Abstract

Agent states and transitions between states are important abstractions in agent-based social simulation (ABSS). Although it is common to develop ad hoc implementations of state-based and transition-based agent behaviors, "best practice" software engineering processes provide transparent and formally grounded design notations that translate directly into working implementations. Statecharts are a software engineering design methodology and an explicit visual and logical representation of the states of system components and the transitions between those states. Used in ABSS, they can clarify a model's logic and allow for efficient software engineering of complex state-based models. In addition to agent state and behavioral logic representation, visual statecharts can also be useful for monitoring agent status during a simulation, quickly conveying the underlying dynamics of complex models as a simulation evolves over time. Visual approaches include drag-and-drop editing capabilities for constructing state-based models of agent behaviors and conditions for agent state transitions. Repast Simphony is a widely used, open source, and freely accessible agent-based modeling toolkit. While it is possible for Repast Simphony users to create their own implementations of state-based agent behaviors and even create dynamic agent state visualizations, the effort involved in doing so is usually prohibitive. The new statecharts framework in Repast Simphony, a subset of Harel's statecharts, introduces software engineering practices through the use of statecharts that directly translate visual representations of agent states and behaviors into software implementations. By integrating an agent statecharts framework into Repast Simphony, we have made it easier for users at all levels to take advantage of this important modeling paradigm. Through the visual programming that statecharts afford, users can effectively create the software underlying agents and agent-based models. This paper describes the development and use of the free and open source Repast Simphony statecharts capability for developing ABSS models.

Keywords: Agent-Based Modeling, Statecharts, Agent-Based Social Simulation, Repast Simphony, Software Engineering Processes

Introduction

1.1 Agent states and transitions between states are important abstractions in agent-based social simulation (ABSS) (Macal & North 2010). Although it is common to develop ad hoc implementations of state-based and transition-based agent behaviors, "best practice" software engineering processes provide transparent and formally grounded design notations that translate directly into working implementations. A number of agent-oriented software engineering processes have been developed (Fortino & North 2013).

1.2 Statecharts (Harel 1987) are a software engineering design methodology and an explicit visual and logical representation of the states of system components and the transitions between those states. Used in ABSS, they can clarify a model's logic and allow for efficient software engineering of complex state-based models. In addition to agent state and behavioral logic representation, visual statecharts can also be useful for monitoring agent status during a simulation, quickly conveying the underlying dynamics of complex models as a simulation evolves over time. Visual approaches include drag-and-drop editing capabilities for constructing state-based models of agent behaviors and conditions for agent state transitions.

1.3 Repast Simphony is a widely used, open source, and freely accessible agent-based modeling toolkit (Repast Simphony 2014a). While it is possible for Repast Simphony users to create their own implementations of state-based agent behaviors by adapting the State pattern in Gamma et al. (1994) and even create dynamic agent state visualizations, the effort involved in doing so is usually prohibitive. The new statecharts framework in Repast Simphony, a subset of Harel's statecharts, introduces software engineering practices through the use of statecharts that directly translate visual representations of agent states and behaviors into software implementations. By integrating an agent statecharts framework into Repast Simphony, we have made it easier for users at all levels to take advantage of this important modeling paradigm. Through the visual programming that statecharts afford, users can effectively create the software underlying agents and agent-based models. This paper describes the development and use of the free and open source Repast Simphony statecharts capability for developing ABSS models.

Background

1.4 Statecharts are a type of state diagram. State diagrams (Shannon 1948) are visual depictions of sequential control procedures or algorithms. Early examples of state diagrams include Moore machines (Moore 1956) and Mealy machines (Mealy 1955). Later examples include Harel statecharts (Harel 1987), the Discrete Event System Specification (DEVS) (Zeigler et al. 2000), and the Object Management Group Unified Modeling Language (OMG UML) state machines (OMG 2009). The latter two describe algorithms for complex software and models. State diagrams have been used in the design or implementation of agent-based models, for example, the PoHill, Izzquierdo, and Gotts (2005) land use change model, the Siebers and Aickelin (2011) retail model, and the Aguirre and Nyerges (2014) sustainability management model.

1.5 Statecharts simulation tools include the National Instruments Statechart Module (http://www.ni.com/labview/statechart/) and VisSim (http://www.vissim.com/products/vissim/state_charts.html), both of which are proprietary. Yakindu Statechart Tools is a free and open source toolkit for "the specification and development of reactive event-driven systems based on the concept of statecharts" (Yakindu Committers 2014). Yakindu was designed for use by the embedded systems industry for such things as automotive system controls and vending machines. It can also be used to design and simulate other kinds of event-driven behavior. The toolkit consists of a graphical editor to create and edit statecharts, a simulator to simulate the behavior of statecharts, and code generation components to transform the statecharts into Java or C++ code. Yakindu's emphasis on embedded system simulation and its use of its own
language to describe behaviors of the state machine are its primary differences from Repast Simphony’s statecharts implementation. Finally, in addition to ABSS applications and embedded systems, gaming systems have adopted a state-driven agent design approach as well.

1.6 Agent-based modeling frameworks include the notion of state to represent agents and agent state transitions, but statecharts are not necessarily used. Of the most widely used ABM tools, only the proprietary AnyLogic toolkit includes capabilities for users to specify agent states and transitions through statecharts (AnyLogic Company 2014). As it does in AnyLogic, the statecharts capability in Repast Simphony supports a subset of Harel’s statecharts.

1.7 The rest of the paper is organized as follows. Section 2 introduces statecharts in Repast Simphony. Section 3 describes their implementation, including the graphical statecharts editor, automated code generation, and runtime visualization and interaction features. Section 4 presents two case studies using Repast Simphony to illustrate the benefits of statecharts-based software engineering methods for developing ABSS models. Section 5 concludes with lessons learned and future work.

Repast Statecharts

Convergent Modeling

2.1 The computational study of complex systems increasingly requires the integration of multiple computational models (Vangheluwe et al. 2002), where larger models are constructed by combining smaller models to address questions that cannot be answered by the smaller models in isolation (Villa 2001). The result is a hybrid or multi-paradigm integrated model. Model integration has increasing appeal. The drivers include a growing interest in leveraging divergent sets of accepted legacy models, an intensifying pressure to reduce development costs by reusing existing models, and expanding user requirements that are best met by combining different modeling methods.

2.2 There have been many published model integration advances including supporting theory (Vangheluwe et al. 2002; North 2014), conceptual frameworks (Vangheluwe & de Lara 2003; Liang & Paredis 2003; Brown et al. 2005), software tools (IEEE 2010, 2012; Villa & Costanza 2000; Villa 2001; Vangheluwe & de Lara 2003; North et al. 2006, 2007b), and applied case studies (Dubiel & Taimorini 2005; Bitelli & Brasington 2009; Teose et al. 2011). As productive as these activities has been, a broader strategy is required. The concept of model integration needs to be expanded to include not only models but also the modeling process itself. The result is convergent modeling.

2.3 Convergent modeling seeks to achieve convergence on every level of the modeling process from stakeholder interests and modeling questions through integrated executable code all the way to combined outputs and final recommendations. We believe that Repast Simphony statecharts provide a tool to help support convergent modeling by offering better ways to communicate model designs and implementations than those offered by typical text-based programming languages.

Why Repast Simphony Statecharts?

2.4 Statecharts allow for implementation independent ways to specify the design of complex behaviors. Used in ABSS, they can clarify a model’s logic and allow for efficient software engineering of complex state-based models. Agent behaviors amenable to a state-based representation can be encapsulated with states and transitions between agent states. If this logic is automatically transformed into model and agent components, as is the case for Repast Simphony statecharts, the agent modeler is able to focus on model design and the testing of behavioral designs in dynamic functioning agent models. This has benefits in developing complex models of real world systems but it also helps in the presentation of the underlying logic of the resulting models. In addition, the clarity with which agent behaviors can be depicted through statecharts without needing to necessarily consider underlying implementation details is beneficial in pedagogical contexts when students may have limited computational expertise.

2.5 The Repast Simphony statecharts framework offers a number of beneficial characteristics over existing ABSS and statecharts modeling toolkits. These are modeling flexibility, leveraging of Repast Simphony ReLogo, modern syntax highlighting and code completion, and the use of nonproprietary and open source software.

2.6 Modeling Flexibility. The statecharts implementation allows for agents to have as many or as few statecharts defined as necessary, while not requiring that all agent behaviors be described through statecharts. Repast Simphony offers many modes for specifying agent behaviors, including Java, Groovy, and ReLogo. By allowing the modeler to choose the appropriate combination of modeling paradigms, the statecharts framework supports flexible and expressive agent-based model specification.

2.7 Leveraging of Repast Simphony ReLogo. Since there is no restriction regarding what types of agents can include statecharts, the Repast Simphony ReLogo (Ozik et al. 2013) Patch, Link, Observer, and Turtle (PLOT) entities can have statecharts-mediated behaviors. By combining the ease of modeling provided by the ReLogo modeling paradigms with the statecharts framework’s ability to quickly build complex state-based agent logic, Repast Simphony is able to offer powerful agent modeling capabilities to a broader range of potential agent-modelers. As shown in text that follows, this combination of simplicity and expressiveness has already proven useful for teaching computational epidemiology to middle school and high school students.

2.8 Modern Syntax Highlighting and Code Completion. Over the last decade, modern integrated development environments have become indispensable in providing support to software developers. The support comes in many forms, including intelligent auto-completion, quick and inline access to application programming interfaces, and templates to generate boilerplate code. The statecharts editor, in addition to enabling graphical editing of statechart components, also includes a fully featured editor for specifying agent behaviors to be triggered and conditions to be satisfied. This assistance helps the agent modeler to explore the available capabilities offered by the code base without leaving the editing environment, and it flags compilation errors and provides warnings in a timely fashion.

2.9 Use of Nonproprietary and Open Source Software. As part of Repast Simphony, the statecharts framework is free and open source software. Its “New BSD” style license (Repast Simphony 2014b) reduces the financial barriers to entry for researchers and prospective agent modelers, regardless of commercial or noncommercial intentions. Having all of the source code that underlies the statecharts implementation freely available within the Repast Simphony distribution (Repast Simphony 2014a) means that the behavior of a model is transparent.

Statecharts Basics

2.10 Statecharts consist of states and transitions between states. Table 1 and Table 2 (which follow after brief discussions) give an overview of the types of states and transition triggers, respectively, that exist in the Repast Simphony statecharts framework. These represent a subset of Harel’s statecharts that were deemed most relevant to modeling state-based agent behaviors. For further details on any of the components refer to the Statecharts guide (Ozik & Collier 2014). Note that Repast Simphony offers two visual programming interfaces: statecharts and flowcharts. For more information on Repast Simphony flowcharts, see North et al. (2007a) and North et al. (2013).

2.11 States are one of the fundamental building blocks of statecharts. Table 1 lists three types of states (simple, composite, final) and five types of pseudo-states.
(entry state marker, initial state marker, deep history state, shallow history state, and branching state). Pseudo states are not agent states per se but are pointers to other states and are exited immediately. For many of the states, actions that will be executed upon entry or exit (so-called On Enter or On Exit blocks) can be defined. This is one of the basic mechanisms by which state-based agent behaviors can be defined.

Table 1: State element types available in Repast Simphony. (The On Enter/On Exit columns indicate whether an action that is triggered upon entry or exit can be specified from the state element.)

| State Type                | Details                                                                 | On Enter | On Exit |
|---------------------------|-------------------------------------------------------------------------|----------|---------|
| Entry state marker        | This element marks the point of entry into a statechart when the statechart is activated. | No       | No      |
| Simple state              | One and only one of the simple states will be active within an active statechart. | Yes      | Yes     |
| Composite state           | Composite states nest other state elements (simple states, other composite states, an initial state marker, history states, final states, and branching states) and are active when a sub-element is active. If a transition is made from outside a composite state directly to a sub-element, the composite state will be entered prior to its sub-elements. In a similar manner, if a transition is followed from a sub-element out of the composite state, the composite state will be exited after the sub-elements are exited. | Yes      | Yes     |
| Initial state marker      | Marks the element within a composite state that should be entered upon entrance to the composite state. | No       | No      |
| Deep history state        | History states keep a record of the last active state within a composite state. For a deep history state, the last active simple state within the enclosing composite state (it does not matter what level the nesting hierarchy is at) is entered. If there was no previously active state, the state pointed to by the initial state marker is entered. | Yes      | No      |
| Shallow history state     | When a shallow history state is entered, the last active element within the enclosing composite state at the same hierarchical level of the history state is re-entered. If there was no previously active state, the state pointed to by the initial state marker is entered. | Yes      | No      |
| Final state               | This element marks the end of all activities for a statechart. When a final state is entered, no further states will be visited, and no transitions will be triggered. | Yes      | No      |
| Branching state           | Branching states represent logical branching within statecharts. | No       | No      |
Figure 1. Sample statechart with annotated state elements. (a = entry state marker, b = simple state, c = composite state, d = initial state marker, e = deep history state, f = shallow history state, g = final state, and h = branching state. Transitions are shown as arrows.)

2.12 Transitions between states make up the other fundamental building block of statecharts. There are two types of transitions: regular transitions that connect different states, and self-transitions that are internal to a state. For any transition, an On Transition action, which will be executed whenever the transition is traversed, can be defined. This is how state-transition-based agent behaviors are defined. A transition is selected for traversal from the set of valid transitions leading out of currently active states. Every transition has a polling time associated with it. This indicates the frequency (in units of simulation ticks) at which the transition is polled for validity. The validity of a transition depends on the type of trigger that is defined on it. Table 2 presents the available transition trigger types.

| Transition Trigger Type | Details |
|-------------------------|---------|
| Always                  | Always triggers are always valid and are commonly used in self-transitions to execute some action at a specified polling time. |
| Timed                   | Timed triggers become valid after a specified time, measured in simulation ticks. |
| Probability             | Probability triggers include a specified probability. The logic specifying the probability is evaluated against a random draw each time the transition is polled for validity. |
| Condition               | Condition triggers are evaluated as being valid based on a specified condition, evaluated at the transition polling times. |
| Exponential decay rate  | Exponential decay rate triggers become valid after a random time following the exponential distribution. A new random interval is chosen each time the transition is initialized. |
| Message                 | Message triggers become valid when a message that meets specific criteria is received by the statechart. There are four types of message triggers: when a message meets a specified condition, when a message equals a specified element, when a message is of a certain type, and when any message of any type is received. |

Repast Statecharts Implementation

3.1 The Repast Simphony Statecharts framework consists of the following components:

- Graphical editor and statechart metamodel,
- Java/Groovy code generation,
- Statechart code editor, and
- Runtime visualization and interaction panel.

This section describes how these components were implemented for the dual purposes of documenting the technical aspects of the Repast Simphony statecharts framework and enabling interested parties to extend or implement similar functionality of their own.

Graphical Editor and Statechart Metamodel

3.2 The statecharts graphical editor implementation is written in Java as an Eclipse (Eclipse Foundation 2014a) plugin, adding the ability to create and edit statechart diagrams inside the Eclipse integrated development environment (IDE). As shown in Figure 2, the editor is divided into three major areas: the workspace area, where the graphical elements of a statechart are manipulated (Figure 2a); the palette of available elements (Figure 2b); and the properties panel, which displays the properties of the currently selected element (Figure 2c).

3.3 The statechart plugin was developed by using the Graphical Modeling Framework (GMF) (Eclipse Foundation 2014b). GMF is a set of Eclipse plugins for developing graphical editors from metamodels. The metamodel specifies the components of the model that are to be edited in the graphical editor. Some of the metamodel components correlate directly with statechart entities, while others are necessary artifacts of the implementation. For example, in our case, the statechart metamodel describes elements such as states, their properties, and their relationships with other parts of the metamodel, together with properties used only by the implementation, such as a universally unique identification (UUID) (see Figure 3).
Figure 2. The components of the statecharts visual editor. (a = the workspace area where the statechart elements are created and arranged; b = the palette panel of available elements, including selection, zoom, and note tools; and c = the properties panel of the selected statechart element in the workspace area a. If no element is selected, the properties of the statechart itself are displayed.)
3.4 Figure 3 shows the statechart metamodel as a Unified Modeling Language (UML) diagram. The root component is the StateMachine. It contains all the transitions (Transition) and states (AbstractState) in the model (as indicated by the "states 0..*" and "transitions 0..*" notation). A Transition contains references to its "from" and "to" states as well as the various properties that describe that transition. For example, the triggerType describes the type of trigger associated with the transition, and the onTransitionString is the code that will be executed when the transition is traversed. States, inheriting from AbstractState, have properties such as onExit and onEnter that define the code that will be executed when that state is exited or entered. GMF leverages the Eclipse Modeling Framework (Eclipse Foundation 2014c) (EMF) for this metamodeling and generates Java code for each of these components. For example, a Java Transition class with accessors for each property and the "from" and "to" states can be generated.

3.5 Additional GMF tools allow the developer to specify a graphical model consisting of a set of figures, each with its own color, shape, and other graphical attributes. These figures are then mapped to the elements of the metamodel. The mapping describes how specific elements in the metamodel should appear in the editor. For example, in our implementation, a state should appear as a rounded rectangle. Once the metamodels and the mappings have been completed by using EMF/GMF utility wizards, GMF can then generate the code for a functional editor. In our case, the generated editor code was extensively and manually customized, resulting in the current statechart editor implementation. See Figure 4 for an illustration summarizing the overall pathway from metamodel to statechart editor code creation.
3.6 We also used GMF and EMF to generate the validation code for the statechart diagram. The validation code checks the diagram for coherence, flagging as errors conditions that result in a nonfunctional statechart (e.g., missing statechart entry points, invalid branching transitions). It also flags as warnings conditions that do not create a nonfunctional statechart but that are unexpected (e.g., states that are included in a statechart but are unreachable). As it was for the editor code, GMF was used to generate the base validation code, which was then customized.

3.7 When creating and editing a statechart model, the user is manipulating instances of the metamodel components via the graphical model. When a new statechart model is created in the editor, a StateMachine object is instantiated. Any states or transitions that are created in the model are instantiations of State and Transition components that are themselves added to the StateMachine as defined in the metamodel (see Figure 5). Similarly, editing an element’s properties edits the corresponding metamodel property (e.g., a state’s On Enter code block). Saving a statechart in the editor instantiates the StateMachine and displays it according to the graphical model mapping.

Code Generation

3.8 The code generation mechanism also utilizes the instantiated metamodel components. A specific StateMachine object is passed to the code generator, which then creates the Java code for creating the actual runtime statechart used during a Repast Simphony model run. The generated code is written to an Eclipse source directory and then compiled by the Eclipse compiler, resulting in a seamless process. Whenever the statechart diagram is saved, the source is generated, and Eclipse compiles it automatically. Figure 5 depicts the process of creating statechart builder source code from metamodel components defined within a statechart diagram.

http://jasss.soc.surrey.ac.uk/18/3/11.html
3.9 Here we note that the generated statechart builder code relies on the underlying statechart engine within Repast Simphony. This means that a user could conceivably choose to forego the graphical statechart creation and editing process and implement a statechart of their own relying solely on Java, Groovy or ReLogo code. The benefit of this approach could be custom extensions of the statecharts engine. However, this would require substantial work that the statechart editor takes care of by default, including creating, correctly connecting, defining the behaviors of, and specifying the triggers that activate the statechart components. In addition, only the logic of the underlying statechart can be defined this way, so there will be no corresponding graphical representation that could be displayed.

3.10 The code generation is implemented by using the Eclipse Xpand framework (Eclipse Foundation 2014d). Xpand is a statically-typed template language that facilitates the generation of textual artifacts, such as source code, from models. A template language allows a developer to define a template. A template consists of text that appears verbatim in the output and text that derives from some other input to the template. Xpand templates take a model as input and use the components and properties of the elements of that model to create the generated text output.

3.11 Figure 6 is the Xpand template for the source code that creates outbound branch transitions. All the blue text gets written verbatim to a Java source file. Anything within the angled brackets is either a control statement or a template construct that is evaluated and then written to the Java source file. The example works with Transition objects from the statechart metamodel such that "this" refers to the Transition object currently being processed. &lt;this.id&gt; then refers to the id property of the transition, &lt;this.from.uuid&gt; refers to the UUID of the state that is the "from" property of the transition, and so on. The Java source that is created from this template will look like Figure 7.

<PRE>
<IF this.default transitions

DefaultOutBranchTransitionBuilder&lt;agentType&gt; tb = new DefaultOutBranchTransitionBuilder&lt;agentType&gt;(&lt;this.id&gt;, stateMap.get(&lt;this.from.uuid&gt;), stateMap.get(&lt;this.to.uuid&gt;));

&lt;EXPAND registerTransition(&lt;tb&gt;)

tb.setPriority(&lt;priority&gt;);
mscb.addRegularTransition(&lt;tb.build();

&lt;ELSE&gt;

OutBranchTransitionBuilder&lt;agentType&gt; tb = new OutBranchTransitionBuilder&lt;agentType&gt;(&lt;this.id&gt;, stateMap.get(&lt;this.from.uuid&gt;), stateMap.get(&lt;this.to.uuid&gt;));

&lt;EXPAND createAllTransitionProps(&lt;agentType&gt;)

mscb.addRegularTransition(&lt;tb.build();

&lt;ENDIF&gt;

</PRE>

Figure 6. An example Xpand template for generating Java source code that represents an outbound branch transition.

3.12 The generated code is not the runtime statechart itself but rather the builder or creation type code, which is typically run once for each agent to create the statechart for that agent. When run, state components are created first and inserted into the stateMap referenced in Figures 6 and 7 by using the UUID of the metamodel state from which they derive as a key. When transitions that require "from" and "to" states are created, the created states are retrieved by using the UUIDs, as seen in Figure 7. In this way, relationships defined in the diagram are created in the runtime statechart.

3.13 The code generation process also performs some cleanup, eliminating any existing source code that is no longer applicable. A scalable vector graphic (SVG) format snapshot image of the statechart diagram is also created. This image is the foundation of the visualization and interaction runtime statechart panel, which displays statechart activity and allows the user to graphically interact with a running statechart during a simulation run.

Code Editor Implementation

3.14 The statechart code editor is the graphical component used to display a statechart's user-specified logic, such as a state's On Enter logic or a transition's trigger condition. The editor provides syntax coloring and code completion (see Figure 8).

http://jasss.soc.surrey.ac.uk/18/3/11.html
3.15 The code editor adapts Eclipse's Java editor and the Groovy Eclipse (Groovy Eclipse Developers 2014) plugin's Groovy language editor for property editing. Both of these editors are designed to work with text files rather than non-file-based text properties; thus, much of the adaptation focuses on making the model code text properties appear as ordinary source code files to the Java and Groovy editors. This is accomplished by creating a proxy file whenever a code property is displayed in the editor. The proxy file is created by using the same Xpand template mechanism just described, the result of which is a file that very closely matches what is ultimately produced by the code generator. The proxy code is a single Java or Groovy class that contains a single method. It is the body of this method that appears in the property editor. However, the Java or Groovy editor component is using the entire proxy file as its source; thus, it can properly perform syntax and error highlighting as well as code completion by using the needed information provided by the entire file.

Runtime Visualization and Interaction Panel

3.16 As indicated above, the statecharts capabilities include the ability to probe and display an agent's active statecharts as a simulation is executing (see Figure 9). The visualization panel is implemented by adapting the capabilities of the Apache Batik SVG Toolkit (Apache Batik 2014). The currently active states are highlighted in green; simple states are completely filled in, and composite states have their frames filled in (see the Condition 1 simple state and the Composite State 1 composite state in Figure 9). The statechart is dynamically updated as the simulation proceeds, providing direct insight into any probed agent’s internal state. In addition, the statecharts can be directly manipulated via mouse clicks, thereby permitting manual activation of inactive states and the forcing of transitions to be followed. This feature allows for experimentation with alternative or rare event paths through agent statecharts.

![Figure 9. The runtime and interaction panel of an active statechart. (Active states are indicated by green highlighting. The panel allows manual activation of states and transitions via contextual menus revealed through mouse clicks; see the "Activate Condition 2" contextual menu option.)](http://jasss.soc.surrey.ac.uk/18/3/11.html)

Repast Statecharts Use Cases

4.1 This section describes two different use cases where Repast Simphony statecharts are used. The intent is to illustrate the benefits of statecharts-based software engineering methods for developing ABSS models. Case study 1 is the creation of a model of Methicillin-resistant Staphylococcus aureus (MRSA) transmission. MRSA is transmitted via contact so modeling MRSA requires explicitly inclusion of the spatial movement of agents, along with the types of interactions that they engage in throughout their daily activities. As such, the MRSA model includes disease state progression that is directly influenced by the location and interactions of each agent. We demonstrate how this type of interaction-rich disease transmission model can be easily constructed by leveraging the statecharts and ReLogo capabilities in Repast Simphony. Case study 2 is the creation of a manpower life cycle costing application. Manpower life cycle costing often involves a variety of different hierarchically related classifications and complex rules for compensating individuals as they pass through the classification hierarchy over the course of their careers. We demonstrate how by utilizing explicit state-based dynamics via Repast Simphony statecharts, the complicated and deep classification hierarchy of the U.S. Air Force can be efficiently encapsulated as a statechart and the resulting model can be used as a tool for policy scenario experimentation. Both case study models have been published to allow for replication (Ozik et al. 2015; Combs & Ozik 2015).

Case Study 1: Simple Model of Community-associated (CA) MRSA

4.2 The first case study shows how the new Repast Simphony statecharts capability can be used to create a model of infectious disease transmission suitable for
use in teaching computational epidemiology (Ozik et al. 2015). Although the model is a simplification of a larger model (Macal et al. 2012), it is complex enough to demonstrate key insights into the problems/difficulties faced by public health officials when confronted with outbreaks of infectious diseases.

4.3 The University of Chicago and Argonne National Laboratory, in collaboration with Santa Fe Institute’s Project GUTS (“Growing Up Thinking Scientifically”), designed, developed, and field-tested a curriculum and interactive learning experience to teach students the essential elements of infectious disease transmission (available at http://nih-midasedu.santafe.edu). This case study presents the Repast Simphony statecharts-based model of CA-MRSA that was developed as part of the curriculum. Here we describe the specifics of the model and demonstrate the benefits of coupling the state-based logic with the simplicity of Repast Simphony ReLogo.

4.4 The CA-MRSA model extends agent-based compartmental models for infectious diseases, including susceptible, infected, and recovered (SIR) disease state models and susceptible, infected, susceptible (SIS) disease state models. These models are often used to demonstrate concepts of infectious disease spread for middle-school- and high-school-aged students in the United States. In order to model CA-MRSA, the following additions were made to the compartmental models by using ReLogo and statecharts:

1. Inclusion of an asymptomatic colonized state. With respect to MRSA, agents can be in one of three states: susceptible (or uncolonized), colonized, and infected. Colonized agents carry MRSA on their skin, are asymptomatic, and can colonize others without knowing they are colonized. Infected agents have visible infections and may be more contagious than colonized agents. It is assumed that susceptible agents can get to the infected state only by first passing through the colonized state, and both colonized and infected agents can cause colonization in susceptibles.

2. State and behavior-dependent disease state duration. Colonizations can last anywhere from a few days to a few months. Infections tend to last between one to three weeks and can depend on whether the infected agent seeks medical attention.

3. Activity-dependent transmission risks. Agents engage in different types of activities in different locations, with differing transmission risks associated with those activities. For example, physical contact may be more prevalent in a home environment than in a school environment, a detail that is very important in modeling CA-MRSA, which is transmitted via direct skin-to-skin contact.

4. Daily agent schedules. Agents have daily schedules, which dictate, for example, when they are at home or in a particular classroom at school. Including the agents’ schedules of hourly activities within the day allows the model to better utilize existing information on disease transmission.

5. Individual decision-making. Since medical attention greatly reduces the length of the infection, an agent’s decision whether to self-care or to seek medical attention can affect the progression of MRSA in the agent population. A model that incorporates these behavioral differences among agents can allow for the exploration of different interventions designed to reduce the incidence of MRSA.

6. Disease-state-based transmission probabilities. The likelihood of a susceptible agent being colonized depends on the disease states of the agents with whom the agent has contact. The probability that an infected agent colonizes a susceptible agent is greater than the probability that a colonized agent colonizes a susceptible agent.

4.5 The CA-MRSA model uses a global activities statechart to coordinate the activities of the agents in the model (see Figure 10). The statechart is part of an environmental ReLogo observer agent that is used to control the overall flow of the model.

http://jasss.soc.surrey.ac.uk/18/3/11.html
4.6 Starting from the top left, the Setup state is entered, and the overall simulation is set up. After a timed transition, the Go state is entered; it initiates the main loop of the simulation. Each day, the branching state is entered, and depending on whether the day is a weekday or occurs on a weekend, the appropriate composite state is entered. (Figure 10 indicates that the simulation is currently in a weekday.) One simplification that the model makes is that every agent is a child of middle school to high school age. This simplification enables the weekday composite state to consist of the following states: begin at home, commute to school (all agents are instructed to go to their individual schools), be at school (all agents are at school engaging in school activities), go home (all agents leave school to go home), and then arrive back home (all agents are at home doing home activities). Each state with an internal transition (states with internal arrows) represents different repeated activities while in that state. For example, while the agents are at school, they move between classrooms at the beginning of every hour. This behavior is defined in the On Transition code block of the transition. In the weekend composite state, all the agents simply stay at home all day.

4.7 Unlike the global activities statechart, each individual agent in the model has its own disease statechart that tracks the state and progression of CA-MRSA for that agent (see Figure 11).

Figure 10. Model activities statechart in the CA-MRSA model.

Figure 11. CA-MRSA model agent disease state progression statechart.

4.8 In the beginning of the simulation, each agent’s disease statechart is activated and goes into the Begin state. From there, depending on the initial state of the agent (uncolonized, colonized, or infected), the appropriate transition is followed from the branching state to the correct disease state. Infected individuals will, after a set time, either seek medical attention (Infected, In Treatment state) or not seek medical attention (Infected, Self-caring state). This affects the length of time until the branching states that lead to either Uncolonized or Colonized states are reached. With specified probabilities, the agent will become either uncolonized (it completes clearing the infection) or colonized (it clears the infection but MRSA remains on its skin). Uncolonized agents will make a transition to being colonized depending on their proximity to colonized or infected agents and depending on the types of activities in which they are engaged. In this model, infected agents are twice as likely as colonized agents to make an uncolonized agent colonized. It is more likely for an uncolonized agent to become colonized being at home than being at school, since physical contact is more prevalent at home than at school. Once an agent is colonized, it remains so, until — with certain probabilities — that agent becomes either uncolonized or infected.
4.9 This complicated disease progression logic is captured within a single statechart. As the model progresses, the current state of any agent can be probed and followed. Both the explanatory power and the direct translation of visual components to model logic make the statecharts approach clear. This clarity is especially relevant in this case, in which the intended audience is being introduced to both infectious disease concepts and computational concepts at the same time. The clarity of the presentation is at a premium.

4.10 As indicated, the model exploits the simplicity of the ReLogo framework as well. Using ReLogo makes it easy to specify the model world (see Figure 12) and elements such as agent mobility. The MRSA model’s world is separated into two areas. The bottom half of the world shows the agents in their households. The households are represented as squares, with colors ranging from light to dark depending on the number of agents within each household (the more agents, the lighter the color). Each agent is represented in the stylized shape of a person, with the color of the person indicating the disease state (red = infected, yellow = colonized, green = uncolonized). This model was initialized with 720 total agents: 10 were infected agents, about 100 were colonized agents, and the rest (about 610) were uncolonized.

![Figure 12. The CA-MRSA model's ReLogo-based model environment.](http://jasss.soc.surrey.ac.uk/18/3/11.html)

4.11 When the activities statechart indicates that it is time to go to school, the agents head to their schools in the top half of the world. There are two middle schools (light brown = 7th grade, darker brown = 8th grade) and a high school (pink gradations from bottom [9th grade] to top [12th grade]). Within each school, each horizontal grade is made up of three classrooms, and the agents are distributed among these classrooms. Each agent has a specific grade and a specific sequence of classrooms that it attends throughout a school day.

4.12 There are some obvious simplifications found in the model. For example, there are only children agents, there are no after-school activities, and the agents stay at home throughout the weekend. However, the ability to specify some of the activity-dependent and behavior-dependent aspects of MRSA colonization and infection leads to important insights.

4.13 The chart in Figure 13 shows the results of 40 different runs of the model for a period equivalent to a year: 8,760 ticks, with each tick corresponding to an hour. The total numbers of colonizations that occur from contacts with infected agents (red line) and those that occur from contacts with colonized agents (yellow line) are shown. Despite the fact that infected agents are twice as likely as colonized agents to colonize uncolonized agents, we see that overall, more colonizations are occurring from contacts with colonized agents. This robust result helps focus classroom discussions on some of the challenges faced by public health officials. Despite the higher infectivity of infected agents, the much larger number of colonized agents appears to drive the total colonizations. Thus, attempting to control MRSA transmission primarily through the quarantining of infected people (a strategy that is effective for controlling many infectious disease outbreaks) would result in only limited success. Although the isolated infected people would be out of circulation, the colonized people would still be colonizing the rest of the population at high rates. The flexibility of statecharts would also allow for many interesting additional experiments, such as modifying the daily agent schedules, perhaps by including adaptive schedules in which agents dynamically respond as they recognize disease states.
Case Study 2: Estimating the Life Cycle Manpower Costs of Individual Military Service Members

4.14 The second case study shows how the new Repast Simphony statecharts capability can be used to create a model to analyze the life cycle cost of military manpower, focusing on U.S. Air Force officers (Combs & Ozik 2015). As an initial prototype, it is primarily intended to show Repast Simphony's capability to handle complicated statecharts, i.e., nested composite states and a variety of transition types, and illustrates the application of statecharts to large-scale and more complex systems.

4.15 In an overview of its Fiscal Year 2014 budget request, the U.S. Department of Defense (DoD) reports that "The cost of military pay and allowances, combined with military health care, comprises about one-third of the Department's budget. These costs have been growing rapidly in recent years — up almost 90 percent since FY 2001 (about 30 percent more than growth in inflation), while active duty end strength has grown by less than 3 percent" (Office of the Under Secretary of Defense 2013, 1–2). Interestingly, DoD currently has no analytical framework that supports the estimation of the life cycle costs of each individual service member (Reserve Forces Policy Board 2013), yet this type of analysis is critical to senior decision making on issues such as the future composition of the military force (e.g., the number of active-duty personnel versus reservists and guardsmen). This case study shows how the new Repast Simphony statecharts capability can be used to create a military manpower life cycle cost analysis model, focusing particularly on United States Air Force (USAF) service members.

4.16 The first step in capturing an Airman's manpower life cycle costs is to model a number of status-related transitions that he or she may make throughout a career. By status, we mean whether the Airman is currently working on active duty, is in the Air Reserve Component (ARC) composed of the Guard and Reserves, or is retired. If the Airman is in the ARC, we mean the type of Reservist or Guardsman. There are four types of ARC members: traditional reservist (TR), individual mobilization augmentee (IMA), air reserve technician (ART), and active guard reserve (AGR). IMAs are further divided into two categories, where category A works the equivalent of one day a month more than category B. The importance of tracking the different types of ARC Airmen is that they get paid differently in each status. For example, an ART collects both civil service and military compensation, while an AGR collects active-duty pay and allowances.

4.17 Figure 14 shows the foundational Repast Simphony statechart representing an Airman's life cycle. When an Airman comes into the force, he enters the composite On Duty state. The On Duty state contains a self-transition (lower right corner) that drives the payment of salary and other benefits (see Figures 15 and 16). The trigger demonstrates using a message to force some action in a statechart. In this case, it is a "Pay Day" message sent by an environment-related object within the model, triggering execution of the code in the On Transition block and forcing payment of pay and benefits to any Airman on duty.

Figure 13. CA-MRSA model output showing the total number of colonizations resulting from colonized agents (yellow) versus infected agents (red) for 40 model runs, each spanning a year (8,760 hours).
Figure 14. Statechart of Airman’s life cycle.

Figure 15. Message trigger activated by monthly “Pay Day” message.
4.18 The On Duty state demonstrates how Repast Symphony can handle complicated statecharts. For example, within On Duty, there is a simple state representing active duty (RegAF), and there is a composite state representing the Reserve Component, called ARC. ARC is a composite state itself, containing simple states representing TR, ART, and AGR, and another composite state representing the two types of IMAs.

4.19 When an Airman enters duty, they enter the RegAF state if they are initially active duty, or the ARC state if in the Guard or Reserves. Upon entering the ARC state, they immediately enter the appropriate category within ARC. Arrows between the RegAF and ARC states, as well as between all of the ARC categories, represent an Airman’s ability to transition between employment categories throughout their career. These state transitions are made through the Condition trigger type (see Figure 17), where an Airman’s component (RegAF or ARC) and ARC category (TR, ART, AGR, IMA-A, or IMA-B) is set in other code within the model. Here it is assumed that once an Airman leaves active duty, they will not return to that state.

4.20 An Airman may transition in two ways from the On Duty state. First, they can completely separate from the Air Force, in which case they enter the Civilian state and no longer accrue manpower costs. Second, they can enter the Retirement composite state once they meet eligibility requirements for an active duty or ARC retirement. Active duty and ARCs who have completed enough years of active service to start immediately earning an active-duty retirement enter the Retired AD state. The self-transition in that state triggers when the “Pay Day” message is sent, paying the members their retirement check and updating their age.

4.21 Retirement-qualified ARC members initially enter a Gray Area retirement state, in which they receive benefits such as access to military commissaries (grocery stores) and base exchanges (department stores). They leave this state when they reach the age of 60, moving to the Retired ARC state and collecting full retirement benefits. The full life cycle of the retired Airman ends when they die and move from the composite Retirement state to a Final state, ending the accumulation of manpower life cycle costs. Figures 18 through 25 trace one Airman’s life cycle, from entering active duty to death.
Figure 18. Airman enters Active Duty.

Figure 19. Airman enters the Reserves as a Traditional Reservist (TR).
Figure 20. Airman becomes an Air Reserve Technician (ART).
Figure 21. Airman moves back to Traditional Reservist (TR) state.

Figure 22. Airman becomes an Individual Mobilization Augmentee, Category B (IMA-B).

Figure 23. Airman moves into Gray Area.
Figure 24. Airman begins collecting Reserve retirement.
4.22 We conclude this section with results from executing the developed model. We ran the model for 100 years, bringing 500 active duty and 100 new ARC members into the force each year. For the purposes of sensitivity analysis, we ran a variety of scenarios varying three parameters: 1) the seed used for the Repast Simphony random number generator, with values of 1 through 3; 2) the age at which Reservists move into full retirement and collect their retirement check, from 50 to 60 in one year increments; and 3) the retirement Cost of Living Allowance (COLA), an annual increase in the retirement pay to keep up with inflation, from 0.010 to 0.030 in 0.002 increments. Figures 26 and 27 below show the average life cycle costs for military officers completing the entire life cycle, from initial duty to death. Modeling the individual officers and/or their characteristics (e.g., RegAF or ARC, military rank, etc.) allows the estimation of manpower costs by both highly aggregate (average RegAF cost versus average ARC cost, Figure 26) and more disaggregated measures (costs by officer rank, Figure 27). Figure 26 shows that at the highest aggregate level there is little change in the average costs based on seed. This is primarily due to sample size, which is large. The output for each of the three random seed values contained 121 runs (11 retirement ages x 11 COLA) and more than 1.7 million records. Figure 27 shows more variation, e.g., the average life cycle costs of a retired major in the seed 2 run was about $209K (6%) more than in the seed 1 run.

4.23 Here we note that the simulation runs were executed in parallel on the Blues high-performance cluster at Argonne National Laboratory (http://www.lcrc.anl.gov/info/Blues) using Repast Simphony's built in batch capabilities, enabling an effectively up to 363 time (i.e., 121 parameter combinations x 3 random variations) speed up when compared to running the individual simulations serially. For the presented version of the model each individual simulation took about 20 minutes to run, making the total time required for all simulations to run serially 121 hours. This dramatic speed up was possible because a Repast Simphony model that utilizes statecharts is just like any other Repast Simphony model and can therefore take advantage of the built in capabilities of the toolkit.

4.24 Figure 28 shows a contour plot of ARC life cycle costs when the ARC retirement age is varied from age 50 to 60 and the retirement COLA is varied from 0.01 to 0.03. The retirement age change is made by simply changing the age in the Gray Area to Retired ARC conditional transition with the parameter value used for each run. The retirement COLA is another model input parameter that is set prior to starting each model run.

4.25 Historical rates for the retirement COLA range from 0% in recent years to up to 14.3% back in 1980 (Military Benefits 2014). The average annual COLA over the last 25 years has been about 2.8%. Figure 28 shows that with this rate of increase, even a modest reduction of 5 years in retirement age moves costs into the upper bracket ($4.5M - $5M). The data underlying the chart shows the costs increase about 10%, from $4.12M to $4.54M. Government leaders would need to balance this cost increase with the benefit of rewarding the Reserves for the larger operational role they have played in recent history. The Repast Simphony statecharts framework provides a free tool to support such decision making.
Figure 26. Average manpower life cycle costs for U.S. Air Force officer, by component and random seed.
Figure 27. Average U.S. Air Force Reserves officer manpower life cycle costs by rank and seed.

Figure 28. Effects of changing the ARC retirement age and the annual retirement cost of living allowance (COLA) on life cycle costs (LCC).

Conclusions

5.1 This paper presents the recently introduced statecharts capability in Repast Simphony. Repast Simphony statecharts enable "best practice" software engineering processes, which provide transparent and formally grounded design notations that translate directly into working implementations of state-based ABSS models. Statecharts in Repast Simphony offer modeling flexibility by allowing the agent modeler to combine the most appropriate modeling paradigms.
state-based and other, in order to capture the essential elements of a complex system. Statecharts are also combined with Repast Symphony ReLogo to create accessible and expressive agent-models. The statecharts editor consists of a graphical editor and a fully featured code editor. Statechart elements are created, arranged, and connected in the graphical editor. Agent actions and transition conditions are specified in the code editor, which includes intelligent auto-completion, quick and inline access to application programming interfaces, and templates to generate boilerplate code. These capabilities are freely available as part of the open source Repast Symphony distribution, lowering barriers to entry for researchers and prospective agent-modelers.

5.2 We intend to explore a number of future directions. First is porting the statecharts capabilities in Repast Symphony to the Repast HPC toolkit (Repast HPC 2014). Repast HPC is a C++ high-performance computing agent-based modeling toolkit for executing very large agent-models on Top 500 class computing resources (http://www.top500.org). Currently the statecharts framework is exclusive to the Java-based (including Groovy and ReLogo) Repast Symphony toolkit. The generality of the graphical editor and of the code generation capabilities, combined with the potential ease of mapping the statecharts engine between the object-oriented languages Java and C++, will facilitate the migration of the statecharts capabilities to run at unprecedented scales with Repast HPC. The second direction relates to the use of statecharts in agent modeling, which is still in its nascent stages. To promote the utility of this software engineering methodology in ABSS, we intend to develop useful design and process patterns (North & Macal 2014) for capturing idiomatic state-based agent behaviors.

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