995). This allows to create an execution framework that accesses and invokes the fragments.

3.1 Model and Program Code Pattern

The model type we will use for teaching purposes are in this case state machines. The language chosen for this implementation is Java (Gosling et al., 2005) with its Annotations enhancement for meta data inclusion (Sun Microsystems, Inc., 2004). The program code pattern is illustrated in 1. The class at the top represents a state with the class name being the name of the state. The method in the state class represents a transition. It is decorated with meta data referring to the target state class and a “contract” class containing guards and updates. An instance of an interface type referred to as “actor” that encapsulates the application’s business logic is passed to transition methods. Its methods are interpreted as action labels since they are called when the transition fires.

Guards and updates are implemented as two methods in a so-called “contract” class which is shown at the bottom of figure 1. Both evaluate expressions to a boolean value. The guard uses the current variable values of the state machine to determine if a transition can fire, the update compares the current values with the values from the point in time before the transition fired to determine the changes to the state space.



```
public class WombatHungryState implements IState
{
   @Transition(target = WombatHungryState.class, contract = WombatEatContract.class)
   public void eat(StatefulWombat actor)
   {
       actor.eat();
   }

  // . .
}
```

State and Transition Definition in Source Code

```
public class WombatEatContract implements IContract< IWombatVariables >
{
  public boolean checkCondition( IWombatVariables vars )
  {
    return (vars.getCalories() < 100);
  }

  public boolean validate( IWombatVariables before , IWombatVariables after )
  {
    return (after.getCalories() == before.getCalories() + 20);
  }
}
```

Contract Definition in Source Code

Figure 1: The program code pattern with the program code itself and the related state machine model semantics. At the top, a state class and an emanating transition can be seen. At the bottom, the related guard and update are depicted. These structures are unambiguous so that the complete state machine model can be extracted.

Both methods access for this purpose a “variables” type which is a facade type representing the variables constituting the state space of the state machine. This type contains “get” methods for each variable, which are by this means defined with a label and a data type.

In addition, channels can be represented by classes implementing a given interface `IChannel` containing a method `enable`. This method provides the channel class with a list of all transitions that try to send and receive on this channel and allows to chose a pair of them. It can in addition execute any business logic on the given actors to notify them that this channel was selected.

3.2 Execution

At run time the state machine model contained in the program code pattern is executed by a small framework. This framework takes basically a set of initial state, variables implementation and actor implementation for each state machine and executes the state machines roughly as follows:

1. All transition methods in the current state of each state machine that want to send or receive on channels are considered. They fire when the guard evaluates to `true` and the related channel allows them to fire.
2. For all other states, one transition method whose guard evaluates to `true` is invoked.
3. The updates of all invoked transitions are called to validate the transition execution.
4. For each transition invoked, the target state is set and the procedure repeated until each machine reaches a finite state, i.e. a state without transitions.

This execution algorithm thus interprets the static program code structures so that a sequence of actions is created that matches the execution semantics of a state machine model. The program code pattern manages a separation between well-defined model semantics and arbitrary business logic: Execution control is passed to application components in transition methods as well as inside the variable interface implementation and returns to the state machine accordingly.

4 IMPLEMENTING STATE MACHINES IN GREENFOOT

The objective of this contribution is to create a connection between different abstraction levels for teaching formal methods. The higher level of abstraction level is that of UPPAAL state machine models, which can be verified and simulated. It requires the existence of precise models defining states, transitions, variables, and channels. The low abstraction level is that of programming in Greenfoot, which requires the student to write detailed algorithms that address the specifics of the simulation environment. This includes controlling the graphical appearance of the simulation world and its entities as well as accessing their properties, for example to find intersecting entities.

4.1 Concept

The design of Greenfoot can roughly be summarized as follows: A world provides the background for the simulation. This includes the size and graphical appearance of the visual background, and allows to access all entities currently available in this world. Single entities can move, change their appearance, and gather information about their vicinity in the world. Apart from that, they can implement almost arbitrary business logic. Actions in Greenfoot are performed in cycles. In each cycle, a pre-defined method “act” of each entity and the world is called. In this method, the objects must determine their current state and decide which actions to take. If and how often these cycles are called is controlled by the user and can thus not be influenced by the objects running in the simulation. This concept is easy to map to the execution of embedded state machines as described in section 3.2:

- A state machine corresponds to a single entity in the simulation. The fact that the entities must know about their current state complies to explicit states of a state machine.
- The decisions that are made based upon a certain state can be represented by outgoing transitions.
- The actions that modify the system state in transitions correspond to action labels.
- A system of communicating state machines corresponds to a world containing different entities that can interact.

In this section we will describe the implementation of a Greenfoot simulation called “Stateful Wombats”, which is adapted from Greenfoot’s default “Wombats” example. Our simulation has the following rules:

- The world has two interacting types of objects, wombats and leafs. The interaction is that wombats eat leafs when they are hungry and find them.
- Wombats determine if they are hungry by the number of calories they have eaten. They are hungry with less than 100 calories. Whenever they eat a leaf, they gain 20 calories. When wombats are hungry, they appear walking randomly through the world.
- When wombats are fed, i.e. the number of calories equals 100, they stop eating and digest until the number of calories reaches 0. In every cycle, a wombat digests 5 calories. As long as a wombat digests, it is laying on its back and does not move.
- When a leaf is added to the world, it is fully grown. This is determined by the variable `growth` having the value 100. When a leaf is grown, it appears in the simulation in its normal size.
- When a leaf is eaten, its growth is set to 0. From now on, leafs start to grow by 1 in every cycle. They do not appear visually at all.
- When the growth reaches 50, the leaf is considered half-grown. It appears in a smaller size in the world again, but continues to grow until its growth reaches 100 again.

The two Greenfoot actors, wombats and leafs, contain their “business logic” that manages calories and growth and also determines if wombats and leafs intersect. The running simulation in Greenfoot with its actors can be seen in figure 2.

4.2 Greenfoot World

With these principles, a world is the foundation of every embedded state machine in Greenfoot. Figure 3 contains the implementation of an exemplary world we will use now to present the realization of our concept in Greenfoot. In the constructor of the world, a super constructor is called that constitutes the size of the visual background. Afterwards, an object of the type `EmbeddedStateMachineSystem` is created, which represents the system of communication state machines. Added to this system is a channel deciding if objects can interact with each other. In the world, no state machine itself is added to the system. This will be done for each entity instance separately. Most important in the world class is the `act` method that integrates the state machine system to Greenfoot: In every cycle, the next step of the system is called, which invokes the next transition for each entity by considering the channels, if applicable.

4.3 Actors

The source code of the wombat is shown in figure 4. Its purposes are to manage the calories (methods `eat` and `digest`), to manage the appearance (methods `beginDigest` and `getHungry`), and to determine if leafs are available (method `canEat`). The

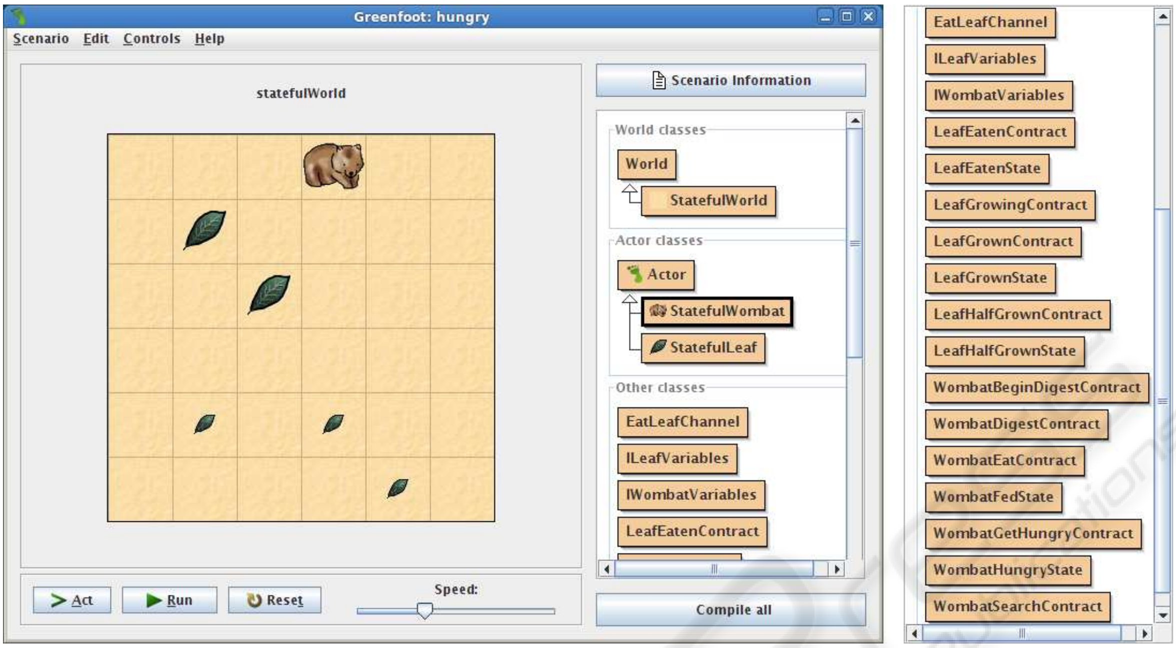


Figure 2: The communicating state machines as running in Greenfoot. The wombat is currently in the “hungry” state. The large leafs are in the state “grown”, the small leafs in the state “halfgrown”. Some leafs are currently not visible at all because they are in the state “eaten”. Right hand one can see the classes constituting the system: The two actors, and the “other classes” with the actual states, transitions, contracts and channels of the state machine.

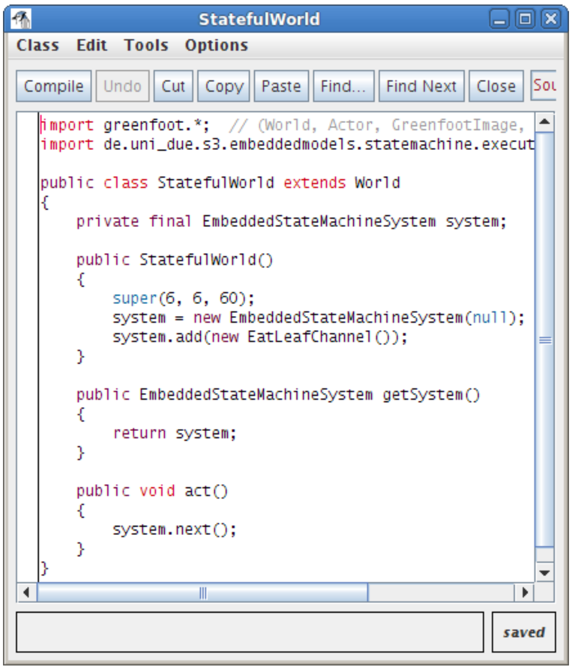
appearance and the interaction with other objects are business logic that is specific to Greenfoot and thus hard to represent in any formal model at all. These methods represent everything a wombat can do, however, they do not trigger any actions. The actual sequence of actions at run time is determined by a state machine, which is created and registered in the world in the wombat’s constructor. According to the rules defined in section 4.1, the wombat is modeled with two states – one for the wombat being hungry (class `WombatHungryState`), and one for the wombat being fed and digesting (class `WombatFedState`). The model is shown in figure 5. It references the state classes as well as the channel class `EatLeafChannel`, in this case for sending. The variable `calories` used in the guards and updates refers to the method `getCalories` of the interface `IWombatVariables`, which defines the related method of the `StatefulWombat` class as a variable. The channel class invokes the wombat’s `canEat` method and thus accesses the Greenfoot-specific business logic to determine if the state machines can communicate.

The implementation of the leaf is analogous as shown in figure 5. The states comply to the requirements defined in section 4.1 with the variable influencing the guards called `growth`. The channel is also accessed, but receiving. In summary, it is possible to create complete interacting state machines in the program code pattern which can be run in Greenfoot.

5 VERIFICATION

In section 4 we described how embedded models can be used to teach programming by using a model systematically to derive an implementation of it. The visualization that is possible with UPPAAL is of most interest. In addition, UPPAAL provides a simulator that visualizes each step of a running state machine and visualizes current states, activation of transitions, and current variable values. This is already desirable as it makes the influence of the model on the program comprehensible and thus makes manual verification possible.

However, teaching formal methods should consider formal properties of the related models that allow for automated verification. For the given implementation, the verification feature of UPPAAL can be used to verify not only the state machines themselves, but at the same time the program code containing the state machine. The separation of model and business logic in the program code defines starting points for this: On the one hand the variables being used in guards and thus controlling the program flow, and



```
import greenfoot.*;  // (World, Actor, GreenfootImage,
import de.uni_due.s3.embeddedmodels.statemachine.execut

public class StatefulWorld extends World
{
    private final EmbeddedStateMachineSystem system;

    public StatefulWorld()
    {
        super(6, 6, 60);
        system = new EmbeddedStateMachineSystem(null);
        system.add(new EatLeafChannel());
    }

    public EmbeddedStateMachineSystem getSystem()
    {
        return system;
    }

    public void act()
    {
        system.next();
    }
}
```

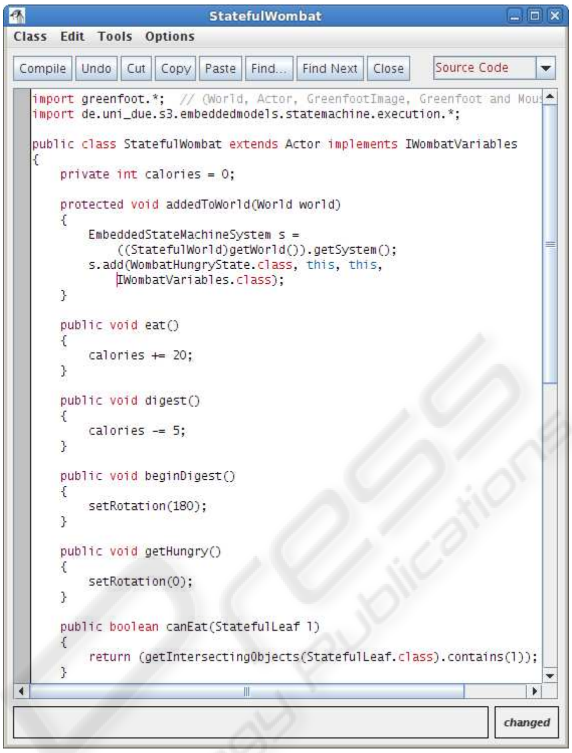
Figure 3: The source code of the Greenfoot world. Since a system of communication state machines is being used, it must be controlled from the world instance in order to coordinate the single actors. The system is created at the beginning by providing a listener that is notified about failed contract validations and the channel that coordinates if a leaf can be eaten by a wombat.

on the other hand the updates that constitute how the state space is expected to change during transitions.

The example introduced above relies on the two variables `calories` and `growth` for wombats and leafs, which have clear ranges in this example. The verifier can thus, for example, be used to ensure that both variables never exceed the range $[0, 100]$. Figure 7 shows the query and the results for the given model. This verification can be used to track errors in the guards and updates. These, in turn, determine the program flow and validate the business logic. In our tests, the most common errors that could be found using the verifier were caused by the usage of wrong operators in guards and updates, for example with the expression `growth < 100` instead of `growth <= 100`.

6 EVALUATION

From a theoretical point of view, the approach is successful: The program code structures can not only represent the model syntax, but also be integrated in Greenfoot seamlessly. Different to other modeling techniques, the use of a special environment for teaching purposes is thus possible. Considering state machines, the related program code is separated: On the one hand we have “business logic” that is specific to Greenfoot and its simulations, in our case the Wombat world. On the other hand, external classes exist that represent the state machine and are responsible for determine the current state of the application, deciding which actions to take, and invoking the related business logic. Although this leads to a higher effort when the related classes must be created, an existing tool allows to extract the model into UPPAAL to allow for



```
import greenfoot.*;  // (World, Actor, GreenfootImage, Greenfoot and Mous
import de.uni_due.s3.embeddedmodels.statemachine.execution.*;

public class StatefulWombat extends Actor implements IWombatVariables
{
    private int calories = 0;

    protected void addedToWorld(World world)
    {
        EmbeddedStateMachineSystem s =
            ((StatefulWorld)getWorld()).getSystem();
        s.add(WombatHungryState.class, this, this,
            IWombatVariables.class);
    }

    public void eat()
    {
        calories += 20;
    }

    public void digest()
    {
        calories -= 5;
    }

    public void beginDigest()
    {
        setRotation(180);
    }

    public void getHungry()
    {
        setRotation(0);
    }

    public boolean canEat(StatefulLeaf l)
    {
        return (getIntersectingObjects(StatefulLeaf.class).contains(l));
    }
```

Figure 4: The source code of the leaf actor with the overridden method that initiates the state machine and the methods providing the business logic of a leaf.

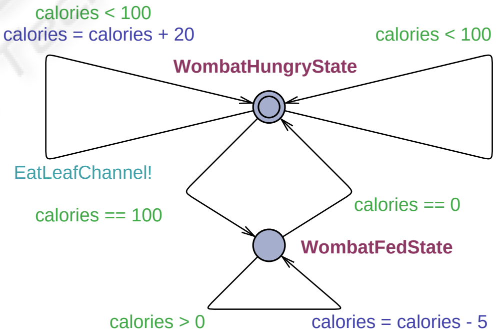


Figure 5: The state machine controlling the wombat’s behavior as extracted from the program code and edited in UPPAAL.

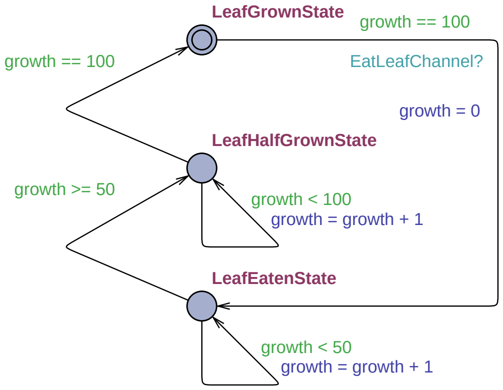
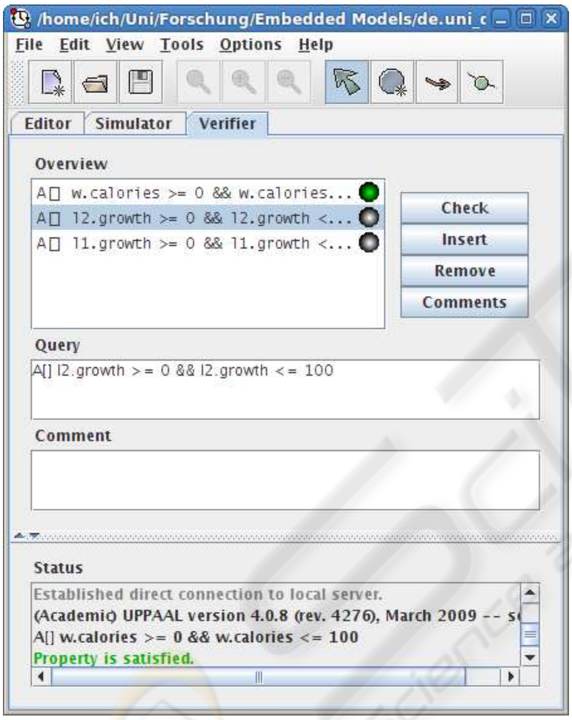


Figure 6: The state machine controlling the leaf's behavior as extracted from the program code and edited in UPPAAL.


/home/ich/Uni/Forschung/Embedded Models/de.uni_c
File Edit View Tools Options Help
Editor
Simulator
Verifier
Overview
Check
Insert
Remove
Comments
Query
Comment
Status

A□ w.calories >= 0 && w.calories...
A□ l2.growth >= 0 && l2.growth <...
A□ l1.growth >= 0 && l1.growth <...

A[] l2.growth >= 0 && l2.growth <= 100

```
Established direct connection to local server.
(Academic) UPPAAL version 4.0.8 (rev. 4276), March 2009 -- s
A[] w.calories >= 0 && w.calories <= 100
Property is satisfied.
```

Figure 7: The UPPAAL verifier used to ensure the range for the variables `calories` and `growth`.

visual feedback. This does not only structure the program design and implementation, but also perfectly matches the purpose of a state machine model. The state machine itself can be visualized and its functionality comprehended easily.

In addition to supporting the design, the formal foundation of models like state machines is of course of interest for teaching formal methods: Using an appropriate tool, students can detect errors and inconsistencies not only in the model, but also in the application. At the same time, they can refer to the visual simulation in Greenfoot to see the practical influence of the model's properties on the simulation. From our point of view, the concept is already appropriate to teach development with formal models.

The practical evaluation will consist of two steps. First, the approach will be introduced as described here in a formal methods course at our working group in the next year. We will rely on manual programming this time, thus requiring the students to deal with the program code pattern in detail. A tool will be available that extracts the UPPAAL model from the program code afterwards to visualize, simulate and verify it. The second step work will include an enhancement of Greenfoot to integrate a visual editor that manages the program code structures. This editor will also allow to extract the model more easily to UPPAAL. We also plan to create a monitoring tool that visualizes the executed state machines, their variables, and their interactions at run time. The two steps will be compared afterwards considering the practical understanding the students gain regarding the programming as well as the use of formal methods.

7 CONCLUSIONS

In this contribution we presented an approach to teach formal methods for software engineering by combining the game-oriented visual simulation environment Greenfoot with the state machine model checker UPPAAL. The key to this combination is the concept of embedded models which represent the syntax of formal models in well-defined program code patterns. Formal models can thus be integrated in arbitrary program code, even within a specific environment like Greenfoot. An execution framework that can run the state machine by using reflection mechanisms of Java is integrated in Greenfoot and controls the actors and their interactions.

This approach is successful from our point of view because different abstraction levels can be combined and the use of formal models for software development can be illustrated to students. Not only does the approach facilitate a separation of business logic and the controlling model. It also allows to visualize, simulate and verify the state machine model. Since it is embedded in program code, students can thus easily gain feedback regarding the correctness of model and business logic. Future work will include the development of appropriate tools. With these we intend to make programming with formal models an integrated part of computer science teaching and lead students to gain insight to the practical use of formal models.

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