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Data Visualization in ProB

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Bachelorarbeit

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Erklärung

Hiermit versichere ich, dass ich diese Bachelorarbeit selbstständig verfasst habe. Ich habe dazu keine anderen als die angegebenen Quellen und Hilfsmittel verwendet.

Düsseldorf, den 14. Juni 2013

Joy Clark

Abstract

Hier kommt eine ca. einseitige Zusammenfassung der Arbeit rein.

Contents

1 Introduction

ProB is the name given to a group of software tools dealing with the verification of models written in formal specification languages. The main specification language that ProB deals with is the B-Method. The B-Method is a method of specifying and designing software systems that was originally created by J.R. Abrial [3]. Central to the B-Method are the concepts of *abstract machines* that specify how a system should function [4].

In order to verify a formal model, ProB simulates the state space that corresponds to that model. A *state space* is a directed multigraph whose vertices represent every possible state in the system. The edges in the graph represent all of the transitions between any given states. ProB verifies a model primarily by performing *consistency checking*. This is the systematic check of all states that are accessible from the initial state. A model is found to be correct if its state space contains no deadlocks (i.e. all vertices in the graph have at least one outgoing edge) and if no state violates the *invariant* for the model. The *invariant* is a predicate that must evaluate to true for every state in the model. The user can also use ProB to perform animation of a particular model, i.e. to interactively create a trace of states throughout the state space.

During the course of model verification, ProB produces a great deal of data. The purpose of this work is to generate visualizations based on this data.

1.1 Visualization of the State Space

Since the concept of the state space is so central to ProB, the focus of this work will be on generating a visualization of the state space. Algorithms for drawing graphs are not trivial; therefore this visualization problem is not trivial. However, the focus of this work is in applying existing graph algorithms to create visualizations as opposed to writing a new algorithm or modifying an existing algorithm. Therefore, it is necessary to find a suitable library to take care of the drawing of the state space.

ProB already includes support for the creation of a graph description of the state space in the DOT graph description language. These description files can then be visualized with GraphViz[1]. However, the graph algorithms available in GraphViz are relatively inefficient. During verification, the state space often grows exponentially. For state spaces that have a very large number of vertices, the GraphViz algorithms take too long to be useful. The graph generation in GraphViz is also inherently offline. If any thing changes in the state space, the whole graph must be rerendered. During consistency checking or animation, states are constantly being added to the graph. We therefore want a graph engine that can easily add vertices and that can handle state spaces with a large number of vertices.

We also want the user to be able to manipulate and interact with the graph. For instance, ProB supports the ability to create smaller graphs that are derived from the original state space [1]. Because state spaces become so large so quickly, a derived graph can be much more meaningful and useful for a user. One of the features that we want to implement for the visualization of the state space is to enable the user to apply these algorithms to their

[1]http://www.graphviz.org

state space to simplify its representation. The user should be able to seamlessly transfer between the representation of the whole state space and derived state spaces.

1.2 Other Visualizations

Although the visualization of the state space is the focus of this work, there are visualizations that can be generated which will be useful for the user. For instance, ProB supports the generation of a DOT file which, when rendered, shows how a given formula is broken down into subformulas [2]. The formula and its subformulas are also evaluated for a given state, and the resulting nodes are colored so as to specify the value of the formula (e.g. if a given predicate evaluates to true at the specified state, the predicate would be colored green). During the course of this work, we will also recreate this visualization using the new graph engine.

One of the features that is currently being integrated into ProB is the simulation of multiple models concurrently. In this case, the user is less interested in viewing the state space and more interested in being able to see what value a particular expression takes on over the course of a given animation. We will therefore also create a chart to visualize this information.

1.3 Integration of the Visualizations into ProB

The graph engine that we have have chosen is D3. Instead of a graph engine in the traditional sense, D3 provides a domain specific language to enable the user to generate elements based on data that is provided. D3 is written in JavaScript, and the visualizations that can be produces are pure HTML and SVG documents.

The visualizations that are produced using D3 will be integrated into the ProB 2.0 Java application using the Jetty server that is already present. The visualizations will also make use of the existing listener framework that is triggered when changes in the state space or the current animation take place. It should also be possible to create and view multiple visualizations at any given time.

2 Background

2.1 ProB

ProB is a tool created to verify formal specifications [5]. In addition to verifying Classical B and Event-B specifications, ProB also verifies models written in the CSP-M, TLA+, and Z specification languages. ProB differs from other tools dealing with model verification in that it is fully automated. Several tools have also been written to extend ProB and add functionality.

ProB verifies models through consistency checking [6] and refinement checking [7]. Consistency checking is the systematic check of all states within a particular specification. In order to do this, ProB checks the state space of the specification in question. The state space is a graph with *states* saved as vertices and *operations* saved as edges. Refinement checking examines the refinements of a machine to ensure that they are valid refinements.

The concept of the state space is central to the ProB application. The state space is a directed multigraph. The states are saved as vertices in the graph and the operations within the graph are saved as directed edges that transition from one state to another. The main purpose of the ProB software is to verify this state space for inconsistencies. For instance, it is possible to use ProB to find states within the graph that violate the invariant for specification. It is also possible to find states from which there are no further operations possible. This is called a deadlock.

2.1.1 ProB Tools

ProB consists of several different tools that will be referenced throughout the course of this work.

ProB CLI
The ProB kernel is written in primarily in SICStus prolog [5]. The ProB CLI is available as a binary executable, and all of the other tools listed here are built on top of it. The ProB CLI provides support for the interpretation of Classical B, Event-B, CSP-M, TLA+, and Z specification languages. These specifications are interpreted and translated into an internal represenation that can then be animated and model checked.

ProB Tcl/Tk
The ProB Tcl/Tk was created at the same time as the ProB CLI to provide a user interface for the ProB CLI. In addition to providing a UI for the ProB CLI, ProB Tcl/Tk also enables the user to edit specification files before animation, and provides the user with visualizations of different data that is generated during animation or model checking. For instance, ProB Tcl/Tk includes graphical visualizations for the state space, the current state, and for B predicates that are evaluated at the current state in the animation [2] The ProB Tcl/Tk application uses the DOTTY tool available from the Graphviz graph layout software.

ProB Plugin
Work on the ProB Plugin began in 2005. This is an Eclipse plugin for the Rodin software [8], which is an easy to use and extensible tool platform for editing specifications written in the Event-B specification language. At this point, a socket server was integrated into the ProB CLI which allowed the ProB Plugin, which is written in Java, to communicate with the ProB CLI. The communication between the two takes place using queries and answers.

ProB 2.0 API
Development of the ProB 2.0 API began in 2011. The main goal of the ProB 2.0 API was to adapt and optimize the existing Java API to build a user interface on top of a programmatic API. One of the main improvements made available in this tool was the introduction of a programmatic abstraction of the state space. The ProB 2.0 API also provides a programmatic abstraction called a *history* for the represenation of

animations. This history consists of the trace of operations that have been executed for a given animation. A given state space can have an arbitrary number of animations. The user can switch between animations and work on any given animation at any given time. Thus, for the ProB 2.0 API, the notion of a *current state* corresponds to the current states of the animation that the user is currently executing.

During the course of animation and model checking, the state of the ProB 2.0 API changes. The state space grows (i.e. new operations and states are cached), and the current state changes. In order for developers to be aware of these changes, a listener framework is offered. A developer can therefore implement classes that react when the current state in the animation changes, when new states are added to the state space, and when the specification that is being animated changes.

The API is programmatic and harnesses the power of the Groovy programming language. The ProB 2.0 API integrates a fully functioning groovy console into the final product. It is now possible for users and developers to write Groovy scripts that carry out desired functionality. There is also support for creating web applications that communicate with ProB. The console is actually a user interface that makes use of the jetty server that is integrated in the ProB 2.0 API. There are no eclipse dependencies present in the ProB 2.0 API, so it can be deployed as a jar file and integrated into any Java based application.

ProB 2.0 Plugin

Similar to the original ProB Plugin, the ProB 2.0 Plugin is an Eclipse plugin created for the Rodin platform. Much of the UI code has been directly imported from the original Plugin, so it appears to be very similar. However, the graphical interface is now built on top of the new programmatic abstractions that are available from the ProB 2.0 API, and changes that take place within the graphical interface are triggered by the ProB 2.0 API listener framework.

2.2 D3 and JavaScript

Since a jetty server was already available in the ProB 2.0 Plugin, it was plausible to create visualizations using javascript and HTML. Because the ProB 2.0 Plugin is an Eclipse application, it also would have been possible to create visualizations using a native Java or Eclipse library. I carried out an experiment at the beginning of this work to determine the feasibility of the different graph libraries. JUNG was considered because it is the software framework that is the ProB 2.0 API currently uses. It would have been relatively simple to embed the visualizations into the existing ProB 2.0 Plugin, but customizing JUNG graphs is extremely difficult. The ZEST graph library was a feasible option, but in the end, I chose to use the D3 library.

D3 (Data-Driven Documents) is "an embedded domain-specific language for transforming the document object model based on data" which is written in JavaScript [9]. Developers can embed the library into a JavaScript application and use the D3 functions to create a pure SVG and HTML document object model (DOM). The focus of D3 is not on creating data visualizations. It is on providing the user the capability of defining exactly which elements the DOM should contain based on the data that the user has provided.

Because the objects that are being manipulated are pure SVG and HTML, the user can use D3 to create objects that can be styled using CSS or by dynamically manipulating the style tags of the elements.

2.2.1 Core Functionality

D3 provides a selector API based on CSS3 that is similar to jQuery[2]. The user creates visualizations by selecting sections of the document and binding them to user provided data in the form of an array of arbitrary values [9]. D3 provides support for parsing JSON, XML, HTML, CSV, and TSV files. Once the data is bound to the desired section of the document, D3 can append an HTML or SVG element onto the section for each element of data. This is where the real power of D3 lies because the user can define the attributes of the element dynamically based on the values of the datum in question. By changing these attributes (e.g. size, radius, color) the resulting document already presents the data in a way that the viewer visually understands. The core also provides support for working with arrays and for defining transitions that can be used to animate the document. In order to better understand how D3 works, we have provided a simple example of a how a developer can use D3 to create an HTML dropdown menu (see Listing 1). The generated HTML snippet is also provided (see Listing 2). A more complicated example using the force layout is available in the appendix (see Appendix A).

2.2.2 Further Functionality

D3 also provides further functionality for manipulating the DOM. Developers can define a scale based on the domain and range of values that are defined in the data provided by the user. The placement of elements within the document can then be placed according to the desired scale. D3 provides support for many different types of scales including linear scales, power scales, logarithmic scales, and temporal scales. Axes can also be created to correspond to the defined scale.

The user has the ability to change the DOM as needed. However, D3 also supports a large number of visualization layouts so that the user does not have to define the positions for the elements in a given visualization. The two layouts that are of relevance for this work are the tree layout and the spring layout.

The tree layout uses the Rheingold-Tilford algorithm for drawing tidy trees [10]. The force layout uses an algorithm created by Dwyer [11] to create a scalable and constrained graph layout. The physical simulations are based on the work by Jakobsen [12]. The implementation "uses a quadtree to accelerate charge interaction using the Barnes–Hut approximation. In addition to the repulsive charge force, a pseudo-gravity force keeps nodes centered in the visible area and avoids expulsion of disconnected subgraphs, while links are fixed-distance geometric constraints. Additional custom forces and constraints may be applied on the "tick" event, simply by updating the x and y attributes of nodes" [13].

To help the viewer interact with the visualization, D3 provides support for the zoom and

[2]http://jquery.com

drag behaviors. This listens to the mouse clicks commonly associated with zooming (i.e. scrolling, double clicking) and enlarges the image as would be expected. With this same mechanism, the developer can enable the user to grab hold of the canvas and pan through the image to inspect it closer.

Despite the considerable functions that D3 offers, it is very easy for the user to begin developing with D3. The API is described in detail on the D3 Wiki [13], and the D3 website[3] includes an extensive array of examples that new developers can use as a jumping off point. The D3 developer community is very large, so it is easy to find answers to almost every question online.

Listing 1: Dynamically create a dropdown menu.

```
// Select element with id "body" and append a select tag onto it. When it
    changes, the defined function will be triggered.
var dropdown = d3.select("#body")
            .append("select")
            .on("change", function() {
              var choice = this.options[this.selectedIndex].__data__;
              // handle choice
            });

var options = [{id: 1, name: "Option 1"},
         {id: 2, name: "Option 2"},
         {id: 3, name: "Option 3"}];

// Create an option tag with id and text elements for each option that is
    defined in options
dropdown.selectAll("option")
    .data(options)
    .enter()
    .append("option")
    .attr("id", function(d) { return "op" + d.id; })
    .text( function(d) { return d.name; });

// Select option 3 by default
dropdown.select("#op3")
    .attr("selected", true);
```

Listing 2: Html generated from Listing 1

```
<div id=body>
    <select>
        <option id="op1">Option 1</option>
        <option id="op2">Option 2</option>
        <option id="op3" selected=true>Option 3</option>
    </select>
</div>
```

[3]http://d3js.org

2.3 GraphViz integration with emscripten

The current visualizations available in the ProB Tcl/Tk application are powered using the GraphViz[4] graph visualization software. In the ProB CLI, there is support for generating graphs for the state space in the DOT graph language. The problem with this, and the reason that we are researching other alternatives, is that drawing GraphViz graphs is extremely inefficient. However, for the state spaces that are derived using the signature merge algorithm, or for the transition diagrams that can be created from a state space, these graphs are quite pleasing to the eye. The derived graphs are also usually small enough that they can be drawn efficiently.

For this reason, we wanted to some how be able to visualize small graphs written in the DOT language. In order to do this, we took advantage of the emscripten compiler [14]. This is a compiler that compiles LLVM bitcode to JavaScript so that it can be run in any browser. Any C programs can be compiled to LLVM. We used the Viz.js JavaScript library[5] developed by Mike Daines which has compiled GraphViz from C to JavaScript and provided a wrapper function to produce svg visualizations. For example, the code shown in Listing 3 will produce Figure 1.

Listing 3: Create a visualization with viz.js and insert it into an html page.

```
svg = Viz("digraph { a -> b; a -> c; }", "svg");
$("#elementId").replaceWith(svg);
```

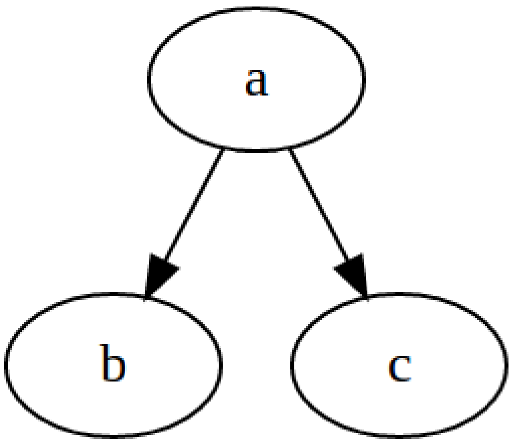


Figure 1: Generated graph image from Listing 3.

[4]http://www.graphviz.org
[5]https://github.com/mdaines/viz.js

3 Contribution

3.1 Visualization framework

3.1.1 Structure

One of the main issues that we had to be deal with at the beginning of the development process was the issue of how to integrate the visualizations into the ProB 2.0 API. A functioning jetty server was already available, so we had to integrate our JavaScript visualizations into the existing framework. We ran into problems at the beginning, because a Java servlet is a singleton object. We needed to create a way to let the servlet know for which visualization it should be calculating. In order to do this, we created a session based servlet. When the user wants to open a visualization, the servlet is contacted. The servlet then creates a servlet responsible for the visualization and a unique session id. When a visualization sends a `GET` request, it includes its session id. The session based servlet then forwards the request to the the servlet that is responsible for the data calculations.

The visualization communicates with the servlet by setting up a polling interval. It tells the state space if it needs the complete data set or just the changes since the last polling interval. The servlet then responds by sending the correct data (see Figure 2).

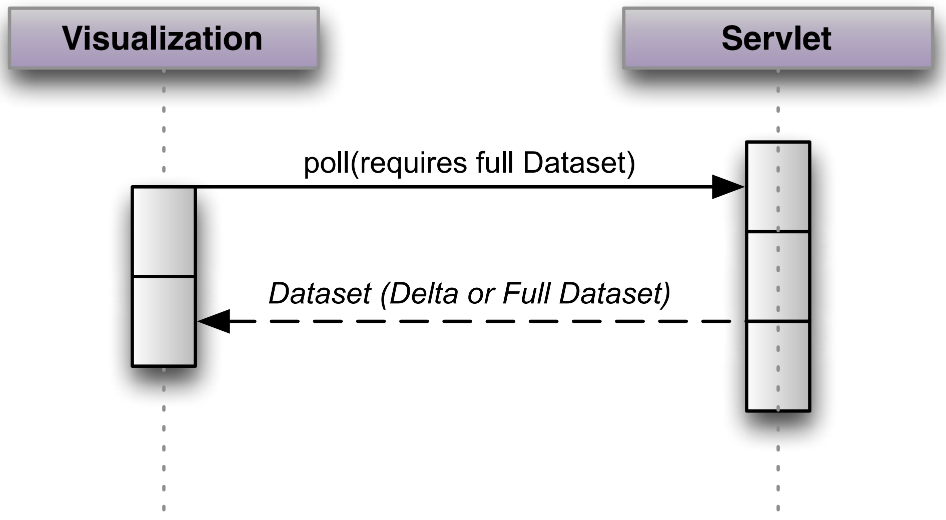


Figure 2: How visualizations communicate with the servlet that is responsible.

The servlet is also connected to the ProB 2.0 API through the listener framework. Depending on the data that is needed for a particular visualization, the servlet registers either to receive notifications about changes in the current animation or about changes in the state space (see Figure 3). Every time the servlet receives a new notification, the data needed for the visualization is recalculated.

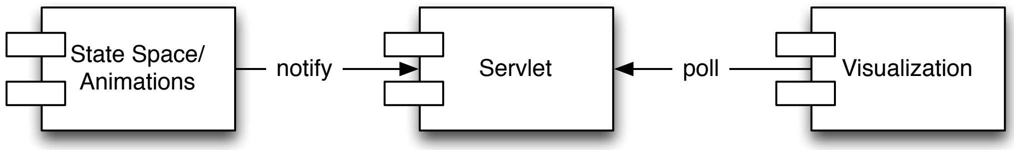


Figure 3: Model of the program flow.

3.1.2 User interaction with the visualizations

Once we implemented a way to integrate the visualization servlets into the ProB 2.0 application, it was still necessary to implement an easy way for the user to interact with the visualizations. One of the main advantages of the D3 visualization framework is the flexibility for the user. Using the D3 selectors, it is possible for the user to select and change the attributes of any of the elements of the visualization. In order to offer this functionality to the users from within the ProB 2.0 application, we decided that we needed to lift the functionality from the JavaScript level into the existing groovy console in the Java 2.0 API. This was accomplished by creating a `Transformer` object that represents the action that the user wants to carry out in the visualization. Then the `Transformer` object is added to the particular visualization and is applied the next time the visualization is redrawn. The `Transformer` object was written so that its functionality is similar to what the user would actually write using the D3 library.

We wanted how the user interacted with the visualization to be as natural as possible. The user should not have a hard time learning how to manipulate the visualization. For this reason, we decided to create a small DSL that would enable the user to specify which attributes should change within a particular visualization. It is possible for the user to create `Transformers` in the console (see Listing 4). To do this, the user can specify a selection based on the W3C Selection API. It also specifies the attributes that should be changed for the specified selectors. The user can then apply this `Tranformer` to the servlet that is responsible for generating the data for a given transformation. To this purpose, when a new servlet is created, a variable is created in the groovy console that corresponds to the servlet in question so that the user can apply `Transformers` to the visualization directly.

Listing 4: Define rules for the transformation of visualization elements

```
// Select elements with ids "rroot" and "r1" and set their fill and stroke
    attributes
x = transform("#rroot,#r1") {
        set "fill", "red"
        set "stroke", "gray"
}
```

```
// Apply to visualization
viz0.apply(x)
```

It is also possible to harness the power of the Groovy closure in order to create a Transformer that can be parameterized (see Listing 5).

Listing 5: Use Groovy closures to generate Transformers

```
// Create a closure that can be parameterized
colorize = { selection, color ->
                transform(selection) {
                    set "fill",color
                }
           }

// Color elements "rroot" and "r1" green
viz0.apply(colorize("#rroot,#r1","green"))
```

These `Transformers` are sent to the visualization every time that it is polled. The visualizations can then apply them. It is therefore possible for the user to manipulate the visualization. Unfortunately, in order to define these `Transformers`, the user needs to have some idea of how the elements are named internally. For the state space visualization, we also introduced an abstaction that filters a state space by predicate and produces a `Transformer` based on the states that are calculated (see Listing 6). When new states are added to the state space, these will also be filtered based on the given predicate and the `Transformer` will be updated accordingly.

Listing 6: Create a `Transformer` based on the states that match a given predicate

```
// Define your formula
predicate = "active\\/waiting={}" as ClassicalB

// Create a Transformer that will filter the given state space (saved in
    space0) according to the given predicate
x = transform(predicate, space0 ) {
    set "fill", "blue"
    set "stroke", "white"
}

// Apply the Transformer to the visualization
viz0.apply(x)
```

3.1.3 Extensibility

In addition to creating visualizations that are useful to the user, we also wanted to make it easy for other developers to create similar visualizations. In order to help with this, we encapsuled certain elements common to all of the visualizations into a separate script. In order to have access to these elements, a developer simply needs to include the script before that of his visualization. Currently, there are two main elements included in this script. Firstly, the user can use the `createCanvas` function to create a D3 selection that includes support for zooming (see Listing 7). Secondly, if the user wants to be able to apply the `Transformers` that are described in the last section, there is a built in function to apply a list of `Transformers` to the visualization (see Listing 8). In the future, it will also be possible to add more functions to this script to make it even easier to create visualizations for ProB.

Listing 7: Append a D3 selection to an element that includes support for zooming

```
var width = 600, height = 400;
var svg = createCanvas("#elementId", width, height);

// Append all further elements to this selection
svg.append(...);
```

Listing 8: Apply list of `Transformers` received from servlet

```
// The servlet has been polled, and a response has been received
var styling = response.styling

// ... Render the visualization
// ... Then apply the user defined styling
applyStyling(styling);
```

3.2 Visualization of the State Space

3.2.1 Main visualization

When a state space visualization is opened, the visualization servlet responsible for the state space visualization takes the state space associated with the current animation and extracts the information about the nodes and edges contained within the graph. This information is then processed by D3 using the force layout and rendered to create a visualization (see Figure 4). As a basis for the visualization, we used the Force Directed Graph example created by Michael Bostock (see Appendix A).

Unfortunately, the state space contains an extremely large amount of information that has to be processed. This includes the values of the variables and the invariant for every state in the graph and the names and parameters of the operations that correspond to every edge in the graph. Because of this, it is rather difficult to create a useful visualization of the whole state space because the user not only wants to inspect how the state space appears as a whole but also the individual states within the operation. As a proposed solution of this problem, we used the zoom functionality that is available in D3. The main problem was that if the visualization of the nodes was large enough for the user to read the values of the variable at the given state, it would no longer be possible to see the state space as a whole. Instead of trying to meet both requirements at once, we simply made the text that is printed on the node and edge objects very small. When the

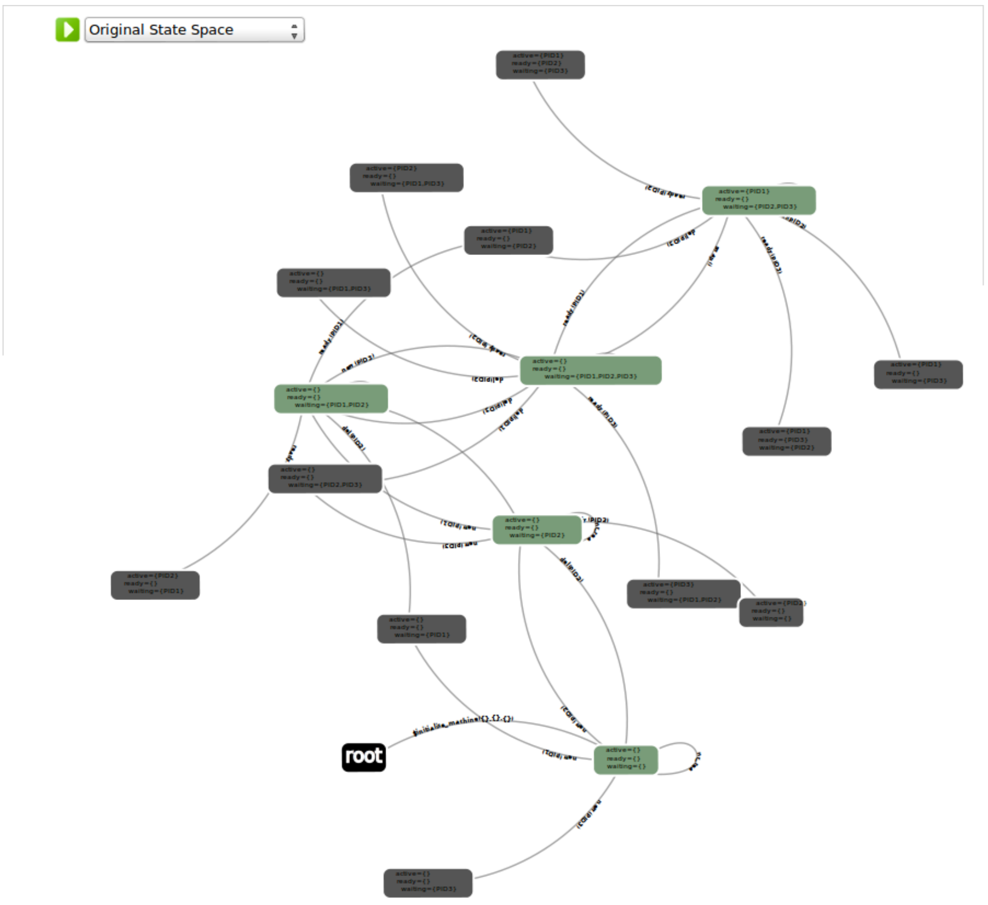


Figure 4: Visualization of the state space for the Scheduler example

visualization is created, the user can inspect the graph as a whole how the graph appears as a whole. The text for the given nodes, however, is virtually indiscernable. If the user wants to inspect a particular node, they can do so by zooming into the visualization. The text is then larger, and the user can see the nodes that are in the direct neighborhood of the node in question (see Figure 5). Then user can also click on the background of the visualization in order to pan through the visualization and inspect other nodes and edges. The visualization is also interactive. The user can grab a node and move it around to a desired position.

We had some performance issues that were associated with very large state spaces. The force layout keeps adjusting the graph until it reaches a fix point. The problem was that as the state space grew, there were more and more objects that had to be accounted for. The force layout just kept calculating and moving the the nodes. This didn't only affect the appearance of the visualization. It cost enough resources that the whole eclipse plugin would become unresponsive. A quick fix to this problem was adding a play/pause

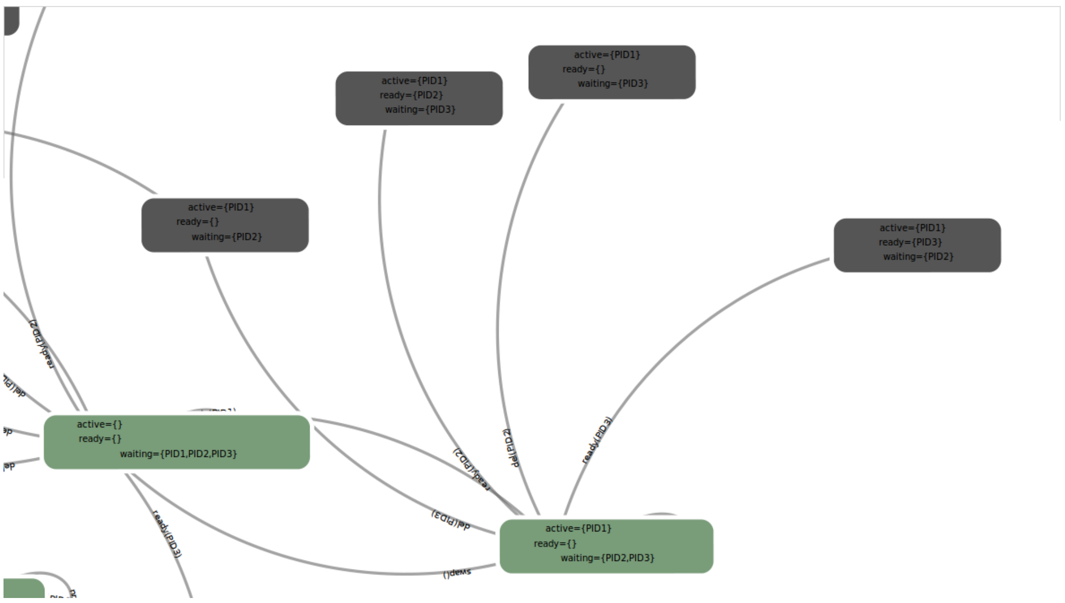


Figure 5: By zooming in, the user can inspect the neighborhood of a given state.

button to the upper left hand corner of the visualization (see Figure 10). When the user is satisfied with the visualization and how it is laid out, he can press the pause button, and the graph will stop being rendered. When he presses the play button, the rendering will begin again. The iterative force layout keeps running in the background, so when the rendering begins again, the visualization has had time to stabilize.

When new states are added to the state space, these states are added to the graph when the visualization receives them in the next poll. The graph is then updated. This results in a nice animation.

Status about the invariant is a available in the graph based on the color of the nodes. If an invariant violation is present, the node is colored red. If the invariant is ok, the node is colored green. Otherwise, if the invariant has not yet been calculated for the given node, the node is colored gray.

3.2.2 Visualization of Derived Graphs

There is also support for the visualization of graphs that are derived from the state space. The ProB CLI support the generation of smaller graphs that are derived from the state space in question. These graphs show information about state space that is not obvious when dealing with the state space as whole. Two algorithms for derived graph generation are currently supported. The signature merge algorithm is supported (see Figure 6). The user can also create a transition diagram based on a user defined expression (see Figure 7).

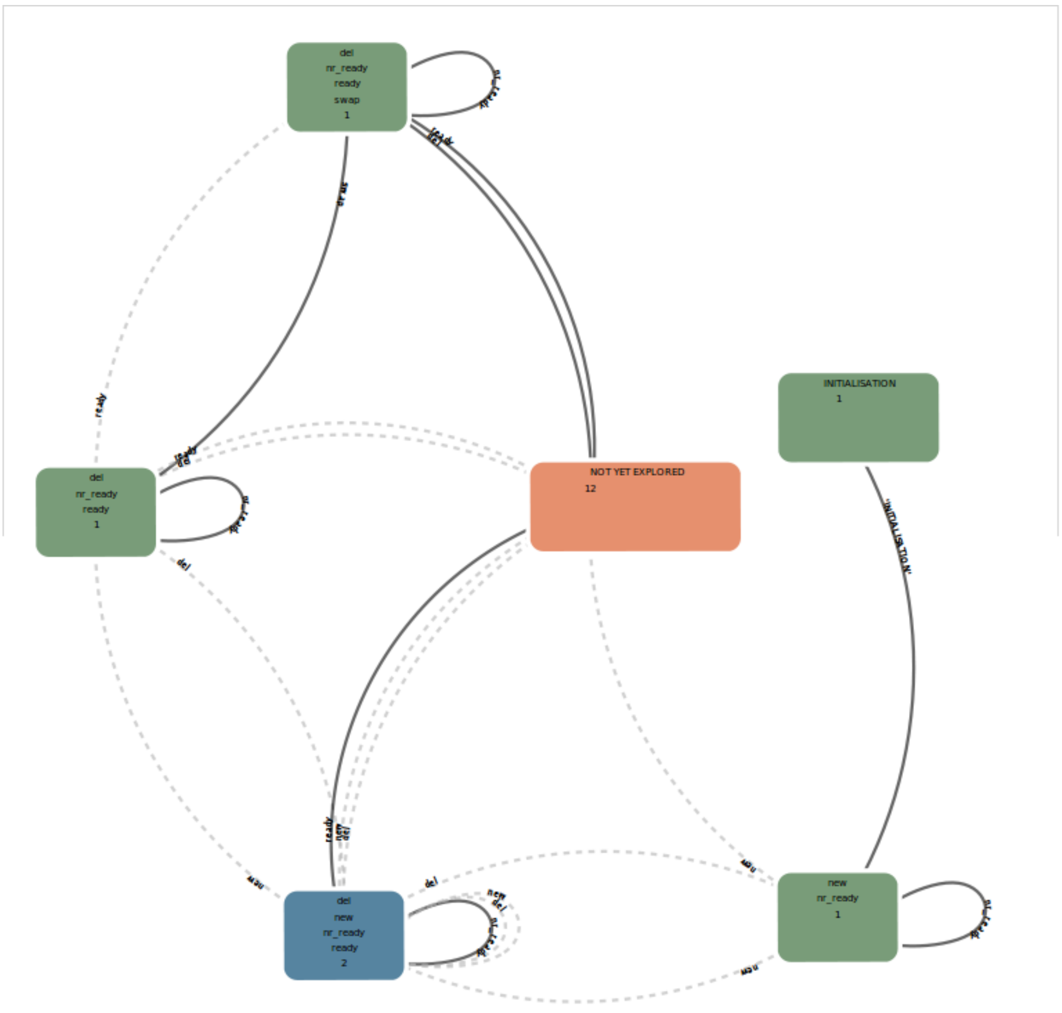


Figure 6: D3 Visualization of signature merge for Scheduler example

If the user wants to use the GraphViz algorithms and rendering engine, there is also support for both the signature merge (see Figure 8) and transition diagram (see Figure 9).

3.2.3 User Interface

There is also a basic user interface for the user to interact with the state space visualization. There is a drop down menu from which the user can decide which visualization he wants to view (see Figure 10).

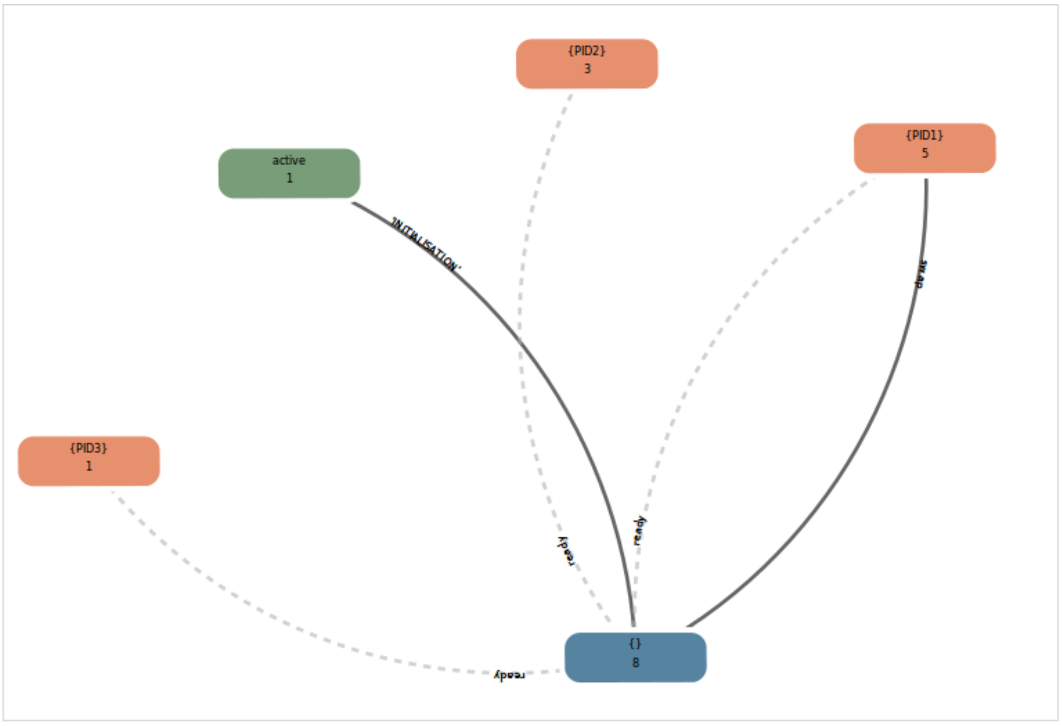


Figure 7: D3 Visualization of the transition diagram of `active` in Scheduler example

The signature merge algorithm is calculated based on the events in the model that is being animated. By default, all events are selected, but it is also possible for a user to disable events when calculating the signature merge algorithm. In the state space visualization, if the user is dealing with the signature merge graphs, a settings icon appears and the user can click on it and select or deselect the events that are of interest to him (see Figure 11).

When the user chooses to create a transition diagram from the menu, a prompt appears and the user can input the desired transition. When the transition diagram is calculated, a text field appears. In order to change the expression for a given transition diagram, the user can type it in the text field and submit it (see Figure 12). The algorithm will then be recalculated and the graph will be rerendered.

3.3 Visualization of a B-type Formula

The ProB CLI already supported the functionality of expanding a formula into its subformulas and finding its value at a given state. However, the expanding of the formula took place lazily. A formula would be sent to the ProB CLI and then the direct subformulas of this formula would be sent back. The software would then have to contact ProB

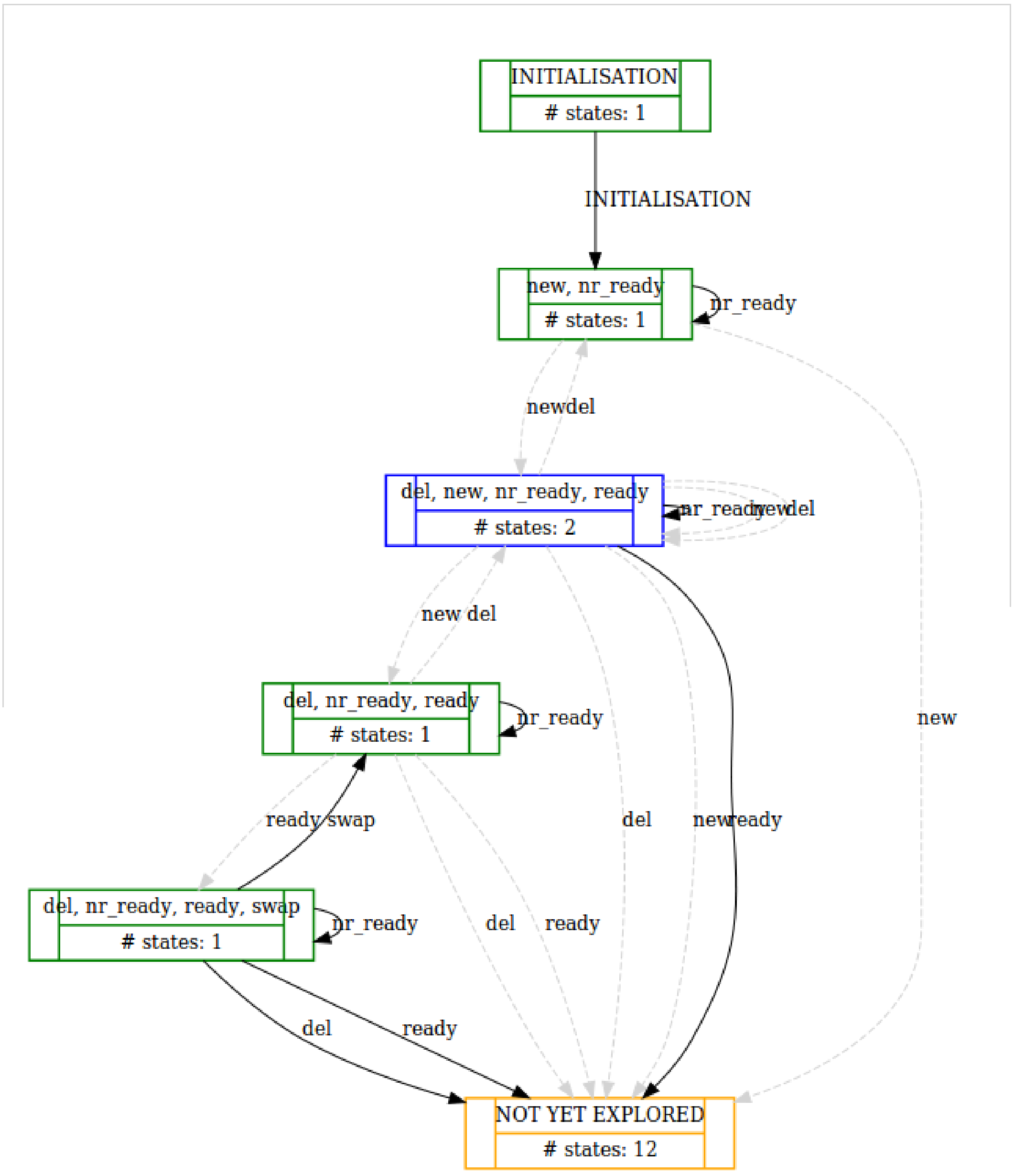


Figure 8: GraphViz powered Visualization of signature merge for the Scheduler example

CLI recursively until all of the subformulas had been calculated and cached on the Java side. For the predicate visualization, we wanted the formula to be completely expanded and then sent in its entirety to the ProB 2.0 API. In order to do this, we implemented a prolog predicate within the ProB CLI that performs the recursive expanding of a B formula before it is sent back to the Java API. The predicate also delivers the value of each subformula for the given state. This ensures that performance will not an issue.

The final visualization is interactive (see Figure 13). If a formula has subformulas, the user can select it from within the visualization to expand or to retract the subformulas.

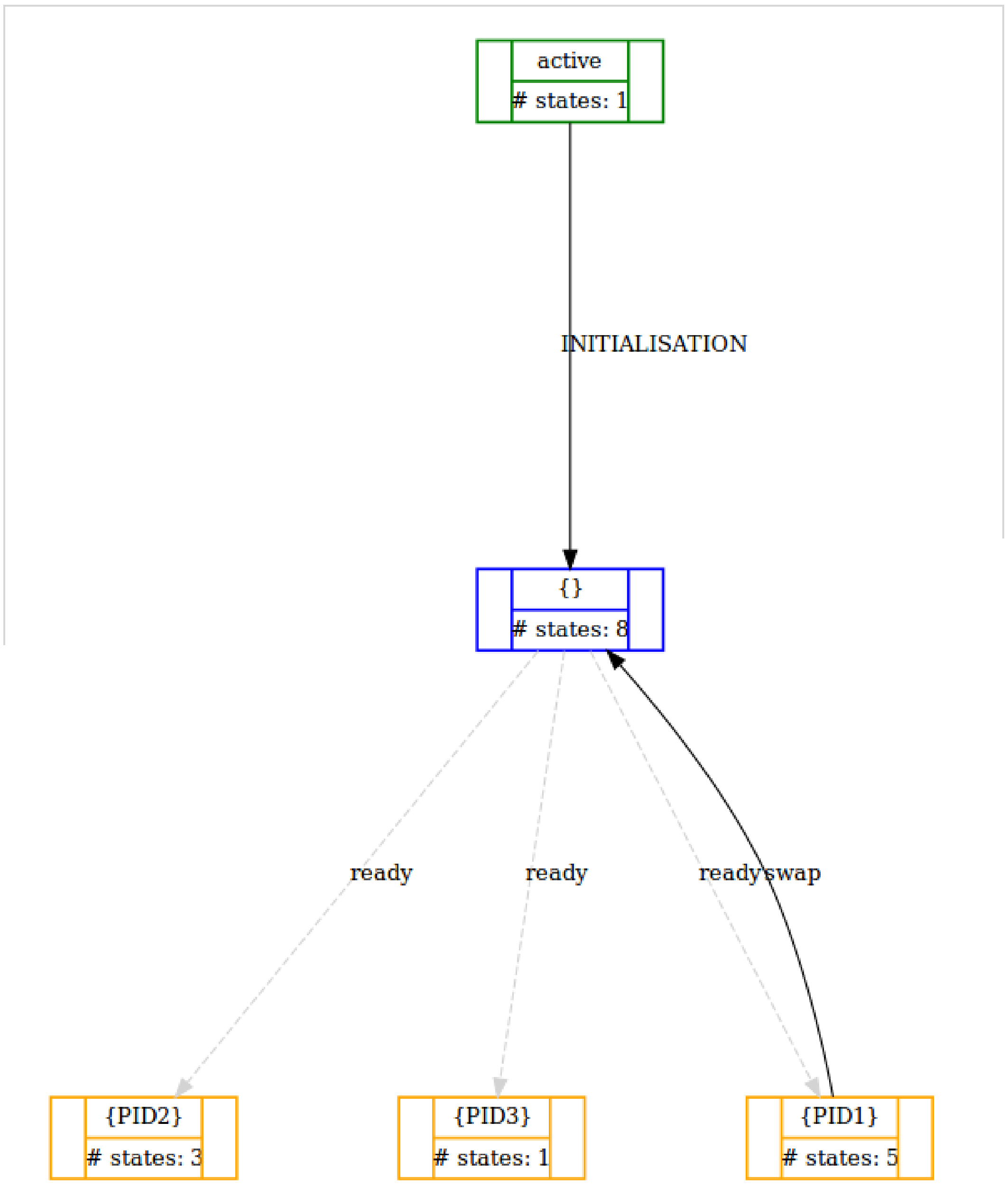


Figure 9: GraphViz powered Visualization of the transition diagram of `active` in Scheduler model

The subformulas are always either predicates or expressions. If they are expressions, they are colored white or light grey depending on whether they have subformulas or not. If the formula is a predicate that has evaluated to true for the given formula, the node is colored green. If the formula is a predicated that has evaluated to false, node is colored in red. The value of the given formula is also printed beneath the formula. This allows the user to visually identify the parts of the formulas and their given values.

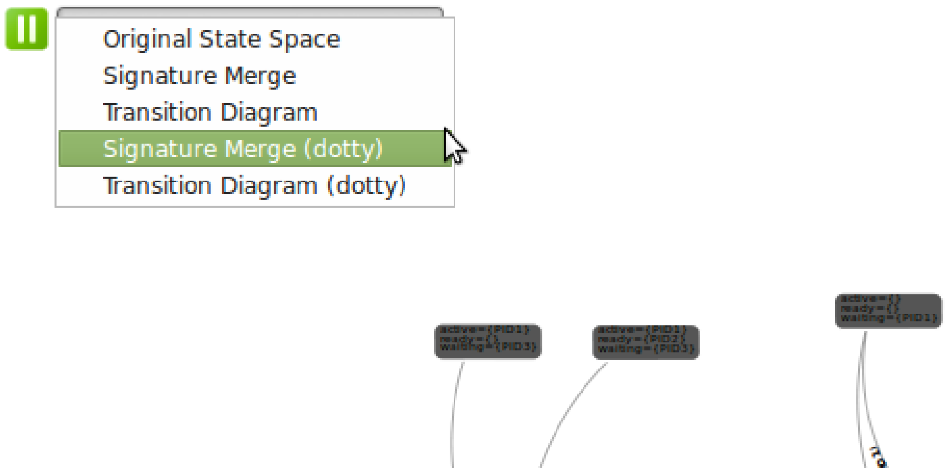
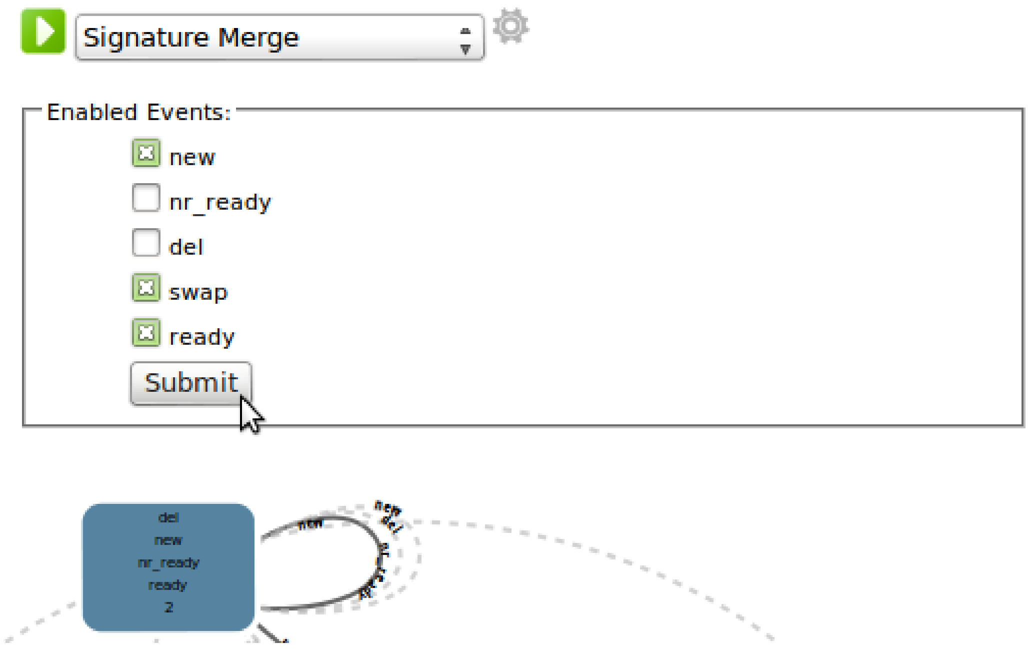


Figure 10: The user can select the desired visualization and play and pause the rendering.



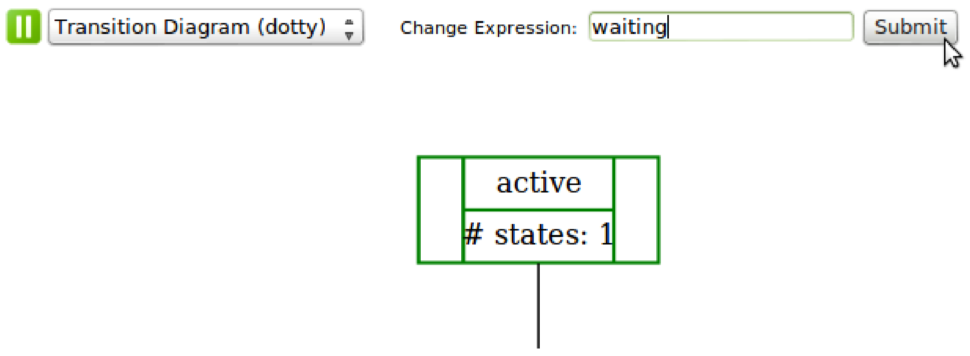
Enabled Events:

- [✓] new
- [ ] nr_ready
- [ ] del
- [✓] swap
- [✓] ready

Submit

Figure 11: User interface to chose events for signature merge.

In the implementation of the formula, the D3 tree layout is used. The expanding and collapsing of the nodes takes place with a simple JavaScript function. This visualization is based on the Collapsible Tree Layout from the D3 website (see Appendix B). By harnessing the power of the D3 zoom behavior, it is also possible to zoom in and out of the visualization and to pan the image to inspect it closer. The servlet responsible for the visualization implements a listener to identify if any changes in the animation occur. If they do, the formula is recalculated for the new current state, and the visualization is redrawn.



Change Expression: waiting

Figure 12: The user can input a new expression to recalculate the transition diagram.

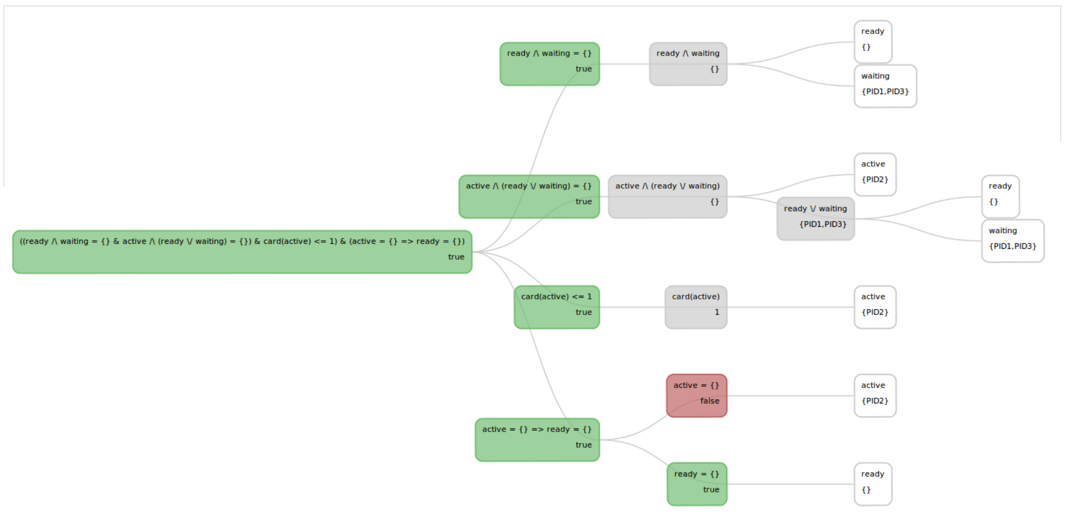


Figure 13: Visualization of the invariant of the Scheduler model

3.4 Visualization of the Value of a Formula Over Time

The ProB 2.0 API supports the evaluation of a given formula over the course of the history of an animation. Because a state is defined by the values that the variables take on when dealing with B type specification languages, it can be particularly interesting to be able to examine the value of a variable over the course of a trace when dealing with a Classical B or Event-B formula.

In order for the ProB 2.0 API to evaluate a formula, it extracts the list of states that the animation visits over the course of its history. Then it contacts the ProB CLI and extracts the value that the formlua takes on for each state in the list. This information is then processed by D3 to produce a simple line plot (see Figure 14). As of now, formulas can only be visualized if they take on integer values. In the future, we plan to support the visualization of formulas that take on boolean values. The visualization also interacts with the ProB 2.0 API. If the current state changes, the formula is recalculated and a new plot is produced.

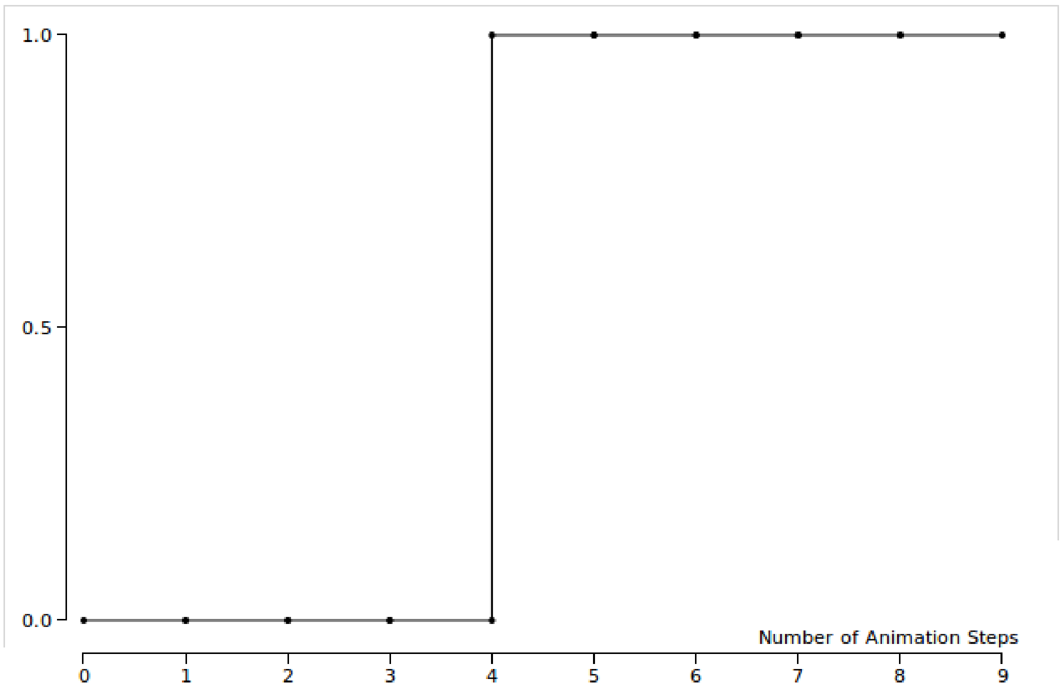


Figure 14: Visualization of value of *card(active)* from the Scheduler model over the course of an animation.

4 Future Work

One of the main features we implemented in this work was the creation of a visualization framework. Each visualization has its own unique elements, but some elements have been encapsulated so that they can be reused in other visualizations. This is true both on the server and the client side. The basic elements of a ProB visualization have been extracted into a JavaScript library. For instance, developers can now use this library to create a basic canvas which can be zoomed and panned. We have also implemented a basic servlet that can handle the communication between the visualization and the servlet responsible for the visualization. This can easily be extended to create new servlets.

We are currently developing a worksheet element for the ProB 2.0 Plugin. This will serve as documentation and a means to run groovy scripts within the ProB application. In the future, the visualizations created in the scope of this work will be embedded within this worksheet feature.

It will also be necessary to implement other data visualizations in ProB 2.0. For instance, there is currently no graphical represenation of a state. This visualization is available in the ProB Tcl/Tk application, but it still needs to be implemented within ProB 2.0.

The state space visualization and the visualization of a formula over time are not language specific. It is possible to use the visualizations for any specification language that ProB supports. For the visualization of the breakdown of a formula, however, this is not the case. The current implementation supports only Classical B and Event-B formulas. In the future, work could be done to support formulas from other formalisms.

Current visualizations will also need to be maintained and updated to add functionality. For instance, it might be possible to integrate the proposed state visualization with the existing state space visualization. Then, when a user would select a state, a window would pop up displaying the state visualization for that particular state.

5 Conclusion

Over the course of this work, we have shown the feasibility of using D3 to create data visualizations within ProB. It is not only possible to create the desired visualizations, it is also easy to adapt the servlets so that the visualizations are updated to reflect changes made in the course of model animation. The styling for these visualizations can be easily defined by the user. This gives the user a large amount of control over the visualization.

The visualization of the state space was the focus of this work. The visualization that was created is interactive and is automatically updated as soon as states are calculated and cached in the state space. It also can handle relatively large state spaces (TEST THIS OUT TO DETERMINE HOW LARGE!!!!).

The decision to support GraphViz visualizations in the state space visualization in addition to D3 visualizations took place relatively late in the development process. Using the existing visualization framework, it was possible to implement this feature in a relatively short period of time. This shows that the visualization framework is relatively flexible and can be easily extended.

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List of Figures

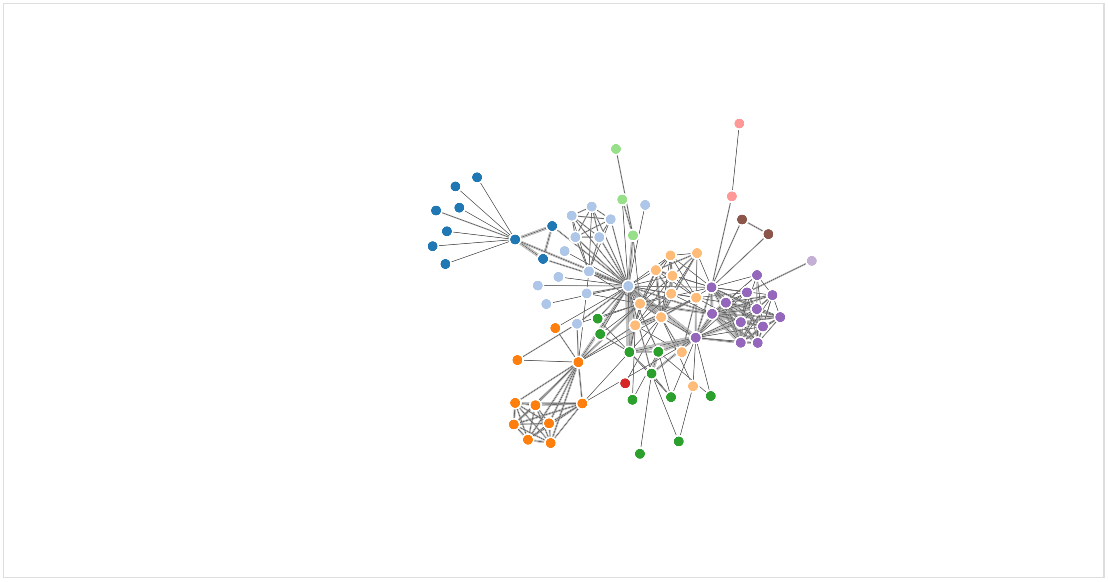
Listings

A Force Directed Graph

mbostock's block #4062045

Force-Directed Graph

May 8, 2013



This simple force-directed graph shows character co-occurence in *Les Misérables*. A physical simulation of charged particles and springs places related characters in closer proximity, while unrelated characters are farther apart. Layout algorithm inspired by Tim Dwyer and Thomas Jakobsen. Data based on character coappearence in Victor Hugo's *Les Misérables*, compiled by Donald Knuth.

Open in a new window.

index.html

```
<!DOCTYPE html>
<meta charset="utf-8">
<style>

.node {
  stroke: #fff;
  stroke-width: 1.5px;
}

.link {
  stroke: #999;
  stroke-opacity: .6;
}

</style>
<body>
<script src="http://d3js.org/d3.v3.min.js"></script>
<script>

var width = 960,
    height = 500;
```

```
var color = d3.scale.category20();

var force = d3.layout.force()
    .charge(-120)
    .linkDistance(30)
    .size([width, height]);

var svg = d3.select("body").append("svg")
    .attr("width", width)
    .attr("height", height);

d3.json("miserables.json", function(error, graph) {
  force
      .nodes(graph.nodes)
      .links(graph.links)
      .start();

  var link = svg.selectAll(".link")
      .data(graph.links)
    .enter().append("line")
      .attr("class", "link")
      .style("stroke-width", function(d) { return Math.sqrt(d.value); });

  var node = svg.selectAll(".node")
      .data(graph.nodes)
    .enter().append("circle")
      .attr("class", "node")
      .attr("r", 5)
      .style("fill", function(d) { return color(d.group); })
      .call(force.drag);

  node.append("title")
      .text(function(d) { return d.name; });

  force.on("tick", function() {
    link.attr("x1", function(d) { return d.source.x; })
        .attr("y1", function(d) { return d.source.y; })
        .attr("x2", function(d) { return d.target.x; })
        .attr("y2", function(d) { return d.target.y; });

    node.attr("cx", function(d) { return d.x; })
        .attr("cy", function(d) { return d.y; });
  });
});

</script>
```

miserables.json

```
{
  "nodes":[
    {"name":"Myriel","group":1},
    {"name":"Napoleon","group":1},
    {"name":"Mlle.Baptistine","group":1},
    {"name":"Mme.Magloire","group":1},
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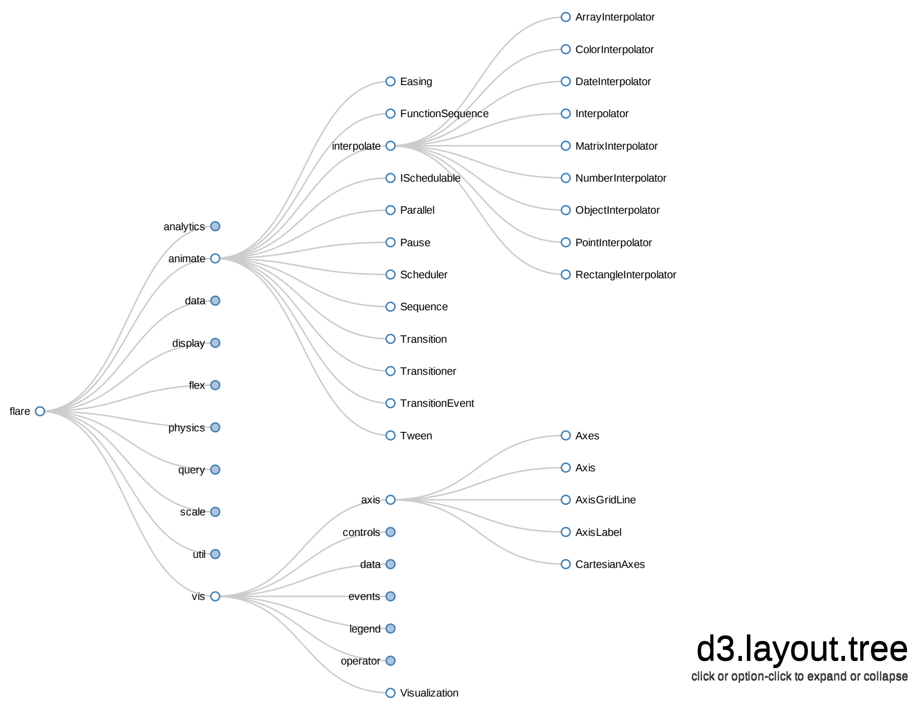
mbostock's block #4062045 May 8, 2013

B Collapsible Tree Layout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events
legend
operator
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Axes
Axis
AxisGridLine
AxisLabel
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d3.layout.tree
click or option-click to expand or collapse