GCM 4.0 Modeling Guide

# Chapter 1: Introduction

## Who is this for?

The General Computation Model (GCM) is a Java based simulation framework for building disease progression models. Users of GCM should have a general familiarity with Java and object oriented programming and would benefit from some exposure to event based modeling.

## High level overview

### Simulation

GCM is an event based simulation composed of data managers, actors and an event engine. The data managers contain the state of the simulation and generate events when that state changes. The actors contain the business logic of your model and act on the data managers. The engine transports events generated by the data managers to any data managers and actors that subscribe to those events.

### Plugins

Data managers and actors are organized into plugins. A GCM model is thus composed of the core simulation and a suite of plugins. The plugin architecture provides for the scalable reuse of concepts and capabilities between models. GCM is provided with a set of existing plugins that define many of the concepts useful to a broad range of models such as the management of people, their properties, social group structures and the like. The modeler is free to compose a model from their choice of plugins.

### Experiment

GCM also provides an experiment management system. Each plugin contains zero to many data objects that define the initial state of its actors and data managers. Each such data object may be altered freely. The complete set of all combinations (scenarios) of the variant plugin data objects form an experiment and a separate simulation instance is executed for each combination.

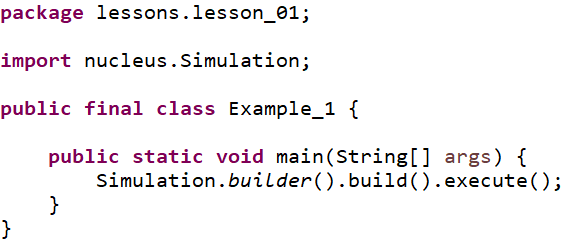
# Chapter 2: Getting Started

We start with a set of practical lessons that will help clarify the core concepts of GCM. The lessons generally build on one another and should be taken in order. You are encouraged to code along with the lessons.

## Lesson 1: Hello World

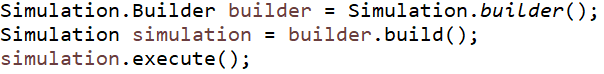
Our first lesson is a very reduced “Hello World” example where we will execute the simulation with one line of code.

***Figure 2.1.1***



With this one line we have created and executed a simulation. Since the simulation had no actors or data managers there was nothing to do and so it terminated immediately. Let’s analyze the line in a more drawn out form:

***Figure 2.1.2***

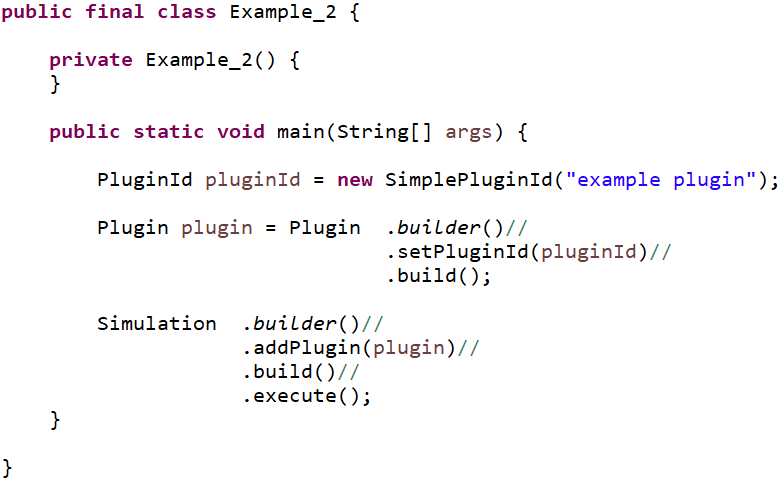


The simulation does not have a constructor. Instead it uses a static builder class that creates the simulation from various arguments. The builder is immediately capable of building a simulation instance so we will skip giving it any more information. The simulation is only capable of executing, so we execute it.

## Lesson 2: Plugins

Models are made of plugins. In this lesson we will add a single plugin to the simulation and execute it.

***Figure 2.2.1***



The first thing we will need to do to build a plugin is to identify it. The PluginId is a marker interface – it has no methods and serves to help differentiate between plugin id values and other identifiers. The SimplePluginId is a convenience implementor of PluginId and will wrap any object as an identifier. In this case we use the string “example plugin”, but you are free to implement them however best fits your needs.

Next we build the plugin. The Plugin class implements all plugins and you can provide several arguments to its builder to specify the contents and behavior of your plugin. A plugin is composed of four items:

1. An id
2. Dependencies on other plugins
3. Data objects used to initialize data managers and actors
4. An initializer to load the data into the simulation

For now, we will only need to add the plugin id and build the plugin.

Finally, we build the simulation by adding the plugin and then executing as usual. The result is the same as the previous lesson: nothing happens. However, internally, the simulation did add the plugin and found it had no information other than its id.

## Lesson 3: Actors

### Contexts

In all that follows, we will encounter various context objects. Contexts are interfaces into the simulation that are tailored to the thing using the context. For example, an ActorContext provides everything that an actor will need to interact with the simulation. Similarly, a DataManager context provides the capabilities needed by data managers.

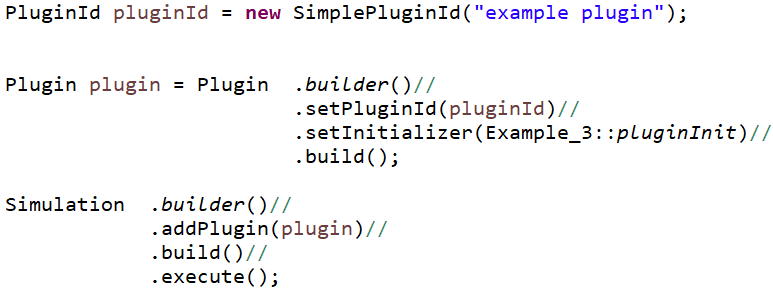
The first context we encounter is the PluginContext. It provides the plugin with the following abilities:

1. Add an actor to the simulation
2. Add a data manager to the simulation
3. Get plugin data

The PluginContext is passed to the plugin’s initializer and is used to add all data managers, all initial data and any actors that need to exist at the beginning of the simulation run.

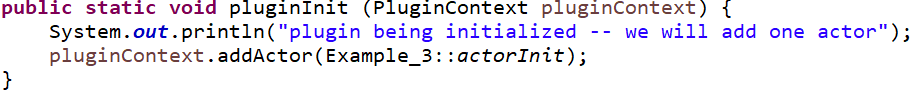
The next context will be the ActorContext. It provides actors with a wide array of capabilities that we demonstrate later. For now, the important takeaway is that being granted a context implicitly identifies the recipient as having a particular role in the simulation.

***Figure 2.3.1***



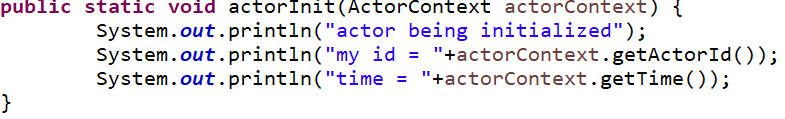
We are setting the plugin’s initializer. The initializer is a method that consumes a PluginContext and returns void. For this example, we use a static local method for our initializer:

***Figure 2.3.2***



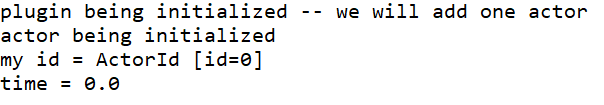
When the simulation starts up its execution, one of the first things it will do is to execute each plugin’s initializer to give the plugin an opportunity to add actors and data managers to the simulation before time and events begin to flow. Adding an actor is done with another consumer, but this time it is a consumer of ActorContext.

***Figure 2.3.3***



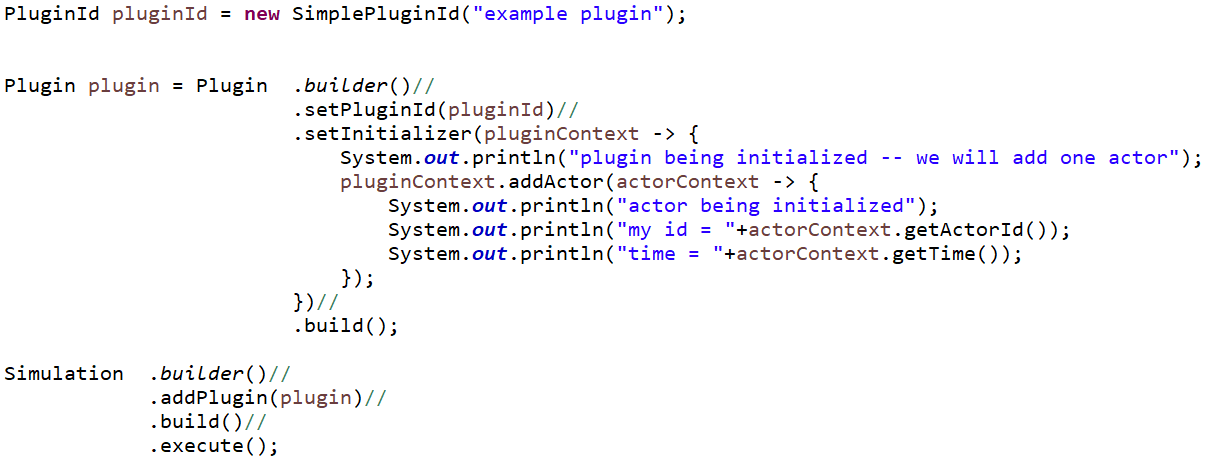
After the plugins are initialized, the actors and data managers are next. For this example, the actor is initialized and it prints a few statements and ceases activity. Here is the resulting console output:

***Figure 2.3.4***



We can replace the local method references above with lamdas to be more succinct.

***Figure 2.3.5***



## Lesson 4: Data managers

We extend the previous lesson by slightly altering the actor and adding a data manager. But first let’s list some of the attributes of data managers and actors to better understand the roles they play in the simulation.

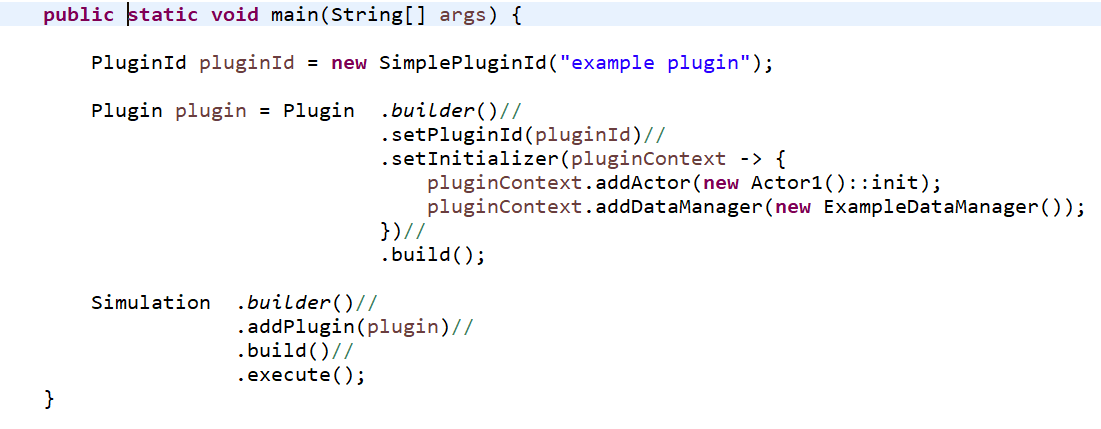
Data Managers

* Exist for the full duration of the simulation
* Contain and maintain the entire state of the world.
* Are highly stateful
* Produce events in reaction to state changes
* Interact with other data managers via events
* Do not have a set of objectives. They are not trying to achieve some particular state of the world
* Are narrowly focused on some particular aspect of the world, but are concerned with all instances of that aspect
* Are added as instances and are limited to a single instance per class type

Actors

* May be added and removed over time
* Are not considered to be part of the world
* Are generally stateless
* React to but do not produce events
* May access any data manager
* Have objectives. They contain the business logic of the model and are trying to achieve some particular state of the world
* Are concerned with many aspects of the world, but often focused on a particular subset of world
* Are added as consumers of ActorContext and may be composed of any such consumers

***Figure 2.4.1***



We add an instance of ExampleDataManager to simulation. Unlike the actor, where we pass a consumer of context, we need to provide an actual instance of a data manager. Note that the ExampleDataManager extends the base class DataManager. The base class provides the only init() method to override and you must include the super.init(dataManagerContext) call as its first line. This is done to ensure that each data manager is initialized exactly once by the simulation.

The ExampleDataManager has two (completely arbitrary) data fields alpha and beta and provides both getters and setters for each.

***Figure 2.4.2***



The actor is now specified via the ExampleActor class. Most actors contain enough code that we usually put that code into a separate class rather than a lambda statement as we did in the previous lesson. Note that the init() method has the correct method signature of being a consumer of ActorContext.

### Plans

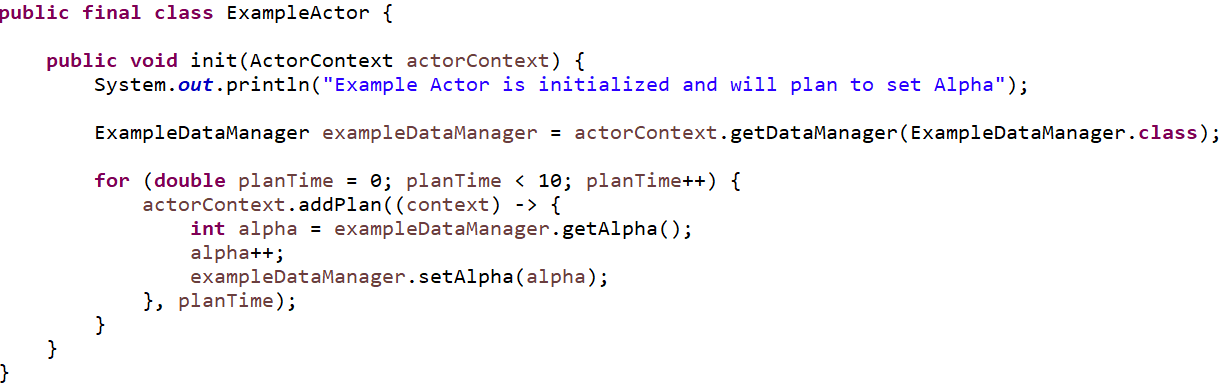
In GCM, an actor can do three things:

1. **Observe**: Observation can be done directly by gaining access to a data manager and then getting a value from that data manager. Observation can be done indirectly by subscribing to events. We will cover that option later.
2. **Act**: A mutation to some data manager’s managed data.
3. **Plan**: At some time in the future, the actor will take some particular action

Actions in GCM are always executed in the current moment in the simulation. Unlike many future event simulations where events are queued for future execution, GCM allows an actor to plan for an action or observation in the future. The plan is a consumer of ActorContext and can be a static method, member method or a lambda. The plan is registered with the simulation and is executed only when time has moved forward to the plan’s scheduled time. There is no requirement that the plan do anything at all. This allows the flexibility to re-evaluate the circumstances of the planned action and choose to take appropriate action at that time. Plans are queued in GCM by their associated planning times and it is this queue that dictates the flow of time. For example, suppose the simulation finds the first plan is scheduled for time= 2.4 days. The current time = 0 days and the simulation progresses time to 2.4 days and then invokes the plan. Plans are always privately managed by the actor that owns the plan and no other actor or data manager has any insight into those plans. See the planning chapter for more details on planning.

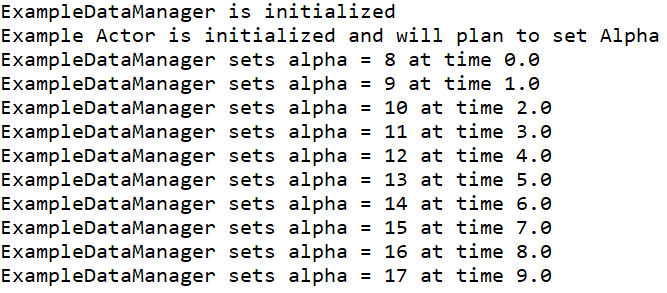
In this example, the actor is initialized at time= 0 and generates 10 plans to increment the value of the alpha in the ExampleManager. Each time the ExampleManager changes the value of alpha, it outputs to the console a description of the change.

***Figure 2.4.3***



The output from the simulation is:

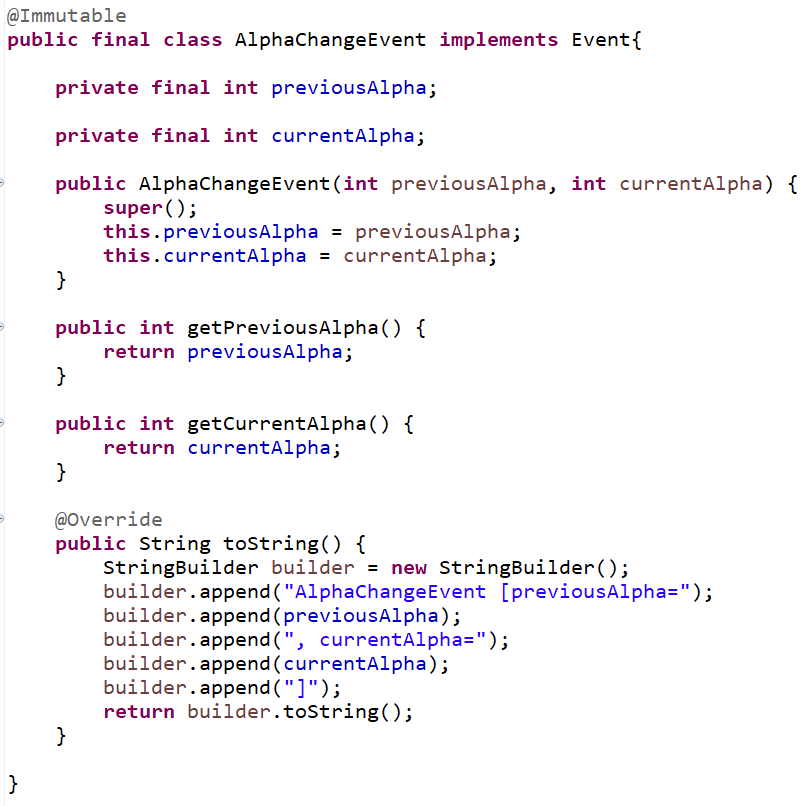
***Figure 2.4.4***



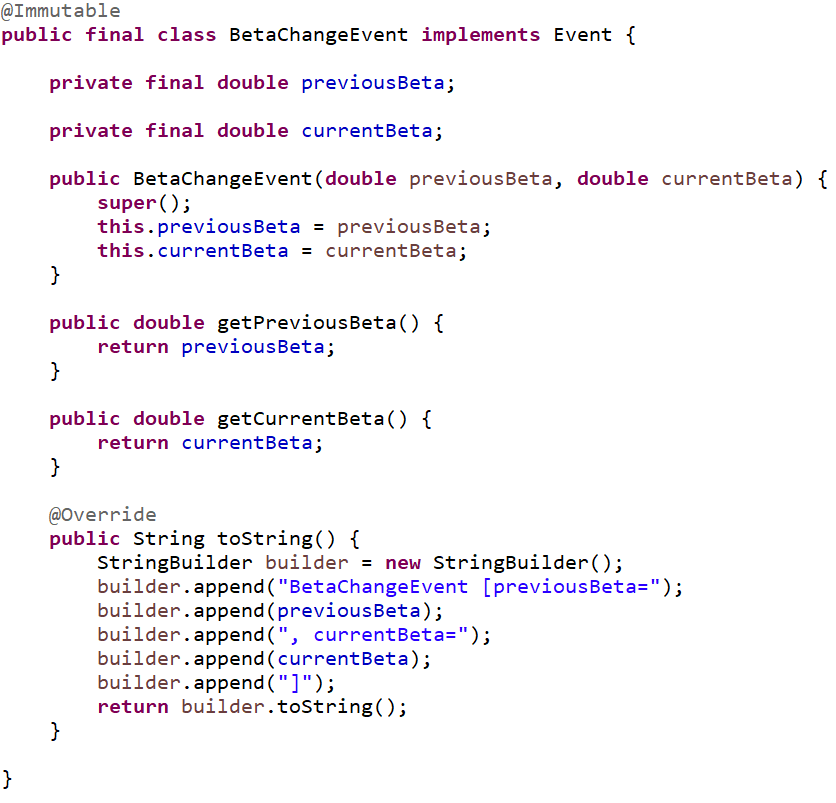
## Lesson 5: Events

An event in GCM is a notification of a data change to the state of a data manager. In this example we will introduce two events corresponding to the two changes to the ExampleDataManager. Both events document the previous value and current value (at the time when the event was generated) and are immutable data classes.

***Figure 2.5.1***

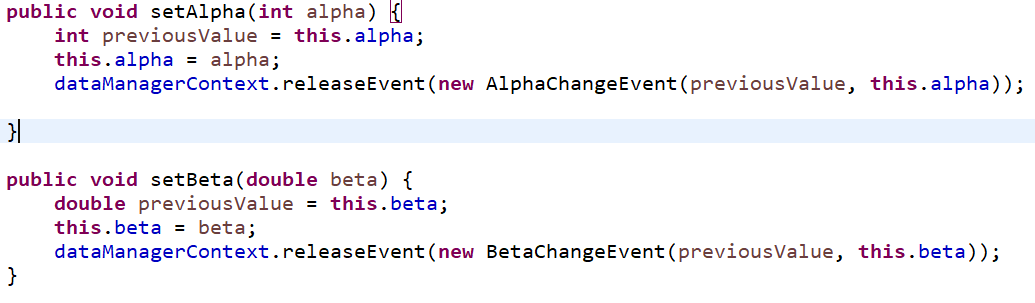


***Figure 2.5.2***



Each is generated by the ExampleDataManager when the alpha or beta values are mutated by releasing the events through the DataManagerContext to the simulation:

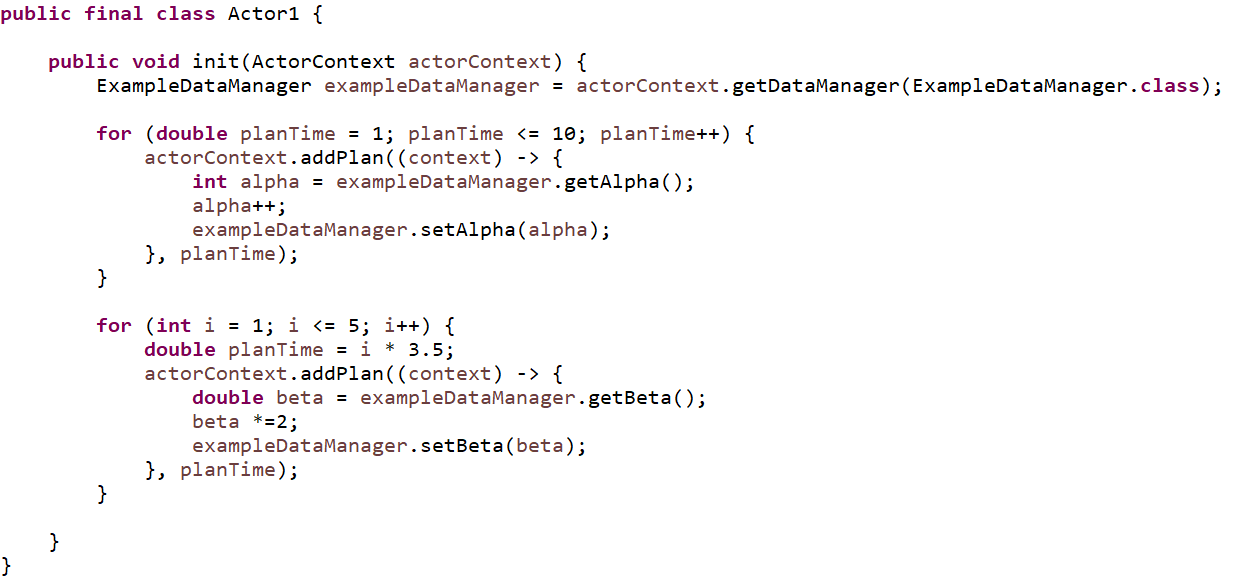
***Figure 2.5.3***



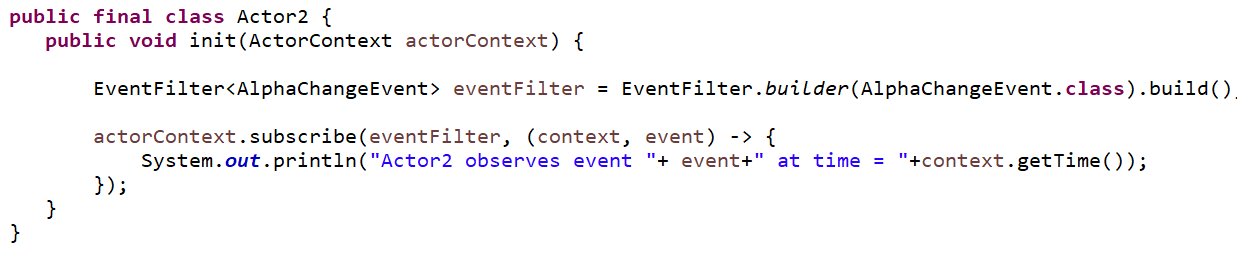
There are three actors in this example:

1. Actor1 makes changes to both the alpha and beta values at 1 and 3.5 day intervals respectively
2. Actor2 subscribes to AlphaChangeEvent events and reports to console what it receives
3. Actor3 does the same for BetaChangeEvent events

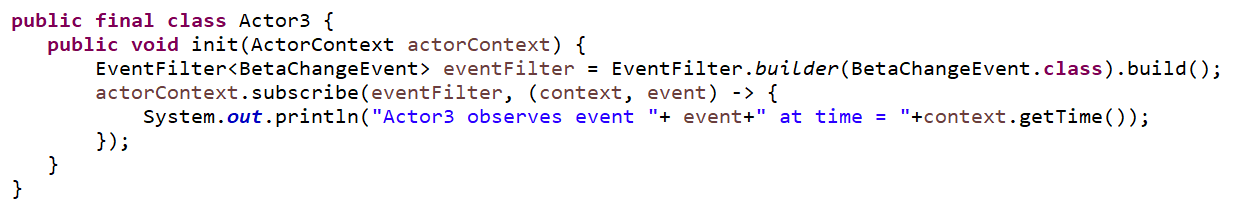
***Figure 2.5.4***

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***Figure 2.5.5***

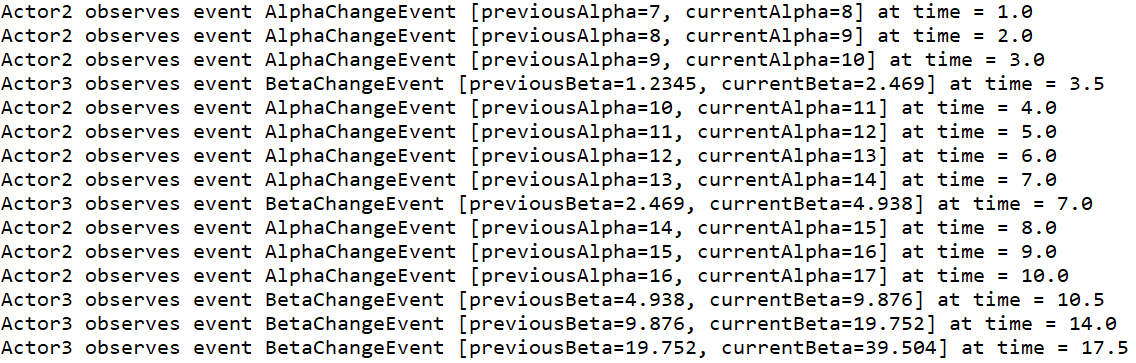


***Figure 2.5.6***



The resulting console output shows Actor2 and Actor3 observing the expected events at the expected times:

***Figure 2.5.7***



### Event Filters

Subscription to events for data managers and actors differ a bit. Data managers subscribe directly to the event type since they are generally interested in all events of some given type. Actors are often more selective and would like a predicate (in Java, the predicate is a function that returns a Boolean) to return true before they handle an event. For example, an actor wants to subscribe for person property change events, but is only interested in those events indicate a change to a particular person property. Since there will likely be dozens of person properties, the actor would get stimulated many times over, only to ignore the event most of the time. Unfortunately, a simple predicate added during the subscription process will not suffice since that predicate would have to be executed for each event and we will have gained little efficiency. Instead, GCM uses the EventFilter class that is essentially a predicate grouping mechanism that allows the subscription engine to group subscribers into a tree structure so that a single predicate execution might suffice to allow an event to be passed to multiple subscribers.

The event filter is logically composed of functions and target values as pairs. Each function takes in an event and releases a value. If that value is equal to the target value, then the event passes that function. An event passes the event filter if it passes all the functions that compose the filter.

The construction of the builder for event filters requires the event class reference. The addition of function-value pairs requires that the functions take in only events of the given class reference, but may return any non-null object value. The simple examples given so far have only specified the event class and thus every event of that type will pass the event filter.

The functions that compose the event filter are often non meaningfully comparable. For example, two functions that return the same values for every event may be separate instances of lambda code that are logically equal, but are not equal in from the point of view of Java. To get around this, each function is associated with an id value and the id and function pair are called an IdentifiableFunction. Two such functions will be equal if and only if their ids are equal without regard to what their functions actually do. Thus is it very important that the mapping of id to actual logical function be stable and the usual best practice is to manage that mapping in a curated manner via the data manager that is associated with the plugin that defines the event. As we examine plugins that define events, we will encounter event filters that are managed by data managers and will not generally generate event filters directly in the actor code.

## Lesson 6: Plugin dependencies

So far we have covered what actors and data managers do and that they are introduced into the simulation via plugins. Over the next lessons we take a closer look at the plugins. This lesson starts with creating a more realistic set of plugins each arranged into separate java packages.

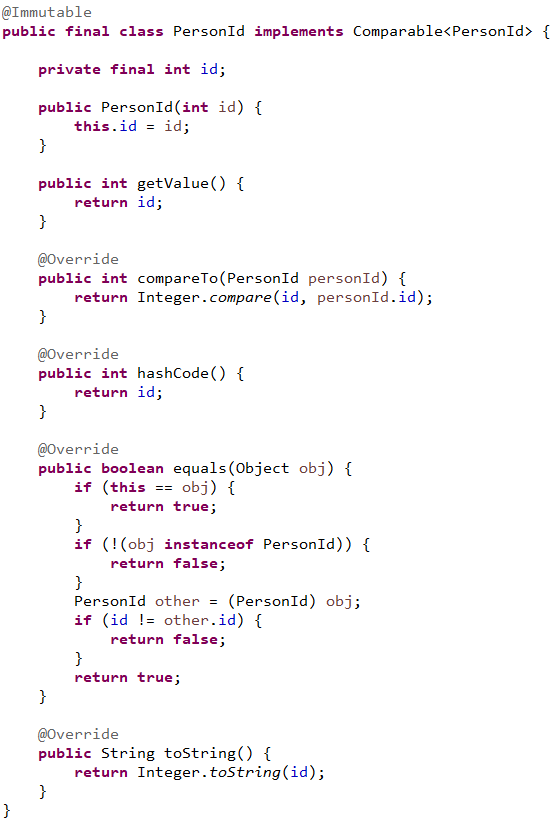
* People plugin
  + Defines a person id
  + Adds the PersonDataManager for tracking people
  + Adds events for the the addition and removal of people
* Family Plugin
  + Defines a family id
  + Adds the FamilyDataManager for grouping people into families
* Vaccine Plugin
  + Adds the VaccineDataManager for tracking which people have been vaccinated
* Model Plugin
  + Contains the ModelActor class to add people organized into family structures and vaccinate some of those people

Here are the classes that implement this example:

### People Plugin:

The people plugin defines a PersonId as a simple, immutable wrapper to an int value. The PersonDataManager tracks people via PersonId values and allows for the addition and removal of people. PersonId values are generated in order and never reused. Events are generated when people are added or removed.

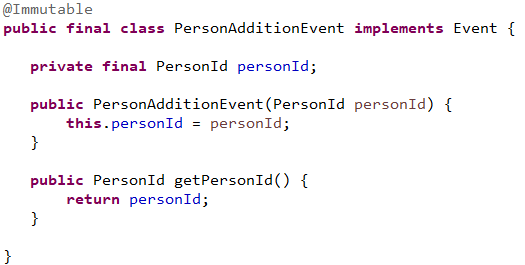
***Figure 2.6.1***



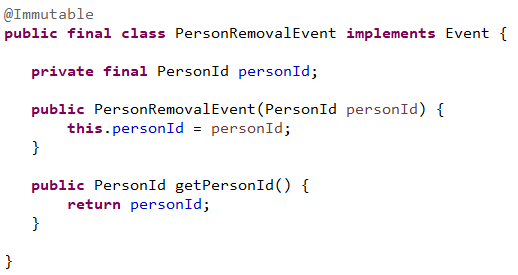
***Figure 2.6.2***



***Figure 2.6.3***



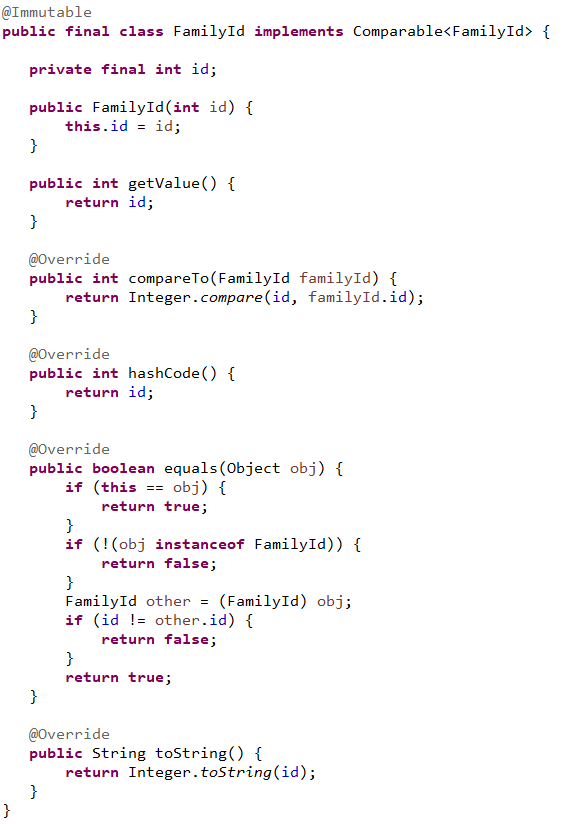
***Figure 2.6.4***



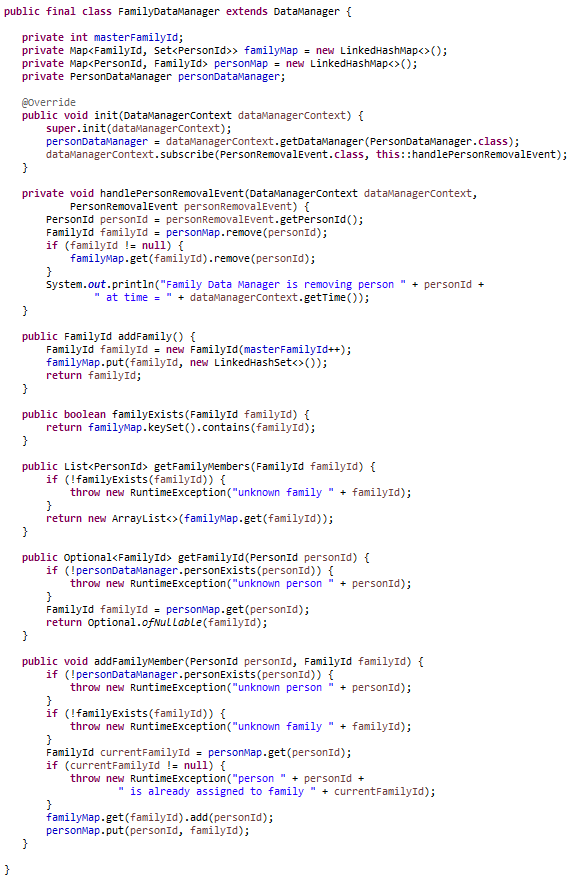
### Family Plugin

The family plugin defines a FamilyId as a simple, immutable wrapper to an int value. The FamilyDataManager tracks family membership via two-way mappings of PersonId to FamilyId. In this example families can only be added and people can only be added to families. However, people can be removed via the PeoplePlugin so the FamilyDataManager subscribes for PersonRemovalEvent and thus removes the people from families.

***Figure 2.6.5***



***Figure 2.6.6***



### Vaccine Plugin

The vaccine plugin contains only the VaccineDataManager which tracks by PersonId which people have been vaccinated. Like the FamilyDataManager, it too subscribes to PersonRemovalEvents and adjusts its data accordingly.

***Figure 2.6.7***



### Model Plugin

The model plugin contains a single actor, the ModelActor, that serves to:

* Add people to the simulation
* Group them into families
* Vaccinate some people
* Demonstrate that events cascade

### Connecting the Plugins

Both the family and vaccine plugins depend on the concept of a person as implemented by the PersonId class. They also need to respond when a person is removed from the simulation and do so by handling the corresponding PersonRemovalEvent generated by the person plugin. We build these dependencies via the Plugin.Builder class in the example code below.

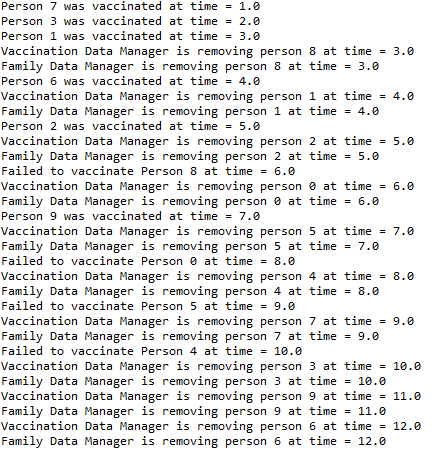
***Figure 2.6.8***



Note the addition of the dependency on the people plugin via its id when adding both the vaccine and family plugins. The order of addition of the plugins to the simulation is relatively unimportant as is ordering in general in any of the builder patterns used in GCM.

The resulting output:

***Figure 2.6.9***

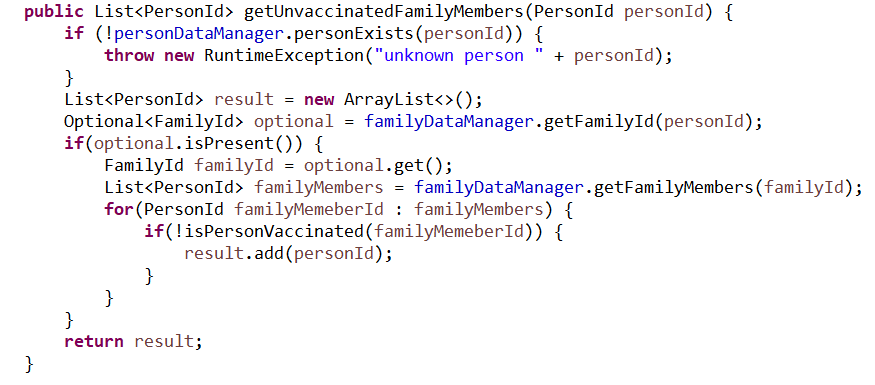


## Lesson 7: Plugin Dependency Graph

We extend the previous lesson by adding an additional dependency of the vaccine plugin on the family plugin. This will allow the VaccineDataManager to answer queries about which members of a family have yet to be vaccinated.

From the VaccineDataManager:

***Figure 2.7.1***



The plugins in this example form a dependency pattern:

***Figure 2.7.2***

people

family

vaccine

All plugin dependencies in GCM form similar directed, acyclic graphs (DAGs). There can be no loops in the dependency graph, but the graph does not have to be fully connected. The dependencies reflect the requirements of the data managers within a plugin to access data managers in other plugins. This pattern drives the order in which events are presented to data managers.

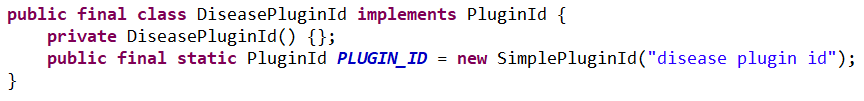
In this lesson, the VaccineDataManager and the FamilyDataManager have both subscribed to the PersonRemovalEvent generated by the PersonDataManager. Since the VaccineDataManager also has a dependency on the FamilyDataManager, the VaccineDataManager should receive the event after the FamilyDataManager. Events cascade through the subscribed data managers in an order that is consistent with the plugin dependency DAG.

## Lesson 8: Plugin Data

The Example code in the last lesson was a bit verbose and can be improved. Identifying and generating the plugins can be included in the plugin packages by introducing classes for each id and classes for each plugin’s contents.

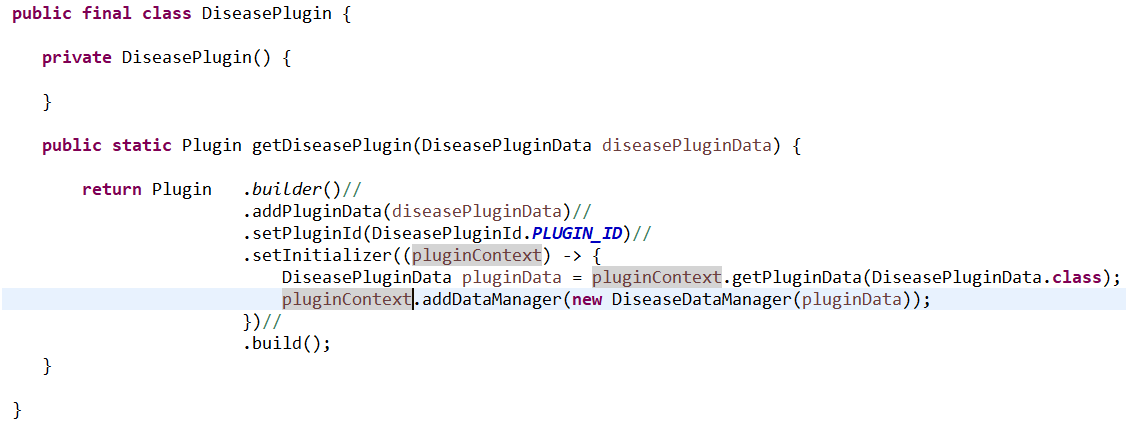
In the disease package we add a unique plugin identifier with a final static id field:

***Figure 2.8.1***



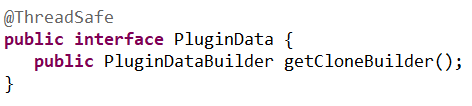
We also add a static class (DiseasePlugin) that implements the construction of the plugin from the required plugin data.

***Figure 2.8.2***



The plugin is initialized with a DiseasePluginData object that contains the initial values for r0, asymptomatic days and symptomatic days. Most plugins will have a single plugin data object, but some may not need any and some may be designed with multiple such classes. All such classes must implement the PluginData interface:

***Figure 2.8.3***

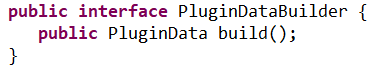


Plugin data classes must be threadsafe since they will be shared between multiple simulations running on separate threads. This stands in contrast to the actors and data managers which are created and managed in the thread of a single simulation. The best practice is to make plugin data classes immutable since immutable classes in Java are guaranteed to be threadsafe. For a class to be immutable in Java it must meet three conditions:

1. It cannot be mutated, i.e. it has no setters and no public fields.
2. All its fields are marked final.
3. Its constructor(s) do not pass reference to self. No reference to the newly created object leaks out before construction is complete.

Besides carrying whatever data is needed by the plugin, the PluginData implementor must provide a PluginDataBuilder:

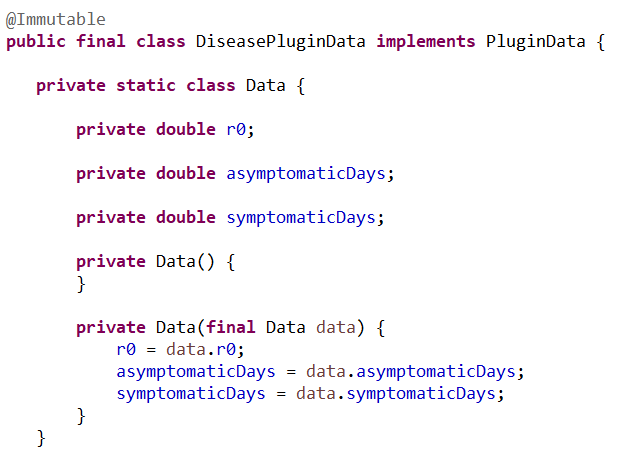
***Figure 2.8.4***



The role of the plugin data builder will be explored in the next lesson where it will be used to make alterable copies of plugin data to drive the experiment. For now, let’s examine the DiseasePluginData class. It is composed several sections:

* A data class
* A static builder class
* A single data field and private constructor
* Getter methods for the data
* A clone builder method

***Figure 2.8.5***



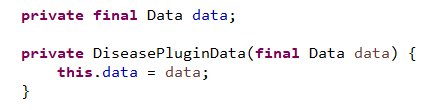
The Data class is private and just contains the fields needed by the plugin. Note that it is a mutable class and that its fields are not final. It will be used by the builder class later to store values. Its constructors are private and allow one Data object to be copied from another.

***Figure 2.8.6***



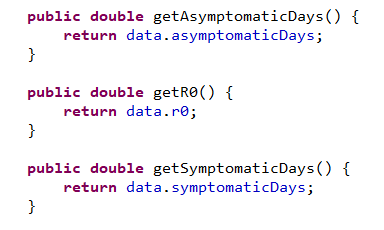
The static builder class is used instead of a constructor. The use of builder classes for plugin data objects is key to the creation of experiments covered in the next lesson. For now, let’s concentrate on what the builder does. First, it has setter methods for each of the data fields and each such method returns the builder instance to support method chaining. Next, the build() method returns the DiseasePluginData via a try finally block so that if anything goes wrong, the builder instance will uncorrupted and ready for reuse. Note that after invoking the build method, the data object gets replaced with a fresh version. Finally, the builder’s own constructor is private and is accessed via a static method. This is done to grant a syntax that is more compatible with the method chaining. We will defer discussion of the private dataIsMutable field until the end of this section.

***Figure 2.8.7***



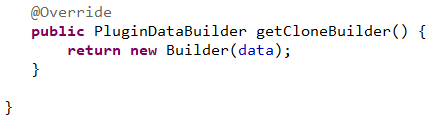
After the builder collects the data, it passes that data to the instance of the DiseasePluginData which is stored as a final field. Recall that the field must be final in an immutable class.

***Figure 2.8.8***



The getter methods for each field value in the data are added. There are no corresponding setter methods.

***Figure 2.8.9***



We end the class with the getCloneBuilder method.

*Our use of the term clone is intuitive but may cause some confusion. What we are doing is copying the data in the DiseasePluginData and placing into a builder so that it can be further mutated later in the experiment. Java formally defines the term clone as a part of the Object class definition and implements it with a protected method clone(). Use of the Object.clone() method has generally fallen out of favor in Java but still has some proponents/use cases.*

The method returns a new Builder that has reference to the current data object. The builder starts out with the private field **dataIsMutable** set to false. This is to ensure that we do not pay the cost of copying the data object if we never invoke any of the setter methods before invoking **build()**; While such considerations seem trivial with only three values, in most models there will be plugin data classes that contain millions of data values.

The resulting example class is easier to read and more succinct:

***Figure 2.8.10***



## Lesson 9: Experiments

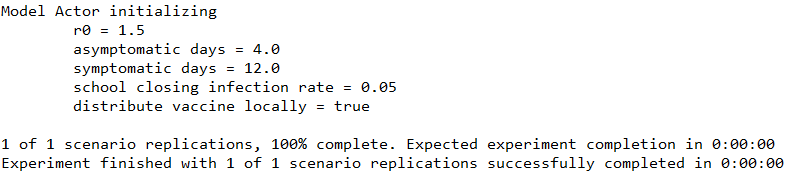
So far we have mentioned that the plugin data classes play a role in executing an experiment via the **getCloneBuilder** method. Let’s start with the simple experiment. We will update the last example class by replacing the Simulation execution with an Experiment execution:

***Figure 2.9.1***



The experiment class has a very similar builder to the Simulation class so we only have to swap out the Simulation reference for an Experiment reference. The resulting execution created an experiment containing exactly one simulation that runs in the main thread. However, the output contains information about the status of the experiment.

***Figure 2.9.2***

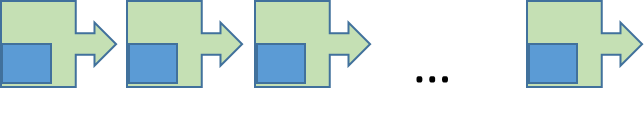


### What happens when the experiment executes?

You have contributed several plugins to the experiment and on execution the experiment generates multiple simulation runs on multiple threads. Let’s examine how this is accomplished as a way to motivate this lesson’s code examples.

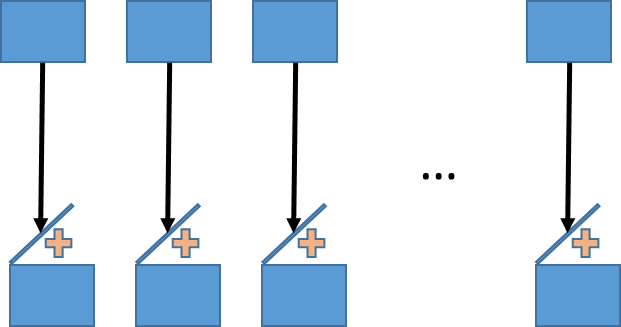
The experiment is composed of several plugins, each with zero to many plugin data objects. For purposes of the diagrams we will assume that each plugin has a single plugin data object.

***Figure 2.9.3***

**plugins**

The experiment gathers the plugin data objects and gets the plugin data builder for each. These plugin data builders will come pre-filled with the data from the original data objects.

***Figure 2.9.4***



By altering the data in these builders, we generate new scenarios for the simulations to execute. GCM manages the instructions to alter the plugin data via Dimensions. Each dimension contains one to many levels.

***Figure 2.9.5***



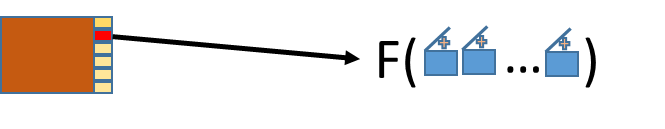
For example, we may have a dimension that alters the value of **alpha** from **plugin data A** and the value of **beta** from **plugin data B**. Each level in the dimension will set specific values for alpha and beta via the builders.

***Figure 2.9.6***

|  |  |  |
| --- | --- | --- |
| level | alpha | beta |
| 0 | 2.3 | FALSE |
| 1 | 3.6 | TRUE |
| 2 | 4.8 | FALSE |

Each level in a dimension is actually a function that takes in the builders and manipulates the content of each plugin as needed.

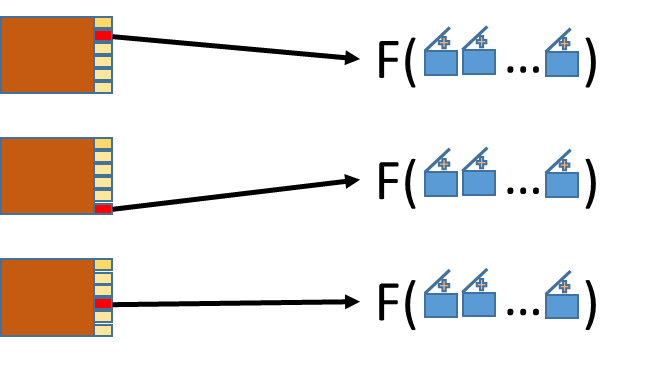
***Figure 2.9.7***



Consider an experiment with two dimensions having 3 and 5 levels respectively. The number of level permutations is 3x5 = 15. Each such permutation is referred to as a scenario and the scenarios are numbered from 0 to 14.

As the experiment executes, it works with each scenario id and determines for that id which levels are active for each dimension.

***Figure 2.9.8***



Each level (via its function) alters the contents of the builders in turn, resulting in a unique set of content for that scenario.

***Figure 2.9.9***



The builders are then instructed by the experiment to build the plugin data objects. The resulting data objects are inserted into copies of the original plugins to produce a unique set of altered plugins that are specific to the scenario id and executed via a single simulation instance.

***Figure 2.9.10***



You may have noticed that the initializer code above acquires the DiseasePluginData via the context rather than the instance passed to the getDiseasePlugin() method. This is a necessity due to experiment design and will be covered in the lessons that follow. **In general, the initializer code should always retrieve plugin data from the plugin context.**

We expand the example by adding a single dimension that set r0 to two values, generating two simulations.

***Figure 2.9.11***



In the dimension we see that there are two levels and the addition of some meta data in the addMetaDatum(“r0”) invocation. The meta data here represents the information that each level is altering in the experiment. The main purpose of each level is to alter the state of a builder(s) but must also return meta data values to match the meta data for the dimension. The meta data of the dimension acts as a header to a table while the meta data for each level are the values in that table.

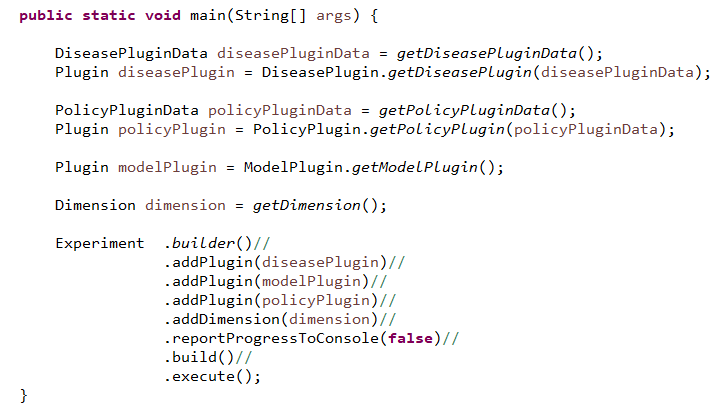
The building of the dimension can be streamlined without typing out each level:

***Figure 2.9.12***



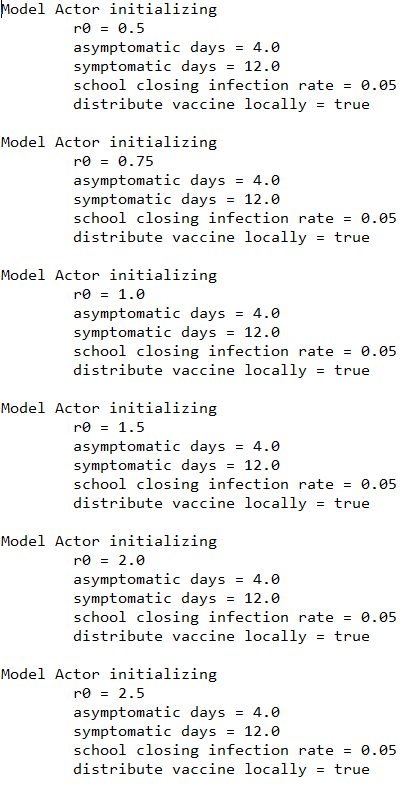
The resulting experiment execution is more streamlined:

***Figure 2.9.13***



We have turned off the experiment report progress to console in the code above. We have chosen six values for r0 in our dimension and thus we have 6 simulation executions, each having the model actor print out the contents of the DiseaseDataManager:

***Figure 2.9.14***



We are extending the example again, reducing the r0 dimension to just three levels and introducing a dimension over the policy data. This new dimension has four levels controlling local vaccine distribution and school closing infection rates:

***Figure 2.9.15***



We add the new dimension to the experiment:

***Figure 2.9.16***



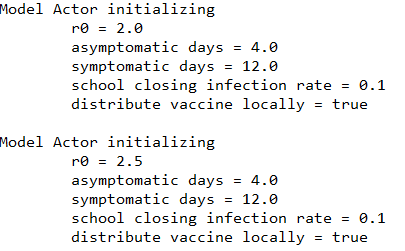
The result is now 12 executed scenarios:

***Figure 2.9.17***



…

***Figure 2.9.18***



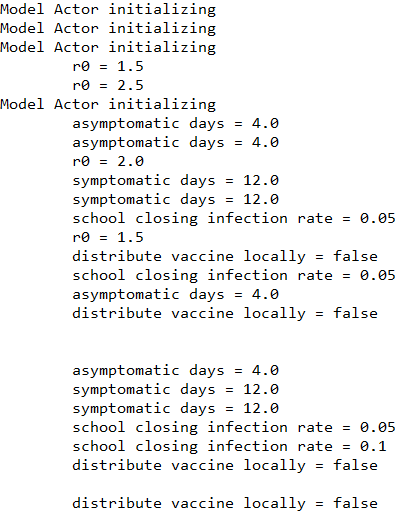
So far, the experiment has run in a single thread. We now run it in four threads by adding a single line to the experiment giving is a thread count:

***Figure 2.9.19***



The experiment runs in the main thread and the scenarios now run the four additional threads. The resulting console output a bit jumbled since the writes to the console are now coming from four simultaneous simulation runs:

***Figure 2.9.20***

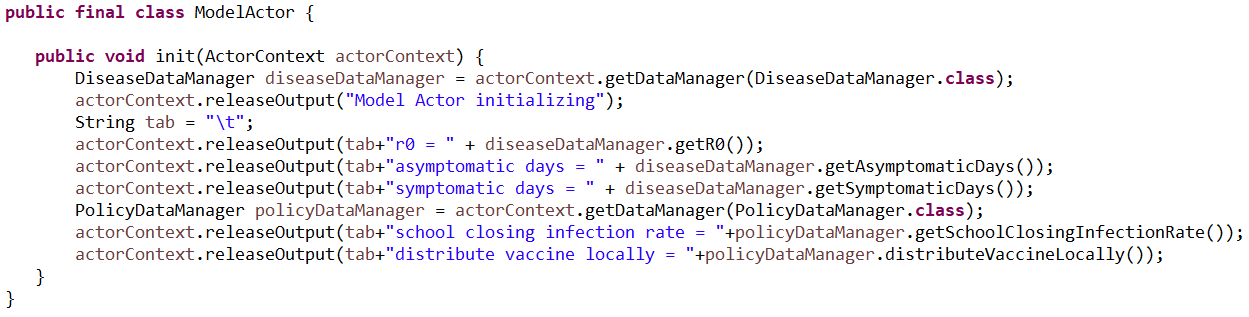


We will alleviate this problem as we explore how the simulation and experiment manage output.

## Lesson 10: output

So far we have only produced output by writing directly to the console in the various actors and data managers. The simulation contexts (ActorContext/DataManagerContext) provide for the release of output objects to an external handler (outside the simulation). In this lesson, the ModelActor class has been altered to use this mechanism:

***Figure 2.10.1***



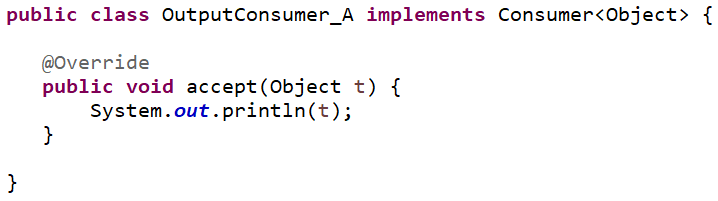
Data managers can release output in a completely similar way. The output objects are handled by an external handler presented during the build of the simulation:

***Figure 2.10.2***



Released output objects are sent to the output consumer. In the current example, that consumer is an instance of the class OutputConsumer\_A and it simply prints the object to the console:

***Figure 2.10.3***



At first glance this mechanism seems simple and not particularly useful. In practice, one rarely uses the simulation directly and instead favors the experiment which has a somewhat more sophisticated handling of output. With experiments, GCM is potentially using multiple threads to execute each simulation, so output handling must be threadsafe.

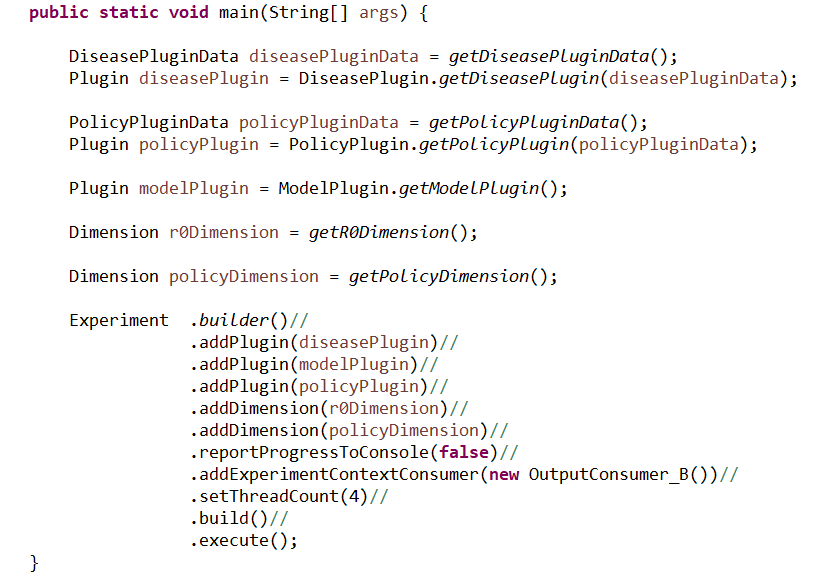
### Experiment Context

Just as the simulation supplies contexts, the experiment uses the ExperimentContext to give output consumers a view into the ongoing experiment. It gives each output consumer several capabilities:

* Subscription to output by output class type
* Subscription to the opening and closing of the experiment
* Subscription to the opening and closing of each simulation
* Scenario status information
* Experiment and Scenario meta data

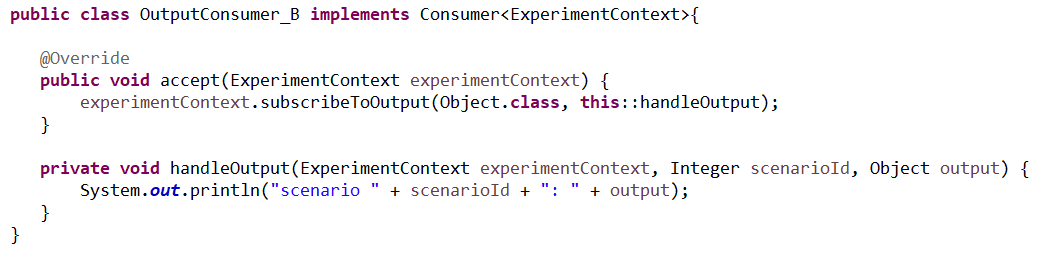
In Example\_10\_B, we bring back the dimensions from previous lessons and will excerpt just the main method:

***Figure 2.10.4***



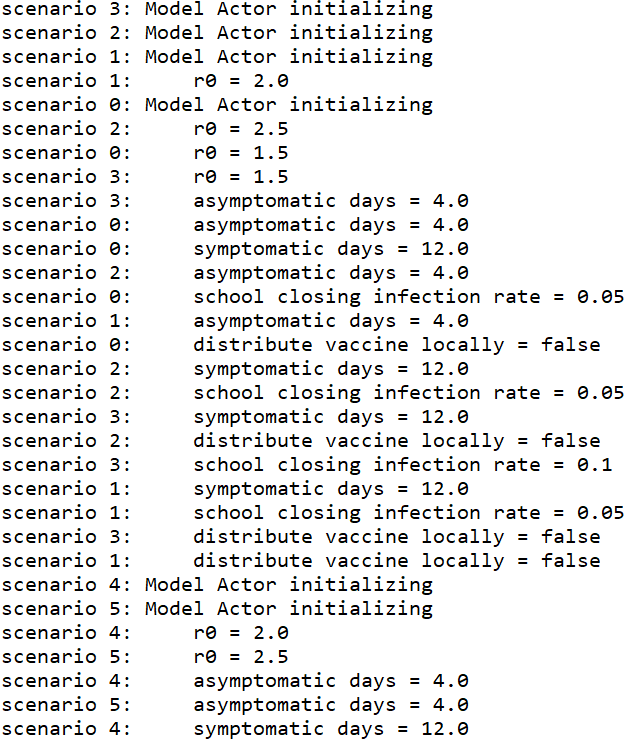
Like the simulation, the experiment is adding a consumer for output, but this time that consumer is “consuming” an experiment context. Once the consumer receives that context, it will use it to further subscribe to output and various experiment level events.

***Figure 2.10.5***



The experiment can have any number of ExperimentContext consumers and initializes each at the beginning of its execution via the accept() method. In OuputConsumer\_B, the only action the consumer takes is to subscribe to all output and have that output handled by the handleOutput() method. The resulting output shows the scenario id for each line:

***Figure 2.10.6***



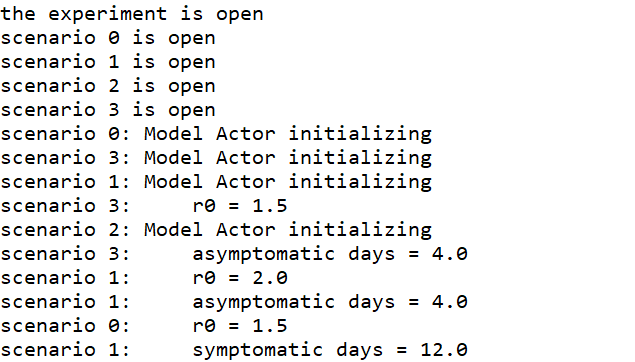
Example\_10\_C switches the experiment context consumer to an instance of OuputConsumer\_C which subscribes to all output types as well as the opening and closing of the experiment and all simulations (scenarios):

***Figure 2.10.7***



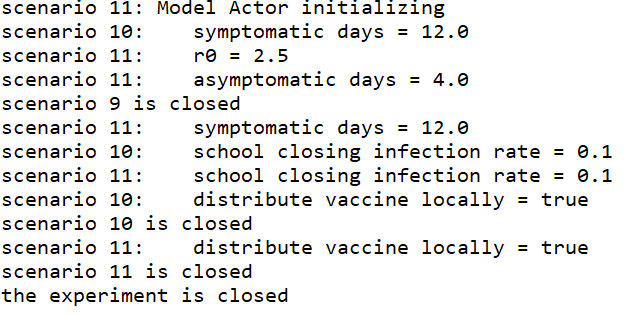
The resulting output shows the usual released output along with the opening and closing of each simulation:

***Figure 2.10.8***



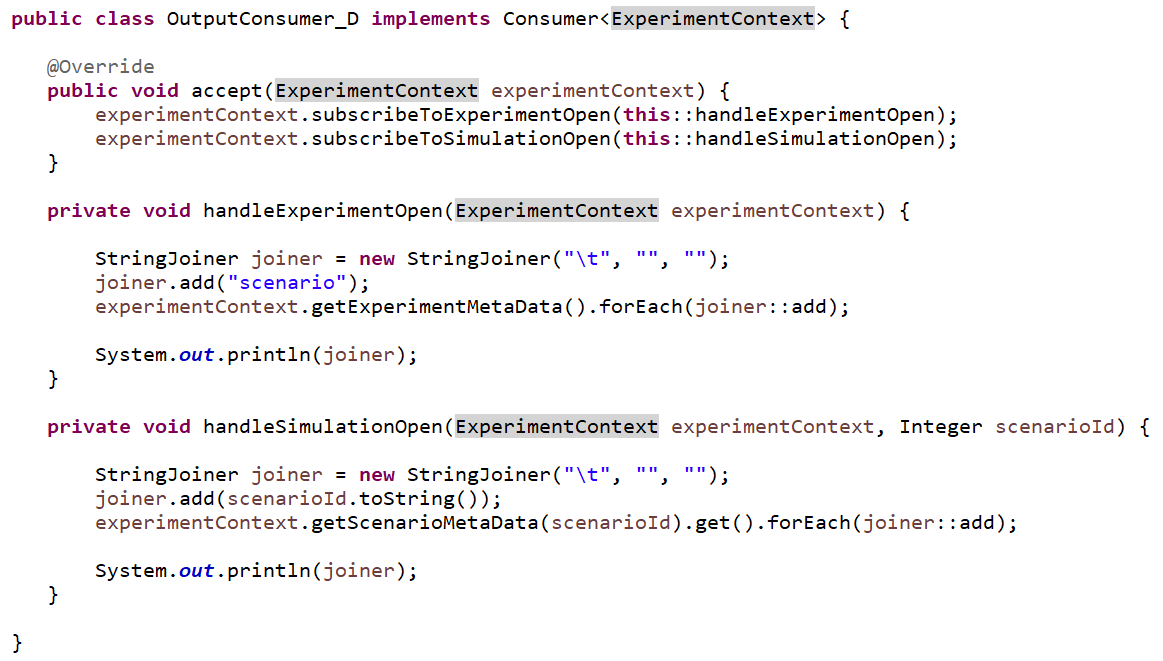
…

***Figure 2.10.9***



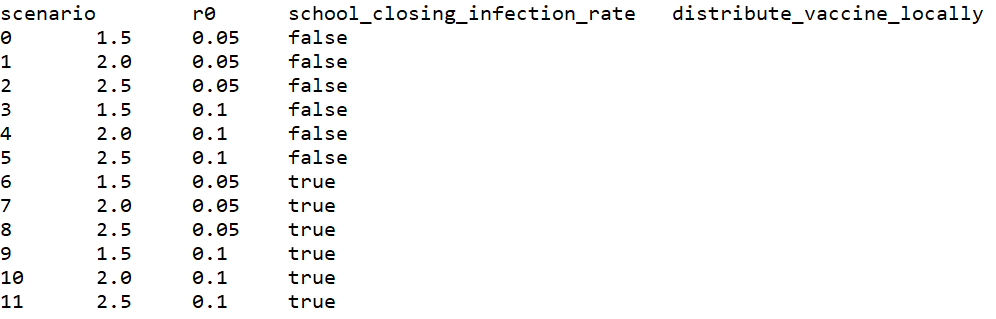
In the final example, OuputConsumer\_D, we drop the output handling and demonstrate that the meta data used to build the dimensions of the experiment can be retrieved from the experiment context and used for reporting:

***Figure 2.10.10***



The resulting output shows for each scenario the meta-data that defines that scenario:

***Figure 2.10.11***



Recall that as the experiment executes, it utilizes multiple threads to execute the individual scenarios. Thus every experiment context consumer must be threadsafe. We have accomplished this by making each such consumer stateless. In practice, it is often necessary for experiment context consumers to be stateful and this can involve careful consideration of the use of synchronization and other concurrency issues. Fortunately, GCM provides a reporting plugin that deals with these issues and provides a general method for producing tabular reports.

# Chapter 3: Stochastics Plugin

The stochastics plugin provides for the management of random number generators. It contains a default random number generator (RNG) as well as any number of RNGs associated with identifiers.

### Plugin Data Initialization

The plugin is initialized using a StochasticsPluginData object that collects a starting seed value for the default RNG as well as any number of RNG identifiers. These identifiers are implemented via the RandomGeneratorId interface which only specifies that such an identifier have a non-null, non-empty and stable implementation of the Object.toString() method.

### Plugin Behavior

The plugin adds a single data manager to the simulation as an instance of the StochasticsDataManager that is initialized with the StochasticsPluginData.

### Data Manager

The data manager provides access to its RNGs via various getter methods. The RNGs are implemented as org.apache.commons.math3.random.Well44497b instances and are subject to seed manipulation. RNG seed management should be left to the data manager and never directly managed by any client. The default RNG is seeded with the plugin data’s seed. All other RNG’s have their seeds set to a function of their associated ids: rngSeed = id.toString().hashCode()+ pluginData.seed().

Our first example lesson uses the disease, model and policy plugins again. This time we will have the single ModelActor schedule three random times to set the R0 value to a random number between 1 and 2. Four scenarios will result from a policy based dimension that alters the school closing infection rates, which will not influence the ModelActor.

***Figure 3.1.1***

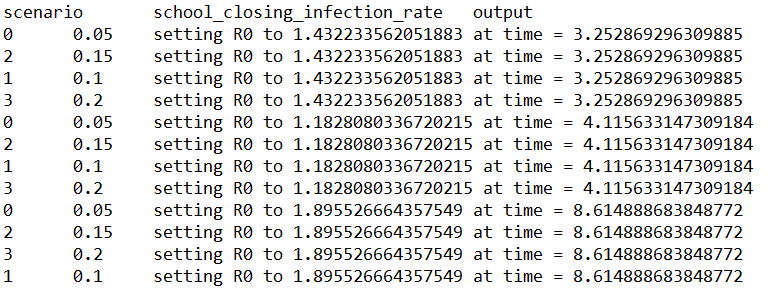


***Figure 3.1.2***



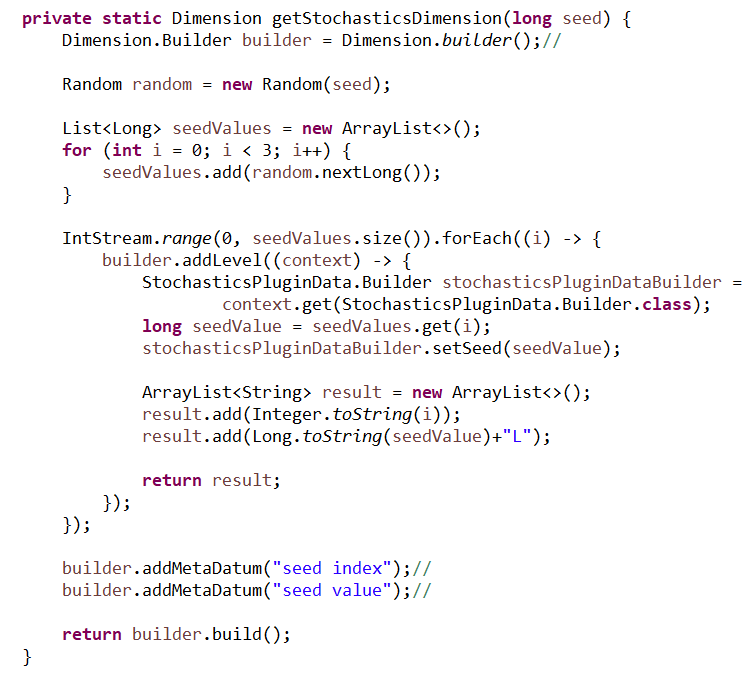
The stochastics plugin is initialized with a seed value of zero and that seed will be used in each scenario as the initial seeding for the default random generator. Thus we expect that each scenario will have identical output.

***Figure 3.1.3***



Our next example lesson adds a dimension used to alter the initial seed value of the stochastics plugin data to one of three values. Combined with the policy dimension, this will result in 12 scenarios.

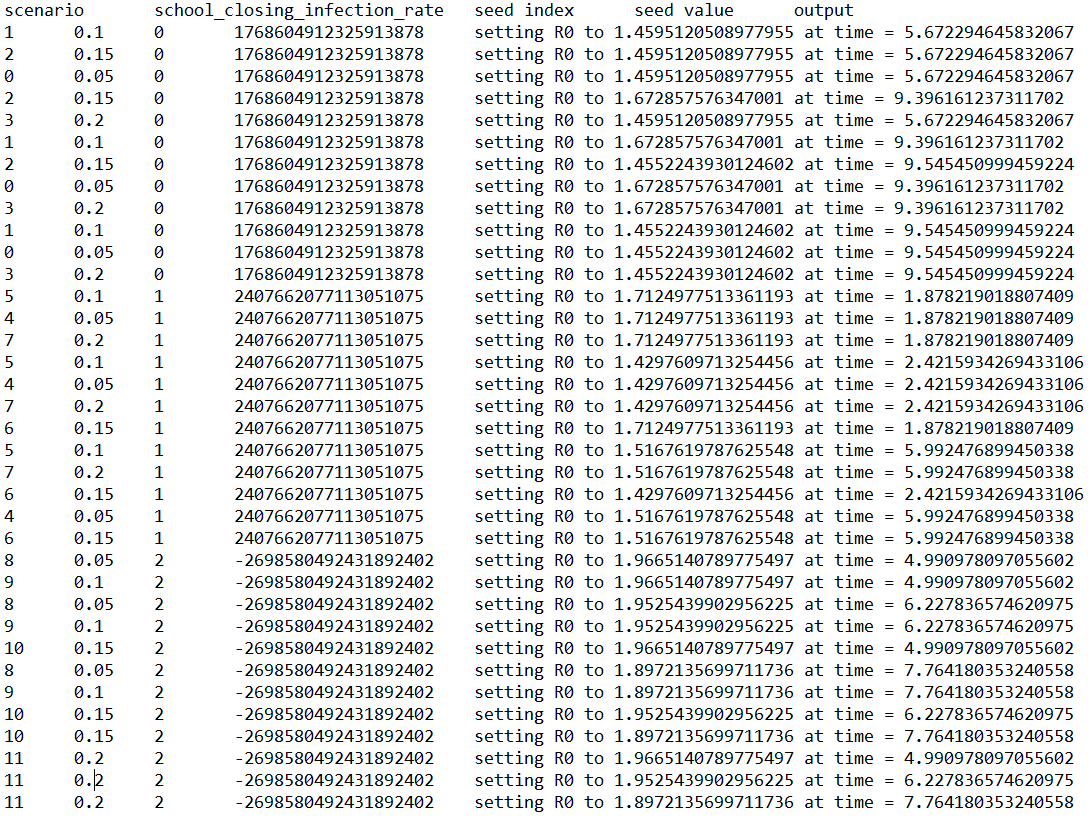
***Figure 3.1.4***



***Figure 3.1.5***



The resulting output shows the varying random number generation:

***Figure 3.1.6***

# Chapter 4: Reports Plugin

The reports plugin implements an experiment context consumer that records output into tab-delimited text files via the java.nio library using blocking file writes. Three new concepts form the core of the reports:

1. Report Id – a unique identifier for each report
2. Report Header – the header content for the report
3. Report Item – the data content(strings) for each line in the report

The report id is a unique identifier used to mark every report item that the plugin processes and helps associate each item to the specific file where it will be recorded. Report items are a flexible list of values that have an associated report id as well as a report header used to build the header of the file. A report file is built from the report items that are associated with a specific report id in the order received. The first report item is used to build the header of the report file. All other lines of the file are an ordered, tab-delimited listing of the string values contained in each report item. No attempt is made to ensure that the header matches the report lines or that all report lines have equal field lengths.

While any data manager or actor can release report items, in practice most reports are managed solely by special purpose, passive actors that simply observe events and do not act on any data manager. These report actors often subscribe to multiple event types and aggregate several events into a single report item. This reduces the amount of information recorded in output files and thus output files are often more complex than simple event trace files.

### Plugin Data Initialization

The plugin initialization data contains the initialization logic of report actors. Recall that plugin initialization data is shared across multiple scenarios in an experiment and that experiments can execute in multiple threads. This requires that this initialization logic be threadsafe. We achieve thread safety by contributing suppliers of consumers of ActorContext. Formally, these are Supplier<Consumer<ActorContext>>. When a particular scenario is executed in a simulation’s thread, each such supplier is invoked to produce the new consumer of ActorContext. Generally, this will be accomplished by having the supplier generate a new instance of the relevant report actor class with thread-safe content.

### Plugin Behavior

The Plugin processes the reports plugin data at the beginning of each simulation and adds an actor for each supplier of consumer of actor context.

### Experiment Context Consumer

So far we have seen that reports tend to be produced by specialized actors and that those actors can be added to the simulation via the plugin initialization data. This covers the production and release of the report items from each simulation instance but not what happens to the report items afterward. The output files that receive the report items must work with multiple threads. We manage this with a threadsafe experiment context consumer, the NIOReportItemHandler, that is added to the experiment. The NIOReportItemHandler is created via a builder pattern that allows the modeler to associate report ids to file paths.

### Example Reports

We reach back to the previous lessons where we introduced plugins for people, families and vaccines for a demonstration of reports. The reports will center on the vaccination of families in various forms and are implemented by three dedicated actor classes in the vaccine plugin:

* FamilyVaccineReport – Immediate reporting based on observed events
* HourlyVaccineReport – Hourly reporting based on observed events
* StatelessVaccineReport – Hourly reports based on inspection of current state

### General Setup

This example uses the following plugins

* Person Plugin – provides containment for person identifiers
* Stochastics Plugin – (GCM plugin) provides random number generation
* Reports Plugin – (GCM plugin) provides reporting mechanisms
* Family Plugin – defines families and associates people with families
* Vaccine Plugin – maintains vaccine assignments with people and families and defines the three reports
* Model Plugin – provides an actor for loading the initial population and an actor for scheduling vaccinations

The general flow of action in the simulation is that the PopulationLoader actor will add people and families to the simulation based on the initial plugin data provided in the family plugin. The VaccineScheduler actor will then schedule people at random times to be vaccinated. As people and families are created, people join families and people are vaccinated, the various data mangers will generate the relevant events for observation by the three report actors. The report actors will observe these events and correspondingly generate report items that will flow out of the simulation into the experiment level report mechanisms that will result in report files being written.

Let’s examine Example\_12. In figure 4.1 we see that the plugins are generated with the person, vaccine and model plugins requiring no input data. The stochastics plugin is generated with a fixed seed value. Next, the family plugin is created with initial data specifying that 30 families will be created and that each family will have a random number of members up to 5 people.

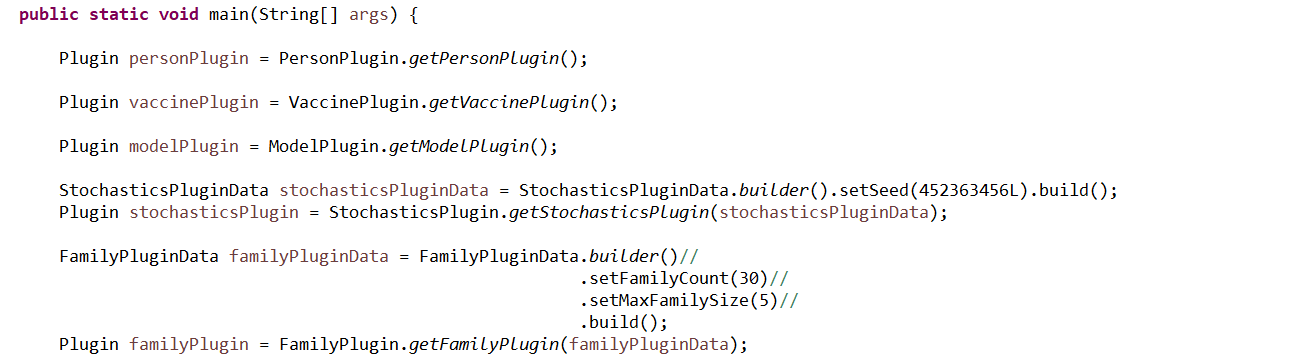
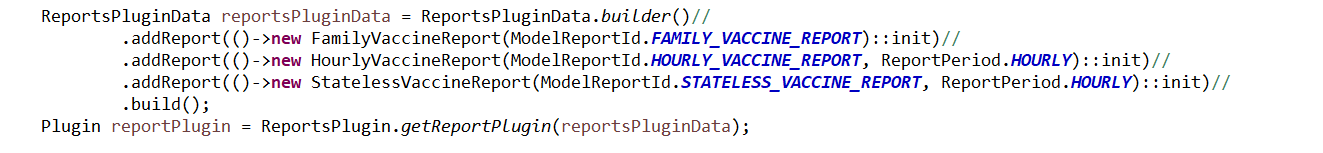
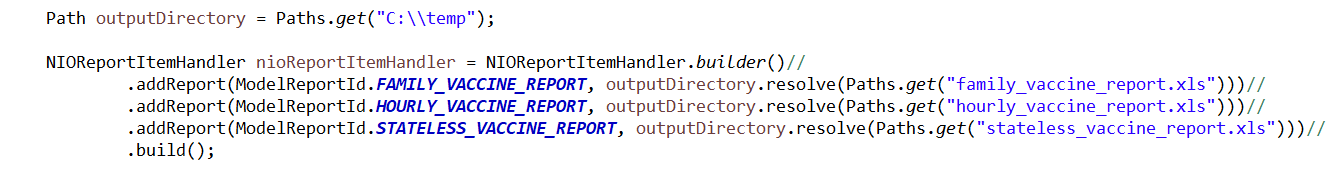
***Figure 4.1***

Figure 4.2 continues with the addition of the three report actors. These actors are defined in the vaccine plugin, but that plugin does not add them to the simulation since report actors are created at the discretion of the modeler based on their analytic needs. Thus the control of report actor creation is generally left to the report plugin. Since the report plugin was written without knowledge of how to implement these actors, we must provide the construction mechanisms. Further, each simulation instance will have to create these actors in its own thread, so a threadsafe mechanism must be employed. A new instance of the report is created with each invocation of addReport. Since the report id is an enumeration (and thus immutable) the total construction is threadsafe.

***Figure 4.2***

So far we have given the reports plugin three report actor classes and each simulation instance will create those report actors. The report actors will in turn generate report items that will be released to the experiment level. In figure 4.3 we now indicate to the experiment how to distribute those report items to files.

***Figure 4.3***



Each report id is now associated with a particular file path. Although each file is a tab-delimited text file, we use the .xls file extension so that they can be automatically opened as a spreadsheet. Had we skipped adding these last specifications, the report items would flow out of the simulation and into the experiment but would not find an associated file and would be ignored.

Finally, in Figures 4.4 and 4.5, we create a single experiment dimension that will override the maximum family size with four values and thus create four scenarios for the experiment.

***Figure 4.4***

***Figure 4.5***



### The Family Vaccine Report

The first report documents the changes in the number of families that are vaccinated over time as individual people receive the vaccine. The field headers for the report are:

* scenario – the id of the scenario
* max\_family\_size – the maximum family size dictated by the scenario
* time – the time in days for each item in the repot
* unvacinated\_families – the number of families that have no members vaccinated
* partially\_vaccinated\_families – the number of families that have at least one, but not all members vaccinated
* fully\_vaccinated\_families – the number of families that have all members vaccinated
* unvaccinated\_individuals – the number of people who are unvaccinated and have no family assignment
* vaccinated\_individuals – the number of people who are vaccinated and have no family assignment

The experiment report mechanisms are responsible for reporting the scenario and the max\_family\_size fields since they are part of the experiment design. The remaining fields are contributed by the report actor. Note that family membership is not guaranteed and that some people may not be associated with any family id. The report accounts for these people in the last two fields.

There are four events that drive the report:

1. the addition of a person to the simulation
2. the addition of a family to the simulation
3. the assignment of a person to a family
4. the vaccination of a person

Note that the model logic does not allow for the removal of a person from the simulation, the removal of person from a family or loss of vaccination coverage for a person. In a more nuanced model, there would likely be more events that would influence the report actor.

The FamilyVaccineReport has several private fields and class for maintaining the five counts of the reports. In figure 4.6 we have the list of two convenience enumerations for families and individuals that help with the creation of the report header and with maintaining counts.

***Figure 4.6***

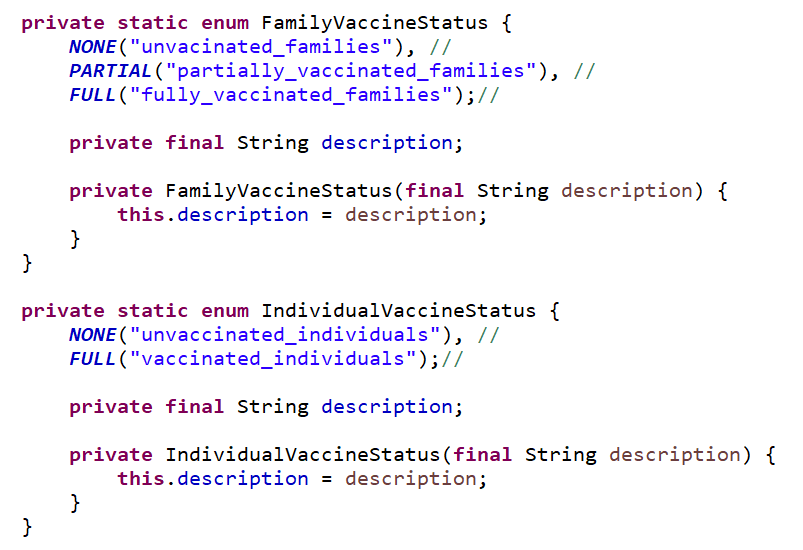
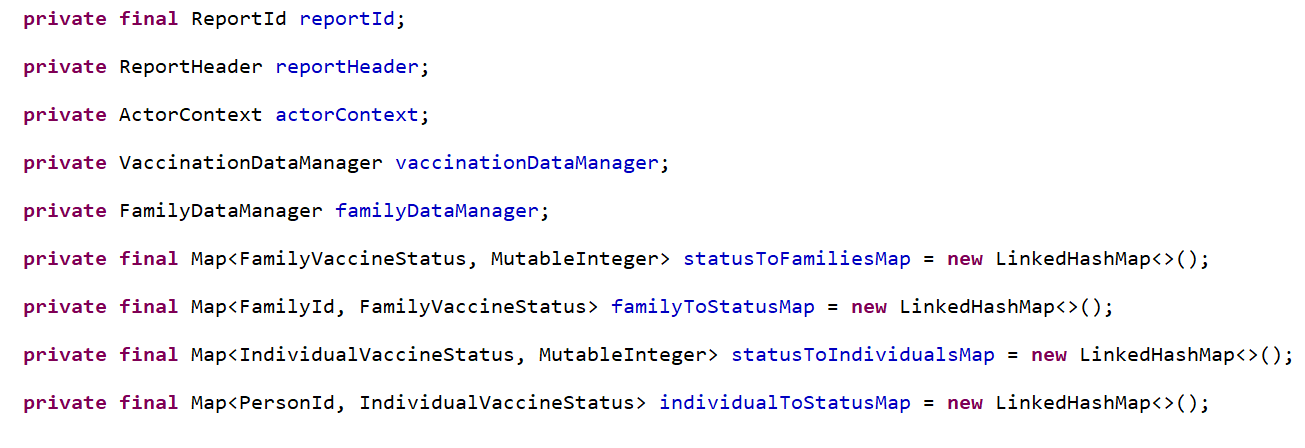
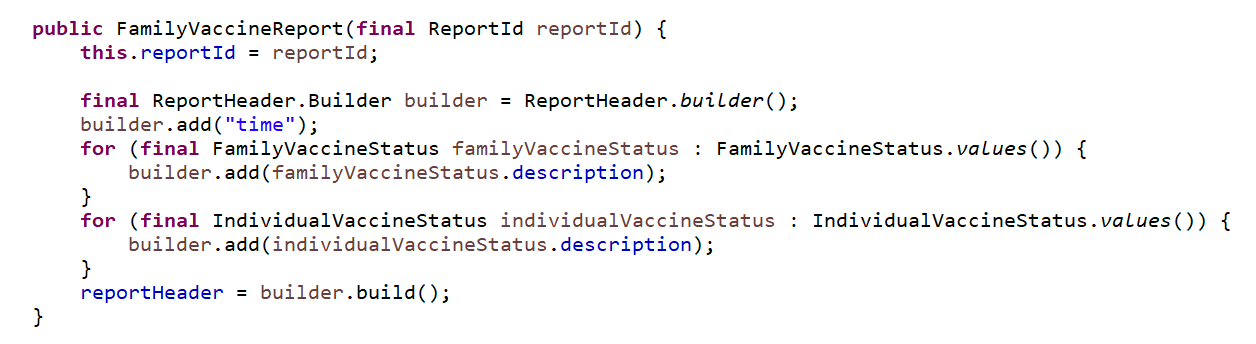


Figure 4.7 show the remaining private fields.

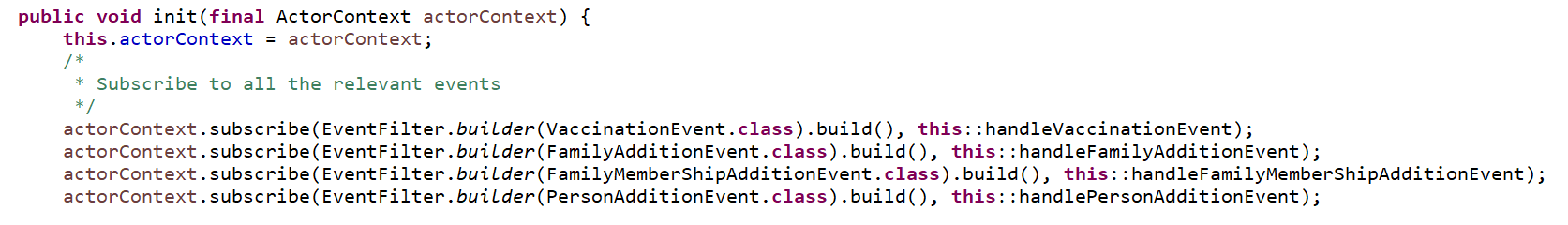
* report id – remains fixed from construction and is used to mark every report item
* reportHeader – is constructed once and used in the construction of every report item
* actorContext – a convenience reference kept by the actor to retrieve the simulation time
* vaccinationDataManager – a convenience reference to retrieve the vaccination status of each person
* familyDataManager – a convenience reference to retrieve the family members associated with a given person who has just been vaccinated
* statusToFamiliesMap – a map from family vaccine status to a mutable counter
* familyToStatusMap – a map for recording the current family vaccine status for each family
* statusToIndividualMap – a map from individual vaccine status to a mutable counter
* individualToStatusMap – a map for recording the current individual vaccine status for each person not assigned to a family

***Figure 4.7***

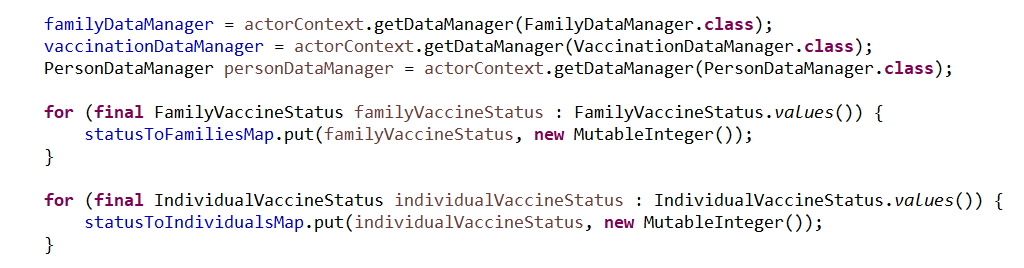
The report actor’s methods start with its constructor in figure 4.8. The report id is recorded and the report header field is built from the support enumerations.

***Figure 4.8***

Next is the initialization method that was used as the Consumer<ActorContext> that was passed to the simulation. This is invoked by the simulation just once at time zero and gives the report a chance to register for events and to initialize the private fields from figure 4.7. Figure 4.9 shows the report recording the actor context and subscribing to the four events of interest. These subscriptions reference local private method that will be described later.

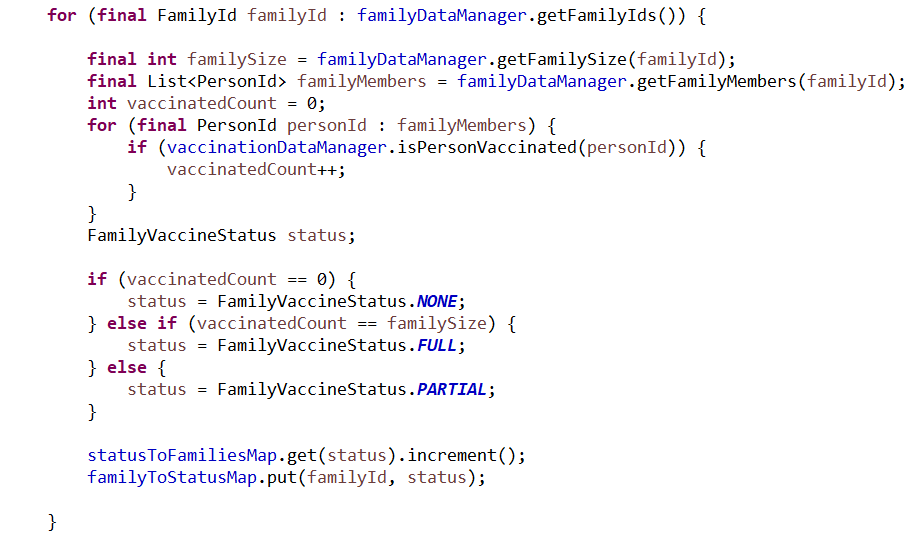
***Figure 4.9***

In figure 4.10 we continue with the retrieval of the person, family and vaccination data managers. The maps containing the counts are initialized to zero.

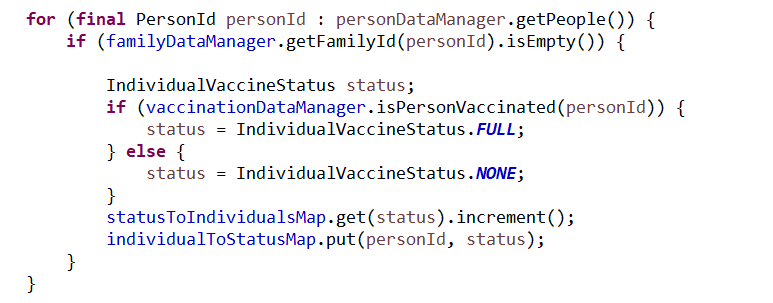
***Figure 4.10***

Figures 4.11 and 4.12 use the data managers to fill the count structures with the current state of the population.

***Figure 4.11***



***Figure 4.12***



Initialization finishes with the release of a single report item that summarizes the state of family vaccination at time zero.

***Figure 4.13***



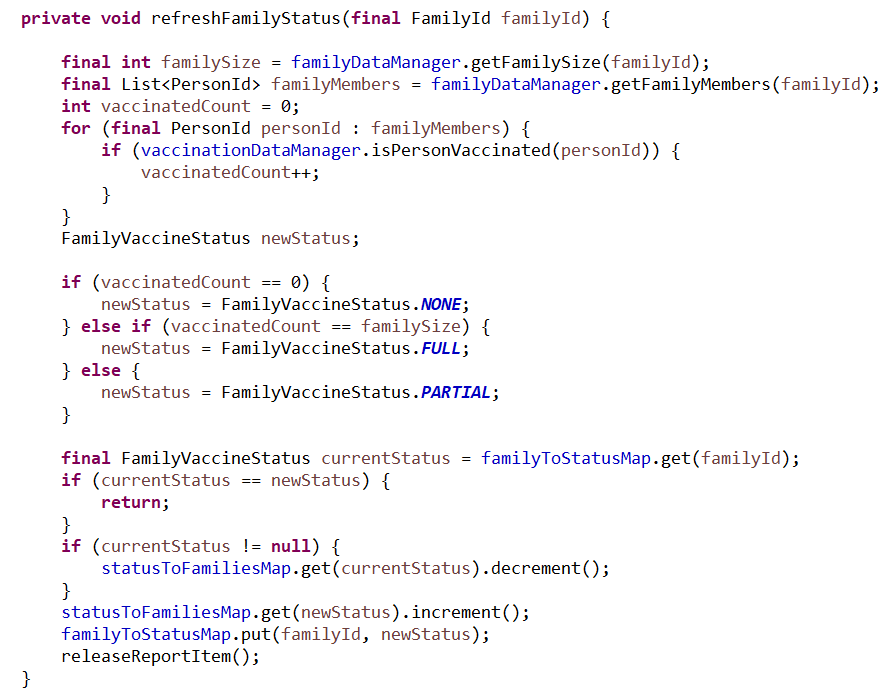
The methods for handling each event are shown in figure 4.14. All four methods select some relevant family id or person id and process changes to the counting data structure using the refreshFamilyStatus() and refreshInidividual() methods. The accounting for reports that are synthesizing multiple events can be somewhat tricky. No assumptions are made as to how and people are created, vaccinated and added to families so that changes to those processes in future versions of the model do not cause errors in the report.

***Figure 4.14***

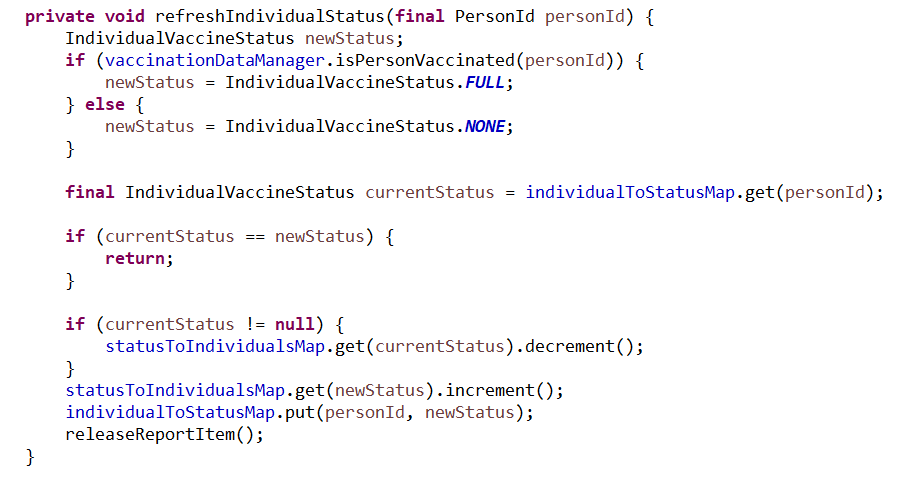


The refresh methods in figures 4.15 and 4.16 compare the current vaccination state of the families and individuals against the corresponding states tracked in the counting maps. If a change in the counts has occurred the counts are corrected and a new report item is released.

***Figure 4.15***



***Figure 4.16***

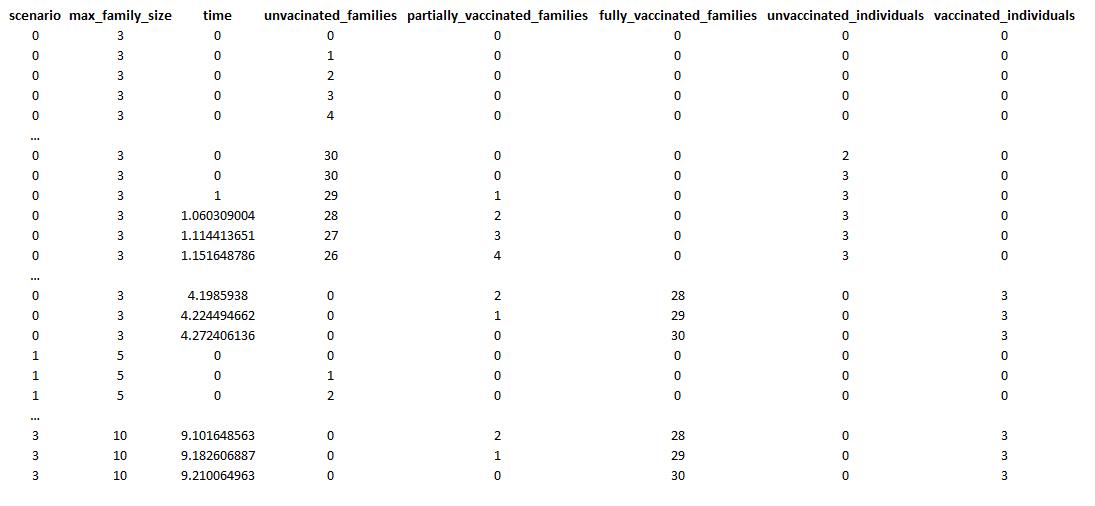


Releasing the report items that summarizes the family vaccination counts requires building a new report item with the fixed report id and report header values determined in the constructor. We then go on to add the time and count values in the order dictated by the helper enumerations so that they follow the header values established in the report header. Once the report item is complete it is released as output via the actor context. The simulation will in turn release the report item to the experiment where it will be distributed to the NIOReportItemHandler and then on the specific file manager(s) that record the items.

***Figure 4.17***

The resulting output in figure 4.18 contains the four scenarios showing the buildup of the population with all families and individuals being unvaccinated. Over time the number of vaccinated families increase and each simulation ends when all people have been vaccinated. The increase of max family size over the experiment causes there to be more people and thus the number of days to reach full vaccination also increases as expected.

***Figure 4.18***



## Periodic Reports

Producing a new report item each time a relevant event changes the internal tracking variable of a report actor will often produce too much output. An alternative is to periodically release one or more report items, usually on an hourly or daily basis. The reports plugin defines an abstract report actor class, the PeriodicReport, that manages the periodic flushing of the state of the report actor. This allows the descendant report actor class to concentrate on responding to the events while leaving the periodic production of report items to the base class.

The PeriodicReport provides several protected methods:

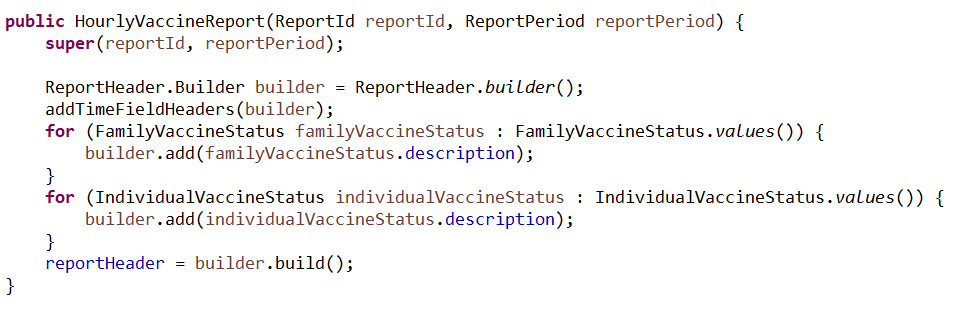
* two methods for filling in the time-based fields for the report header and report items
* three methods for subscribing to events that mirror the subscription methods of the actor context
* a method for retrieving the report id
* an abstract method for flushing the content of the report actor that must be implemented by the descendant report actor class

In addition, the PeriodicReport introduces a constructor that requires both a report id and a reporting period. If the constructor is overridden, the super() constructor must be invoked. The init() method is a consumer of actor context and if overridden, must also have the super() method invoked. The key takeaway is that by using the subscription methods supplied instead of the those on the actor context, the PeriodicReport is able to detect when time has reached the next reporting period and can force a flush of the current state of the descendant report **before** the next event is processed.

Our next example report actor class is the HourlyVaccineReport. It produces the same output as the FamilyVaccineReport, but does so on an hourly basis. This will cause the output of a report item every hour whether there are no stimulating events or many. The implementation of this report is nearly identical to the previous report and we will concentrate on highlighting the differences between the two approaches.

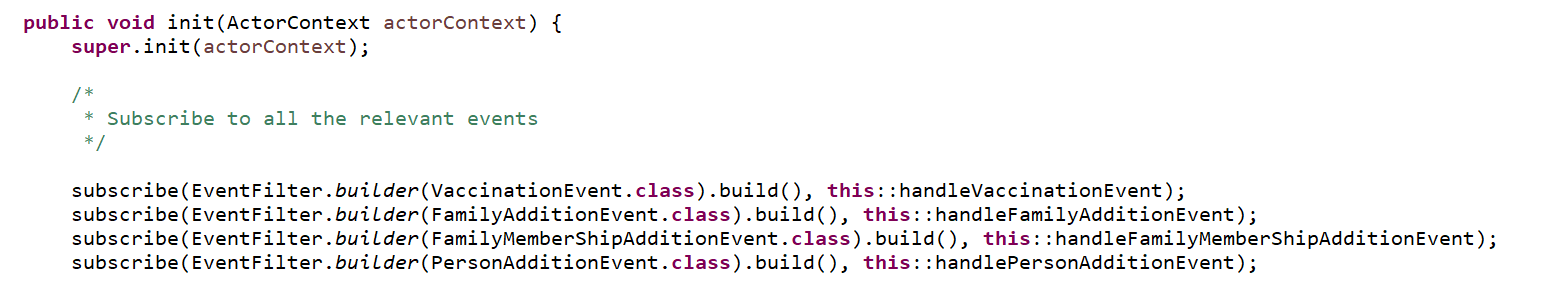
In figure 4.19 we see that the constructor invokes the super constructor. The construction of the report header is aided by the protected method addTimeFieldHeaders() which should be invoked as the first inputs to the report header builder. Note as well that we do not store the report id locally.

***Figure 4.19***



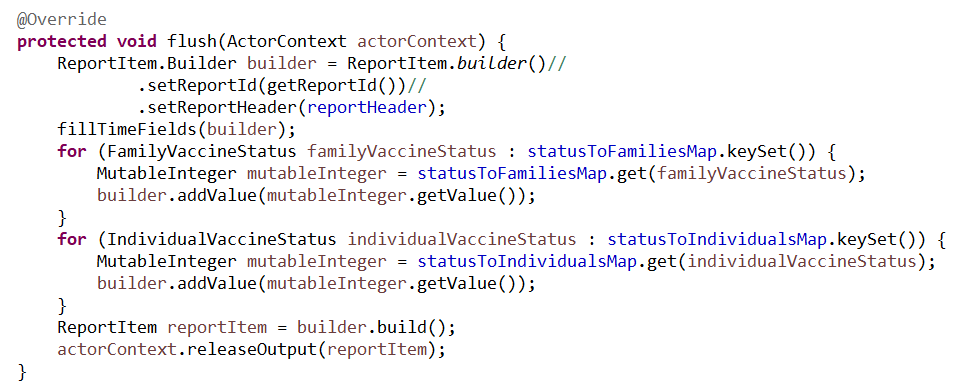
The init() method is nearly identical to the previous report. The only differences are:

* the invocation of the super constructor
* the subscription to events through the parent class rather than the actor context that allows the report to force report item flushing in the proper order

***Figure 4.20*** 

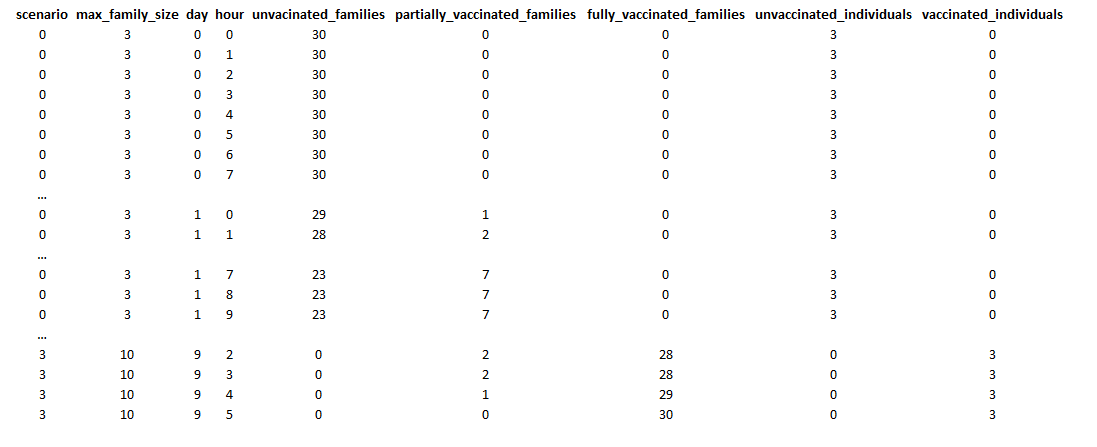
The releaseReportItem() method is now replaced by the flush() method override in figure 4.21.

***Figure 4.21***



The corresponding invocations of the releaseReportItem() that would have generated a new report item each time an event changed the internal counting variables are dropped. The flush() method will be invoked each time the parent report class determines that the planned next period has occurred. Note also that the time fields of the report item are filled by invoking the fillTimeFields() method which will add the correct time value for the period being reported rather than the current time. Otherwise, the implementations are identical.

The resulting output in figure 4.22 contains the four scenarios showing the buildup of the population with all families and individuals being unvaccinated. It shows the same overall pattern as the previous report, but treats the reporting of time in integer days and hours. Note that some of the output values repeat over the days and hours since there were no vaccinations during those periods.

***Figure 4.22***

Our final example, the StatelessVaccineReport in figure 4.23, continues from the HourlyVaccineReport but eschews the stateful counting mechanisms. Like the previous report, it is a periodic report actor but it does not store any state and does not subscribe to any events. Instead, it simply derives the report item on each flush() invocation.

***Figure 4.23***

This approach may seem wasteful since there is the potential for a great deal of recalculation, but since this is done on a daily basis, it may be well worth the reduction in memory if the model was actively tracking millions of families.

# Chapter 5: Properties

Modelers often need to associate properties with concepts found in plugins. For example, you may want to associate an integer number of times a person has been given a vaccine booster or have a double valued disease detection threshold that can be defined regionally. Most plugins will have a flexible, modeler-defined, set of properties that can be associated with people, groups or any other concept defined by the plugin. The core plugins included with GCM use a common property utility that introduces property Ids, property definitions and property values. It also provides several property value container classes to aid in efficient storage and retrieval.

### Property Identifiers

Property Ids are generally marker interfaces used to force unambiguous types in method signatures dealing with property related concepts. Each plugin that uses properties will introduce its own marker interface(s) and instances of the identifier are left to client (other plugins) to implement. This is often accomplished with enumerations.

### Property Definitions

Property definitions supply each plugin with:

* A class reference that defines the type of the property values
* A Boolean value indicating if property values are mutable
* A time tracking policy indicating whether a time value is stored each time a property value is assigned
* An optional default property value

The class reference dictates that type of all property values associated with the definition.

The mutability indicator controls whether property values can be set after the initial value is established. For example, consider the integer property “age” that is defined for people. Each person has a distinct integer age upon initial value assignment. If the property definition asserts that the property is not mutable, then the age value cannot be changed during the simulation’s execution. This is often used to fix global property values so that there is no chance that they can be reset by mistake.

It is often useful to know when a property was last assigned. The time tracking policy allow the definition to specify whether these time values are recorded. Some plugins will use this policy to avoid recording such time values where there would be tens of millions of entries and no use of these values by the modeler.

Default property values are used to spare the modeler from having to set property values when introducing new items to the simulation. For example, when adding a person to the simulation it might be useful to have a default of false for the property of “vaccinated”. However, for some properties there may be no meaningful default value. For example, consider the “age” property for a person. What would constitute a good default value? For this reason, supplying a default value as part of the property definition is optional.

### Concurrency Requirements

Property ids, property definitions and property values must be thread safe since they are shared across multiple scenarios (different simulation instances). It is usually best practice if they are implemented as immutable classes.

* Property ids are usually marker interfaces and are often implemented by static enumerations and are thus generally threadsafe
* The PropertyDefinition class is provided by the utility and is threadsafe subject to the thread safety of its default value
* Property values are often boxed primitives and are generally threadsafe. In general, mutation of a property value in GCM does not mean that the property value is mutated. Rather, it usually means that a new immutable value is now associated with the property id.

### Immutability

For a class to be immutable in Java it must meet three requirements

1. Its internal fields must not be mutated. There can be no setter methods or any other mechanism that changes an assignment post construction
2. All fields are declared final
3. No reference to the immutable object may be passed during its construction

### Expected Behaviors of Plugins using properties

All implementations of property mechanisms in GCM are expected to meet the following requirements:

* Property values are never null
* Property definitions that do not supply a default value must be supported by other mechanisms that ensure that property values are never null
* Property instance values must always assignment compatible to their corresponding property definition’s property type reference

# Chapter 6: Global Properties Plugin

The global property plugin implements a flexible property system for properties that have global scope. Specifically, global properties have no association with a specific person, place or other instance-based concept.

### Plugin Data Initialization

The plugin is initialized using a GlobalPropertiesPluginData object that collects global property definitions and global property values. Even though the property definitions can contain default property values, the ability to set property values is included to add some flexibility to the collection process since the client model may separate definitions from values in its input files.

### Plugin Behavior

The plugin adds a single data manager to the simulation as an instance of the GlobalPropertiesDataManager that is initialized with the GlobalPropertiesPluginData.

### Data Manager

The data manager provides access to the global properties and provides the ability to:

* Define new global properties (not contained in the initial data)
* Retrieve global property definitions
* Retrieve global property ids
* Retrieve global property values and the times when they were set
* Set global property values

The data manager also produces observable events when a new global property is defined or when a global property value is assigned. The plugin provides the GlobalPropertyReport that subscribes to these events and produces a trace report of property value assignments.

### Example Code

Example\_13.java shows a simple usage of the global properties plugin. In it we will add three double valued properties: ALPHA, BETA, and GAMMA. ALPHA and BETA will be used to vary the scenarios in the experiment and DELTA will be set to a simple function of ALPHA and BETA that will change over time in the simulation. This will culminate in a report that shows each time the global variables are defined or their values are set.

The example includes three plugins:

* Global properties plugin – (GCM core plugin) used to manage the properties
* Reports plugin – (GCM core plugin) used to manage the report
* Model plugin – (local plugin) used to introduce a single actor that will alter the value of DELTA over time

The example’s main method in figure 6.1 adds the three plugins:

* Global properties plugin
  + initialized with the three global properties
* Reports plugin
  + adds the GlobalPropertyReport (defined by the Global properties plugin)
  + uses the NIOReportItemHandler to associate an output file with the report
* Model plugin
  + Uses no inputs, but will add a single instance of the GammaActor class

The main method then forms a dimension for the experiment from variant values of ALPHA and BETA. Finally, it executes the experiment.

***Figure 6.1***

Initialization of the global properties is shown in figure 6.2

***Figure 6.2***

Figure 6.3 shows the construction of the experiment’s single dimension.

***Figure 6.3***

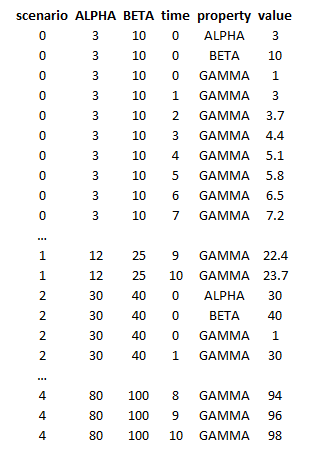


The GammaActor class in figure 6.4 schedules 10 plans, set one day apart, to change the DELTA value as a successive interpolation between the ALPHA and BETA values that are in turn controlled by the experiment.

***Figure 6.4***

The resultant global properties report shows the correct interpolated values for the five scenarios in figure 6.5.

***Figure 6.5***



# Chapter 7: People Plugin

The people plugin implements the dynamic management of person identity. Each person is identified with an immutable PersonId object that wrappers a int value. People are generally numbered with non-negative values, generally starting with zero and filling a contiguous range, but may contain any number of gaps in that range.

### Plugin Data Initialization

The plugin is initialized using a PeoplePluginData object that collects person id values. Note that there is not auxiliary data about any person, only their existence as a person at the start of the simulation is captured. Other plugins that deals with the various characteristics of people will deal separately with adding that data via their own plugin data structures.

### Plugin Behavior

The plugin adds a single data manager to the simulation as an instance of the PeopleDataManager that is initialized with the PeoplePluginData.

### Data Manager

The data manager provides access to people and provides the ability to:

* Add or remove a person
* Answer questions about person existence
* Get the current set of PersonId values
  + Get the total number of people
* Transform PersonId objects to and from int values
  + Answer questions about int value ranges used in managing internal data structures in various data managers

The data manager also produces observable events when people are added or removed from the simulation:

* PersonImminentAdditionEvent – notifies that a person is about to be remove
* PersonAdditionEvent – notifies that a person is removed
* PersonImminentRemovalEvent – notifies that a person is being added
* PersonRemovalEvent – notifies that a person is fully added

### add/remove event patterns

A common pattern used throughout many plugins for events signifying the addition or removal of an item from the simulation is to represent each of these with two events. The first event is to notify all concerned actors and data managers that an item is about to be removed, but the removal has not yet occurred so any reference to the item will still be available and any finalization or bookkeeping can be performed. The second event will act as an instruction to remove the item and it is expected that the item will not be available for further inspection.

As an example, let’s consider the removal of a person by an actor. The person to remove is PersonId[47] and the actor requests the person be removed by the PeopleDataManager. The data manager first **plans** to release the PersonRemovalEvent as soon as possible. This will schedule the release of the event onto the planning queue and time will not move forward before the execution of this event. However, this is a plan and it will only take place after the all current activities are complete. The data manager next releases the PersonImminentRemovalEvent. This event will propagate immediately to the other data managers and to any actors that are subscribed to person removals. Since the data managers generally do not act on the imminent removal, the actors are able to retrieve any information about the person they need to take final actions or produce reports. Once everyone has had a chance to see that the person will be removed, the planned PersonRemovalEvent will be released and the data managers will finally remove any information related to the person from their data structures. This two-phase removal pattern is useful and practical but does present one problem: Consider the original actor that was deleting person 47. On the very next line of their code after they request the removal of the person, the person still exists. The removal is not immediate, but is slightly delayed in that it will occur only after flow of control has returned to the simulation. This delay will not correspond to any time flow, so the removal of the person will occur at the same time as the request for the removal.

The addition of a person follows a similar pattern. To understand this, we first need to look at the PersonConstructionData used to add a person. The PersonConstructionData is a container for zero to many objects that carry information about the new person to be used by the various data managers who will need to integrate corresponding data about the person. For example, if the Regions plugin is being used, it requires that every person has a region assignment and thus a RegionId will need to be included in the PersonConstructionData. The people data manager does not understand this auxiliary data but simply repackages it into the PersonImminentAdditionEvent. The event is released and all the relevant data managers take what they need from the data stored in the event to fully initialize the state of the person. Once all data managers have initialized the person, the people data manager releases the PersonAdditionEvent and actors, such as reports, will now see that the new person has been added to the simulation and will have access to the person’s full initialized data.

In summary, the general convention is:

* imminent addition event
  + used by data managers to piecemeal add an item’s details
  + ignored by actors
* addition event
  + ignored by data managers
  + used by actors to work the item now that all the details are in place
* imminent removal event
  + ignored by data managers
  + used by actors to have a last chance to reference details on the item
* removal event
  + used by data managers to fully remove all stored data on the item
  + ignored by the actors since the item will be fully removed

### Example Code

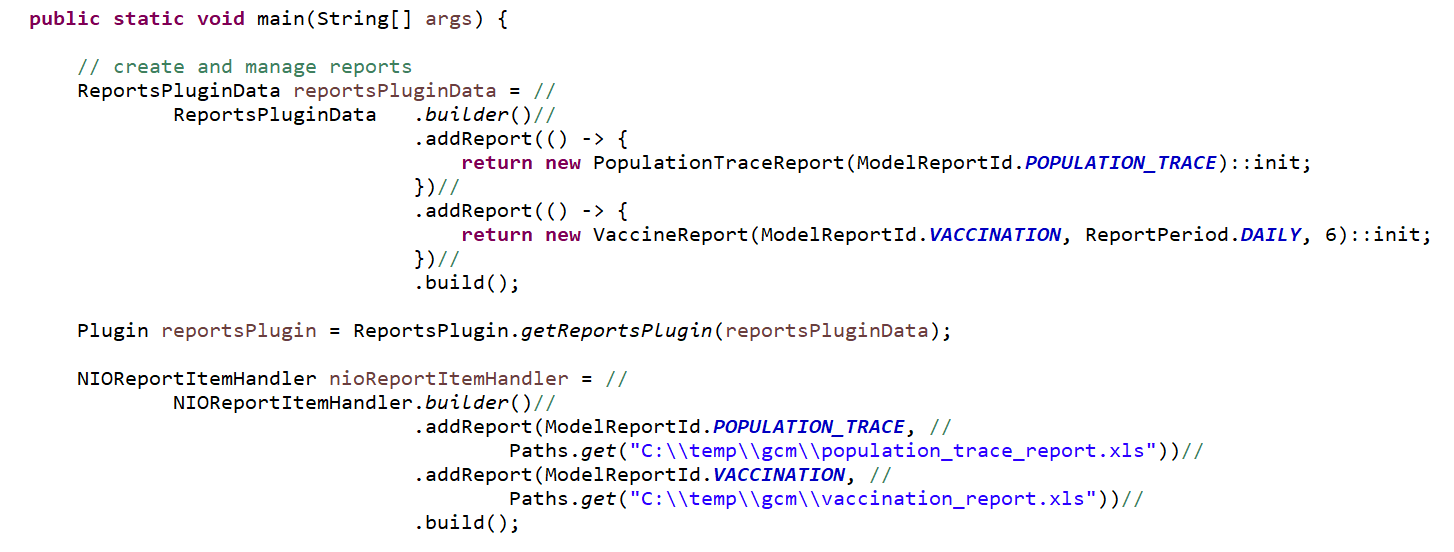
Example\_14.java shows the use of the people plugin. In it we add

The example includes three plugins:

* People plugin – (GCM core plugin) used to manage people
* Reports plugin – (GCM core plugin) used to manage reports
* Model plugin – (local plugin) used to introduce two actors that will
  + add/remove people
  + vaccinate people
* Vaccine plugin – (local plugin) used to track vaccinations for each person

The example’s main method starts in figure 7.1 by establishing two reports:

* The population trace report simply lists the additions and deletions or people by time. The report is managed by the PopulationTraceReport actor introduced by the model plugin
* The vaccination report shows a daily accounting of the number of people having 0, 1…6+ vaccinations. The report is managed by the VaccineReport actor introduced by the vaccine plugin

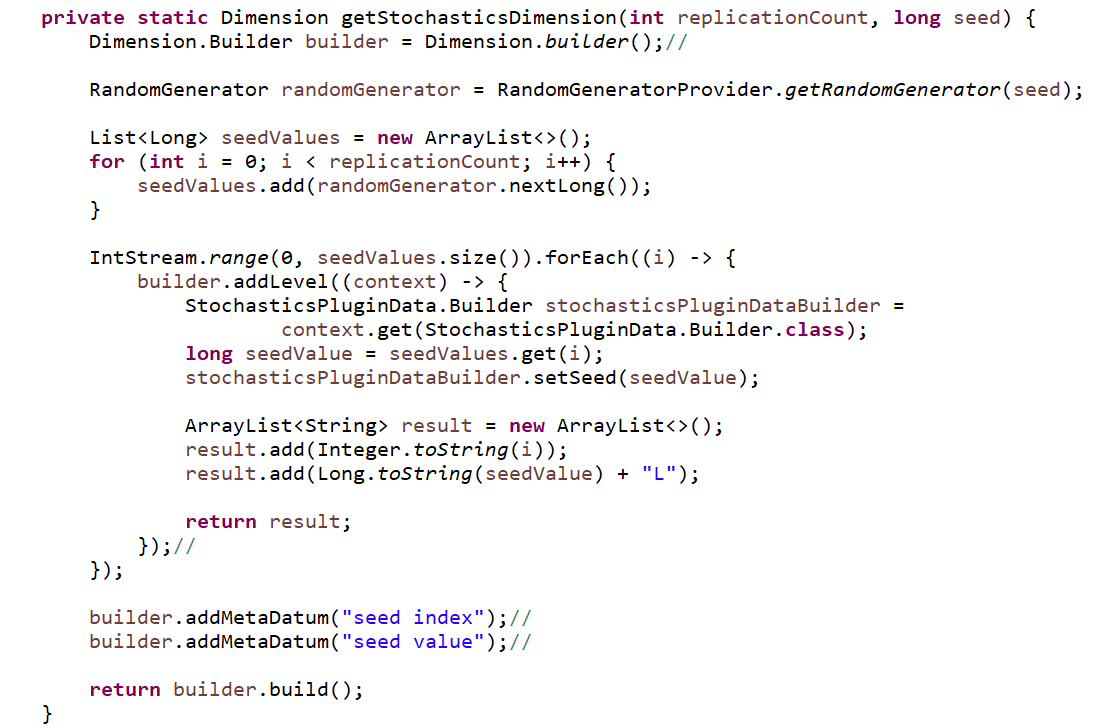
***Figure 7.1***

The main method continues by creating the people plugin and initializing it with 10 people. Note that the people will have id values of 1, 3, 5, … ,19 showing that any set of non-negative values are acceptable. The stochastics plugin is next and is initialized with a seed value. We will be controlling the random seed values via a dimension as presented in figure 7.3. As a result, the experiment will have 5 scenarios, with each scenario differing in only the random seed value that starts the simulation.

***Figure 7.2***



***Figure 7.3***



There are two actors provided by the model plugin. The first is the PopulationManager (figure 7.4) that upon its initialization plans 100 future actions to randomly remove (10%) or add (90%) people to the simulation. For people who are added, an initial vaccination count is included in the request to add the person so that the vaccine data manager can set the proper count.

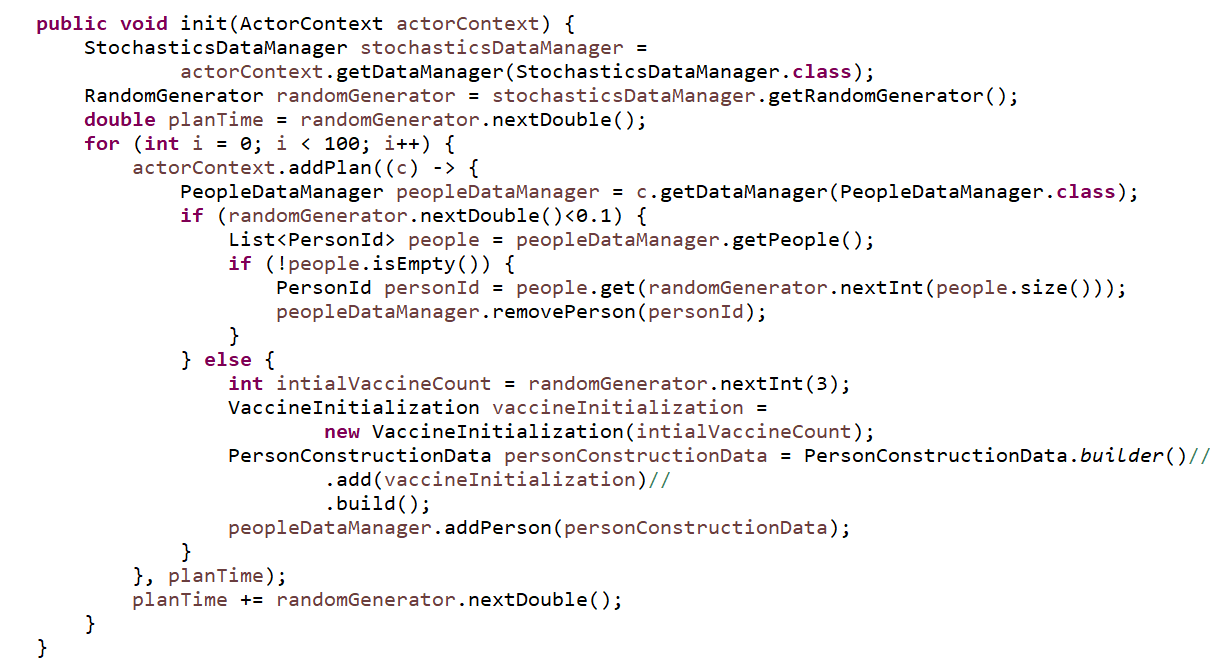
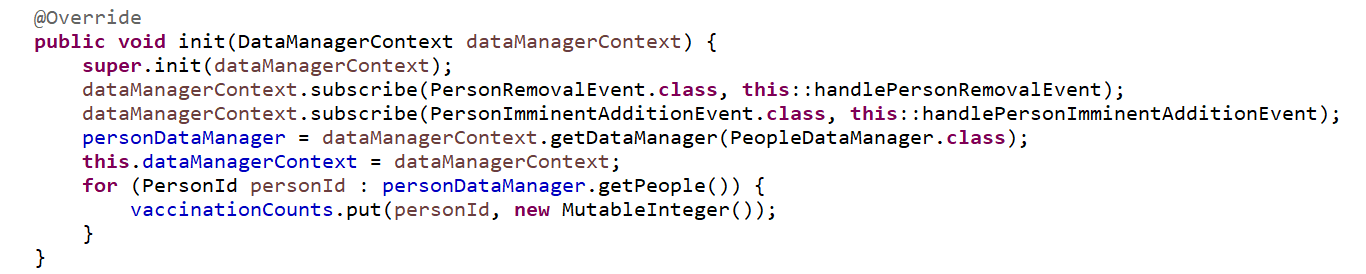
***Figure 7.4***

Figure 7.5 shows the second actor, the Vaccinator. It plans 300 vaccination actions over a period of approximately 100 days, selecting a random person to vaccinate each time. There is no limit to the number of vaccinations a person can have and we would expect that some people will have a relatively high number of vaccinations in the vaccine report.

### Interacting with the addition and removal events

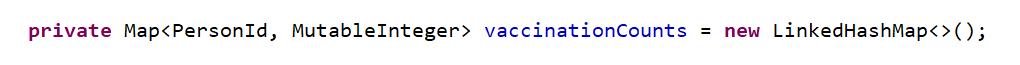
The remaining figures will focus on the handling of the four person addition and removal events in the vaccine data manager and the population trace report. The vaccine report is periodic and does not subscribe to any events and is left for the reader to examine.

Following the general conventions above, the vaccine data manager subscribes to the PersonRemovalEvent and the PersonImminentAdditionEvent during its initialization in figure 7.5.

***Figure 7.5***

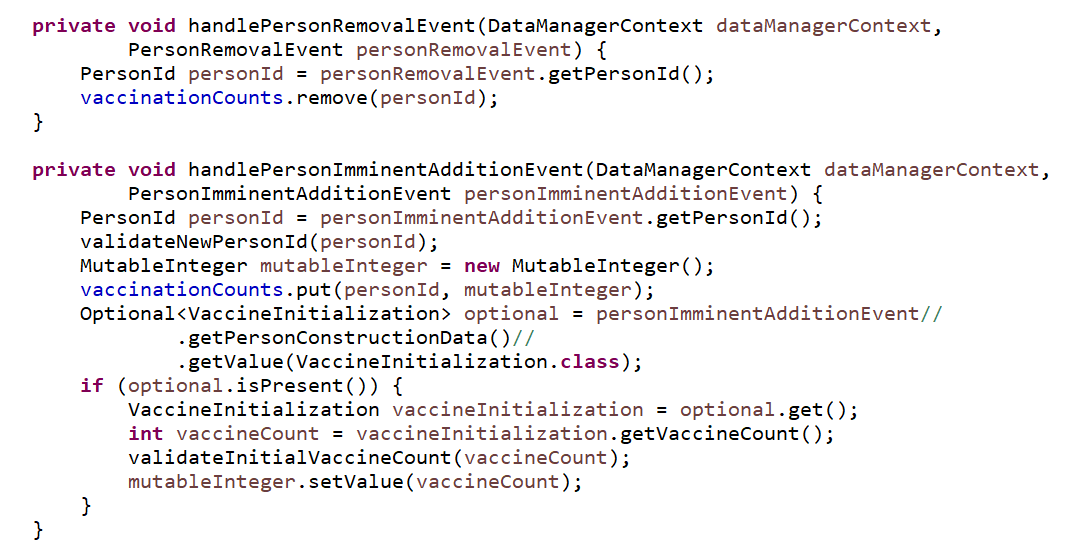
The vaccine data manager uses a simple map from person id to a counter to track the number of vaccinations for each person:

***Figure 7.6***



These subscriptions refer to the local method of the vaccine data manager in figure 7.7. Handling the removal of a person is simple; the person id dropped from the map. Handling the addition requires that the manager try to locate a VaccinationInitialization object (which is just a wrapper around and integer count) contained in the construction. If the VaccinationInitialization is present, then the manager further validates the count is not negative.

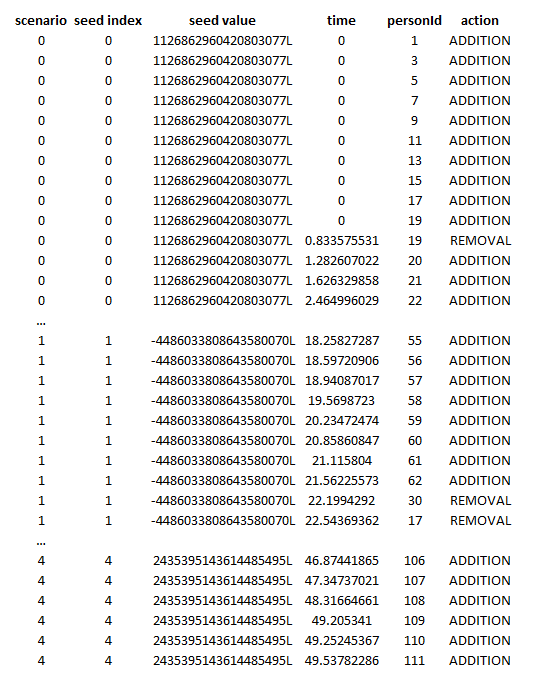
***Figure 7.7***



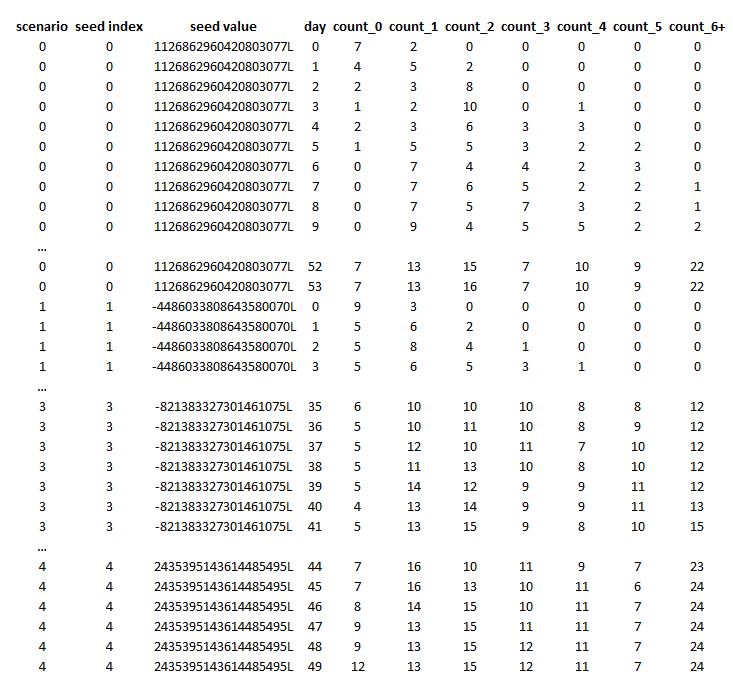
### Inspecting the output

Figure 7.8 shows the population trace report spanning the five scenarios and 500 additions and removals of people. In figure 7.9 we have the vaccination report showing the number of people having from 0 to 6+ vaccinations over each day of the simulation across the five scenarios. As expected, the number of people having six or more vaccinations starts out at zero and monotonically increases as the days progress.

***Figure 7.8***



***Figure 7.9***



# Chapter 8: Regions Plugin

The regions plugin manages the assignment of people to regions. As such, it is dependent on the people plugin. A region does not have an associated geo-location and does not specifically designate a county, state or any other regional concept. The interpretation of what defines a region is left to the modeler, although it will usually represent some sort of contiguous land area. When the regions plugin is being used, each person has a region association at all times and regions can be associated with zero to many people. Regions may also have a set of associated property values that can be dynamically defined. Regions are identified via the RegionId marker interface that does not define any methods. It is left to the modeler to implement a RegionId data type. When the number of regions is fixed and relatively small this can be accomplished via an enumeration. For larger or dynamic sets of region id values it is typical to implement a simple immutable class that wraps an integer.

### Plugin Data Initialization

The plugin is initialized using a RegionsPluginData object that collects person to region assignments and region property values.

### Plugin Behavior

The plugin adds a single data manager to the simulation as an instance of the RegionsDataManager that is initialized with the RegionsPluginData.

### Data Manager

The data manager controls regions, their properties and the assignment of people to those regions. The data manager provides public methods that:

* Add a region
* Define a region property
* Set a region property value
* Move a person from one region to another
* Answer various questions about:
  + Person membership in regions
  + Region property values

The data manager also produces observable events:

* PersonRegionUpdateEvent – when a person is moved from one region to another
* RegionAdditionEvent – when a region is added to the simulation
* RegionPropertyDefintionEvent – when a new region property is defined
* RegionPropertyUpdateEvent – when a region property value is assigned

### Example Code

Example\_15.java shows the use of the regions plugin. In it we will examine

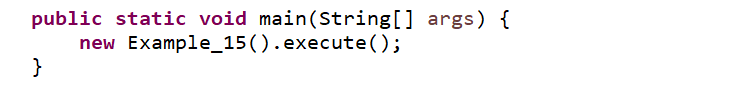
* The initialization of the regions plugin
* The movement of people between regions
* The dynamic addition of regions
* The dynamic addition of resource properties
* The update of resource property values

The example includes six plugins:

* Regions Plugin– (GCM core plugin) used to manage regions, their properties and person membership in regions
* People plugin – (GCM core plugin) used to manage people
* Stochastics plugin – (GCM core plugin) used to generate random numbers used in various decisions
* Reports plugin – (GCM core plugin) used to manage reports that:
  + Show changes to region property values
  + Show movements of people between regions
  + Show vaccinations of people
* Model plugin – (local plugin) used to introduce three actors that will:
  + Move people between regions
  + Create new regions
  + Vaccinate people, reacting to changes in region properties
* Vaccine plugin – (local plugin) used to track vaccinations for each person

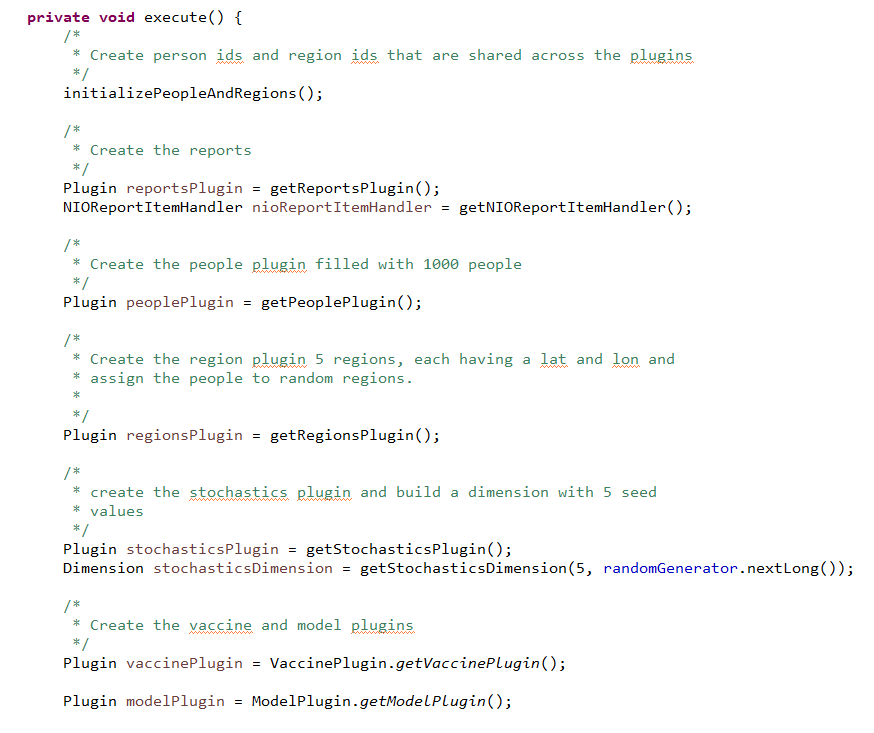
The example’s main method starts in figure 8.1 by creating an instance of the example class rather than building the experiment directly since this example is somewhat more complex than previous examples.

***Figure 8.1***



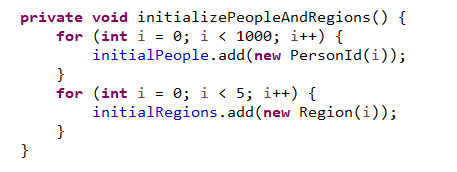
The execution method first gathers together the six plugins in figure 8.2:

***Figure 8.2***



The first action is to create 1000 people and 5 regions that will be used in the creation of both the people plugin and the regions plugin.

***Figure 8.3***



The regions plugin defines a region id with a marker interface. Marker interfaces are used to differentiate arguments and reduce variable type ambiguities while not imposing any particular implementation on the modeler. Region ids might reasonably be implemented as integer based identifiers or as strings that represent place names. In this example we will implement the region ids with an integer based class, the Region (figure 8.4), which is a boiler-plate wrapper around an int id value.

***Figure 8.4***



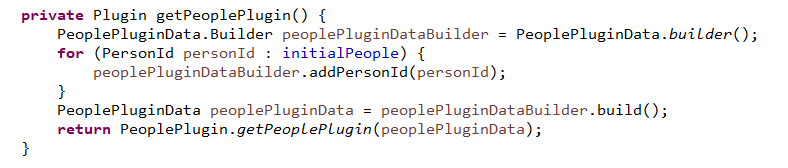
The three reports are added to the reports plugin in the usual manner in figure 8.5:

***Figure 8.5***



The people plugin is created from the 1000 people created earlier in figure 8.6.

***Figure 8.6***



Creating the regions plugin (figure 8.7) is a bit more involved. First, the five regions created before are added to the plugin. Since the plugin requires that every person always have a region assignment, we assign a randomly selected region to each person. We define the LAT and LON properties to give the regions a geographic location. Notice that the definitions do not have default values since it does not make sense to say a region has a default position. This then will require that we assign specific latitude and longitude values for each region. Later on we will examine adding a new region property definition dynamically as the simulation is running.

***Figure 8.7***



Adding the stochastics plugin with a corresponding dimension that will create five scenarios proceeds in the usual way in figure 8.8:

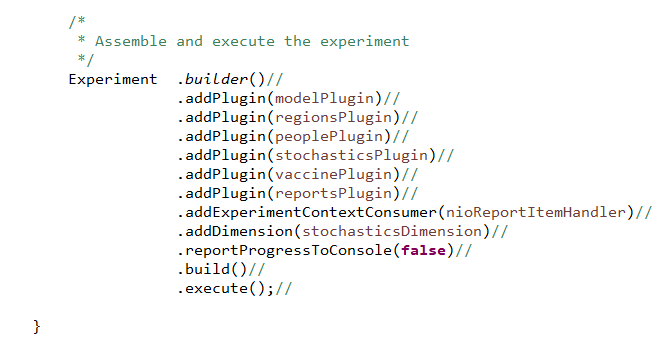
***Figure 8.8***

Finally, we add the vaccine and model plugins. This will add the vaccine data manager as well as three previously mentioned actors that will be used to demonstrate the various capabilities of the regions plugin.

* + PersonMover – used to move people between regions
  + RegionCreator – used to create new regions during the simulation run
  + Vaccinator – used to vaccinate people, reacting to changes in region properties

The execute method finishes (figure 8.9) by constructing and executing the experiment:

***Figure 8.9***

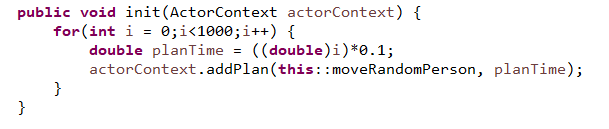


### The actors

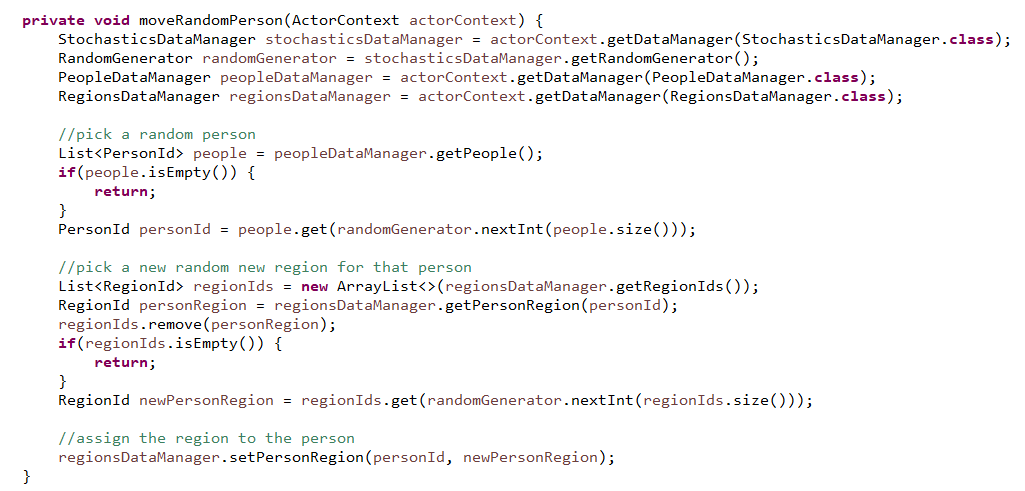
We will finish this chapter by reviewing the three actors of the model plugin and then examining the three reports.

The PersonMover actor, in figures 8.10 and 8.11, schedules 1000 random moves of a person from one region to another over the course of 100 days.

***Figure 8.10***

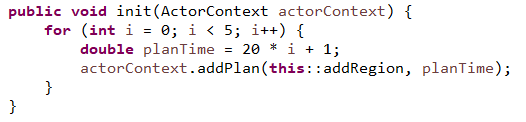


Moving the person requires that we use the stochastics plugin and the people plugin to select a random person. We next use the regions plugin to first select a random new region for the person and then move the person to that region.

***Figure 8.11***

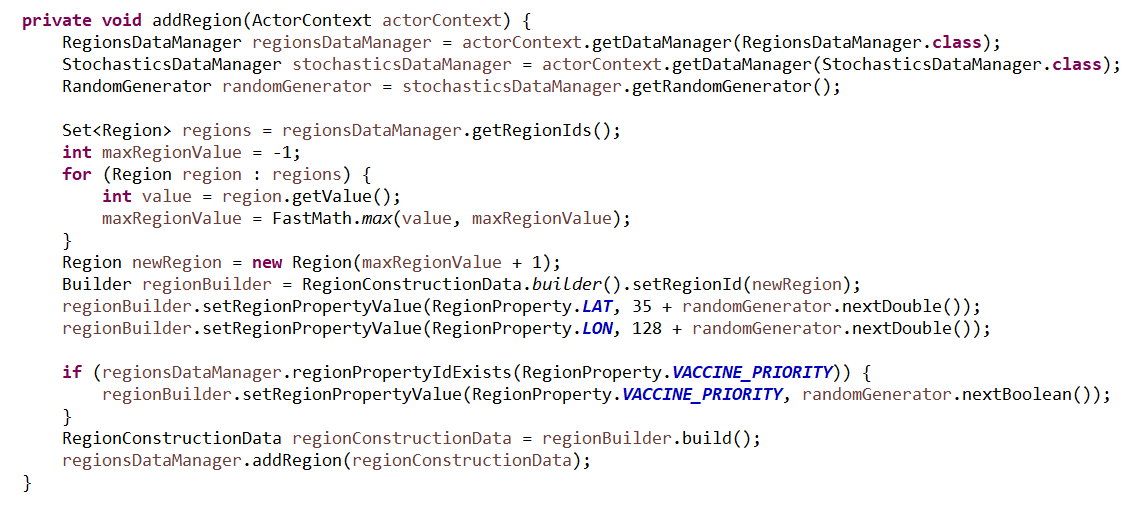
The RegionCreator actor, in figures 8.12 and 8.13, follows a similar pattern, scheduling the creation of five new regions over 101 days.

***Figure 8.12***



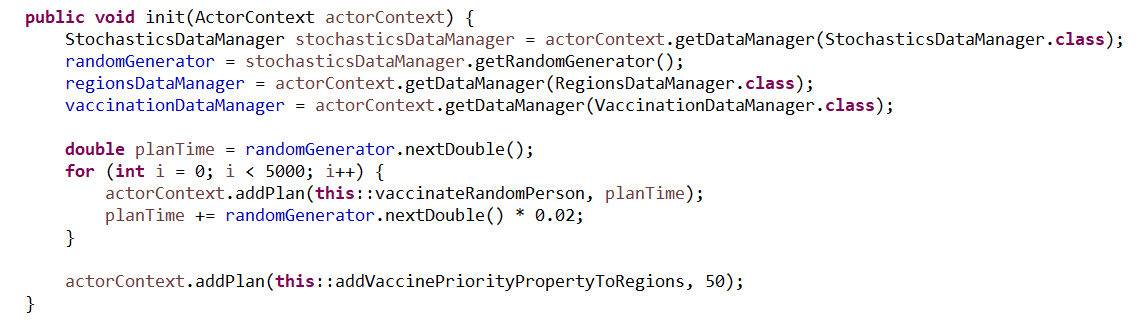
When adding a region, we have to be aware that the region will have LAT and LON properties and that these properties were not defined with default values. Thus we must supply values for the region’s latitude and longitude as part of the RegionConstructionData object that is passed to the regions data manager. We will similarly assign a new random Boolean value for the VACCINE\_PRIORITY property. The VACCINE\_PRIORITY is a dynamically added property that is introduced later. Note that we first check for the existence of the property and only then set a value since setting such a value before the property is defined will result in a runtime exception.

*Such considerations are unusual since properties are usually defined in the plugin initialization data or added very early in the simulation before any actors have initialized. We do so here for the purposes of demonstrating dynamic property definitions.*

***Figure 8.13***

The Vaccinator actor is somewhat more complicated than the other actors. It initializes (figure 8.14) by storing references to various data managers for convenience and then plans 5000 vaccinations spread over 100 days. It also plans to add the VACCINE\_PRIORITY property on day 50.

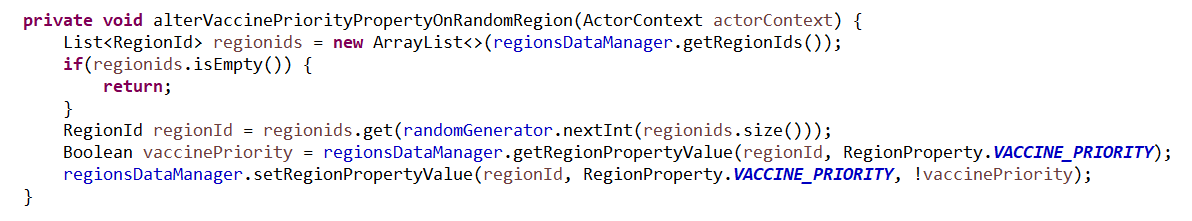
***Figure 8.14***



Let’s first look at the addition of the new region property on day 50 in figure 8.15. The new property is a Boolean value defaulted to false and indicates whether people should be chosen from regions randomly or by preferring people with the fewest vaccinations. Since the property has a default value, we do not have to set values for each region in the RegionPropertyDefinitionInitialization object that is passed to the regions data manager when creating the region. We do anyway to demonstrate such value assignments. Once the new property is in place, the Vaccinator schedules the switching of the value for random regions once per day for the next 50 days.

***Figure 8.15***

In figure 8.16 the Vaccinator performs this value switching:

***Figure 8.16***

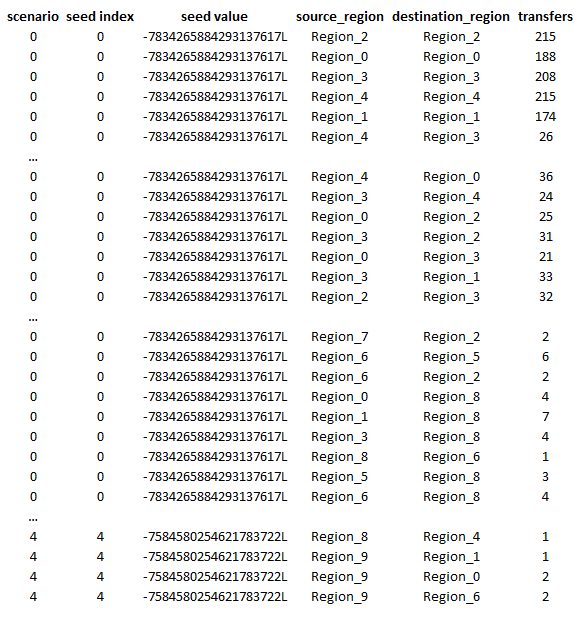
The Vaccinator vaccinates people at random (figure 8.17) by first selecting a random region and then selecting a random person in that region. The selection of the person is subject to the presence of the VACCINE\_PRIORITY property and whether the value of the property is true for the selected region. If the priority selection is being used, then a first pass through the people in the region establishes the lowest number of vaccines received by any person. A second pass through the same people now selects only those having this number of vaccinations. Finally, a person is selected at random from the eligible people.

***Figure 8.16***

### Inspecting the output

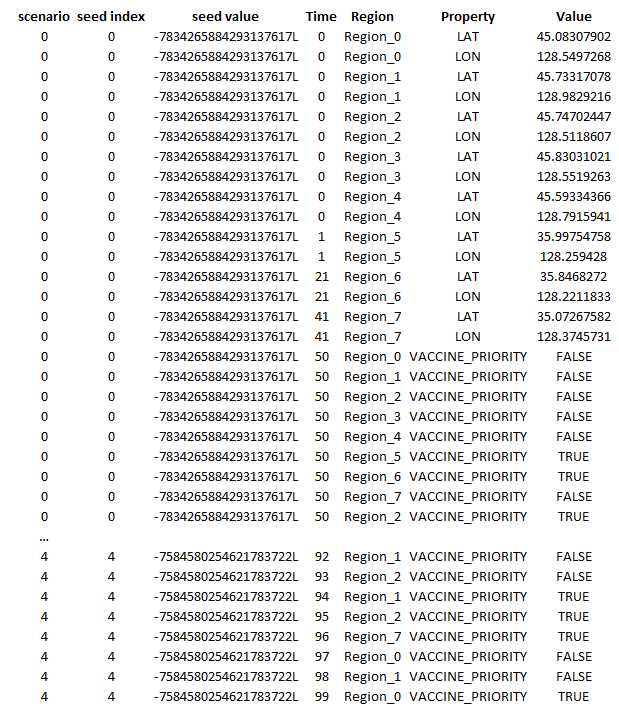
The region transfer report shows the number of transfers of a person from one region to another across all days in the simulation. The rows where the source and destination regions are the same represent the addition of people at the start of the simulation and, as expected, the sum of such transfers equals to 1000. We also expect to see regions that were added beyond the original five regions and that transfers in and out of those regions should be reduced compared to the original regions since they start out with no people and come into the simulation only after day 50.

***Figure 8.17***



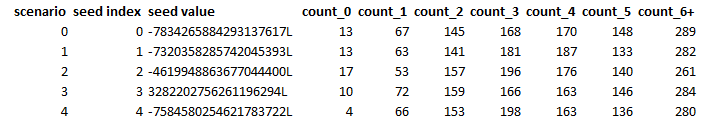
In the region property report (figure 8.18) we see that the LAT and LON properties were set for the first five regions at the start of the simulation. Starting on day 1, new regions were added and each has an assigned LAT and LON value at that time. Beginning on day 50, all regions are assigned a VACCINE\_PRIOITY value and assignments to that property continue daily for random regions.

***Figure 8.18***



Finally, the vaccine report shows the number of people having various vaccine counts at the end of each simulation. Although the priority policy was being used, most vaccinations were for randomly selected people so we expect a fairly wide distribution in those values.

***Figure 8.19***



# Chapter 9: Person Properties Plugin

The person properties plugin manages the assignment of properties to individual people. As such, it is dependent on the people plugin. It also depends on the regions plugin for reports. Property definitions apply to every person in the simulation and are generally added to the person properties plugin data. However, person property definitions can be added dynamically and thus other plugins can contribute person property definitions directly rather than as inputs to the person properties plugin data.

### Plugin Data Initialization

The plugin is initialized using a PersonPropertiesPluginData object that collects person property definitions and person property value assignments for the initial population.

### Plugin Behavior

The plugin adds a single data manager to the simulation as an instance of the PersonPropertiesDataManager that is initialized with the PersonPropertiesPluginData.

### Data Manager

The data manager manages person properties and stores their property values in a memory dense fashion that is transparent to the modeler. The data manager provides public methods that:

* Define a person properties
* Set a person property values
* Answer various questions about:
  + The value of a person property for particular people
  + The people associated with a particular property value
  + The existence and value of property definitions

The data manager also produces observable events:

* PersonPropertyUpdateEvent – when a person is assigned a person property value
* PersonPropertyDefintionEvent – when a new person property is defined

### Example Code

Example\_16.java shows the use of the person properties plugin. In it we will examine

* The initialization of the person properties plugin
* The assignment of values to individuals
* The dynamic addition definition of person properties

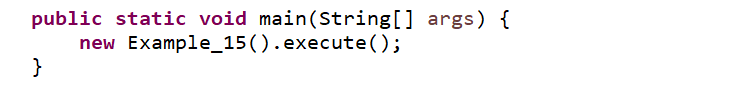
The example includes seven plugins:

* People plugin – (GCM core plugin) used to manage people
* Person properties plugin– (GCM core plugin) used to decorate properties onto people
* Global properties plugin– (GCM core plugin) used to store policies and initial conditions affecting vaccination
* Stochastics plugin – (GCM core plugin) used to generate random numbers used in various decisions
* Reports plugin – (GCM core plugin) used to manage reports that:
  + Show changes to person property values
  + Show vaccinations of people
* Regions Plugin– (GCM core plugin) used to by reports
* Model plugin – (local plugin) used to introduce three actors that will:
  + Load the population
  + Vaccinate people
  + Educate people on the vaccine

The example’s main method starts in figure 9.1 by creating an instance of the example class rather than building the experiment directly since this example is somewhat more complex than previous examples.

The population starts out being unvaccinated and some proportion of people initially refuse the vaccine. Attempts to both vaccinate and educate people are ongoing until a person is vaccinated. This will demonstrate the planning capability as well. If education is successful, the person is immediately vaccinated, demonstrating the cancellation of planning. At some point in the timeline immunity will become discoverable during vaccine attempts and immune people will no longer pursue vaccination. The simulation is terminated at one year and output reports are then generated.

***Figure 9.1***



The execution method first gathers together the seven plugins in figure 9.2:

***Figure 9.2***

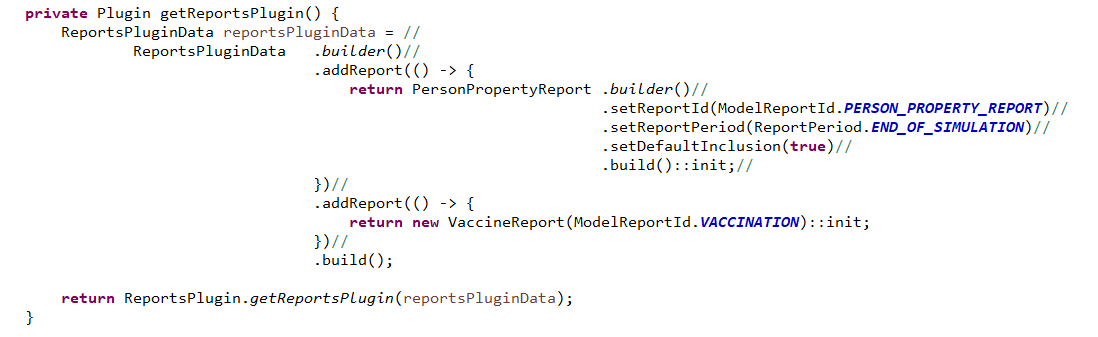


The first action is to generate the global properties plugin (figure 9.3). All of the global properties are marked as immutable since they will not change over the course of the simulation:

* VACCINE\_ATTEMPT\_INTERVAL – The maximum time between attempt to vaccinate an unvaccinated person. Specific intervals are chosen using a uniform random time between zero and the maximum
* EDUCATION\_ATTEMPT\_INTERVAL – The maximum time between attempt to educate an unvaccinated who is currently refusing vaccination. Specific intervals are chosen using a uniform random time between zero and the maximum
* VACCINE\_REFUSAL\_PROPBABILTY – The initial probability that a person will refuse vaccination. Used to initialize the person property REFUSES\_VACCINE
* EDUCATION\_SUCCESS\_RATE – The probability that an attempt to educate a person to accept vaccination will succeed
* IMMUNITY\_START\_TIME – The time when immunity is detectable in people. Used to halt attempts at vaccination and to demonstrate the dynamic addition of the person property IS\_IMMUNE
* IMMUNITY\_PROBABILITY – The probability that a person will be immune when the immunity person property is added
* POPULATION\_SIZE – The number of people in the simulation
* SIMULATION\_DURATION – The maximum time (in days) that the simulation will execute.

***Figure 9.3***

The execution method then loads reports (figure 9.4). The person property report will be quite large and is set to only show the state of each person at the end of the simulation for brevity. The vaccine report will show the state of vaccination and immunity at the end of the simulation to allow for analysis of the experiment.

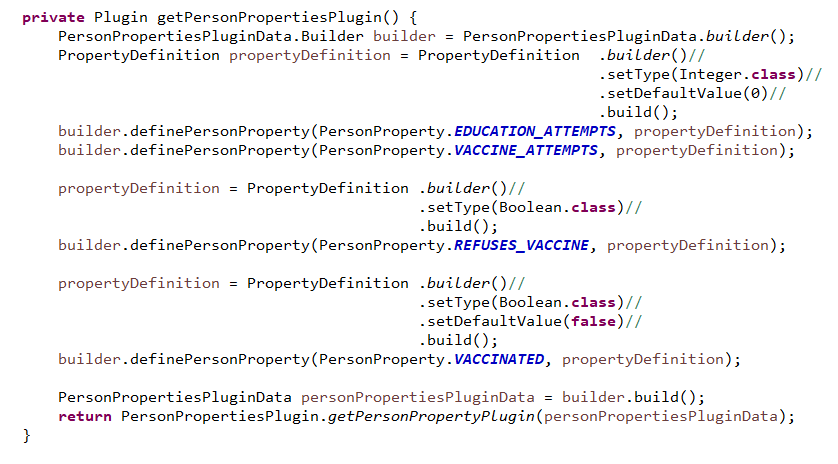
***Figure 9.4***

The people plugin is created without any initial people since that will be handled by one of the model plugin’s actors. The regions plugin is initialized with five regions and only plays a role in the person property report.

The person properties plugin is generated in figure 9.5. All of the person properties are mutable since they will change over the course of the simulation:

* EDUCATION\_ATTEMPTS – The number of attempts to change a person’s vaccine refusal
* VACCINE\_ATTEMPTS – The number of attempts to vaccinate a person
* REFUSES\_VACCINE – Boolean indicating whether the person will refuse vaccination attempts. Note that there is no default value and that new people must have this property set as part of the addition of the person to the simulation
* VACCINATED – Boolean indicating that a person has been vaccinated. People all start out with no vaccination and receive at most one vaccination

Note that the final person property, IS\_IMMUNE, is not added at the beginning of the simulation as a demonstration of the dynamic addition of person properties.

***Figure 9.5***

Adding the stochastics plugin involves only setting the seed that will be used in every simulation instance. It will not play a role in defining the experiment space since that will be quite large already with various global property variants

Finally, the execution method generates the model plugin which in turn adds three actors:

* Vaccinator – vaccinates people at random times
* Vaccine Educator – seeks to get people to accept vaccination
* Population Loader – initializes the population

The execute method finishes (figure 9.6) by constructing and executing the experiment.

***Figure 9.6***



Five dimensions are added to the experiment that define alternate values for five of the global properties resulting in 810 scenarios. The values are:

* Immunity start time – 120 and 180 days
* Immunity probability – 0, 10 and 20 percent
* Vaccine attempt interval – 30, 45 and 60 days
* Education attempt interval – 30, 60 and 180 days
* Education success rate – 0, 10 and 20 percent
* Initial vaccine refusal – 0, 25, 50, 75 and 100 percent

### The actors

We will finish this chapter by reviewing the three actors of the model plugin and then examining the vaccine report.

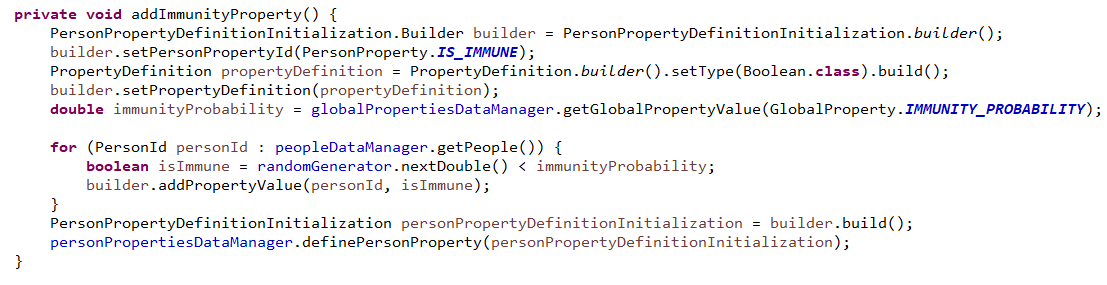
The PopulationLoader actor, in figure 9.7, adds people to the simulation bases on the number in the POPULATION\_SIZE global property. Each person is assigned a random region and the person property, REFUSES\_VACCINE, is randomly assigned based on the global property VACCINE\_REFUSAL\_PROPERTY.

***Figure 9.7***



The actor finishes its initialization by scheduling a time to halt the simulation based on the global property SIMULATION\_DURATION. It also schedules the addition of the person property, IS\_IMMUNE, based on the global property IMMUNITY\_START\_TIME. Figure 9.8 shows the details of this dynamic definition.

***Figure 9.8***

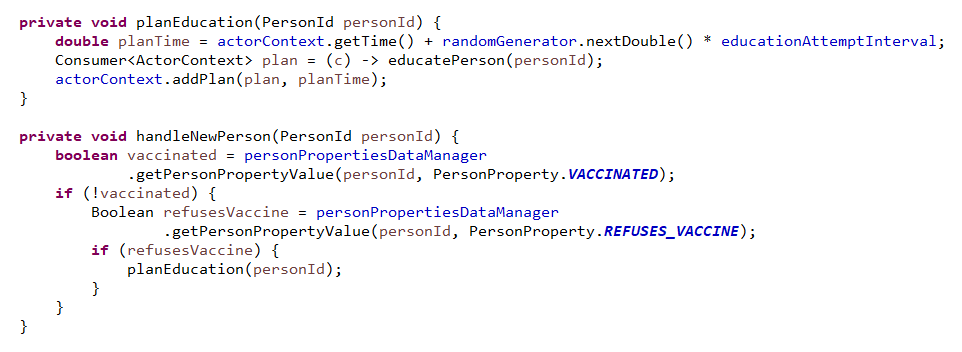


The vaccine educator (figure 9.10) attempts to change unvaccinated people who refuse vaccination to vaccine acceptance. It initializes by planning an educational attempt for each person in the existing population who has not been vaccinated and who will refuse vaccination. It also subscribes to the addition of people so that it might plan education for newly added people.

***Figure 9.10***

Planning the education of a person (figure 9.11) is accomplished with planning that schedules the education at a random time between the current time and a globally defined attempt interval.

***Figure 9.11***



The education attempt sets the vaccine refusal to false on a random draw based on the EDUCATION\_SUCCESS\_RATE global variable in figure 9.12.

***Figure 9.12***



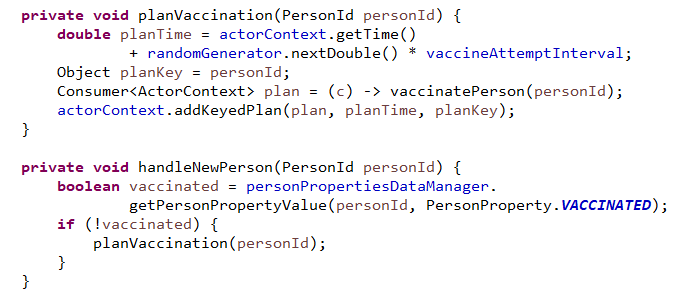
The Vaccinator (figure 9.13) tries to vaccinate the population. It initializes by planning a vaccination attempt for each person in the existing population who has not yet been vaccinated. It subscribes to the addition of people so that it might plan vaccination for newly added people. It also subscribes to changes to the VACCINE\_REFUSAL person property so that it can immediately attempt vaccination.

***Figure 9.13***



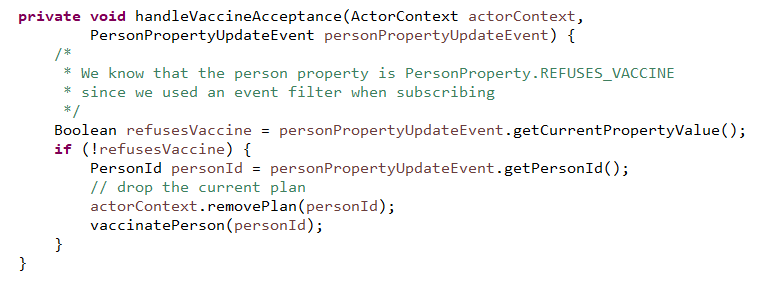
Planning the vaccination of a person (figure 9.14) is accomplished with planning that schedules the vaccination at a random time between the current time and a globally defined attempt interval.

***Figure 9.14***



Note that the plan uses a key value set to the person id. This is used when reacting to a person changing from refusal of the vaccine to acceptance. Instead of waiting to the next vaccine attempt (figure 9.15), the current plan to vaccinate is removed and the person is immediately vaccinated.

***Figure 9.15***



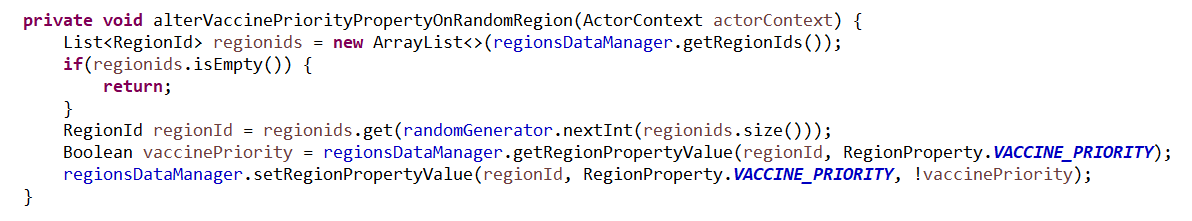
The vaccination attempt (figure 9.16) first considers whether the IS\_IMMUNE property has been added. If it has then immunity for the person is determined. Immune people do not receive the vaccine and no more attempts to vaccinate the person will be scheduled. If the person is still refusing the vaccine, then a new attempt to vaccinate the person is scheduled. Otherwise the person is vaccinated and no further attempts are scheduled.

***Figure 9.16***



***Figure 9.15***

In figure 8.16 the Vaccinator performs this value switching:

***Figure 9.16***

The Vaccinator vaccinates people at random (figure 8.17) by first selecting a random region and then selecting a random person in that region. The selection of the person is subject to the presence of the VACCINE\_PRIORITY property and whether the value of the property is true for the selected region. If the priority selection is being used, then a first pass through the people in the region establishes the lowest number of vaccines received by any person. A second pass through the same people now selects only those having this number of vaccinations. Finally, a person is selected at random from the eligible people.

### Inspecting the output

The 810 scenarios result in a large amount of output in the person properties report with over 125,000 entries. The vaccine report is a bit large to fully present here. Its fields are:

* Scenario – 0 to 809

Experiment fields that show what differentiates each scenario

* immunity start time
* immunity probabilty
* vaccine attempt interval
* education attempt interval
* education success rate
* intial refusal probability

The metric field produced as a result of the experiment choices

* vaccinated immune
* vaccinated susceptible
* unvaccinated immune
* unvaccinated susceptible

Analyzing the output yields no surprises. Higher education attempt rates and greater the probabilities of education success yield more people getting vaccinated. Similarly, early and high levels of immunity have a slight dampening effect on vaccinations.

# Chapter 10: Groups Plugin

asdf

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# Chapter 11: Resources Plugin

asdf

# Chapter 12: Materials Plugin

asdf

# Chapter 13: Partitions Plugin

Asdf