

RELIABILITY AND STATE MACHINES IN AN
ADVANCED NETWORK TESTBED

by
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ABSTRACT

Complex distributed systems have many components that fail from time to time, adversely affecting the system's overall reliability. Our advanced network testbed, Emulab, also known as Netbed, is a complex time- and space-shared distributed system, composed of thousands of hardware and software components. Early versions of the Emulab system had reliability problems, could support experiments of only limited size, and were inefficient in resource use.

Our thesis is that enhancing Emulab with better monitoring and control through a flexible framework based on state machines improves the reliability, scalability, performance, efficiency, and generality of the system. Reliability is key, because of its effect on scalability, performance and efficiency. Any solution used to address these issues must be general across a variety of workloads, and portable across different software and hardware configurations.

Our results show improvement through faster error detection and recovery, better monitoring of testbed nodes, and prevention of race conditions. The state machine framework has also contributed to Emulab's generality and portability by expanding the accepted workload, providing graceful degradation for less capable node configurations, and making it easier to add new node types to the testbed.

For my family, past, present, and future

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CHAPTER 1

INTRODUCTION

Distributed systems are hard to design, develop, and test. An important tool in evaluating a distributed system is a testbed. Our Emulab network testbed[26], also known as Netbed, is an advanced network testbed that provides a controlled environment through combinations of simulation, emulation, and live networks. The testbed itself is a complex distributed system, composed of hundreds of clustered PCs, hundreds of participating nodes on the Internet, a variety of special purpose hardware, and thousands of virtual and simulated nodes. The system is time- and space-shared, and provides an automated way to configure computers and network hardware into a synthetic network environment. This synthetic environment is known in Emulab as an experiment.

Emulab began as a testbed of 10 PCs in April 2000, and opened for public production use with 40 PCs in October 2000. Since then, it has grown to over 180 PCs, with hundreds of nodes around the Internet, and thousands of virtual and simulated nodes. It has been used by over 750 users in more than 150 projects at about 75 institutions, allocating over 155,000 nodes in over 10,000 experiment instances. Seventeen classes at 12 universities have used it for coursework. Emulab software currently runs production testbeds at six sites, with about six more sites in the planning or construction stages.

Emulab is a large and complex production software system. During normal operation, the system includes about 35 daemons running on Emulab's servers, with 12 more running on each node. About 30 of those daemons were written by our team, and another 15 have been modified or integrated as a necessary part of the testbed's infrastructure. The others are standard daemons that are required for

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My advisor and friend, Jay Lepreau, has patiently worked with me during my undergraduate and graduate studies, and has given me many opportunities that have shaped my career. I am grateful for the confidence and trust that he has placed in me. His guidance and support has been invaluable in my research and this thesis.

I can say nothing about Emulab or my part in it without first mentioning the team that is responsible for its success. Many faces have come and gone, and each has made my work possible through their work on Emulab and in the Flux research group, but there are some who stand out in my mind as being especially influential in my life. Mike Hibler and Leigh Stoller have taught me innumerable lessons with their expertise and patience. They are truly masters of the art they practice. I am grateful for Robert Ricci and Kirk Webb, for their many talents and their willingness to share them, and for their friendship. Other colleagues and friends who should be mentioned by name are Shashi Guruprasad, Abhijeet Joglekar, Parveen Patel, Eric Eide, Chris Alfeld and Brian White. Numerous others have contributed to Emulab, and are remembered with gratitude.

proper operation. Our team's software base is composed of over 300,000 lines of code in about 450 programs and scripts, about 150 of which are the web scripts that make up Emulab's web interface. The remainder includes daemons, programs, and scripts that run on Emulab servers, nodes, or on a user's desktop machine.

As we gained experience with Emulab, and as it continued to grow in size, it became evident that it had reliability problems that needed to be dealt with. Many things can cause failures in a large system like Emulab, including any combination of hardware and software errors, user errors, and interference by users at inopportune moments. In addition to reliability issues, failures limit the maximum size of an experiment, degrade performance, and cause testbed resources to be used less efficiently with lower throughput.

Reliability, scalability, performance, and efficiency are all closely related, and directly affect throughput and usability of the testbed. Failure rates in part determine the maximum scale that can be achieved on the system, as well as the speed at which the system can complete its tasks. Decreased reliability also adversely impacts efficiency, causing resources that would normally be utilized effectively, to be unavailable for a longer time than necessary.

While generality and portability are not directly related to reliability, they constrain our solution to the problems in Emulab. One aspect of generality is workload generality – the range of workloads for which the testbed is appropriate. Rather than affecting performance in degree, generality has an absolute effect, and often determines whether a task is possible or impossible, rather than simply being slower or faster. Any software that is required to run on Emulab test nodes must be easily portable to a variety of operating systems and hardware architectures, including highly-constrained embedded environments. A testbed cannot compensate for a lack of generality by improving in any of the other aspects.

Our thesis is that enhancing Emulab with better monitoring and control through a flexible framework based on state machines improves the reliability, scalability, performance, efficiency, and generality of the system.

State machines, also known as Finite State Machines (FSMs) or Finite State Automata (FSAs)[11], are comprised of states, representing the condition of an entity, and transitions between states, which are associated with an event or action that causes a change in the condition of the entity. They provide several desirable qualities for addressing the design issues described above. First, they are an explicit model of processes¹ in the testbed, which improves error checking and verification. Second, they are generally well known and are simple to understand and visualize, which aids in software design. Third, they provide a powerful, expressive, and flexible model that can accommodate nearly any process occurring within a system, and a wide variety of implementation styles, including the event-driven, process-driven, or component-based styles used in Emulab.

In order to monitor a process in the testbed, Emulab developers need to create a state machine model of the process. This model may be created either before or after the implementation. The careful thought required to build an explicit model benefits system design. Incorporating an explicit representation of the model into the implementation ensures that the model accurately reflects the implementation, and vice versa.

Figure 1.1 illustrates at a high level how state machines are used in Emulab. First, a developer makes a model of the process in question, and designs it to match the implementation of the process being monitored. The developer then inserts the model into the Emulab database. The `stated` state monitoring daemon reads the description from the database, and uses it to determine if the process is properly following the model. An iterative refinement process typically occurs when a new model is incorporated, where both the model and the implementation are refined until the developer is confident that the model accurately reflects the implementation, and that the implementation achieves the desired result. When differences between the model and the implementation are found, it is up to the developer to decide which one is correct, and fix the other to match.

¹Throughout this thesis, the term “process” is generally used in the traditional sense, referring to a series of steps, actions, or tasks, rather than to a program running as a Unix process.

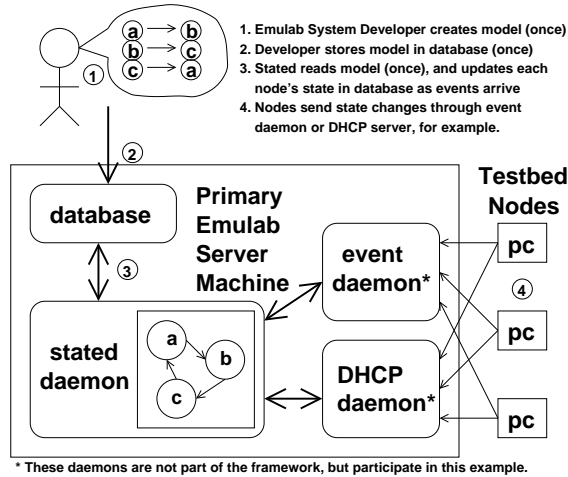


Figure 1.1: State machine framework overview

In this example, the process in question is the node boot cycle, in which the system is notified of state changes through the DHCP server, which sends an event when nodes boot, or from the nodes themselves, when they send notifications to the event daemon. The state daemon records the current state for each node in the database, where the state information can be used by the rest of the system for more accurate decision making and control.

There are currently three primary areas in Emulab where a state machine approach has been applied: the node boot process, the node allocation process, and the experiment life-cycle and configuration process. Our node boot state machines are controlled by a centralized service, called `stated` (pronounced STATE-dee), that

provides monitoring and aids in recovery when timeouts occur, or when nodes make unexpected or invalid state transitions. The node allocation machine is used while nodes are configured and prepared for use in an experiment. One use of the experiment status state machines is for access control checks, which depend not only on the user’s identity and privileges, but also on the current status of the experiment and which action the user has requested.

Modeling processes within Emulab as state machines has provided better monitoring and control capabilities, which in turn has had a variety of benefits in reliability and performance. Our framework has made error detection faster, and has improved our timeout mechanisms, which contributes to a decreased number of false positives and aids in faster recovery.

Our results include arguments about the benefits and shortcomings of our state machine framework, anecdotal reports from years of use, and empirical results from experiments we have performed. Overall, the state machine framework has been successful at addressing the issues of reliability, scalability, performance, efficiency, and generality. It has helped avoid race conditions, detect errors faster, recover from failures more quickly, and provides improved monitoring and control for nodes and experiments as they go through state changes. It has also helped us achieve our goals in terms of generality of accepted workloads, and portability to other operating systems and hardware devices.

This thesis is organized as follows: Chapter 2 gives relevant background information about the Emulab network testbed. Chapter 3 discusses reliability and the other challenges addressed by our framework, and gives a brief overview of state machines and why they are used as part of our solution. In Chapter 4, we discuss state machine representation, interaction, and models of control, along with `stated`, our centralized state management daemon. Chapter 5 describes nodes and the node boot state machines. The experiment status and node allocation state machines are presented in Chapter 6. In Chapter 7 we present our results, followed by related work in Chapter 8. We conclude in Chapter 9 and discuss some possible future work on the ideas presented in this thesis.

CHAPTER 2

EMULAB ARCHITECTURE

Emulab, also known as Netbed, is an advanced network testbed, and falls into the class of testbeds known as Multi-user Experimental Facilities, as defined by the NSF Workshop on Network Research Testbeds[17]. Figure 2.1 roughly outlines the major components of the Emulab system. More detailed information about Emulab is available in several conference publications and technical reports, including [9, 10, 24, 25, 26, 27], and others listed on the Emulab web site at www.emulab.net on the Internet.

2.1 Software Architecture

Figure 2.2 depicts Emulab’s software architecture. Actions are initiated by users or testbed administrators, shown at the top of the diagram, through one of Emulab’s user interfaces. The primary interface is the web site, www.emulab.net, where users and administrators can log in to view and change the current state of the Emulab system.

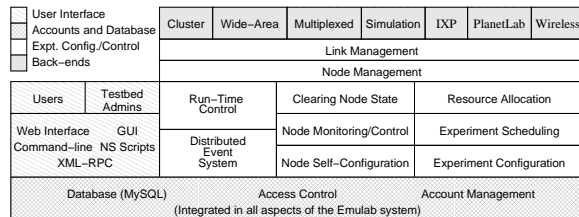


Figure 2.1: Emulab system architecture

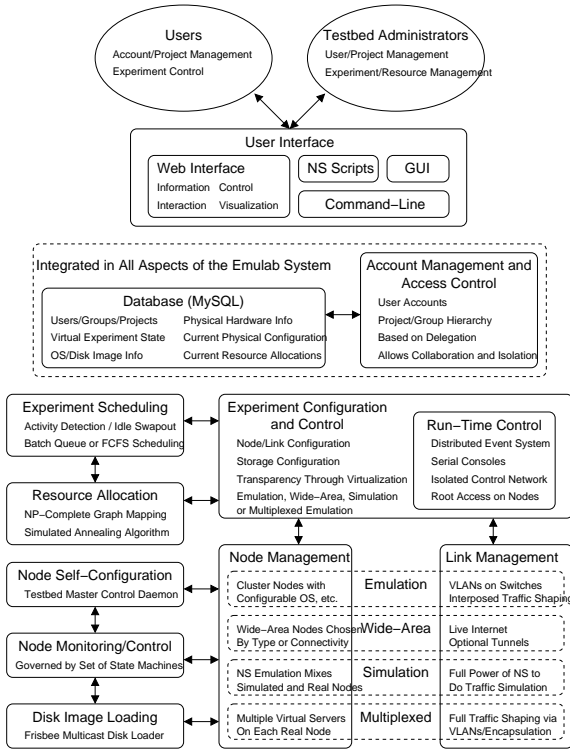


Figure 2.2: Emulab software architecture

on switches and interposed traffic shaping to control latency, bandwidth, and loss rate. The wide-area model uses nodes from around the world as endpoints, and the live internet (and optionally, overlay tunnels) as the links for the experiment's topology. The simulation model runs instances of the *ns* Emulator, *nse*, where simulated nodes and links can interact with the real network and other types of nodes and links. The multiplexed model uses physical nodes as hosts for virtual nodes that are multiplexed onto the physical nodes, and made to appear and behave as near to the behavior of the real physical nodes as possible. Other "back-end" implementations that have recently been added to Emulab are shown in Figure 2.1, including IXP, PlanetLab, and wireless implementations. The IXP[12] model uses Intel's IXP Network Processors as hosts or high-capacity traffic shapers. The PlanetLab implementation refers to Emulab's capability to provide access to nodes in the PlanetLab[18] testbed and use them seamlessly in conjunction with other Emulab nodes. Emulab also now includes nodes with wireless connectivity that can be used in experiments, in addition to the ability to emulate wireless connections with limited precision and accuracy that was previously available.

The node management component also works with three other subsystems that help carry out the various node management tasks.

2.2 Hardware Components

Emulab is composed of a wide variety of hardware components, as shown in Figure 2.3. Central to the architecture are the Emulab servers, *usershost* and *masterhost*. *usershost* serves as the file server for the nodes, one of several serial console servers (not shown), and as an interactive server for Emulab users. *masterhost* is the secure server that runs critical parts of the infrastructure, including the web server and the database server, and securely accesses power controllers and switches.

The network infrastructure for Emulab is composed of a control switch/router that serves as gateway and firewall for Emulab, and a set of switches that form the backbone of the experimental network. The experimental network switches serve as a

Secondary interfaces include *ns* scripts and a Java graphical user interface (GUI) that are used for submitting experiment descriptions, and a command-line interface to many of Emulab's features. There are also various programmatic interfaces and APIs (not shown) that advanced users may choose to use. The user interfaces operate on Emulab's central database, populating it with information provided by the user, and retrieving information requested by the user, as well as dispatching actions the users requests.

At the center of the Emulab software is a relational database. It stores information about nearly every aspect of Emulab's operation. The database is not directly accessible to users, and access to the information it contains is governed by the account management and access control components of the architecture. They limit a user's visibility to those projects, experiments, and features for which access has been granted. This component functions both in an isolation role as well as a collaboration role.

The core components of Emulab's software are closely linked with one another, but can be divided into several large categories. Experiment scheduling determines when an experiment can be instantiated ("swapped in") on physical resources, and when an experiment should be "swapped out". The resource allocation component determines if and how an experiment can be instantiated, given the currently available resources in the system. These two components work together with the experiment configuration and control subsystems, which perform the actual work of setting up the hardware and software in the requested configuration for carrying out the experiment. Various methods for run-time control allow the user to interact with the experiment very flexibly.

During experiment configuration and control, the node management and link management subsystems come into use. They configure the individual nodes and links required for the experiment. These two components operate directly on the hardware with one of several "back-end" implementations, similar to a "device driver" for different implementations of nodes and links. The typical cluster model is emulation, where nodes are physical PC nodes and links are made with VLANs (Virtual LANs)

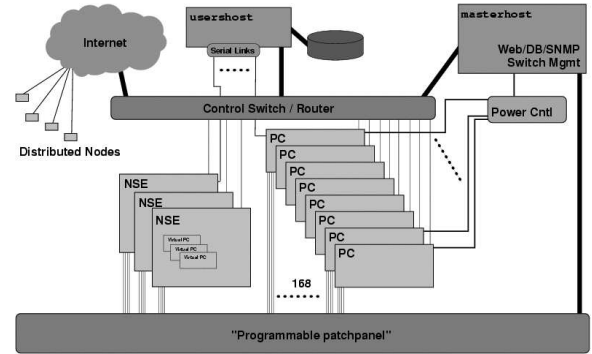


Figure 2.3: Emulab hardware components

"programmable patch panel" to dynamically configure the network connections that users need in order to perform their experiments.

The Emulab cluster is currently composed of 180 cluster PCs (Pentium III-class or better), which are standard rack-mount servers configured with five network cards each. One network interface card in each node connects to the control router, and the other four connect to the experimental network switches. The nodes also are connected to power controllers, to allow remote power cycling for unresponsive nodes, and have serial console access available for kernel debugging and an interaction path separate from the control network. These nodes can serve directly as physical nodes in experiments, or can host a variety of nonphysical node instantiations: "simulated nodes" inside a special instance of the *ns* Network Simulator, multiplexed "virtual nodes"[9] (not shown) implemented via FreeBSD's *jail*[14] or Linux *vservers*[15, 5]. They can also be used to host special hardware devices like IXP Network Processors[12] (not shown) and provide remote access and other tools

for the devices. Emulab also has nodes connected with wireless networking (not shown), which can be allocated to user experiments.

Emulab's control router connects the cluster to the Internet and Internet2[13] and to the Emulab resources available through the wide-area network¹. Emulab provides access to shared machines located around the world that have been dedicated to experimental use. These machines run either FreeBSD or Linux, and can be used in most of the ways that the local cluster nodes can be used. Necessarily there are some differences in security, isolation, sharing, and other aspects. These nodes allow experimenters to use the live Internet to perform measurements or run tests under more realistic conditions than the cluster can offer.

2.3 Central Database

At the core of the Emulab system is a relational database. It brings the full power of relational databases to bear on the information management issues inherent in managing a large-scale multiuser testbed. It also functions as a repository for persistent data, and frequently, as a communication channel between different parts of the system. Some of the key information that is stored in the database is described below.

Users, groups, and projects: Users can be members of groups, and groups belong to projects. Each user may be a member of many groups and projects, and may have a different level of trust in each of those groups. This information is used for access control for data that may be viewed or changed on the web site, and for any other actions the user may wish to perform in Emulab.

“Virtual” experiment state: When a user loads an experiment configuration into Emulab, either from an *ns* file or through our graphical interface, the information needed to configure the experiment is loaded into the database as abstract

¹Sometimes the local Emulab cluster is referred to as “Emulab Classic” or simply “Emulab,” while the entire system including the wide-area resources, simulated nodes, and other features is called “Netbed.” For the purposes of this thesis, Emulab will be used to refer to the entire Emulab/Netbed system as well as the local cluster installation unless otherwise noted.

“virtual” experiment data that is not tied to any particular hardware. It is preserved while an experiment is inactive for use later to reinstantiate the experiment on physical hardware again.

OS/Disk image information: The database also stores information about each operating system and disk image that is used in Emulab, including the owning user, group and project, operating system features, disk image contents, etc. This information is used by Emulab to determine what image to load when a given OS is requested, as well as what features the OS supports that may be used by Emulab in order to monitor or control nodes using the OS.

Physical hardware configuration: In order to configure experiments, all hardware that is being managed by Emulab or is used in its management is stored in the database. This includes information about nodes, switches, power controllers, and every network cable in the testbed cluster.

Current physical configurations and allocations: Emulab uses the database to allocate nodes and other resources to different experiments that may be running at any given time. Experiments are mapped to currently available physical hardware, and experiment-specific configuration information is prepared for use by the system in configuring the nodes. Much of this data is later downloaded by the nodes for use in their self-configuration process.

The database is a critical part for Emulab's operation, and is integrated into almost every aspect of the system. Because so much depends on the integrity of the information it contains, the database is served on Emulab's secure server, **masterhost**, and direct access to it is not permitted to users. All changes that a user makes to information in the database are done indirectly through interfaces, like the web pages, that perform access checks as well as validity checks on all submitted data.

2.4 User Interfaces

Emulab provides a wide variety of interfaces to its functionality to meet the widely varied needs of its users. These interfaces include human-centered as well

as programmatic methods of control that provide different levels of expressive power, flexibility, convenience, and automation to the user or the user's programs and scripts. These interfaces include a web interface, *ns* scripts, a Graphical User Interface (GUI), command line tools, and other programmatic interfaces.

2.4.1 Web Interface

Emulab's web site is the primary place for viewing and changing testbed data and configurations. It is the principal method for interacting with the system for experiment creation and control. It serves as a front end to the database, both for reading and writing. It works hand in hand with the interfaces provided by *ns* scripts and the GUI, and provides visualization tools to experimenters. It also serves as the central repository and communication method for Emulab users and the general public, providing documentation, publications, software downloads, etc.

2.4.2 *ns* Scripts

Specialized scripts written in TCL and based off of the system used by the *ns* Network Simulator[23] serve as a primary method for describing experiment configurations. They may be passed to the Emulab system through the web interface or the command line interface. These scripts describe nodes, links, and their respective configuration information, as well as events that should be automatically carried out at specified times during the experiment. In Emulab, standard *ns* syntax has been extended to provide additional data and functionality, including selection of node hardware types, operating systems, software to be installed, and programs to be executed. A compatibility library is also provided to allow these Emulab *ns* scripts to be used unmodified with the *ns* simulator.

2.4.3 Graphical User Interface (GUI)

Because many users of Emulab do not have a background that includes familiarity with *ns* scripts, we also provide a graphical user interface in the form of a portable java applet that is downloaded and executed through our web interface. It

provides a simple method to draw a topology of nodes and links, then configure their characteristics, without ever needing to write or read any *ns* files.

2.4.4 Command Line

The command line (i.e., Unix shell) is the most popular way to interact with the nodes in Emulab, but is the least popular way to interact with the main body of the testbed software. We have found that the command line is typically used mostly by programs or scripts written by users, and that users usually favor using the web interface for activities other than direct interaction with an individual node. The command line interface is a critical part of the automatability that Emulab provides, allowing users to fully automate their experiments, from creation to termination.

Part of the command line interface consists of a set of command line tools that are available on the nodes themselves. Others are run on one of the Emulab servers (**usershost**) where users are given full shell access. Tools on the nodes include a variety of scripts to gather Emulab-specific node configuration information and to provide runtime control for the experiment. Operations that can be performed on the server include rebooting nodes, changing link parameters, and starting and ending experiments.

2.4.5 Programmatic Interfaces (APIs)

Many of Emulab's systems are designed to be easily accessible programmatically for users who desire a higher level of automation in their experiments, or who need to take advantage of special features we provide. In particular, users can interact directly with the distributed event system Emulab uses for control and communication. Users can also directly access **tmcd** servers hosted on the **masterhost** server, which provides controlled access to certain database constructs and information used for node self-configuration.

2.5 Access Control

Permissions and access control in Emulab are based on the principles of hierarchy and delegation, and there are three primary entities involved in the permission system: Users, Groups, and Projects. A user may sign up for an individual account by providing an email address and some personal information. For security, the email address is verified to belong to the user before the account is activated. These individual accounts provide strong accountability, which is necessary in a system like Emulab, because users are frequently granted elevated privileges, like “root” system administrator access on nodes in the testbed.

A user’s account is not fully active until it has also been approved by a responsible party who knows them personally, who will be in part accountable for their actions on Emulab. This may be an advisor, professor, principal investigator, or senior researcher who has started a project on Emulab which the user applies to join. Qualifying researchers and instructors may apply to create a new project, and are approved directly by Emulab’s approval committee. Project heads are delegated authority to approve users in their project, granting them access to the testbed’s resources. The project head decides what level of trust to place in the user, including levels representing normal Unix user-level access, root-level access on nodes in the project, and root-level node access with administrative privileges within the project. These administrative privileges allow the project head to delegate to that user the ability to approve other users in the project.

By default, each project consists of exactly one group, and all the project members belong to that group. When desired, other groups may be configured within the project that are made up of subsets of the project members. This configuration allows for easy collaboration within a project or group, while allowing for isolation between different projects and between different groups inside a project. This provides a good environment for groups that need to share things, yet still maintain a set of data that is private to a single group within the project. One place where this is particularly useful is a class that is using Emulab, because the instructor can provide a set of resources to the whole class, while grouping students in other groups where

their work is not accessible to other student groups. It also is being used by a DARPA-funded research program to provide sharing and isolation for the different groups funded under the program.

Throughout the Emulab system, including web pages, nodes, and command line tools, access controls are enforced that ensure that only authorized users have access to private information about a project, group, user, or any data belonging to them, including experiment configurations, OS images, and membership information.

2.6 Link Configuration and Control

Emulab’s current cluster hardware includes only 100Mbps LAN links for experimental use. But it can artificially slow down, constrain, or hamper the network connection in a way that lets it accurately and precisely emulate wide-area connections.

When a user specifies a link other than 100Mbps bandwidth with 0ms latency and no fixed packet loss rate, the system determines that the link needs traffic shaping. Normally, this traffic shaping is done by a node that is transparently interposed on the link to do the shaping, using FreeBSD and its Dummynet[19, 20, 21] features. A sample of this interposition is shown in Figure 2.4. Alternatively, Emulab also supports traffic shaping by the end-nodes themselves.²

When using remote wide-area nodes instead of cluster PCs, typically extra link shaping is not desirable. In most cases, researchers want to see the raw characteristics of the live internet path between the nodes they are using. Emulab also optionally provides overlay tunnels between the nodes, using private IP addresses, so to increase the amount of transparency between cluster and wide-area nodes and ease in transitioning between node types.

Using Emulab’s simulation features based on *ns* network emulation, traffic shaping can be controlled using the full power of *ns*. Packets can be subjected to simulated cross-traffic as they pass through the simulated network, and the different statistical

²Currently end-node traffic shaping is supported only on FreeBSD nodes, using a kernel with Dummynet support. Support for Linux is being developed.

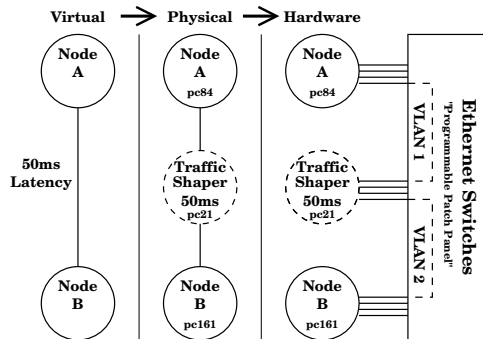


Figure 2.4: A link with traffic shaping

models that are available in *nscan* be used for traffic shaping. Packets can also be routed through large networks simulated in *ns* by a single PC without using a physical PC to emulate every node in the network.

Emulab’s support for multiplexed “virtual” nodes uses end-node shaping techniques in combination with the node multiplexing, by doing traffic shaping on the physical host node for links to or from any “virtual” nodes being hosted on that PC.

CHAPTER 3

ISSUES, CHALLENGES, AND AN APPROACH

Four challenges in Emulab are primarily relevant to this thesis:

- Reliability
- Scalability
- Performance and Efficiency
- Generality and Portability

In addition to directly affecting usability of the testbed, reliability has an important role in determining how scalable the system is, how well it performs, and how efficiently it uses its available resources. Generality and portability place constraints on the methods that can be used to solve these problems. This thesis deals with one method used in Emulab to address these issues, namely, the use of state machines.

3.1 Reliability

As complexity of a system increases, the reliability of the system generally decreases, due in part to increased likelihood that at least one component of the complex system will have problems. Because they are complex devices, personal computers (PCs) inherit this unreliability. The vast array of hardware and software components, many of which are themselves very complex, fail from time to time, and often in ways that are unpredictable, and not infrequently, unpreventable.

In an advanced network testbed, there are many opportunities for things to fail, decreasing the testbed’s reliability. In the case of a cluster of PCs, these factors

include a variety of hardware, software, and network problems. In a cluster, the local-area network (LAN) is usually quite reliable, but like any network, does not operate perfectly. Many network failures are transient, and can be resolved by retransmission. The PC nodes in the cluster are typically a more common source of reliability problems, many of which have a corresponding automatable recovery process. Information stored on a hard drive may become corrupt, or get changed or erased. Through automatic disk loading procedures, this can be remedied by recopying a disk image onto the node. A node that hangs and becomes unresponsive can be power cycled using remote power control hardware. Some recovery steps require manual intervention, such as the repairs required to replace bad hardware.

In the case of remote nodes that are connected to the testbed via the Internet or other wide-area networks, the situation is more complicated. The network can be a frequent source of problems, effectively disconnecting nodes from the server, and making communication with any other devices at the same location impossible. The nodes themselves are also at least as unreliable as nodes in a cluster would be, and often suffer from more frequent software problems due to the increased difficulty of reloading the hard drive of a remote node. Many remote nodes also have fewer recovery capabilities than the cluster nodes, for instance, they may lack power control hardware and serial consoles. Automated recovery for short network outages can be accomplished through retries. Long outages can be worked around by using a different node instead of the one that is unavailable. Far fewer options are available for recovery from nodes that are hung or cannot be reloaded with new software in the remote case, and bad hardware always requires human intervention.

Human error is also a significant source of reliability problems. Testbed developers make mistakes, and anything that can make them more successful in designing, developing, and debugging the system improves the overall reliability of the system. Users can be an even greater source of problems. Whenever there is anything that a user can do that could cause problems for the system, someone will inevitably find a way to do it. The system can limit user-induced errors by improving monitoring and access control.

Indirectly, however, the testbed has much more stringent requirements on its performance and efficiency. The requirement that the testbed scale well places high demands on the different parts of the testbed system. Together the performance and efficiency of the system determine in large part the practical limit on Emulab's scalability, and on the maximum useful utilization of resources that can be achieved. As the testbed has higher and higher demands placed on its resources and becomes increasingly busy, the time that elapses between one user giving up a resource and another user being able to acquire and use it becomes very important.

3.4 Generality and Portability

Another goal of Emulab is that it be general enough to be used for a very wide variety of research, teaching, development, and testing activities, as well as being useful and portable in a wide variety of cluster configurations. Everything we do must be designed to work as well as possible in as many different node and testbed configurations as possible, including node hardware and operating systems as well as clustered, nonclustered, and wireless node connectivity.

An important aspect of generality is workload generality, namely that the design or implementation of the system should place as few limitations or constraints as possible on the experiment workload that the testbed can support. This helps ensure that the testbed is as generally applicable as possible, and allows for the widest range of uses. A good indicator of generality in the case of Emulab has been the things that Emulab is used for that were unforeseen by the testbed's design team. There is an important tradeoff between generality and optimization, and often the priorities involved can change over time.

In particular, Emulab must be able to support, at least minimally, a poorly instrumented or uninstrumented system. For example, a custom operating system image that was made by a user, which we cannot change or enhance, may not have any support for being used inside of Emulab, such as sending hints to the server regarding state transitions. The testbed must be able to gracefully handle this situation, even

Another principle that affects reliability is the observation that as the number of unreliable systems increases, the more likely it is that at least one of those systems will be in a failure mode at any given time. As a testbed increases in scale, it tends to become less reliable overall, which increases to the point where the majority of the time, some part of the system is broken.

3.2 Scalability

Almost everything the testbed provides is harder to provide at a larger scale. Supporting a larger testbed and more nodes requires more bandwidth from the network, more horsepower on the servers, and so forth. As scale increases, the level of concurrency between different events increases. In order to maintain the same level of service, throughput must be increased. Time to completion of any action on the entire testbed will go up if our capacity to perform that action is not correspondingly increased. Either the testbed needs to do things faster, or everything will happen slower as scale increases.

Because of the increased load on the network, servers, and services as the testbed grows, reliability is adversely affected. Higher loads are much more likely to cause congestion or overload conditions in the various parts of the system, causing more frequent failures. In our experience with Emulab and its scaling limits, we have also seen larger scales and higher loads lead to failures of a different nature than was previously observed.

3.3 Performance and Efficiency

One of the primary usage models for Emulab calls for users to be able to use the testbed in a very interactive style, starting experiment configuration tasks, then waiting briefly for the testbed to do its work. This means that configuration of experiments, changes to configurations, etc., all must happen in a timeframe on the order of a few minutes or less. This is the only direct performance requirement that is placed on our testbed design.

though the functionality the OS can provide may not be the same as an OS image that has been customized for use within Emulab.

Any special support that Emulab provides or requires on nodes should be easy to port to other operating systems, so that as many systems as possible can take full advantage of the benefits the testbed provides. The Emulab-specific software for the nodes must also be unobtrusive, so that it does not interfere with any experiments that users may want to perform on the testbed.

3.5 State Machines in Emulab

In Emulab, one method used to address these issues and challenges is the use of state machines, also known as finite state machines (FSMs) or finite state automata (FSAs).¹ A state machine (as applied in Emulab) consists of a finite set of states and a set of transitions (or edges) between those states[11]. State machines can be graphically represented as directed graphs called state transition diagrams. States in a machine are identified by their unique label, and transitions are identified by their endpoints. Transitions are also often associated with a particular event or action that happens when the transition is taken. The associated event or action may be either a cause or an effect of the transition.

An illustration² of a state machine is shown in Figure 3.1. In this example, entities start in the NEW state, then must be verified and approved to enter the READY state. After becoming ready, they may be locked, unlocked, frozen and thawed to move between the FROZEN and LOCKED states. In the case that they need to be reappraised or reverified, they may reenter the UNAPPROVED, UNVERIFIED or NEW states.

¹A variety of other terms also apply to various types of state machines, including Deterministic Finite Automata (DFAs), Non-Deterministic Finite Automata (NFAs). Abbreviations like FSA, DFA, and NFA are also used to refer to a single finite automaton.

²Throughout this thesis the following convention is used for state machine diagrams: States are shown as ellipses, and are labeled with the state name. Transitions or edges are shown as directional arrows between states, and are labeled with the event that is associated with that transition. The majority of the state machine diagrams shown throughout this thesis are generated automatically from their descriptions in Emulab's database, and they are shown without any manual retouching.

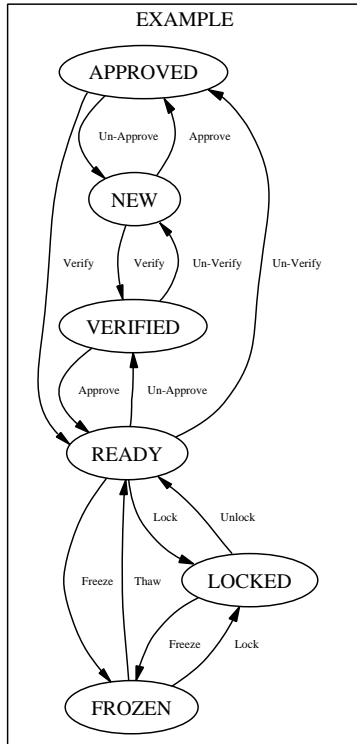


Figure 3.1: A simple state machine, or state transition diagram.

3.5.1 Why State Machines?

There are several qualities of state machines that make them a very appropriate solution to the problems they address in Emulab. First, they are an explicit model of processes occurring in the testbed. Second, the finite state automata approach is well known and easy to understand and visualize. Third, state machines provide a powerful and flexible approach that can accommodate many implementation styles, including event-driven, process-driven, or state-based components.

An explicit model of testbed processes is valuable to the testbed system both in terms of reliability and in terms of software engineering. The explicit model that a state machine defines contributes to redundancy and allows for runtime checking to ensure correct operation or detect errors. A state machine also provides a degree of formality that allows software developers to reason about the software, and eventually, could aid in using formal verification methods to check or prove aspects of the testbed system.

Finite state automata are an important part of computation theory, and can be classified as part of the core knowledge every computer scientist should have. There are a wide variety of tools in existence for dealing with and reasoning about state machines, and the approach is conceptually simple, easy to understand, and readily visualized using very simple state machine diagrams. In Emulab, these features have helped lead us to software design patterns that emulate the simplicity of the state machines. The state machine abstraction also contributes to improved portability for the code and abstractions used in the testbed system.

The state machine approach is also very powerful and flexible in terms of the implementations it can accommodate. One part of Emulab uses state machines in an event-driven approach, where a central event handler uses the state and an incoming event to choose the right state transition and perform any associated actions. Another part of Emulab uses a process driven approach to move through a series of states in a state machine as part of a process that includes more than one state transition.

CHAPTER 4

STATE MACHINES IN EMULAB

This chapter discusses the uses and implementations of state machines in Emulab. The rationale for state machines and the problems they help address are discussed in Section 3.5. First we describe the representation we use for our state machines, followed by a description of state machine interactions, including direct and indirect interaction. The two models of control, centralized and distributed, are also discussed in detail. This chapter concludes with a description of `stated`, the state daemon Emulab uses for centralized monitoring and control of the node boot state machines.

4.1 State Machine Representation

Conceptually, state machines are directed graphs, with nodes in the graph representing states, and unidirectional edges representing transitions from one state into another. In the purest sense, this directed graph is all that is required for a state machine; however, within Emulab, some additional conventions are used. Each state machine is labeled with a name, and each state in a machine is given a unique identifier as the name of the state. Transitions are identified primarily by their two end points, as no two transitions may have the same endpoints in the same order, and optionally have a label that describes the event associated with it by being either the cause or the effect of the transition.

While many processes are typically described using a single state machine, our use of state machines allows for multiple state machines that govern the same entity, and for transitions¹ between the different machines. We have added to this the

concept that state machines have an inherent type (e.g., node boot), and within that type, are mutually exclusive, meaning that an entity (e.g., a node) is in one state in exactly one machine of a given type at any time. The different state machines within a type are also called “modes,” and moving from a state in one machine into a state in another machine is called a “mode transition,” as opposed to normal “state transitions” between two states in the same machine.

While the state machines within a mode could be expressed by a single, large, state machine, using an abstraction that breaks the system down into smaller state machines can make it easier to understand, and can improve our ability to take advantage of similarities between the different machines. Examples of a set of small state machines and their equivalent representation as a single machine are shown, respectively, in Figure 4.1 and Figure 4.2.

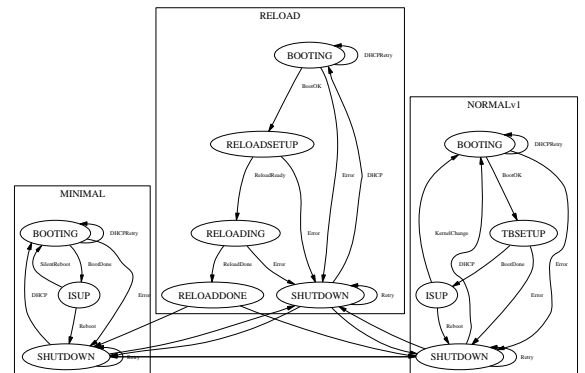


Figure 4.1: Interactions among three state machines

¹This method is somewhat related to “scenarios” commonly used with Message Sequence Charts, as described in Section 8.2.

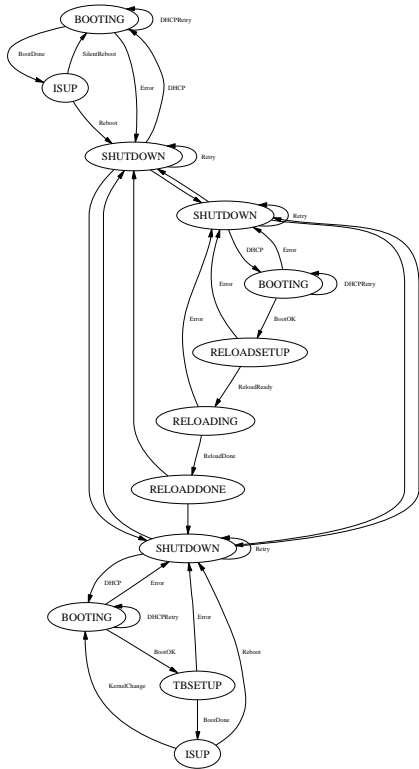


Figure 4.2: Three state machines viewed as one larger machine

In the Emulab database, a state machine is represented as a list of transitions. Each transition is a tuple of mode, initial state, final state, and the label for the transition. Transitions between states in different machines (“mode transitions”) are similar, but include both a mode for the initial state and a mode for the final state. Each state may also have a state timeout entry, which lists mode, state, timeout (an integer representing seconds), and a string describing the list of actions to be performed when a timeout occurs (e.g., requesting a notification or a node reboot). Trigger entries consist of node ID, mode, state, and a string describing the trigger actions. Entries may be inserted dynamically for specific nodes. Static entries in the trigger list typically specify the “wildcard” node ID, indicating that the trigger should be executed any time a node reaches that state.

An example of the notation for representing state machines on paper has been shown and explained in Figure 3.1. The notation for transitions between modes is shown in Figure 4.1.

4.2 How State Machines Interact

As described earlier, state machines in Emulab have an inherent type, and there are currently three types of machines in the system. The first type are node boot state machines, which describe the process that a node follows as it cycles between rebooting and being ready for use, and there are several machines of this type. The second type consists of the node allocation state machine, which manages nodes as they cycle through being allocated, deallocated, and prepared for use in an experiment. The third type is composed of the experiment state machine, that describes the life-cycle experiments follow as they are created, swapped in or out, modified, or terminated.

Two types of interactions occur between state machines, namely direct and indirect. Direct interaction can only occur between machines of the same type, and is used with the node boot state machines. Indirect interaction occurs between machines of different types, due to the relationships among the entities traversing the different

Another aspect of state machines as implemented in Emulab is that states may have a “timeout”² associated with them. This timeout establishes a length of time during which it is acceptable to remain in that state. If an entity remains in the state beyond the time limit, a timeout occurs, and the configured “timeout action” is taken. This is typically used for error reporting and recovery.

We also allow actions to be attached to states, such that when an entity enters that state, the configured action, if any, is performed for that entity. These state actions are called “triggers” because of the way they are triggered by entry into the state.³ They provide a modular and extensible way to attach special functionality to certain states. In practice they are often used for maintaining certain invariants or performing tasks related to a particular state. They are especially useful when an action is associated with a state without being associated to any particular transition into the state. For instance, every time a node finishes its boot cycle, some unique tasks must be performed, without regard to how it arrived in that state. These triggers provide a hook for such tasks that do not depend unnecessarily on how the transition was caused, and can be easily reused for multiple states, and for states in other modes.

Generally, triggers are set on a per-state basis and are meant to be used with all nodes that arrive in that state, but triggers can also be set for specific nodes. This is used, for example, to delay actions until a particular state transition has occurred, even though the decision to carry out that action was made in an earlier state. As an example, triggers are used when nodes finish reloading their hard drives to cause the node to be placed into the free pool the next time it finishes booting. They are also used to provide special handling to determine when a node has booted, for a nodes using OS images that do not send a notification event.

²Others have defined “timed automata,” which are state machines that have the concept of a global clock that advances as they execute. They are further described in Section 8.1.1.

³Similar functionality is also defined for UML Statecharts, where triggers are called “entry actions.” This is described further in Section 8.3.

machines, and the states of each of the entities in the machines. These interactions occur between all three types of state machines in Emulab.

4.2.1 Direct Interaction

Machines of the same type interact with each directly, because an entity (i.e. a node) can follow a transition from a state in one machine to a state in another machine. Using separate state machines better preserves the simplicity of and symmetry between the individual state machines, while still retaining all the power that could be provided by modeling the set of machines as a single, larger state machine. Figure 4.1 and Figure 4.2 show the same set of states and transitions, both as three separate machines and as a single larger machine, respectively.

This method of changing state machines (also known as “modes”) is used frequently with the node boot state machines. Different operating systems or OS image versions may follow different patterns during their boot process, making it necessary to have a state machine that describes the proper operation of that boot process. When a node changes which operating system or disk image it is running, it may need to change to a different state machine to match the new OS.

For example, whenever a node reloads its hard drive with a new image, it reboots into a special disk reloading operating system image that is loaded over the network. This OS image follows a specialized sequence of boot state transitions and must use a different state machine. When the reloading finishes and the node reboots, the node changes state machines again to match the new operating system image that it will run.

4.2.2 Indirect Interaction

Indirect interactions occur among state machines of different types, due primarily to the relationships between the entities that each type of machine is tracking. The same entity always has exactly one state in machines of a given type at any time, but the same entity can have a place in multiple types of state machines at once. For instance, there are two types of state machines that deal with nodes as their entity:

the node boot state machines, and the node allocation state machine. Every node is in a state in a node boot state machine at the same time that the node also has a state in the node allocation state machine. Other relationships between entities cause indirect interaction as well, like the ownership or allocation relation that exists between an experiment and the nodes that have currently been assigned to it.

In general, transitions occur independently in each of the different state machines, but there are often correlations between transitions in different machines. For example, a node in the FREE_CLEAN state in the node allocation⁴ state machine should always be in the ISUP state in a node boot state machine. When it moves from the FREE_CLEAN state into the RES_INIT_CLEAN state, and then into either the RELOAD_TO_DIRTY state or the RES_CLEAN_REBOOT state, it moves into the SHUTDOWN state, and proceeds to cycle through its node boot machine. The node changes state from RES_WAIT_DIRTY or RES_WAIT_CLEAN to RES_READY when it moves into the ISUP state in its node boot machine. When all the nodes in an experiment move to ISUP in the boot machine and RES_READY in the allocation machine, the experiment moves from ACTIVATING to ACTIVE in the experiment⁵ state machine. Once the experiment is active, the nodes remain in RES_READY, but may cycle many times through any of the node boot machines while the experiment is active.

4.3 Models of State Machine Control

Emulab uses two different models for controlling and managing state machines. The node boot state machines use a model of centralized control. A distributed control model is used for the node allocation and experiment status state machines. Each model has different benefits in reliability and robustness, as well as software engineering considerations.

⁴A diagram of the node allocation state machine is found in Section 6.2.

⁵A diagram of the experiment state machine is found in Section 6.1.

excellent way to monitor and react to state changes in a uniform fashion. It also provides a continuously running service that can easily watch for timeouts and other control events to occur. The central model is also easier to implement and maintain than the distributed model. Because every state transition must pass through the central server, it can use caching to improve performance, and primarily needs to access the database to write changes in the data. It also is better suited to an interrupt-driven style than a distributed model. However, centralized systems have the potential and sometimes tendency to become a bottleneck that hampers the performance of the system. It is not a currently a bottleneck in our system, but the potential is still there. The reliance on a central server also can have a significant effect on the overall reliability of the system, since it cannot function properly when the service is unavailable.

4.3.2 Distributed

The other model of state machine management in use in Emulab is the distributed model, where all the parts of the system that cause transitions in a state machine each take responsibility for part of the management burden. The experiment status and node allocation state machines use the distributed model. Every script or program that wants to check or change the state of an entity directly accesses the database to do so, and performs error checking and validation whenever changes are to be made.

The distributed model does not require a central state management service, which eliminates that service as a source of bottlenecks⁷ in the system. This contributes to better robustness and reliability by not having a dependence on a central state service or the publish/subscribe event distribution system, but also lacks an easy way to watch for timeouts. Each program or script may gain a relatively broad view of the state of all entities, but must do so in a more complex way, and cannot take advantage of the same caching that is possible in a centralized system. Because

⁷The database server can still become a source of bottlenecks, since every user of the data relies on it. However, solutions exist for configuring distributed database servers and otherwise sufficiently enhancing the performance of the database server to address this issue.

4.3.1 Centralized

The node boot state machines are controlled centrally by a state service running on the masterhost Emulab server. This state service is implemented as a daemon server called `stated`⁶ and is discussed further in Section 4.4. In the centralized model, state changes are sent to a central server, where the proposed change is checked against the state machine for validity, and saved in the database. These notifications are sent using a publish/subscribe, content-routed, distributed event system. Any invalid transitions cause a notification email to be sent to testbed administrators. Invalid transitions typically indicate an error in testbed software, or a problem with a node's hardware or software. Some errors may be transient, but their patterns and frequency can indicate problems that would otherwise go undetected.

The central service also handles any timeouts that may be configured for a particular state. For example, if a node stays in a particular state too long, a timeout occurs, indicating that something has gone wrong, and the service performs the configured action to resolve the situation. In addition to timeouts, actions can also be associated with transitions, and a configured action, or "trigger" can be taken when arriving in a state. Some commonly configured actions include rebooting a node, sending an email notification to an administrator, or initiating another state transition.

Various programs and scripts that are part of the Emulab software also watch for these state change events as they are being sent to the server. For instance, a program may need to wait until a node has successfully booted and is ready for use, and it can do this by requesting to receive any events pertaining to the state of a particular node.

The centralized model for state machine management has many of the same benefits that are typical of centralized systems, as well as similar drawbacks. There is a single program that has a full view of the current state of every entity it manages, and the completeness of this knowledge allows it to take more factors into consideration in its decisions that would otherwise be possible. It also provides an

⁶The word `stated` is pronounced like "state-dee," not like the word "stated," which is the past tense of the verb in "to state."

changes may come from many different sources, it becomes necessary to use polling to discover changes, which can be problematic at high frequencies when low-latency notification of changes is necessary. It also means that programs must use locking and synchronization with other writers of the data to have the necessary atomicity in their interactions with the data. The distribution of the management burden across many scripts and programs also complicates the software engineering process, although some of this can be alleviated through the use of a software library call to reuse code. Portability also can cause difficulties, since many of the state management actions may need to be performed from scripts and programs written in different languages, which limits code sharing and reuse, and further adds to the software maintenance difficulties, since the code must be written and maintained in multiple languages.

4.4 Emulab's State Daemon

Emulab uses a central state management daemon for controlling the state machines that use the centralized model of management. This daemon is implemented in `stated`, and runs on `masterhost` at all times. The primary architecture of `stated` follows an event-driven model, where the events may be state transitions, state timeouts, or signals sent to the daemon. At the core of the program is a main loop that continuously alternates between waiting for and processing events. It has been optimized to use a blocking poll whenever possible, and uses a priority queue of upcoming internal events in order to "wake up" as infrequently as possible.

Internally, `stated` uses a cache of state information stored in the database to optimize performance. As the only writer of the state data in the database, cache invalidations are unnecessary, and the data very rarely needs to be read from the database instead of from the cache. It does, however, accept a signal in order to force a reload of the cached data from the database, which can be used when state information is inserted manually into the database by administrators.

The state daemon's event-driven nature helps to make its modular design very natural. Each different kind of event that `stated` handles may have a section of specialized code to handle the event, if necessary, and it is simple to add new func-

tionality to the daemon due to this design. It contributes to a good balance between database configuration and control for the state machines and special functionality inside the daemon that must be added and maintained as new kinds of events are created.

CHAPTER 5

NODE CONFIGURATION PROCESS

In this chapter we discuss in detail the process by which nodes in Emulab boot and self-configure, and the role of state machines in this process. The node reloading process is discussed in further detail, as an example of a complex process that is modeled and controlled by state machines.

5.1 Node Self-Configuration

Emulab's node self-configuration process has several benefits over server-driven node configuration. First, because the process is driven by the node, the server doesn't need to keep any extra per-node state while the node is booting. This allows requests from nodes to be served by stateless multithreaded server that gathers the requested information from the database. The node-driven model also contributes to a simple recovery procedure, where nodes can simply be rebooted if they fail. Because node hard drives have no persistent state, disks can also be reloaded as a recovery step. This model is also highly parallel, and contributes to good scalability as the number of nodes booting at once increases.

When nodes begin to boot, they communicate with `masterhost` using PXE, DHCP, and Emulab-specific services to find out what they should do. The answer may be to load a specific kernel or boot image over the network, or to boot from a certain partition on the hard disk. In the case of failure, the default is to boot from a small partition on the disk that causes the node to reboot, forcing a retry of the failed communications with the server. One application of a network loadable boot image is for use with Frisbee[10] to load the hard drive on the node with a disk image.

The normal case is to boot from a partition on the hard drive. In most cases, the partition contains a disk image that has been customized for use in Emulab, although

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it may be a non-Emulab "custom" OS image that a user has created. Images with Emulab support have hooks in the node boot sequence to perform self-configuration operations. These include configuration of home directories, user accounts, network interfaces, experiment-specific host names, routing, traffic generators, RPM or tar packages, user programs that should be run on startup, traffic shaping, temperature and activity monitors, and notifying the `masterhost` server that the node has finished booting.

5.2 The Node Boot Process

Figure 5.1 shows the typical boot cycle for OS images that have been customized for Emulab support. In a normal situation, when a node starts rebooting, it tran-

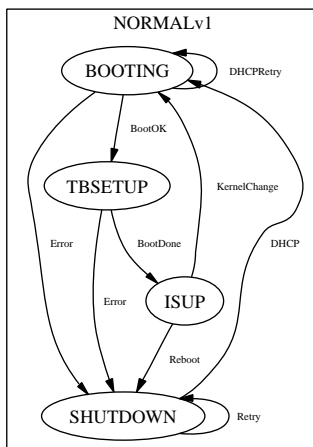


Figure 5.1: The typical node boot state machine

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sitions to SHUTDOWN. When it contacts `masterhost` for its DHCP information, it enters the BOOTING state. When Emulab-specific node configuration begins, it moves to TBSETUP. When setup is complete, and the node is ready, it moves to the ISUP state. A failure at any point causes a transition to the SHUTDOWN state again, and booting is retried a small number of times. Note that it is also acceptable for multiple consecutive SHUTDOWN states to be issued. In certain cases it is impossible to make sure that exactly one SHUTDOWN is sent, so the semantics Emulab has chosen to use are that at least one SHUTDOWN must be sent, even though it means that at times two copies may be sent.

There are several ways that a SHUTDOWN transition may be taken. In Emulab images, a transition is sent when a reboot is started (i.e., with the `shutdown` or `reboot` commands). Reboots initiated by Emulab or from the Emulab servers try several methods to reboot the node, and in cases that indicate that the node was unable to send the transition, the transition is sent from the server. If the node reboots without going down cleanly, an invalid transition is detected, notifying testbed administrators that there may be a problem with the hardware or software.

5.2.1 Variations of the Node Boot Process

Different types of nodes, nodes in other roles, and nodes running different OS images often use state machines that are slightly different than the typical node boot state machine. Nodes that are part of the wide-area testbed use one state machine, while "virtual" nodes being multiplexed on physical nodes in the cluster use a different variation. And custom OS images that have reduced Emulab support use a minimal state machine that requires no OS support at all.

The wide-area state machine is shown in Figure 5.2. This state machine is one of the most flexible and permissive, because of the difficulties that arise in managing a diverse and physically distributed set of nodes. Because disks cannot be reloaded as easily in the wide-area, it is not uncommon for a variety of different versions of standard wide-area OS image to be running at any given time on different physical nodes. In some versions, the SHUTDOWN state was known as the REBOOTING

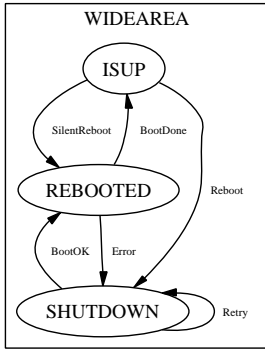


Figure 5.2: WIDEAREA state machine

state, thus the REBOOTING state has all the same transitions as the SHUTDOWN state. Some versions do not use the BOOTING state, so it is acceptable to go from SHUTDOWN directly to the REBOOTED state (the wide-area equivalent of TBSETUP). It is also acceptable to move from ISUP directly to REBOOTED, because at times it is impossible to guarantee that the SHUTDOWN state will be properly sent due to the different software versions on the nodes. The transition from ISUP directly to BOOTING, however, is not allowed.

The “minimal” state machine is shown in Figure 5.3. This state machine is used for OS images that have reduced Emulab support, and may not be capable of giving feedback to the system about their state transitions. This machine does not require any support at all from the node, and adapts to the node’s capabilities to ensure proper operation.

A SHUTDOWN event is sent from the server on any reboot requested from one of the Emulab servers. In MINIMAL mode, a node is permitted to reboot without sending any state change, so a node may also go directly to BOOTING.

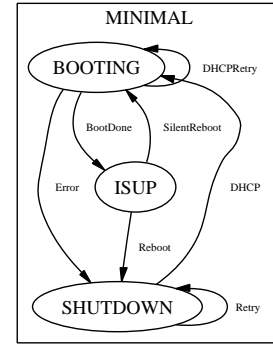


Figure 5.3: MINIMAL state machine

The BOOTING state is generated from the server when the nodes boot, without regard to what OS they will boot.

The ISUP state can be generated in one of three ways. First, an OS or image may have support for sending the ISUP event itself. Second, an OS that does not support ISUP may support ICMP ECHO requests (i.e., ping), in which case the server will generate an ISUP after the BOOTING state as soon as the node responds to an echo request. Third, a node that does not support any of the above will have an ISUP generated immediately following the BOOTING state. This allows a minimal set of invariants to be maintained for every OS that may be used in Emulab, providing best-effort support for OS images that are not completely Emulab-supported.

The PCVM state machine is shown in Figure 5.4. The PCVM machine’s variation is in the TBSETUP state. Because “virtual nodes” do not use DHCP, the BOOTING event must be sent from the virtual node at the point where Emulab-specific setup begins. This is normally the point where TBSETUP would be sent. To eliminate the redundancy, transitions are allowed directly from BOOTING to ISUP. However, when

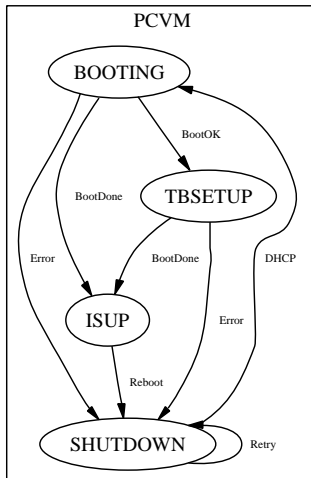


Figure 5.4: PCVM state machine

substantial actions occur between the beginning of Emulab-specific configuration and the time when TBSETUP would normally begin, the TBSETUP state can be included for better indications of progress from the node.

The ALWAYSUP state machine is shown in Figure 5.5. The ALWAYSUP machine is used for special nodes that do not have a booting sequence, but instead are simply always ready for use. For consistency with other nodes, a SHUTDOWN state is allowed. Any time a SHUTDOWN is received by the server, the ISUP state is sent immediately. This allows the Emulab software to treat the node normally, as if it went down, rebooted, and came back up, without requiring special handling.

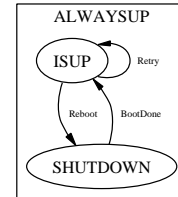


Figure 5.5: ALWAYSUP state machine

5.3 The Node Reloading Process

The node reloading process is depicted in Figure 5.6. The process typically starts out with the node node in the ISUP state in one of the node boot state machines. A user, or the Emulab system itself, then requests a reload of the node’s disk. On **masterhost**, the preparations are made for the reload, then a reboot is initiated, sending the node to SHUTDOWN. When the node arrives at SHUTDOWN, the centralized state service on **masterhost** makes a check is made for a possible transition between state machines. In this case, it is detected that a change to the reload state machine was requested, and the configured entry point to the reload state machine from the SHUTDOWN state of the current machine is the SHUTDOWN state of the reload machine, and the transition occurs between the two states, moving from one state machine into the other.

As the node starts to boot in the reload state machine, the normal BOOTING transition occurs. When reloading, a small OS image is loaded over the network, which performs a different set of self-configuration instructions. In particular, when it arrives at the self-configuration portion of the booting process, the node sends the RELOADSETUP state. Then it attempts to connect to the Frisbee[10] disk image server, running on **masterhost**. When the connection is made and the reload is started, the node sends the RELOADING state. The disk image is downloaded as it is uncompressed and written to the hard disk. When the node finishes, it sends the

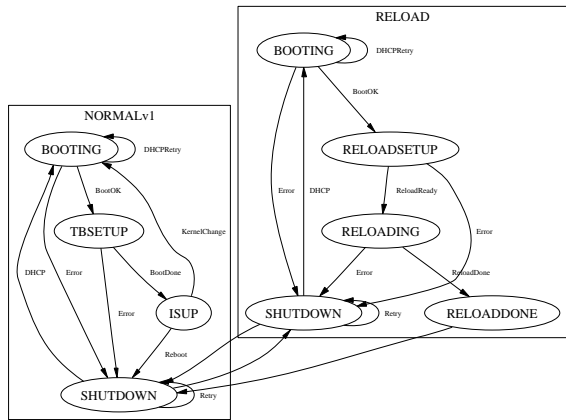


Figure 5.6: The node reloading process

RELOADDONE state, and reboots. At this point, the state service on masterhost finds that another mode transition has been requested, and a transition is made from RELOADDONE in the reload state machine into the SHUTDOWN state of the machine that the newly-installed OS uses. The node then continues to boot normally from the newly installed disk image.

One important use of the reloading state machine is to prevent a certain condition that can easily cause nodes to fail unnecessarily. At one time, nodes reloaded after being used in an experiment were released into the free pool as soon as the RELOADDONE state was reached. This allowed users to allocate those nodes almost immediately, while the operating system on the disk (typically Linux) was booting. During the boot process, the node becomes unreachable by normal means (i.e. ssh and ping), and Emulab detects that a forced power cycle will be necessary to cause

the node to reboot. When power was turned off during the Linux boot process, it left the file systems on the disk in an inconsistent and unusable situation, causing the node to fail to boot. This node failure can be resolved only by reloading the disk again. When this race condition was discovered, the state machines were used to ensure that nodes in the free pool were in the ISUP state, and that only nodes in the ISUP state could be allocated to experiments. This has reduced time to swap in an experiment, since it prevents failures that cause long delays in experiment setup, and has also decreased wear on the nodes, since they typically only get reloaded once between experiments, instead of twice or more whenever this failure occurred.

CHAPTER 6

EXPERIMENT CONFIGURATION PROCESS

This chapter discusses two other types of state machines used in Emulab’s framework, namely experiment status machines and node allocation state machines. Unlike the node boot state machines, these state machines use distributed control rather than centralized, and there is only a single machine for each of these two classes. The experiment status machine is used to monitor and control experiment swapin, swapout, and other operations, and provide access control when operations are requested by a user. The node allocation state machine is used as nodes are allocated to experiments, possibly reloaded with new disk images, and booted with the proper self-configuration information, as participants in an experiment.

6.1 Experiment Status State Machine

The experiment status state machine is shown in Figure 6.1. This machine is used to manage the different states of an experiment as it moves through its life-cycle. Experiments start in the NEW state when they are initially recorded. They move into the PRERUN state while they are being processed, then end up in the SWAPPED state, or in the QUEUED state if it is a “batch” experiment. At this point, all the information is present in the database to be able to initiate a swapin to instantiate the experiment on hardware.

When swapin begins on a swapped or queued batch experiment, it moves to the ACTIVATING state while nodes are allocated and configured, and other experiment setup activities are performed. Then it moves into the ACTIVE state. In case of a failure, it may move back to the SWAPPED state. When an active experiment is swapped out, it moves to the SWAPPING state, then the SWAPPED state as swapout

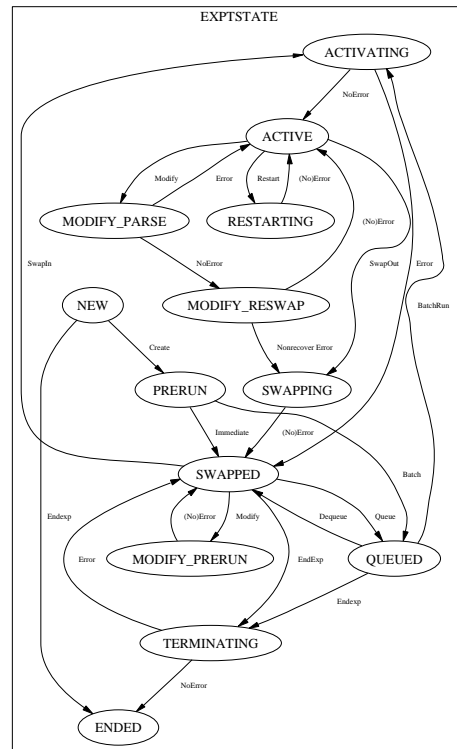


Figure 6.1: Experiment status state machine

finishes. A swapped experiment may be swapped in again, or may be terminated, causing it to pass through TERMINATING to ENDED, where the experiment is deleted.

There are also other actions that can be performed on experiments in some cases. Experiments may be moved between QUEUED and SWAPPED, as they are taken in and out of the batch queue by the user. Experiments may be “modified” while they are swapped or active, passing through either the MODIFY_PRERUN state, or the MODIFY_PARSE and MODIFY_RESWAP states. Active experiments can also be restarted, resetting the experiment as if it was just swapped in, which puts it temporarily in the RESTARTING state.

The variety of different states that experiments help control actions that can be performed on an experiment. There are only three states where experiments may remain indefinitely, namely SWAPPED, QUEUED, and ACTIVE. All the other states are transitional, and the experiment remains in those states for a relatively short amount of time. Actions like swapin, swapout, modify, enqueue, dequeue, or terminate cannot be requested when an experiment is in transition. By having separate states for transitions between stable states, permission checks are greatly simplified.

The experiment status state machine is managed through a distributed process, as described in Section 4.3.2, instead of a centralized server, like the node boot state machines. Each part of the system that performs an action on an experiment checks its state to verify validity of a requested action before carrying it out, and records any state transition as necessary. There is no provision for timeouts or triggers in this machine, and there are no other state machines or “modes” for the experiment status state machine.

6.2 Node Allocation State Machine

The node allocation state machine is shown in Figure 6.2. This machine is used to track the progress of a node as it progresses through the allocation/deallocation cycle that occurs with each node as it is moved into and out of experiments. Unlike

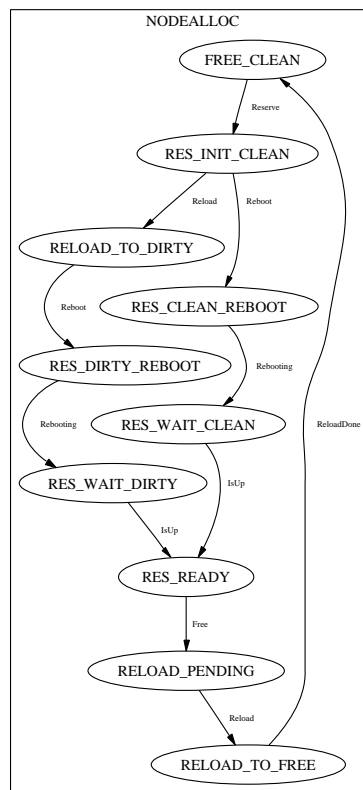


Figure 6.2: Node allocation state machine

the node boot state machines, a node’s state in this machine is not mutually exclusive of a state in a node boot state machine. Nodes always have a state in each class of state machine.

A node that is currently allocated to an active experiment is in the RES.READY¹ state. When it is deallocated, it moves to the RELOAD.PENDING state, then as it begins reloading, it moves to RELOAD.TO.FREE, and then FREE.CLEAN when the reload is complete.

The node then waits in the FREE.CLEAN state until it is reserved, where it moves to RES.INIT.CLEAN. If the user has chosen one of operating systems included in Emulab’s default disk image, the node is rebooted and moved to the RES.CLEAN.REBOOT state. If they have chosen a different OS, the node moves into RELOAD.TO.DIRTY as it gets reloaded with the right image, and then to RES.DIRTY.REBOOT as it boots. When the node finishes booting, it moves from the RES.CLEAN.REBOOT state to the RES.WAIT.CLEAN state (or from the RES.DIRTY.REBOOT state to RES.WAIT.DIRTY), then finally to RES.READY, where it is completely allocated and configured for use in an experiment.

A node has a state in this state machine, as well as a state in a node boot state machine, at the same time that the experiment to which the node may be allocated has a state in the experiment status machine. Transitions and states in each of these machines may or may not be correlated. Most transitions within the node allocation machine occur only during the ACTIVATING and SWAPPING states of the experiment status machine. When an experiment is ACTIVE, its nodes are in the RES.READY state in the node allocation machine, but may be in any state in a node boot machine. The some transitions in the node allocation machine correspond to transitions in the node boot state machine, like RES.INIT.CLEAN to RES.CLEAN.REBOOT corresponds to a transition from ISUP to SHUTDOWN in the node boot machine.

¹In state names, RES signifies Reserved, meaning the node is allocated to an experiment. FREE signifies the opposite. CLEAN signifies that the node is loaded with a pristine copy of the default operating system image. DIRTY means that the node’s disk may have been touched by the user or the system, or may have been loaded with a different image.

CHAPTER 7

RESULTS

Our results are presented in three parts. First, we present some arguments based on the exposition in earlier chapters. Second, we present anecdotal evidence based on our experiences with Emulab’s state machine framework over the last two years. Third, we present the results of an experiment we performed that provides a quantitative analysis of one of the improvements brought about by the state machine framework.

7.1 Arguments

Some of the benefits of the state machine framework are derived directly from the use of the state machine approach. Many of the virtues of state machines that make them appropriate for Emulab are described in more detail in Section 3.5.

1. Constructing an explicit model of the processes within the system requires careful thought and design, both in implementing the system itself and modeling it. This helps improve the design of the Emulab software architecture and the correctness of the implementations.
2. The existence of a model, and the visualization of that model, makes it easier to understand complicated processes involved in managing nodes and experiments.
3. Other benefits have come from the improved monitoring and control that the framework provides, especially with regard to the node boot state machines and the `stated` daemon, as described in Chapters 4 and 5. The addition of a monitoring daemon that can detect incorrect and unexpected behaviors has been especially helpful.

4. By making more accurate and finer-grained information available to Emulab's servers, the framework has contributed to faster and more accurate error detection, and has helped improve recovery from errors and failures.
5. By improving reliability, the framework has contributed to scalability improvements, making it possible to run larger experiments that were previously impractical due to higher failure rates.
6. By improving reliability, our state machine framework has decreased the time required to swapin experiments and increased the experiment throughput. This decrease in the time overhead for running an experiment has also made resource use more efficient.
7. The flexible model has also improved our support for operating system images that have not been customized with Emulab support, and improved the system's workload generality, making it appropriate and capable over a broader range of experiments.

Overall, it appears that the state machine approach and framework in Emulab have been very successful, and have improved reliability, scalability, performance and efficiency, and generality and portability in the system. Of course, our state machine framework is not perfect, and there are a few downsides:

- Because of its incorporation throughout so many critical parts of the system, proper operation of Emulab depends very heavily on the `stated` daemon, and failures occur when it is not functioning properly. By adding another critical link in the chain, it can introduce new bugs and complicate debugging.
- The `stated` daemon has simple rules for what is correct and what is not, and sends email warnings about many errors that are possibly transient in nature, requiring a person's judgment to filter the feedback it provides.
- Because of the centralization of the node boot state machines, it has the potential to cause scaling issues as Emulab grows in size.

data loss in the asynchronous file systems typically in use by the OS, and would leave the file system on disk in an inconsistent and unrecoverable state. Such a node would of course fail to boot as part of the new experiment, even after multiple reboot attempts, and at the time, such a failure caused the entire experiment to fail and abort.¹

State machines were the solution for preventing this race condition. The trigger on `RELOADDONE` was modified to set up a trigger on the `ISUP` state for the node that had finished reloading, that would free the node from the holding experiment. By delaying the release of the node, the race condition between booting and being allocated and forcefully rebooted was eliminated. This prevented the disk corruption, by making sure that nodes were completely rebooted before they could be reserved by a user, which would make it possible for them to be forcefully rebooted. As a result of solving the disk corruption problem, reliability was improved, and a significant amount of time was saved by preventing the node failures and swapin failures and delays that occurred.

7.2.2 Generality: Graceful Handling of Custom OS Images

Emulab gives users the ability to create customized operating system images, with whatever OS or disk contents they desire. Because of this, we cannot assume that any of our standard client side software is running on a node using that image. It is important that these custom images be able to function, at least minimally, in our environment.

Without Emulab customizations in the disk image, a node will not be able to send state notifications to the `stated` daemon, and the node would be unable to follow the standard state machine. Nodes normally send notifications as they enter the `SHUTDOWN`, `TBSETUP` and `ISUP` states. Without the `ISUP` state, the system

¹We have since implemented a swapin retry mechanism that attempts to replace any failed nodes with good nodes and try to boot them, without rebooting all the nodes that already booted successfully. In this case it slows the swapin down by about 15 minutes instead of causing a complete failure.

- When adding or editing new state triggers or other code contained inside of `stated`, it is necessary to restart the daemon, which creates a small window (less than a second) during which the daemon cannot listen for event notifications. While the loss of an event may lead to invalid transitions, failure to make a mode transition, or failure to recognize that a node has booted, these errors require at most a single reboot for recovery. Still, this possibility discourages frequent changes to the daemon, and can complicate testing of changes.

7.2 Anecdotal

Emulab's state machine framework has been observed and evolved over the last two years, and here we highlight some experiences with it that provide further insight regarding its benefits and shortcomings. In this section we can also see some of the important differences between the way the system was before and after the state machines were added.

7.2.1 Reliability/Performance: Preventing Race Conditions

Emulab is configured to reload every node's disk after it has participated in an experiment to ensure a clean environment for the next user of that node. In order to prevent the node from getting reserved before this reload is complete, the nodes are reloaded while in a particular holding experiment. A trigger was configured for the `RELOADDONE` state of the `RELOAD` machine, such that `stated` would free the node when it finished reloading if it was in the holding experiment, and it would finish booting into the newly installed OS after being released into the free node pool.

The problem that was encountered was that during times of heavy use, users would be waiting for Emulab nodes to be freed so they could start their next experiment. As soon as the nodes finished reloading and were released, they would potentially get allocated to an experiment, and after having their new settings stored in the database, they would be rebooted again. Because they hadn't fully booted after the reload, they would typically be unresponsive, and would have to be power cycled by force. Turning off the power to the node during rebooting frequently would cause

will never recognize a node as having completed booting, and will continue to wait for it, or reboot it, or determine that it has failed to boot.

Three steps were taken to use our framework to compensate for these situations. First, we created the `MINIMAL` state machine, which was composed of `SHUTDOWN`, `BOOTING`, and `ISUP` states, and eliminated our dependence on the node for the `TBSETUP` state. The `BOOTING` state was already generated by Emulab servers, so compensating for `SHUTDOWN` and `ISUP` still remained.

Second, we changed the state machines to allow a `SHUTDOWN` notification to be received while in the `SHUTDOWN` state, so that duplicate `SHUTDOWN` events were not considered invalid, and we changed the `node_reboot` script (which reboots a node) to send the `SHUTDOWN` event when rebooting a node. While a call to `node_reboot` is the most common way to reboot a node, it is not the only way. Most operating systems can also initiate a reboot from the node itself (i.e., via the `reboot` or `shutdown` commands). In those cases, no event notification will be sent, and a transition from `ISUP` to `BOOTING` would occur. Because this can occur during normal, correct operation, a valid transition was added to the `MINIMAL` state machine that allowed these "silent reboots."

Third, to compensate for an `ISUP` event that the node may not be able to send, a trigger was added to the `BOOTING` state that would check if an `ISUP` event needed to be generated on behalf of the node. There are three cases that the trigger needs to handle. First, the OS on the node may use the `MINIMAL` machine, but still support sending an `ISUP`² event, and in that case, we can simply wait for the node to issue `ISUP`. Second, if the node doesn't send `ISUP` but does respond to `ping` probes, we can probe it until it responds, then generate an `ISUP` on behalf of the node. Third, if it will not respond to `ping` packets, we will not be able to determine when it is ready, so we send an `ISUP` notification soon after the `BOOTING` state is entered.

²Each OS image has a set of meta information associated with it that describes some of the features it supports. Among the features recorded there are support for sending `ISUP` notifications, and support for `ping`.

These steps allowed us to compensate for SHUTDOWN, TBSETUP, and ISUP events that normally would be sent by the node, and allow Emulab to gracefully handle any operating system image that a user might use in the testbed, even without any client side instrumentation of the OS or extra hints about state transitions from the node itself.

7.2.3 Reliability/Scalability: Improved Timeout Mechanisms

When nodes boot in Emulab, it is important that the system watch for any problems that may occur during the boot process, and retry as necessary by rebooting the node again. Determining that a problem has occurred is accomplished by means of a timeout, and if the node has not booted before the timeout has expired, it is rebooted to try again. Without state machines and the feedback that state transitions provide to the system, the method used was a single static timeout for the entire reboot process.

The single timeout for node reboots suffers from two problems. First, it cannot monitor progress, because it does not receive feedback from the node, and could not adapt to compensate for any feedback that it might receive. Because it is a static timeout and no feedback is present, it has no way of adjusting the timeout based on what stage of the process is currently in progress. Even though we know that a node should not take more than a minute or two to load the BIOS and contact the server for boot information, a failure in that stage cannot be detected until the timeout expires after several minutes.

Second, there is a critical tradeoff involved, between the time between a failure and detection of that failure, and the rate of false positives, where a failure is perceived when none occurred. To eliminate false positives, the timeout would have to be larger than the maximum time that a node could take to boot without encountering a failure, which in our case is estimated at 15 minutes. However, nodes failures most frequently occur during the first 4 minutes of the boot process, and a 15-minute timeout would add a delay of about 11 minutes before a failure would be detected. The way Emulab handled this tradeoff was by setting the timeout a reasonable amount of time greater

machine, or require only slight changes, like adding or deleting a state or transition. The ease of adding new state machines and node types is an important consideration in determining the generality and maintainability of the system.

7.2.5 Reliability/Scalability/Performance: Access Control/Locking

Every aspect of Emulab is controlled by some access control mechanism, based on the user's access levels to various projects and experiments, and on the current node allocations. Along with these access controls are a set of locks that serve to prevent user actions from interrupting system processes as much as possible.

The required permission checks can be quite complicated, and typically get performed quite often, since even viewing a web page requires permission checks to occur. The access controls must verify that the user is a member of the project of the experiment or node in question, and that they have been granted sufficient access to perform the requested operation. Even when a user has access to a project, experiment, or node, the actions that are allowed vary widely over time, depending on the activity in which the entity may be involved. For example, nodes cannot be rebooted while a reboot is in progress under most circumstances, and many actions on experiments are not allowed when the experiment is swapping in or out.

The state machine framework contributes to improved locking and synchronization between different components of the system, and simplifies permission checking on locked entities. The current state of the entity, as recorded in the database, makes access control much simpler, and prevents users from initiating illegal actions. They also serve a similar purpose internally. For example, an experiment cannot move into the ACTIVE state until every node in the experiment has entered the RES_READY state in the node allocation machine, which cannot occur until the node has entered the ISUP state in its node boot machine. Similar constraints provide features similar to barrier synchronization, and automatically "lock" entities against certain actions as state transitions occur.

than the average time to boot, but significantly less than the maximum error-free boot time, by choosing a 7-minute timeout.

State timeouts provide a much improved mechanism for determining when a node has failed during booting. State transitions allow progress to be monitored, and state timeouts provide a much finer granularity, and can be context sensitive, since different states have different timeouts. The value of these improvements was quantified experimentally and those results are described in Section 7.3.

7.2.4 Generality: Adding New Node Types

Emulab is a constantly evolving and growing testbed, and includes a wide variety of different device types, from powerful PCs and network devices to embedded processors and miniature mobile wireless devices. The various aspects of the system must be able to gracefully allow the adaptation and evolution as the hardware base of the testbed becomes more diverse.

The incorporation of a state machine framework inside Emulab began when the hardware base consisted of a cluster of PCs. As time has passed, six more types of emulab nodes have been added, and several others are in progress or planned for addition in the near future. These new node types include IXP Network Processors[12] nodes, "virtual" nodes[9, 6] (jail virtual machines running on cluster PCs), wide-area nodes (with live Internet links), PlanetLab[18] nodes, and "simulated" nodes (nodes simulated inside an instance of *nse*[4], the *ns* emulator). In the near future, several types of wireless nodes will be added, potentially including stationary wireless PCs, low-power stationary wireless devices, mobile wireless PDA devices, including devices carried by people or attached to model trains or radio controlled cars.

We have found that the state machine approach has proven to be very flexible, and is able to elegantly and simply encompass the new needs brought about by the new node types. Of the five types that have already been added, two new state machines were created, and the rest already fit with existing state machines. Only one of the new state machines required any changes to the `stated` daemon, in order to add a new trigger. Typically, new node types either exactly match an existing

7.2.6 Reliability: Detecting Unexpected Behaviors

Because an advanced network testbed like Emulab is a complex distributed system involving hundreds of computers, unexpected things can and do occur. While Emulab's servers are watched closely and keep many logs, the nodes themselves do not generate persistent logs other than the log of the serial console, and any information that can be gathered about a node is very helpful in finding and diagnosing errors and other unexpected results.

One of the first things that state machines were used to accomplish was to attempt to track down some mysterious and apparently spontaneous node reboots. Nodes would appear to reboot for no apparent reason, and in an effort to diagnose it, the state machine framework was used to alert developers when such an error occurred. When a reboot occurs without properly transitioning to the SHUTDOWN state, the node moves from the ISUP state directly to the BOOTING state. This transition is not a valid transition in the state machine, and it generates a message to administrators. By watching for these errors and giving administrators a chance to examine the nodes before their disks were reloaded, these problems were able to be diagnosed and solved. The monitoring that the state machines provide continues to serve as an ongoing watchdog for many varieties of unexpected behavior.

7.3 Experimental

There are very few measurements or metrics that can appropriately measure the benefits of adding state machines to Emulab. One measurement that can quantify one aspect of the benefit of state machines is the time required to swap in an experiment. As described in Section 7.2.3, state machines allow for fine-grained, context-sensitive, timeouts and retries, which can provide big speed and reliability improvements over the alternative of a single static timeout.

In Emulab, the worst-case time to reboot a node without having a failure or undue delays is over 15 minutes, but the average time is under four minutes. If we retry a failed reboot once before giving up on a node, we could end up waiting for 30 minutes. Before state machines were added, a timeout of seven minutes was chosen,

approximately double the normal boot time, because it minimized false timeouts while keeping the maximum delay reasonable. Emulab also implements a swapin retry feature that will replace any failed nodes with new ones, and attempt up to two retries before considering a swapin as a failure.

With state machines handling timeouts during the booting process, progress can be taken into account, and timeouts are all context-sensitive to the current state of the node. To give an idea of the timeouts, Table 7.1 shows some typical state timeouts. With context-sensitive timeouts, we no longer have to assume worst-case performance for states we know we have passed, or for states we have not entered yet. For instance, a single timeout based on the worst case numbers in the table, would be 15 minutes, and the full 15 minutes would have to elapse before a timeout is detected. If a node goes through SHUTDOWN in one minute, and gets stuck in BOOTING, we do not even have to wait five minutes, the worst case time to get through SHUTDOWN and BOOTING. We have to wait until only 3 minutes have elapsed since entering the BOOTING state, or a total of 4 minutes have elapsed since we started. Note that we also do not have to wait 7 minutes, like the normal single timeout would indicate, because we know that we do not have to consider the time taken in TBSETUP.

To provide additional evidence of the improvement provided by state machines, an experiment was devised in which a standard part of the TBSETUP state was prolonged. As Emulab nodes boot, they self configure, including the installation of any RPM or tar packages, as part of the TBSETUP state. An experiment was configured containing a single node that loads an RPM that takes eight minutes to install. This experiment was then swapped in using a version of the Emulab software

State	Timeout
SHUTDOWN	2 min.
BOOTING	3 min.
TBSETUP	10 min.

Table 7.1. Typical state timeout values

CHAPTER 8

RELATED WORK

In this chapter, we describe four categories of research related to the research described in this thesis. First, work in the area of basic state machines and automata is described, including a variation called timed automata. Second, we discuss Message Sequence Charts (MSCs) and some of the similarities they share with our work. Third, UML statecharts are described, including some similarities and analogous functionality in their model. The fourth category is research related to testbeds or distributed systems that describes methods or models similar to our work.

8.1 State Machines and Automata

State machines have been a popular approach for many years, and are the basis for the ideas and implementations presented in this thesis. They are also known as Finite State Machines (FSMs), Finite Automata (FAs), or Finite State Automata (FSAs). They are also often categorized into Deterministic or Nondeterministic automata (DFAs and NFAs). The state machines in this thesis are most closely related to DFAs.

A state automaton is traditionally composed of five parts: a set of states, the alphabet, the transition function, an initial state, and a set of accepting (or final) states[11]. In our case, the set of states is enumerated in Emulab's database, and the alphabet is implicitly defined as the set of events that may trigger a transition. The transition function is specified as entries in a table in the database, identifying the current state and a possible valid next state. Because the state machines in Emulab are designed to run constantly, there is no notion of an initial state or a final state, just a cycle defined by the transition function.

that does not base timeouts on states while preparing nodes for an experiment, and then swapped in again using newer software that does use state timeouts while rebooting nodes.

The result of the attempted swapin with a single timeout was that the node would start booting, entering TBSETUP after about 1 minute, then start installing the RPM package. After another 6 minutes, Emulab would time out, and reboot the node. The same boot process would occur after the reboot, and it would time out again, at which time Emulab determined the node was unusable, and replaced it with a different node, and attempted the swapin again. The new node timed out two more times, leading to another swapin retry, which had the same result. By the time Emulab finally determined the swapin attempt was a failure, it had tried three different nodes, rebooting them a total of six times, waiting seven minutes each time. The total time for the attempted swapin was about 45 minutes, and ended in failure.

The swapin with state-based timeouts had a very different result. The swapin was started, a node was chosen, and it was rebooted, progressing through BOOTING and starting TBSETUP in about 1 minute. Because TBSETUP is currently allowed to take up to 10 minutes without causing a timeout, installation of the RPM completed before a timeout occurred, and the node entered ISUP. The experiment swapin was then complete, without any failures or retries, in about 9 minutes, and was successful.

This example illustrates just one way where state machines provided a tangible and quantifiable improvement to the system. By providing more accurate information to Emulab servers, and allowing fine-grained, context-sensitive timeouts and retries, reliability was increased, and in turn, performance dramatically improved. Better reliability and performance also positively affect scalability and efficiency.

8.1.1 Timed Automata

Previous work with automata introduced the notion of a clock for use in conjunction with a state machine approach. One example is the "timed automata" model[1], which adds a global clock to the state machine approach. The clock's state can be used when deciding when a transition should be made and what new state should be entered. This global clock differs from the notion of timeouts described in this thesis because the timeouts establish time measured from entry into the current state, instead of a global notion of the passing of time, measured from a single starting point.

8.2 Message Sequence Charts and Scenarios

Message Sequence Charts (MSCs) and Live Sequence Charts (LSCs)[3] have a concept of "scenarios" that are linked together in configurations similar to state machines. Each of these scenarios in turn represents a particular MSC that describes operation within that scenario, forming a type of hierarchy similar to the way Emulab uses modes and state machines.

These scenarios and the transitions between them can be compared to the "modes" and mode transitions described in this thesis, where modes and scenarios and the transitions between them form a state machine at one level, and at the same time represent lower-level objects (state machines or MSCs) that define operation within that mode.

MSCs have also been combined with timed automata, as described by Lucas[16].

8.3 Statecharts in UML

The Unified Modeling Language (UML)[2, 22] includes a model of state machines called statecharts[7, 8], which describe a significant amount of extra functionality beyond that provided by the standard automata model. Statecharts include all of the machinery and functionality necessary to describe the designs and implementations described in this thesis, however, because they were conceived independently, the terms used are often different.

In statecharts, the analogue for the state “triggers” used in Emulab are “entry actions,” which are simply actions that get performed when a state is entered. Similarly, the hierarchical features of UML statecharts are similar to the separate state machines and “modes” we use.

Statecharts also are capable of capturing the state timeout functionality we implemented in Emulab, but only in a somewhat awkward and convoluted way. Statecharts may have “internal transitions,” which are transitions in which no state change occurs, and no entry or exit actions are triggered. The UML keyword “after” also allows for events based on the passage of time, “after(10 seconds)” for example. By combining these two features, with appropriate internal data to track total time elapsed within the state, statecharts can provide functionality similar to our state timeouts.

8.4 Testbed Related Work

For detailed information on research related to network testbeds, please see our other publications about Emulab ([9, 10, 24, 25, 26, 27]); future ones will be listed on the Emulab web site at www.emulab.net. At the time of publication, the author is unaware of any related work regarding the use of state machines in combination with testbeds, and unable to locate any publications regarding similar uses of state machines in other large distributed systems.

CHAPTER 9

CONCLUSIONS AND FUTURE WORK

Faced with reliability and performance problems in the Emulab network testbed, we implemented a process monitoring framework based on state machines to address the issues. Three classes of state machines were introduced, including node boot, experiment status, and node allocation state machines. As described in Section 4.4, a centralized service, **stated**, was developed to provide enhanced monitoring and control for the node boot state machines discussed in Chapter 5. This daemon manages transitions from one mode or state machine to another, detects invalid state transitions, and aids in recovery from failures. The experiment status and node allocation state machines, described in Chapter 6, use a distributed control model, and are primarily used to provide access control, locking, and synchronization.

In this thesis we have shown that enhancing Emulab with better monitoring and control through a flexible framework based on state machines improves the reliability, scalability, performance, efficiency, and generality of the system. As discussed in Chapter 7, Emulab’s process monitoring framework has provided formalization and visualization of several processes involved in the testbed. Improved monitoring and control has enabled detection of incorrect behaviors and contributed to faster and more accurate error detection and recovery. The reliability improvements have increased scalability and performance, by helping the system run faster with increased throughput and better efficiency. Generality improvements include better support for customized operating system images, and better flexibility for adding new node types to Emulab. These benefits have been discussed through arguments, anecdotes, and evaluated experimentally.

Although we have made significant improvements in Emulab, there are a number of possibilities for future work involving state machines in Emulab. These include further development of the distributed control model described in Section 4.3.2, better heuristics for detecting meaningful errors, implementing more concepts and functionality from related state machine systems, and migrating more state machine functionality into the database.

At present, the distributed control model used for experiment status and node allocation state machines lacks several of the features used by the node boot state machines that use a centralized model. Some of the features that could be added to the distributed model are timeouts, triggers, and better detection of invalid transitions. There are two obvious possibilities for implementing these changes. The first would be to enhance the distributed model directly, but this may prove problematic for timeouts due to the lack of a monitoring process for detecting the timeouts. The second method would be to change the state machines to the centralized model, where they could take advantage of the existing implementation used by the node boot state machines.

When **stated** detects an invalid transition, it notifies an administrator that there was an error, so that the error can be examined. While useful in general, this can sometimes result in a significant number of messages that are unrelated, and cannot individually be traced back to a cause and resolved. It would be beneficial to add to **stated** more intelligent heuristics for deciding when to notify an administrator. The heuristic most often used by humans is to look for clusters of similar or related errors. The clustering indicates that one cause may be responsible for the cluster, and that the problem is occurring repeatedly, and may be repeatable enough to debug. Heuristics could detect clusters of related messages within a short time frame, such as several nodes with the same error, or a single node with multiple errors, and only notify administrators about those errors. Such heuristics would make it less likely that real problems may get ignored due to too much background noise in the message stream.

A third possibility that seems promising is implementing more ideas from related state machine systems, such as the UML statecharts from Section 8.3, for example. Currently, **stated** has support for analogues to entry actions and hierarchical state machines. Other features, like exit actions, guarded transitions, and others, might be usefully added to Emulab. If this functionality were present in **stated**, it is possible that some of the things currently being modeled with triggers would be better modeled with exit actions rather than entry actions. Guarded transitions would also enhance our state machine approach, making it more rich and descriptive, and would allow for changes simply by changing the model without changing the program that causes the event to be sent.

Another possibility for future work would be to migrate more state machine functionality into the database in declarative form, rather than putting it in imperative program code, like the triggers that are implemented as part of **stated**, for example. Currently each type of trigger must be implemented as a section of Perl code within the **stated** program, which is awkward to analyze and evolve. By describing the actions the trigger should take in the database rather than in **stated**, it would make it easier to make changes, and better separate the code for the monitoring framework from the state machine itself. It would allow more of the transition logic to be included in the state machine description, in a declarative fashion, rather than as imperative code in the program that decides which event to send. If combined with changes to make the framework provide a richer model by adding more statechart-like features, for instance, the task of moving more functionality into the database would likely be significantly easier.

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