Architecture and Design of the Janet Multi-Agent System

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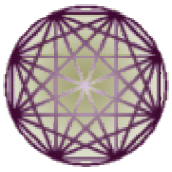

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Abstract

At the time of writing, agents and multi-agent systems are among the most rapidly growing areas of research and development in computer science. Agents are becoming one of the most important topics in distributed and autonomous decentralized systems. The multi-agent paradigm is widely used to provide solutions to a variety of organizational problems related to the collective achievement of one or more tasks.

The idea of Janet is to make use of the multi-agent paradigm for the development of an application-level automatic load balancing system. Firstly, this document presents concept and development of a platform for cooperative distributed agents. The system is lightweight and efficient. It is completely implemented in Java and XML. It offers an execution environment for distributed agents where agents communicate across process boundaries through the exchange of command objects. Commands are executed by interpreters. Agents decide autonomously which interpreter they choose to respond to a command. Secondly, based on this platform, a system for automatic distributed execution is developed where commands can be interrupted and migrated to other workstations in order to balance load changes.

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Introduction

The incentive for the development of Janet is to develop a system for automatic application-level load balancing. The concept for the system is developed using a *multi-agent paradigm*, where distributed agents cooperatively achieve a common goal. The system is entirely developed in Java. Because of the virtual machine approach of Java, the system can be used in a heterogeneous environment. The minimal system requirement is version 1.4 or later of Java (the run time environment or the JDK). The system consists of two layers. The basic layer provides the agent platform for distributed cooperative agents. This layer is application-independent and may be used as a general multi-agent platform. Another layer, based on the basic one, implements automatic distributed execution. Both layers in conjunction constitute the entire system, which is named Janet[1].

Distributed operating systems like Amoeba or Sprite offer load balancing on operating system-level. On the contrary, the system presented in this thesis is implemented on *application-level*. There are several advantages to application-level load balancing: It is possible for a Java application to make use of workload balancing even if it was not designed for workload balancing to begin with. There is also no need to migrate to a special distributed operating system for which often little software exists and that are even discontinued after they are no longer needed as a research vehicle. There is also no need to upgrade the operating system by installing expensive clustering components. Load distribution has to manage the mapping of distribution objects to distribution units [SCH95]. Distribution objects may correspond, for example, to processes, threads, or data structures whereas distribution units may correspond, for example, to computing nodes or application processes. For load balancing on application-level the mapping of distribution objects to distribution units can be adjusted to the implementation of distributed objects. For distributed operating systems this mapping has to be made automatically, which results in a loss of flexibility and additional overhead. An advantage of distributed operating systems is that they provide workload balancing in general for all applications and not only for individual ones. However, it is believed that there is a place for a system like Janet in areas where distributed operating systems or cluster systems are too effortful or expensive. In addition, Janet is not only a system for workload balancing in Java but also a general-purpose multi-agent platform.

The *first part* describes concept development and implementation of an agent-platform for cooperative distributed agents in chapters 1 and 2. The concept for automatic distributed execution and its implementation based on the previously developed platform is described in the *second part* in chapter 3.

[1] In autumn 2001 a hefty storm blew over Europe. This was the time when thinking about building a distributed system in Java began. As the name of the storm was Janet, the system to be built was given the code name Janet. Later on it was realised that Janet contained the words Java and network, which made good sense for the project, and therefore the initial code name became the final name for the system.

1 Overview of Janet

The idea of Janet is to develop a system that provides workload balancing on application-level. Workload balancing has mostly been implemented on operating system-level as in distributed operating systems such as Amoeba [TAN01], Sprite [OUS88] and others. Schnekenburger writes in [SCH95]: “Load distribution is a central problem for parallel programming in distributed systems. Load distribution has to manage the assignment of service demands of a parallel program to distributed resources of the system. More generally, load distribution has to manage the mapping of *distribution objects* to *distribution units*. Distribution objects may correspond for example to processes, threads, or data structures whereas distribution units may correspond for example to computing nodes or application processes”. The idea of Janet is to develop a simple system that provides an object space for developing distributed programs in heterogeneous object spaces. Automatic distributed execution is an application of Janet that is intended to proof the usefulness of the Janet distributed programming object space and to offer a useful system for workload balancing in Java.

As simple as possible, but not simpler.

To use this quote by Albert Einstein, Janet is intended to be made “as simple as possible, but not simpler”. This was also the motto of Niklaus Wirth in the development of the Oberon programming language [RW92]. He says in [RW92] that it is good engineering practice “to strive for economy of means and simplicity of solutions”. One reason for building Janet up from scratch is to use it as a learning vehicle for building an entire system rather than adding new parts to an existing system. The intention here is clearly in having an opportunity to develop such skills mentioned by Wirth rather than developing the “ultimate multi-agent system”. Another reason is that a lot of overhead of existing agent platforms can be avoided if a new system is built using simple means. This is important with regard to workload balancing where a small overall performance penalty of the load balancing system is required for the gains in time out of parallel execution of jobs not to be undone by the sluggishness of the workload balancing system itself.

1.1 Layers in Janet

The goal of this work is to develop a system that can automatically re-distribute jobs to other workstations to balance workload. The core agent system can be separated from the system for workload balancing. This way the core agent system can be used for other purposes as well. It is always good design practice to separate concerns and to strive for a low level of coupling. For this reason, Janet is split into two major layers: Janet.CAS and Janet.ADÉ which are described in brief in the following.

Janet.CAS

Janet.CAS (**C**ooperative **A**gent **S**ystem) is the core layer that provides a distributed agent-oriented platform where agents communicate through the exchange of commands for which they chose interpreters of their own to execute them. Agents are defined by applications that reside on nodes. All nodes that are connected with each other form a cluster. Janet.CAS provides a platform for which users can write applications. An application is a collection of capabilities.

Capabilities consist of interpreters that execute commands. Interpreters constitute the functionality of an agent.

Janet.ADÉ

Janet.ADÉ (**A**utomatic **D**istributed **E**xecution) is based on the Janet.CAS layer. It is the layer that implements automatic workload balancing. Workload balancing is realised using automatic distributed execution of commands. This term originates from distributed operating systems that are based on automatic distribution of operating system-level jobs to balance workload.

1.2 Semi-Transparent Load Balancing

Load balancing requires that a process that was started at a machine can be suspended and can be moved to some other machine where its execution resumes. This way it is possible for the system to readjust to dynamic load changes. The solution implemented in Janet.ADÉ cannot suspend threads and move them to other machines, as this would require additional information that can only be obtained from the operating system or – in case of Java – from the Java virtual machine. The Java virtual machine can be changed to obtain this additional information as this has been done in the Plurix-Project at the University of Ulm, Germany [SM01]. Such an effortful undertaking is beyond the time and resource frame for this work. In Janet.ADÉ threads are therefore replaced with the concept of a command. The user is required to provide some assistance when saving the command context before command migration. This way, load balancing can still be implemented on application-level in Java with only a small sacrifice in transparency.

1.3 Architecture

Architecture is one of those terms that is widely overused but poorly defined in software engineering and computer science. This section describes the high-level software framework within which Janet is implemented.

1.3.1 Development Platform

Java has shown to be a good choice for the development of many agent-based systems such as *AgentBuilder*, *AgentOS*, *Aglets*, *JADE*, *JACK*, *SeMoA*, and many others. One reason for this is Java's ability to span heterogeneous environments. For the implementation of mobile agent systems being able to load classes at runtime, which is straightforward in Java, has proven to be very helpful. This ability is important for Janet as well, because interpreters, that execute commands, are dispatched and loaded at runtime. Java has been chosen as the development platform for Janet for the reasons mentioned above and for other reasons as well. For example, to be able to finish the system within the given time it was important to choose a development platform with good developer productivity.

1.3.2 Middleware

To make nodes in a cluster communicate with each other a middleware system is needed. Java Remote Method Invocation (*RMI*) was chosen as the middleware system. Other middleware systems such as *CORBA*, *JMS*, or *XML-RPC* are also possible choices. The advantage of using RMI is that it is easy to use and thus creates little additional effort to make nodes communicate. This makes it possible to concentrate on design and conceptual issues of the system. If it turns out later that a high-level middleware system such as CORBA is needed, migration from RMI to CORBA would be relatively effortless as these systems are based on a similar user interface. RMI has also been used for the development of JADE, which is widely used in academia and research. Performance measurements of JADE [VQC02] have shown that RMI is well suited to achieve good performance in a distributed agent-oriented system. The same holds true for JavaSpaces, which has been developed with Java and RMI as well. Java RMI, being a Java-centric middleware, is not a good choice to achieve high interoperability with non-Java based systems whereas XML-RPC has been specifically designed for interoperability. XML-RPC is especially interesting since it is widely used to exchange data between web services and clients. With the number of web requests for many sites becoming very large load balancing of web services has become an important issue. It would be an interesting task to develop an XML-RPC interface for Janet to be able to use Janet for load balancing of web requests. However, RMI has been chosen over XML-RPC, because of its simplicity and ease of use, which is important to be able to finish the system within the given time frame. Converting Janet commands objects to XML strings is simple since commands only carry parameters and no code. For this reason, concept and design of Janet would need no modification for any later support of XML-RPC.

1.3.3 Agent Platforms

With the rising popularity of agent-based distributed applications several agent platforms have been developed. JADE has already been mentioned as an agent platform that has been used successfully in several academic projects and research projects. Automatic distributed execution could be implemented using an existing proven agent platform or a shared memory system such as JavaSpaces. An important requirement for a load balancing system is that it is efficient and lightweight. A system that provides workload balancing must not be that inefficient that it counteracts the benefits of workload balancing. When taking the selection of an agent platform for the development of Janet into consideration best possible performance is an important issue. For this reason, it was decided to develop a simple agent platform for automatic distributed execution rather than using an existing heavyweight agent platform. This makes sure that the performance issue can be kept under control. Another reason is that several ideas for the development of an agent platform already existed and automatic distributed execution appeared to be a good reason to turn these ideas into a working agent system.

1.3.4 Simplifications

The goal of this work is to develop a fully functional system that is conceptually clean. It is certainly not possible to develop a system that is complete and offers advanced features that would take a team of developers several years to implement. To be able to concentrate on the main theme of this work, several simplifications had to be defined.

Concentration on Realization of Conceptual Ideas

There is no support for persistence, transactions, or fault tolerance. Security is being taken care of in the way that the system ensures that user-level applications run in a protected environ-

ment and cannot interfere each other, nor communicate directly with each other. However, there are no built-in mechanisms for the authentication of sending and receiving commands, which are not encrypted, either. SeMoA from the Fraunhofer Institute, Darmstadt, Germany, was considered to be used as a secure messaging server for Janet commands. As described in [PPHG02] SeMoA is a Java-based mobile agent platform that protects mobile agents against malicious hosts. Authentication and encryption could be delegated to SeMoA. Because of the SeMoA licensing terms, every user of Janet would have to obtain a license from the Fraunhofer Institute to use SeMoA in conjunction with Janet. As Janet is intended to be a free tool with a liberate license this was considered unacceptable.

No Built-In Support for an Agent Communication Language

For agents to be autonomous they are required to be able to choose their own actions in response to some message they received. Wooldridge states in [WO02, p.164]: "We have two agents i and j, where i has the capability to perform α, which corresponds loosely to a method. (…) There is no concept in the agent-oriented world of an agent j 'invoking a method' on i. This is because an agent is an autonomous agent: it has control, over both its state and its behavior". Janet takes care of this fundamental requirement of the autonomy of agents by executing agents as Java objects that run in their own threads and by decoupling commands from interpreters. An agent sending a command to another agent cannot enforce any action on the recipient agent. The recipient agent decides on his own how to react to this command by choosing the interpreter it considers appropriate.

An agent communication language (ACL) is some lingua franca designed specifically to facilitate communication between two or more agents. Agents need to communicate information, intentions, goals, and so on to other agents. Several ACLs have been developed such as KIF [GF92], KQML [FFMM94], or the FIPA ACL. If agents are to communicate about some domain, then it is necessary for them to agree on the terminology they use to describe this domain.

As Cohen and Levesque have argued in [CL95] KQML, for example, has some deficiencies. The KQML specification is in some points vage and ambiguous. It has no formal semantics, as this is commonly the case for programming languages, which means that it is not guaranteed that a performative is interpreted in the same way by all agent systems that use KQML. ACLs still seem to be in the flux of development and refinement. New ACLs are occurring that seem interesting such as *OWL* (Web Ontology Language) by the W3C group. From this point of view, deciding on an ACL standard appears premature. There seems to be a point in waiting how the development of ACLs is going to continue. For this reason, it was decided that Janet, for the time being, does not make use of an explicit ACL or ontology. Janet system commands are required to know implicitly about the terms they use and how the designer specified them. However, Janet users that develop user-level applications are free to choose their own ACL making use of Janet commands as messengers for ACL statements and develop their own ontologies.

1.4 Distributed Systems and Janet

It is necessary to position Janet against other kinds of distributed systems in order to verify that a system like Janet has applications for which it is well suited and therefore can justify its place.

1.4.1 Linda-Style Tuple Space Architectures

JavaSpaces has been used as a platform for the development of agent-based systems. Engelhardtsen and Gagnes [EG04] have used JavaSpaces to create an adaptive distributed system where agents adapt to changing demands placed on the system by dynamically requesting their behavior from a JavaSpace. They argue that: "… using JavaSpaces technology is a simple way to create adaptive systems, due to JavaSpaces' ability to support messaging as well as distribution of agent behavior".

Wang has used JavaSpaces to implement a mobile multi-agent system [WA00]. An advantage of using JavaSpaces is that distribution of agents is obtained almost for free. This system was first developed using the Aglets agent framework [LO98] and was then migrated to JavaSpaces. Wang writes that: "… experiences show that JavaSpaces can well be used to provide the same functionality as that provided in other mobile agent frameworks like, e.g. Aglets. (…) In addition, the API in JavaSpaces is very high-level, making it efficient to provide distributed services".

Chen has explored JavaSpaces to coordinate multi-agents [CH02]. He argues that: "… the emerging JavaSpaces technology provides a convenient, yet flexible approach to agent coordination in a multi-agent system object space".

The successful use of JavaSpaces to develop agent-based systems as described in the papers mentioned above makes JavaSpaces an interesting system to use as the implementation technology for Janet. However, it is a drawback that the tuple space approach does not provide a familiar computing objects space. Users are forced to adopt the Linda tuple space computing model, which is a producer/consumer model. A consumer spins off a number of producers, which enter the tuple space, perform their work, and the consumer checks back for results. In JavaSpaces all objects in the JavaSpace are in serialized form. They cannot invoke methods without being first extracted from the JavaSpace. Furthermore, JINI, on which JavaSpaces is built, is a heavyweight API, which simple applications might not need, and it makes using JavaSpaces difficult.

The main drawback of JavaSpaces is that a final decision for the middleware technology is made implicitly with the selection of JavaSpaces. Since JavaSpaces makes use of a very specific computing model it becomes very effortful to change from JavaSpaces to some other middleware system (such as XML-RPC for Web requests). Janet is indented to be middleware independent so that the middleware used to transport commands from agent to agent can be easily exchanged. Middleware independence is considered important, as the past has shown that middleware technologies are in a state of constant change. Adaptability to new emerging technologies such as XML-RPC or SOAP/Axis was given preference. For performance reasons, Janet is intended to perform well and be lightweight as well. This is a requirement for the implementation of a load balancing system to perform well. Simplicity and strive for a lightweight system is another reason not to chose JavaSpaces for the development of Janet.

The disadvantage of not using JavaSpaces is that without a shared memory system agents are restricted to pure message passing as a means of communication. However, since JavaSpaces is based on Java RMI message passing, it is also possible to develop a simple shared memory space for Janet if required.

1.4.2 Distributed Operating Systems

The key rationale of Janet is to build an inexpensive system in little time with which it is possible to do distributed programming in a heterogeneous object space without having to use specialized systems. Specialized distributed operating systems like Amoeba or Sprite are very impressing and some of the most demanding systems to build, but from the beginning they were intended to be research vehicles that will be discontinued one day. Commercial solutions that offer protection for earlier made investments like cluster systems that are extensions of existing commercial UNIX systems must be used constantly to pay off. Janet offers an inexpensive alternative for tasks that need to be solved with the means of distributed programming but do not justify for the massive investment into commercial high-end cluster systems.

1.4.3 Parallel Programming Languages

Other specialized systems such as programming languages for parallel programming - like Occam, Concurrent C, Pascal-FC, pC++, and many others - have the disadvantage that they create their own world. For purposes such as supercomputing there is no need to be able to bridge from specialized parallel programming languages to programming languages for general application programming like Java and living in a world separated from others is therefore not a problem. But there are applications where a rift between programming object spaces would create to big an expenditure and where systems such as Janet come into play. There are other ways to avoid this rift, for example by extending the Java VM to build in support for distributed shared memory (DSM) as this has been done in the Plurix project [STS98] at the university of Ulm, Germany. Since memory is shared in Plurix there is no problem of passing messages beyond process boundaries. This would make the implementation of Janet a lot simpler since communication between agents on different computers would not be an issue. While Plurix is more intended to be a distributed operating system Janet is more geared towards supporting development of distributed end-user applications. For this reason, Plurix and Janet are more complementary to each other rather than competing against each other. DSM provided by Plurix in conjunction with the facilities of Janet for developing multi-agent applications could be well-suited complements just as in conjunction with other agent systems such as JADE or Aglets.

1.4.4 Grid Computing

The idea of grid computing is to integrate computers in a seamless and transparent way to create a single integrated system. This involves the sharing of data and all kinds of resources such as CPUs, memory, storage devices, printers, and others. On the contrary, the idea of Janet is to develop a fundamental system for distributed programming that uses an open pluggable architecture for users to add in their own applications rather than integrating other systems. Janet or some of its concepts may be used as a building block for building larger system for grid computing.

2 Janet.CAS

This chapter begins with the description of the conceptual design of Janet.CAS. The section about conceptual design provides an overview of major design decisions and their realization which form the basis of the Janet.CAS layer. The second part describes the detailed design and implementation where solutions were developed to turn conceptual ideas and decisions into reality. When developing a system it useful to implement an application that serves for the validation of its concepts. Such an application, called a driving application in this paper, helps to point out missing functionality and to become aware of inappropriate design decisions so that these decisions can be corrected in an early project state. The driving applications developed are an application to calculate Fibonacci numbers in a distributed environment and an application that provides remote logging of log messages. These driving applications are presented in the third part of this chapter. They are supposed to give the reader an introduction into how to develop applications using Janet.CAS. This chapter concludes with the presentation of measurements. Travel times of Janet.CAS commands and the time required to process them is measured in order to obtain an estimate about performance characteristics and scalability of the system.

2.1 Conceptual Design

The conceptual design describes the major conceptual ideas that form the basis of Janet.CAS. These concepts define high-level design approaches on which the entire system is based.

2.1.1 Commands and Interpreters

The core concept in Janet.CAS is the communication between agents through the exchange of commands. Exchange of commands is always asynchronous and therefore is communication between agents. A command is an object that transports parameters between agents and lets the recipient agent know what event has occurred. It is thinkable that a command transports executable code but it is not executable itself. Only the interpreter is executable. The recipient agent invokes an interpreter it chose of its own to handle the command. In the following, the expression is used that “an agent executes a command”. This is a shortcut for not having to state repeatedly, that an interpreter associated with some command is executed. The command-interpreter pair in Janet.CAS is very similar to an event-handler pair. Since the exchange of commands between agents has been developed as an extension of the command pattern as described in [GA95] this text uses the former terminology. Furthermore, commands are a way to notify a specific recipient that an event has occurred rather than a notification to all objects that have subscribed to a certain event and are then notified indirectly by an event notifier. For the latter purpose a separate event-notification mechanism was developed. The idea of enhancing the command pattern by adding an interpreter object was initially developed in a student’s project at the University of Applied Sciences in Darmstadt. In general, to use the command pattern for distributed computing seems to be an obvious idea. Several other persons have chosen this approach independently from each other. Two authors that use this approach in their books (though on a simpler level than in Janet) amongst others are Grosso [GR01] and Farley [FA98].

The principal idea of agents is that they are autonomous and therefore make their own decisions. If a traffic light changes from green to red an agent controlling a car needs to decide of

its own how to react. It may decide to stop the car. However, if it controls an ambulance on an emergency mission it may decide to turn on the siren and cross the red light. The command-interpreter pattern allows for the implementation of this polymorphic behavior as an agent defines itself which interpreter to invoke when a command is received. Upon receipt of a TrafficLightChangedToRedCommand command, a car agent would invoke the interpreter myNamespace.*car*.TrafficLightChangedToRedInterpreter whereas an emergency vehicle would invoke the myNamespace.*emergencyVehicle*.TrafficLightChangedToRedInterpreter. The split between command object and interpreter object is necessary to ensure the autonomy of agents. If an agent were simply told by a command, sent by some other agent, what to do, it would only be an object receiving a message rather than an autonomous agent receiving an event and reacting to it in a way it assumes to be appropriate for its purposes. In addition, the split between command object and interpreter object makes sure that an agent only executes code that was defined for it and is therefore save from remotely received commands making it behave as intended by some potentially malicious agent. Due to the separation of concerns between commands and interpreters the command objects need not necessarily be a Java object. It could be encoded in XML, which would make integration with non-Java systems possible (XML-RPC, SOAP).

2.1.2 Applications and Capabilities

Before we can carry on the concept of an application and a capability has to be introduced since these concepts will be referred to later on. As already mentioned earlier, Janet.CAS is intended to serve as a simple agent platform that allows the user to plug in applications developed on their own. The application object in Janet.CAS allows the user to register her application with Janet so that the agents needed by these applications will be instantiated and started. An application consists of several capabilities. A capability defines a set of interpreters. Applications with their capabilities can be defined programmatically or in XML node descriptor files that are parsed when a node is started up. Janet.CAS itself defines nodes that have different roles in a cluster by specifying the applicable interpreters for the core capability of the system application individually as required by the role of the node. In the same way, a user would plug in her applications into the Janet.CAS agent platform. By specifying the names of agents needed for a capability the user defines which and how many agents will be created by Janet.CAS to serve the application. When an agent sends a command to another agent it has to specify the name of the destination agent, its application name and the name of capability that defines the interpreter to execute the command.

Figure 2-1 on page 16 shows the classes `Application, Capability, and ObjectSpace` with their main attributes and operations. An application is uniquely identified by its name. It has several capabilities and its own object space. The application's agents may use the object space to store permanent information that needs to remain present after an interpreter has finished execution, which allows the agent to keep track of its internal state. Every capability defines 1 or more agents. An agent may only execute commands that are sent to the capability they are associated with and may only send commands to agents that belong to the same capability and application (which may reside on physically separated sites, but need to have the same names and list of interpreters in each capability). This is a kind of protection that makes sure that agents cannot invoke actions on agents of other applications (e.g. denial of service attacks). Agents of different applications can only communicate through events. Agents decide on their own, which events they want to register for. A capability has a set of interpreters. Each interpreter knows the names of the commands it is supposed to interpret. When an interpreter is executed the message `execute` is sent to it with the command as an argument contained in the

`CommandAccessor`. The `CommandAccessor` provides the means for the interpreter to access its capability and application and shields the node from unprivileged access. Through the `CommandAccessor` an interpreter can also access the node itself as far as access is granted. An interpreter executed by a system agent has full access to the node's inner objects, whereas access is restricted for user-defined applications.

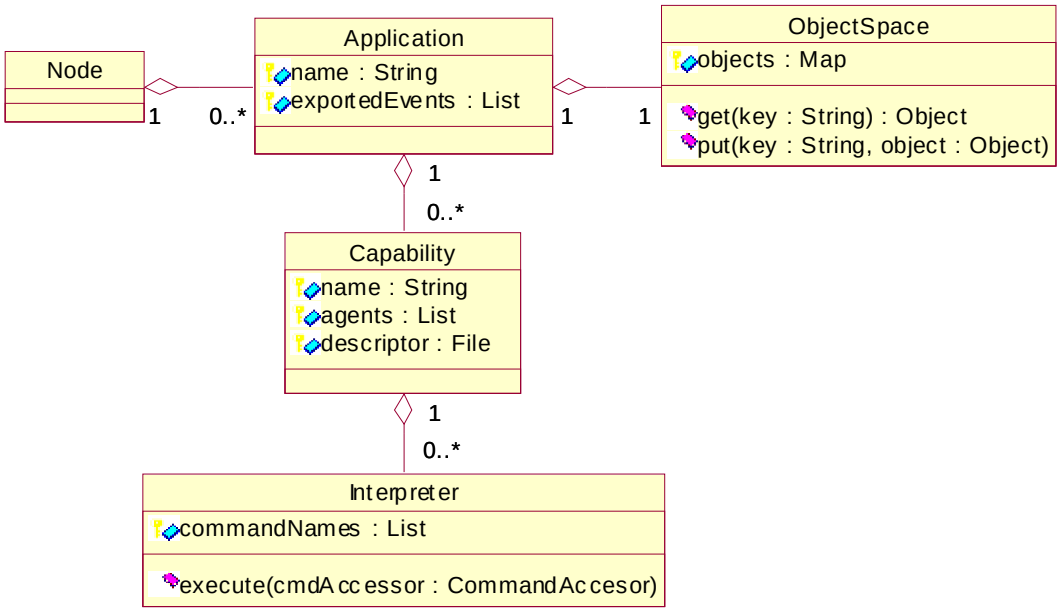

Figure 2-1: Applications and capabilities

The idea of capabilities is inspired from capabilities in Amoeba [TAN01]. Whereas in Amoeba capabilities are descriptors that define user privileges, in Janet they define an agent's executable part. It is thinkable to let an agent dispose of several capabilities. However, this would make the application logic considerably more difficult, especially when evicting commands to other nodes in order to balance load. The agent an evicted command is transferred to needs to have the same capabilities as the agent from which the command was evicted. Otherwise, there is no way to dispatch the interpreter associated with the evicted command at the destination site. In order to strive for simplicity first, an agent can only have one capability, which will remain as is unless evidence appears that shows that it is not possible to cover essential requirements using the initial approach. An application can only be instantiated once. However, the number of agents per capability is unlimited.

Applications and System Application

There is a special application, which is called the system application. The system application defines a capability to run a Janet node, which is called the core capability. An agent that is part of the system application has privilege to access all inner objects of the node.

2.1.3 Schedulers

A common approach to make an agent able to react independently to events is to make it run in its own thread. A scheduler is used to execute interpreters, associated with received commands, on behalf of the agent. Implementation-wise the scheduler is an active object, which means that it runs in its own thread, whereas the agent object merely serves as an anchor object to accept commands and to expose the public interface of an agent. When an agent receives a command from another agent it places the command into the command queue of its scheduler. As long as the scheduler queues contain any commands they are executed one after the other in a consumer-producer-like fashion. Each interpreter runs to completion. The scheduler looks up the interpreter associated with the command, passes the command over to the interpreter - so that the interpreter can extract the required input parameters from the command - and starts it.

Several agents may share the same scheduler, which improves performance considerably in case several thousand agents exist that are running concurrently as shown in [BRHL99]. The more agents share a scheduler the more efficient execution. However, sharing a scheduler reduces the degree of pseudo-parallel execution of commands since a scheduler only executes one command at a time. For shared use of a single scheduler to be efficient, it is important to define commands that execute fast so that crowding out of other application commands is minimized. This also minimizes the likelihood that several commands have to wait long until they can enter a critical section in case it is already occupied by another command, which furthermore improves performance. Since always one command is executed at the same time by one scheduler the number of potential race conditions when accessing shared resources is thereby reduced which simplifies concurrency control and reduces the deadlock potential.

2.1.3.1 Arbitrators and the Supreme Scheduler

Java uses a round-robin thread-scheduling mechanism [OW97]. This means that a thread can interrupt other threads that run at lower priority. However, the behavior of the Java scheduler is not specified in case of several threads running with the same priority. The Java scheduler switches between them but only if the operating system uses time slicing. If it does not, the next thread can only run when the previous one has finished. This is a problem as a thread can cause other threads at the same priority to starve. Janet.CAS as a simple agent platform has to guarantee that an application cannot cause starvation of other applications. This is ensured by the arbitrator that grants each application schedulers a certain amount of time for execution on a time slicing basis. The arbitrator runs at a higher priority than the application schedulers, which makes sure that it always runs when required. The arbitrator controls the application schedulers by changing the priorities of the Java threads that run them. The priority of the single application scheduler that is given the current time slice is increased while the priority of the previously active application scheduler is first decreased.

The arbitrator starts the schedulers of an application once an application scheduler receives the first command. The user cannot start or stop any scheduler. When an application has been registered with the system, the arbitrator may start the schedulers associated with the application at any time but latest when it receives the first command. This makes sure that an agent can always rely on a command to be interpreted by the recipient agent. If this were not the case the application could easily get stuck. Checking whether the application scheduler of an agent is running before sending a command to it would significantly complicate the design of the system and user-level applications. For this reason, registered applications become immediately

visible to all the nodes in the cluster and their agents may always be assumed to be running. Consequently, when an application is deregistered, it is no longer visible to nodes in the cluster.

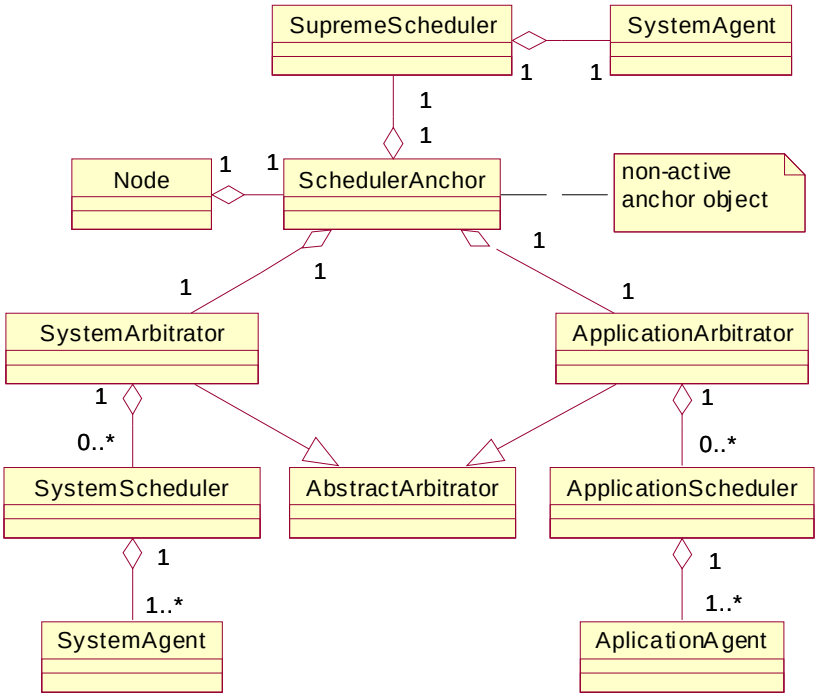

Figure 2-2: Arbitrator class diagram

As shown in Figure 2-2, there are two arbitrators: one to schedule application schedulers and another one to schedule system schedulers. The `SupremeScheduler` is a singleton active object that runs at the highest priority of all schedulers. The supreme scheduler needs to run at a higher priority than all other schedulers so that it can preempt commands of other schedulers and execute its own commands immediately, which is required in some cases for the system to remain responsive. Otherwise, a situation is thinkable where some agent waits for the system to provide some service, which it cannot provide immediately because it is waiting to receive a time slice from an arbitrator.

The system schedulers run at a higher priority than the application schedulers, but at a lower priority than the supreme scheduler. System commands that need not interrupt other commands immediately in order to execute are passed on to a system scheduler. Every agent that has a capability, which is part of the system application, is assigned to a system scheduler. System agents are rarely needed. In fact, they were only introduced to be able to interrupt system commands to implement command eviction and their cancelation. In the following, the term system agent refers to the supreme agent if not explicitly stated otherwise.

2.1.4 Event Notification

Commands in Janet are always asynchronous. They tell an agent that something has happened, but don't tell it what actions to take. This alone is not sufficient to serve as an event-dispatch mechanism since commands are always sent directly to a specific agent. But event and receiver of the event notification need to be decoupled. Events that may occur must be published giving every agent interested in being notified about the event occurrence the opportunity to register for the event. Event registries are a common approach to propagate messages to objects that were not known to the event notifier at compile time. What is specific to Janet.CAS is the question where the event registry should reside and who has to pay for the CPU cost of the execution of the event handler. The cost should be paid by the agent that registered the handler, not by the agent that signaled the event. For that reason the handler is wrapped into a command and sent to the agent that registered for the event. The command containing the handler will then execute the handler and the CPU costs will necessarily have to be paid by the agent that registered for the event. As a result of the handler being executed by an agent as a command, which is executed asynchronously, execution of the event handler is asynchronous as well.

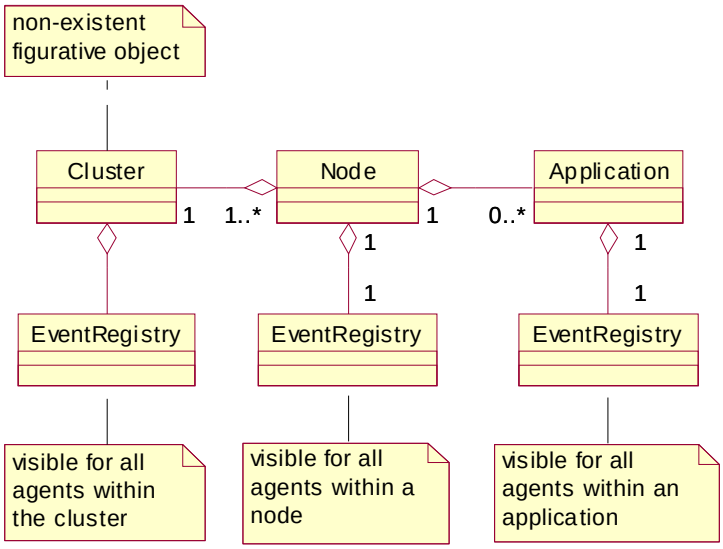

Figure 2-3: Event registries and their scope

Every application has an event registry of its own for events that are not of concern to other applications and which they should not know about. For every node is a node event registry through the use of which agents of different applications residing on the same node may exchange events. Finally, a cluster event registry exists for event registration and notification across node boundaries. An overview of all event registries is displayed in Figure 2-3. These event registries are explained in further detail in the section that describes detailed design and implementation.

2.1.5 Nodes and the Central

The central is a special node that takes care of the management of the cluster. The node is identical to all other nodes in the cluster except that its system application defines a core capa-

bility supplied with the respective interpreters to run a central. The central keeps an image of the cluster with its nodes. When a new node is started up in the cluster it registers with the central, which in turn notifies all already existing nodes in the cluster about the new node. Analogously, when a node shuts down the central removes it from its cluster image and notifies all other nodes about the event. During shutdown race conditions may occur in case two or more nodes are carrying out the shutdown process at the time. The central is needed to synchronize node shutdown.

After a node has registered with the central it registers with all other nodes in the cluster as well. During the registration process nodes exchange descriptors of their applications. In doing so, every node knows about all the applications that are registered with all other nodes in the cluster with their capabilities and agents. An agent is therefore able to look up immediately all existing agents in the cluster that have a specific capability. There is no need to ask a central registry, which takes time. Instant agent lookup is important for being able to transfer commands from a heavily loaded agent to a lightly loaded agent quickly. Nodes may shut down or start up any time, applications with their agents may be newly registered or deregistered while a node is running, agents may be created or closed down any time. This requires agent lookup to be dynamic. Hence, agent lookup cannot be made static in order to optimize performance. Since nodes exchange application descriptors with all other node in the cluster at startup time, startup of a node is a period where command traffic in the cluster is high.

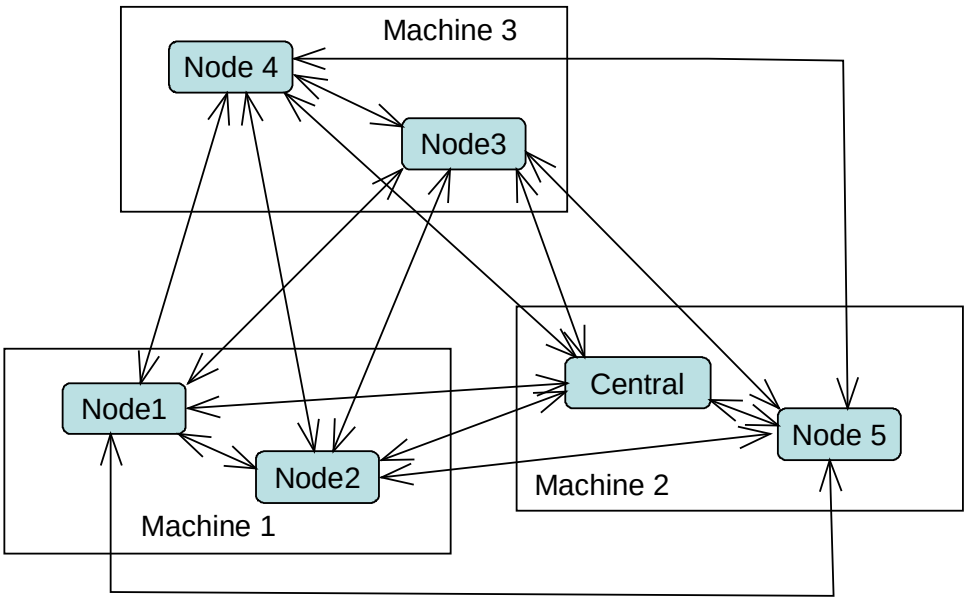

Figure 2-4: Sample cluster with the central and completely connected nodes

The central is required as well to interact with the RMI registry, where RMI node server objects are registered to be visible for other nodes. For security reasons, a RMI server object may only be deregistered from the registry on the same workstation where the RMI registry resides. The central deregisters nodes that may reside on other workstations than the central on their behalf. Another solution would be to let all nodes on the same workstations have their own RMI registry, rather than having a single RMI registry at the location of the central. But this

would result in the user having to specify for every single node in the cluster on which workstations the registries of all other nodes reside to be able to look them up from their RMI registries. Since other middleware might have similar restrictions as RMI for security reasons or other reason, the presence of the central offers the required flexibility that might be needed when plugging in other middleware.

Another reason for the central to exist is to provide some flexibility in case clusters need to be connected. Centrals could help making the connection process of all nodes in every cluster simpler and more efficient.

Figure 2-4 on page 20 shows a sample cluster with the central and several nodes. *It is important to realise that there can be several nodes on one machine and not only a single one.* This is because the user is not restricted to only starting up a single Java virtual machine, but may need to start up several ones, and for each Java virtual machine the user wants to make use of Janet or parts of it. For example, distributed number crunching with more than one node per workstation makes little sense when every machine has a single CPU. On the contrary, one might consider a Janet application that wants to make unused heap memory of a Java virtual machine running a Janet node available to other nodes. If there are several Java virtual machines on one workstation, it makes sense to make the unused heap memory of every Java virtual machine on that workstation available in the whole cluster or for a specific set of nodes.

2.2 Detailed Design and Implementation

Detailed design is concerned with finding detailed design solution to realize conceptual design decisions. This section describes how the conceptual design has been turned into reality and describes the implementation of the most important parts.

2.2.1 Schedulers

Schedulers are active objects, which own their own thread. This thread only executes the methods invoked on an active object by other active objects. Instead of using methods, Janet makes use of the command pattern where agents send commands to other agents. Following the agent-oriented paradigm only agents are active objects in Janet and only agents communicate with other agents. In Janet agents make use of their scheduler, which they may share with other agents for efficiency reasons, for the execution of the commands they received from other agents. This makes scheduling an important task in Janet. Explanation of the detailed design of schedulers is therefore presented first.

All agent schedulers in Janet are derived from class `ActiveSchedulingObject` which itself is derived from `ActiveObject`. These two classes are abstract general-purpose classes defined outside Janet in the subsystem Objectscape.Common in the package `org.objectscape.commons.util.threads` that provides the basic functionality for running an object in its own thread. Class `ActiveObject` has the functionality for starting and stopping the thread owned by the active object and changing its priority. The methods in the Java thread class for thread suspension and resumption must not be used since they are deprecated (as they have shown to be deadlock-prone). Suspending and resuming a thread in Java can therefore currently only be done by blocking and unblocking a thread or by changing the thread's priority. The `ActiveObject` class uses the latter approach since this approach is less intrusive. The stop method in the Java thread class is deprecated for the same reason as the other methods

already mentioned. Stopping is therefore implemented by exiting from the `Runnable run` method.

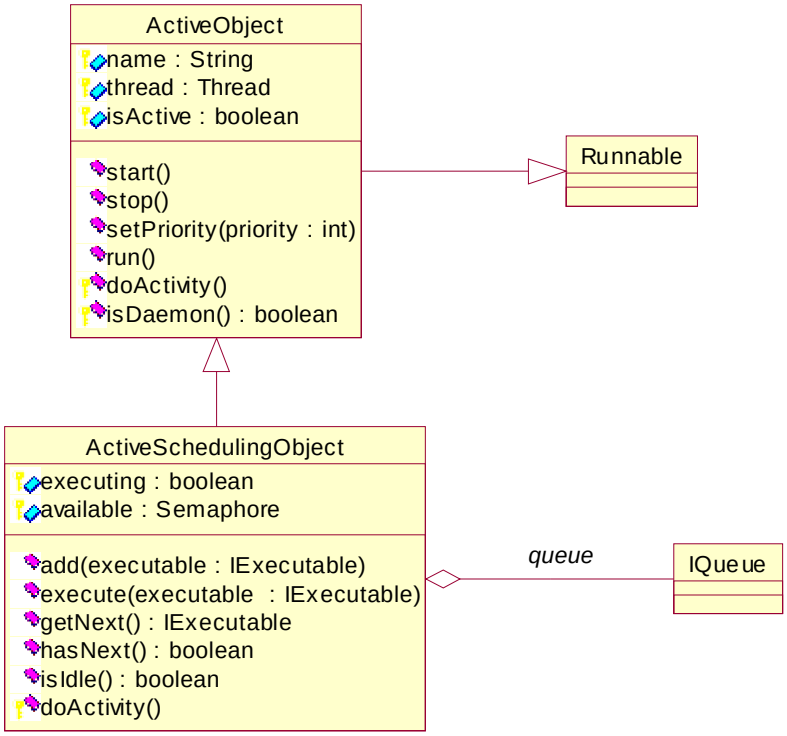

Figure 2-5: General-purpose active object classes

Class `ActiveSchedulingObject` uses a consumer thread that consumes objects from a shared queue and executes them one by one. Agents in Janet act as producers that insert commands they received from other agents into the queue of their scheduler. These schedulers are subclasses of `ActiveSchedulingObject` from which they inherit the functionality for synchronization between threads.

2.2.1.1 Command Schedulers

The kinds of schedulers for executing commands are the supreme scheduler, the system schedulers and the application schedulers. These schedulers are subclasses of the common base class `PriorityCommandScheduler` that inherits from `CommandScheduler`. Class `CommandScheduler` is specialized on scheduling commands. `PriorityCommandScheduler` is a `CommandScheduler` that uses a priority queue. All schedulers are located in the package `org.objectscape.janet.cas.schedulers`. Contrary to the supreme scheduler, the system schedulers and application schedulers interoperate with their arbitrator so that the arbitrator is able to time slice them. These two kinds of schedulers are therefore called arbitrated schedulers.

The arbitrated schedulers notify the arbitrator when they received a command or when they have become idle. A scheduler is considered idle when its queue of commands has become empty and when it is not executing a command. An arbitrated scheduler knows the application

it serves. It is therefore able to calculate the time slice it receives by its arbitrator (depending on the number of agents hosted by the application).

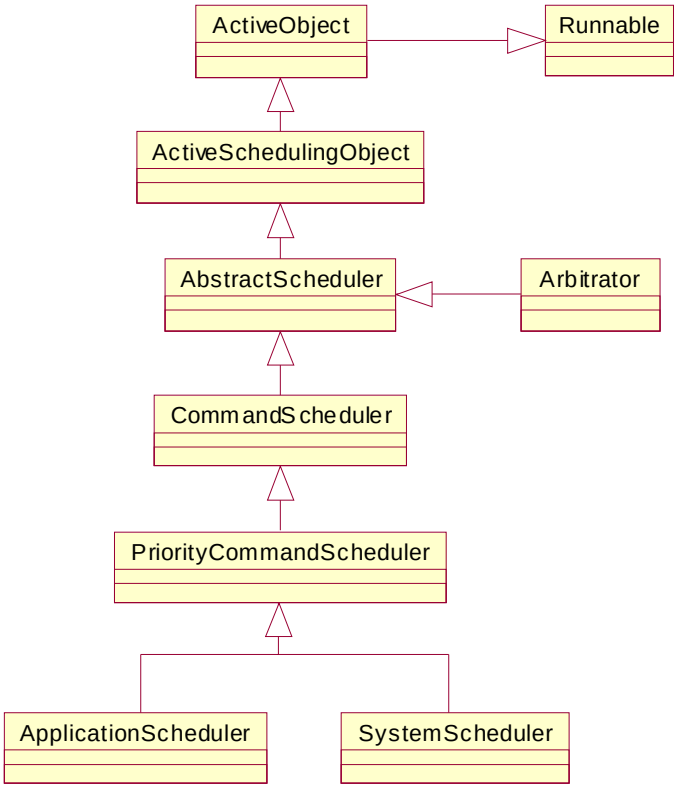

Figure 2-6: Overview of the scheduler hierarchy

It also knows the capability of the agent for logging purposes. The system schedulers run with second highest priority a scheduler must have in the system whereas the application schedulers run with the lowest priority.

2.2.1.2 Arbitrator

The arbitrator makes sure that every arbitrated scheduler receives a fix quantum of the CPU time. When there is only one running arbitrated scheduler present, the arbitrator remains idle as no time slicing is required. The single application scheduler is stored in the attribute `singleScheduler`.

Activating a Sleeping Application Scheduler

When an arbitrated scheduler is created it is added to the list of sleeping schedulers. Whenever a command is added to an arbitrated scheduler the arbitrator is notified by sending the message `commandAddedTo(ApplicationScheduler)`:

- If the arbitrated scheduler was sleeping and there is no running scheduler (neither in the list of running schedulers nor a single running application scheduler), it becomes the single running arbitrated scheduler.

- If the arbitrated scheduler was sleeping and there is a single running arbitrated scheduler present, both arbitrated schedulers are removed from their current locations and added to the list of running schedulers.

- If the arbitrated scheduler was sleeping and there are two or more running arbitrated schedulers, it is added to their list.

No actions need to be taken in case the arbitrated scheduler was not sleeping.

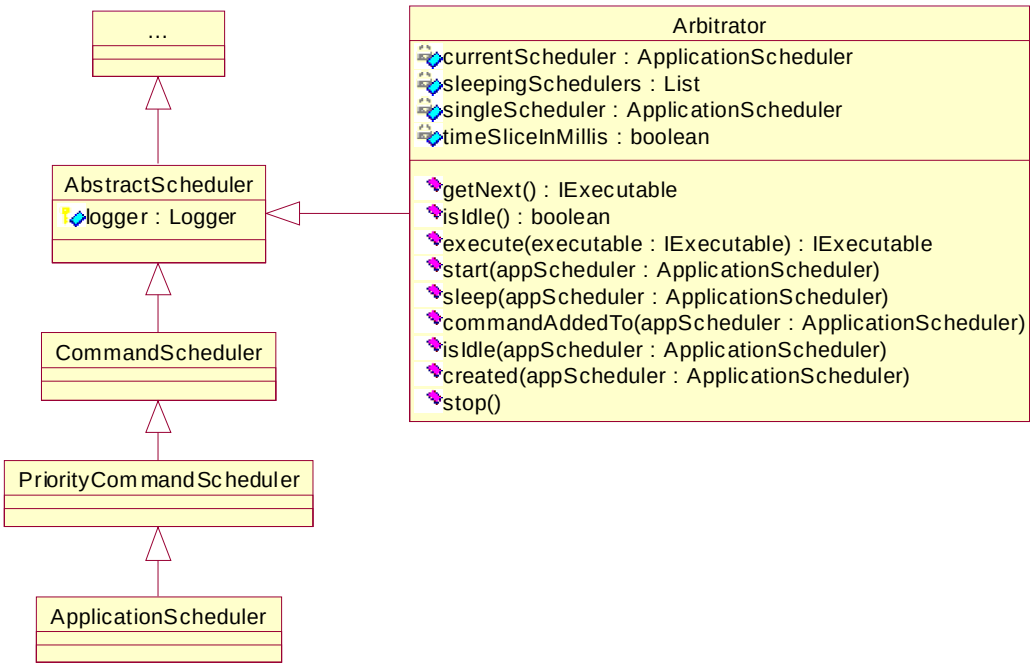

Figure 2-7: Basic arbitrator class hierarchy

Time Slicing Arbitrated Schedulers

The arbitrator starts time slicing arbitrated schedulers when the list of running arbitrated schedulers contains two or more entries. It removes the next running arbitrated scheduler and examines it:

- If the examined arbitrated scheduler is not idle, the arbitrator lowers the priority of the arbitrated scheduler that received the last time slice and raises the priority of the new current arbitrated scheduler. Thereafter, the arbitrator sleeps for the duration of the time slice, which causes the current arbitrated scheduler to be the single running one for the duration of the time slice. The current arbitrated scheduler is then re-inserted at the end of the list of running arbitrated schedulers and the next arbitrated scheduler is picked. If several agents share an arbitrated scheduler, the time slice for the arbitrated scheduler is divided by the number of agents for fairness reasons. If the arbitrated scheduler that receives the current time slice has not been started so far, the arbitrator starts it.

- If the examined arbitrated scheduler has meanwhile become idle, it is added to the list of sleeping schedulers. If this results in a single running arbitrated scheduler being left in the list of running arbitrated schedulers, it is removed from it and becomes the single running arbitrated scheduler and the arbitrator falls asleep till the list of running schedulers contains two or more running arbitrated schedulers.

When an arbitrated scheduler becomes idle it notifies the arbitrator about it sending the message `isIdle(ApplicationScheduler)`. If it was the single running arbitrated scheduler, it is added to the list of sleeping schedulers.

The arbitrator can be asked whether it is idle by sending the message `isIdle` to it. The arbitrator then determines whether any running schedulers and no single running arbitrated scheduler exist.

2.2.2 Commands and Interpreters

Defining an agent's behavior in Janet means to define interpreters and commands. Commands serve as performatives for the agent to invoke applicable interpreters and they serve for carrying input and output parameters of the interpreters. This section describes how to implement commands and interpreters.

2.2.2.1 Implementing Commands and Interpreters

Creating a command that can be sent to an agent requires the construction of a command-interpreter-pair. The user is free to add attributes to a command object. The command object must implement the interface org.objectscape.janet.cas.schuling.ICommand and be serializable:

```
public interface ICommand extends Cloneable
{
      public String getQualifiedName();
      public int getPriority();
      public String toLogString();
}
```

Figure 2-8: The ICommand interface

The method `getQualifiedName` must return the fully qualified name of the command the interpreter receives its input parameters from. This name is used by the interpreter associated with the command to inform a scheduler which commands it is intended to interpret.

The method `getPriority` returns the priority of the command according to which it will be inserted into the respective priority queue of the scheduler it was added to. Note that the order of execution with commands of different priority may not be the same as the order of receipt by the agent. If the scheduler queue is already filled with commands, a newly arrived command will not necessarily be executed immediately but remain waiting in the queue like other commands that were received before or after. A command with a high priority can therefore overtake a command with a low priority that arrived before it. It is therefore important not to make assumptions about the order of execution when defining commands with different priorities.

The method `toLogString` must not strictly be defined, but it is recommended to do so. It is used to write log information to the log stream.

The interpreter associated with the command must implement the interface org.objectscape.janet.cas.schuling.IInterface:

```
public interface IInterpreter
{
	public void execute(CommandAccessor cmdAccessor);
	public StringList getCommandNames();
}
```

Figure 2-9: The IInterpreter interface

The method `commandNames` must return a `StringList` with the command names of the commands that are executed by the interpreter (in most cases the `StringList` contains a single command name). The schedulers use the command names to look up the associated interpreter to execute a command. The scheduler selects the first hit. It is therefore important to specify the fully qualified command name to rule out ambiguities.

The method `execute` is the core method of every interpreter. It is the point where execution starts and where required parameters are passed on from the command to the interpreter.

2.2.2.2 Executing a Command

Executing an interpreter is the core mechanism to make an agent do something. The definition of the `execute` method of a sample interpreter is therefore explained in further detail.

```
public void execute(CommandAccessor cmdAccessor)
{
	if (cmdAccessor.getCommand() instanceof MyCommand)
	{
		MyCommand cmd = (MyCommand) cmdAccessor.getCommand();
		doSomething(cmd.getInput()));
	}
}
```

Figure 2-10: Sample interpreter execute method

The sample interpreter in Figure 2-10 receives its input from the command contained in the method parameter `cmdAccessor which holds the CommandAccessor`. After the `doSomething` method has finished execution, execution of the interpreter is finished and the next command in the scheduler's command queue is executed.

2.2.2.3 CommandAccessor

The `CommandAccessor` passed on to the interpreter `execute` method is the entry point for the interpreter to obtain the command it is asked to execute with its input parameters and to the node object with all its inner objects. The `Node` class defines methods that are declared public so that system interpreters that need to access the node's inner objects in order to manage the

node can call them. But the node's inner objects must not be accessed by application interpreters defined by the user as this would allow the user to endanger the functioning of the system, retrieve information she is not privileged to have, or alter other applications. The purpose of the CommandAccessor is to provide guarded access to the node only allowing the user to access objects it has privilege to.

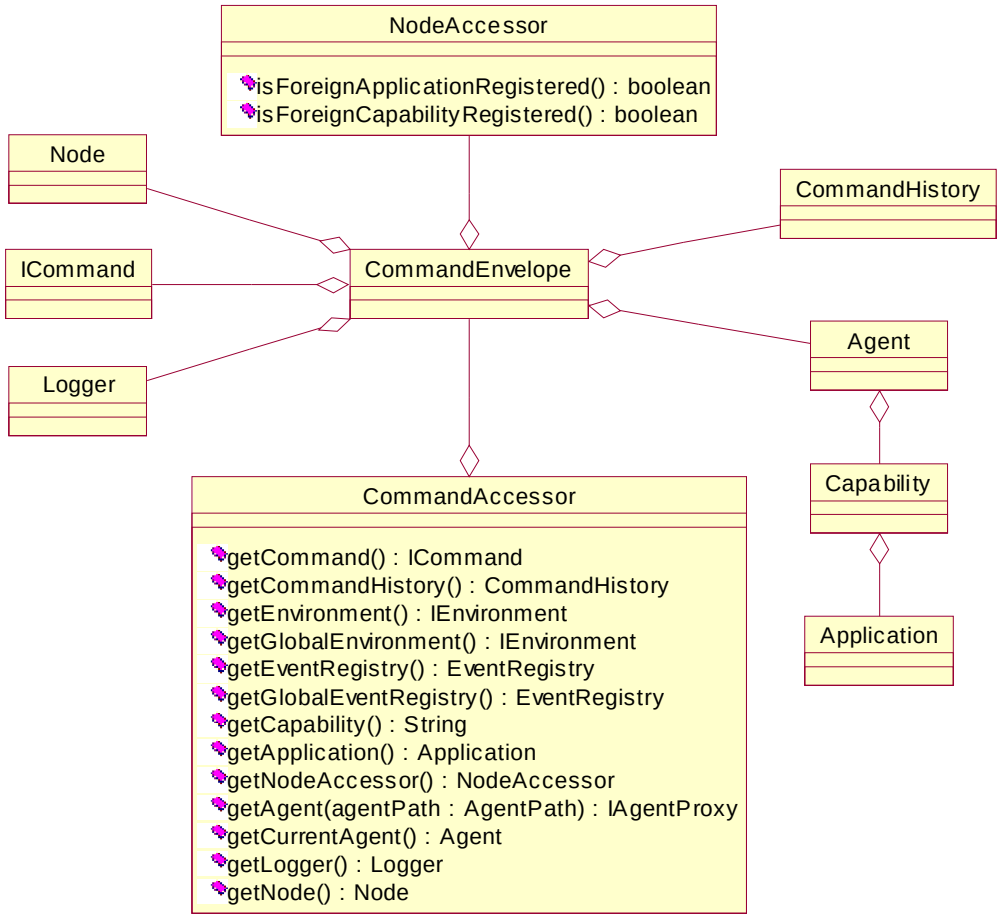

Figure 2-11: Aggregation of the CommandAccessor

If an interpreter executed by an application agent (and not a system agent or the supreme agent) calls methods of the `CommandAccessor` that give access to the node's inner objects an `InsufficientPrivilegeException` is thrown. On the other hand, the CommandAccessor grants the user full access to all objects referenced by its own application.

2.2.3 Sending Commands to Agents

Sending a command to another agent is the core mechanism to make agents communicate in Janet. This section describes in detail how to narrow another agent and how the agent dispatch mechanism is implemented.

2.2.3.1 Agent Dispatcher

When a command is physically sent across the network it is sent to the agent dispatcher RMI server object that resides on the workstation of the destination agent. With the use of the RMI server object a RMI client is able to acquire a reference to the remote object.

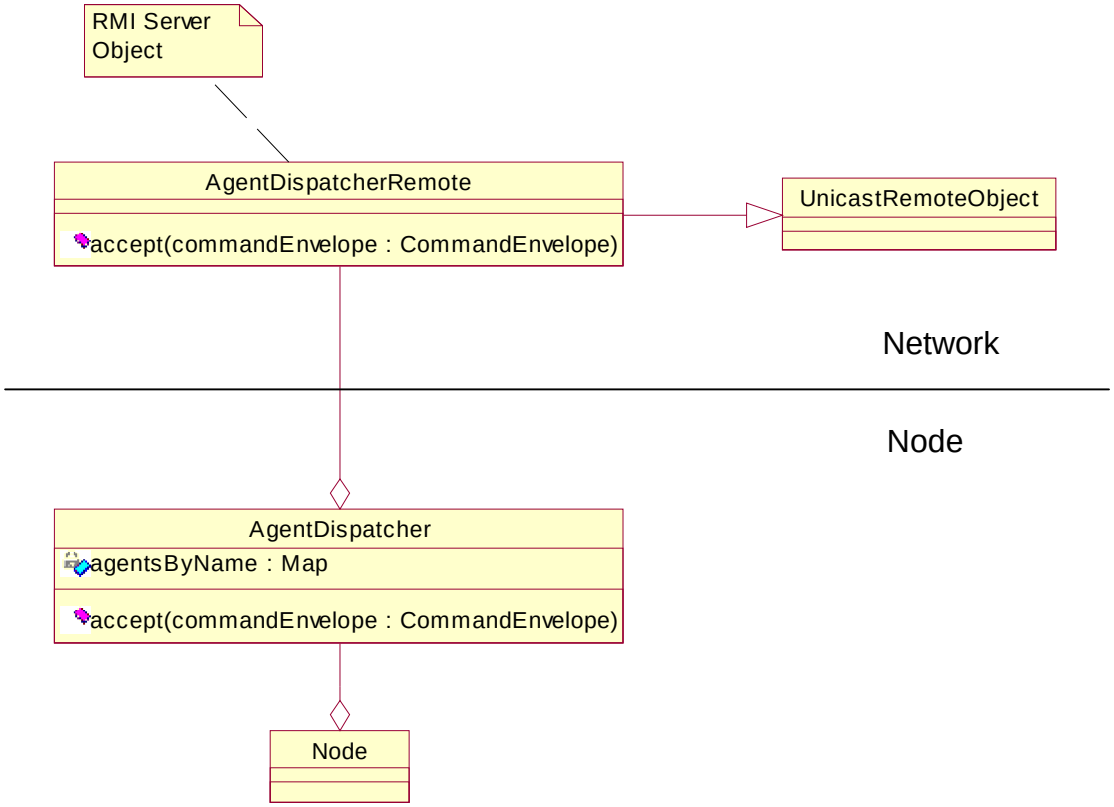

Figure 2-12: Agent dispatcher aggregation

The RMI client passes the command over to the agent dispatcher RMI server object (implemented by class `AgentDispatcherRemote`) that in turn passes it on to the node's agent dispatcher. Class `AgentDispatcherRemote` serves as a network-visible proxy for the agent dispatcher itself. The simplicity of the command pattern as applied in Janet makes it possible for the interface of the agent dispatcher RMI server object to be very simple: it consists of the single method `accept(CommandEnvelope)`. The `CommandEnvelope` is a messenger object that is used to transport a command from agent to agent. It knows the destination agent's location and carries additional information for bookkeeping and other purposes from node to node. The `CommandEnvelope` is explained in further detail later in this chapter.

Need for an Agent Dispatcher

The main purpose of the agent dispatcher is to minimize the number of RMI server objects. The more of them are registered with the RMI registry the more open network connections exist. There should be no limitation to the number of agents that can be started on a node. For this reason, it makes sense to use a single agent dispatcher for every node that receives all com-

mands that are sent to any agents on the same node. The agent dispatcher then passes the command on to the respective agent. Another problem is that binding and unbinding a RMI server object with the RMI registry, which makes it visible within the network or removes it from the network, is a time consuming process that typically takes up to half a minute or more even on a simple network. Quickly creating a new agent when one is needed and registering it would not be possible. In addition, sending an agent from one node to another would require it to be unbound at the source node and be bound at the destination node which would take unacceptably long time. Agents in Janet are not mobile. Nevertheless, the use of an agent dispatcher results in a more flexible design, which leaves options open for sake of extendibility, for example, extensions for mobile agents.

Dispatching Commands

The command object, when sent across the network, is contained by a command envelope. The command envelope contains the fully qualified name of the destination agent. The agent dispatcher contains a map to store agents by their fully qualified name. When the system starts an agent it registers the agent with its fully qualified name with the agent dispatcher. When dispatching a command the agent dispatcher looks up the agent from its store and passes the command on to the agent. Before doing so, the agent dispatcher adds some bookkeeping information to the command envelope's travel history.

2.2.3.2 Sending Commands to Agents: User Interface

Sending a command to an agent with the use of a command envelope and an agent dispatcher requires good understand of the inner workings of Janet.CAS. A user interface has therefore been designed to shield the inner workings from the user when sending commands to agents.

Agent Proxies

Agent proxies are introduced to make sending a command to an agent a simple process for the user. The agent proxy hides the complexity of sending a command to an agent from the user. The user can obtain an agent proxy from the application she created. An agent acts by executing an interpreter in response to a received command. This means that sending a command from an agent to another has to be done within the `execute` method of an interpreter or within methods being called from it.

```
public class MyInterpreter implements IInterpreter
{
    // …
        public void execute(CommandAccessor cmdAccessor)
        {
                if(cmdAccessor.getCommand() instanceof MyCommand)
                {
                    ICommand myCommand = new MyCommand();
                    IAgentProxy agent = cmdAccessor.getAgent("nodeName");
                    agent.accept(myCommand);
                }
        }
        // …
}
```

Figure 2-13: Using an agent proxy

Figure 2-13 on page 29 shows some sample code where a command is sent to an agent on the node `nodeName` from within the interpreter `MyInterpreter`. The destination agent has the same agent path as the sending agent, but resides on the node `nodeName`. An agent path is used to uniquely identify an agent within the cluster.

Agent Path

The sample code in Figure 2-14 shows how a command is sent to an agent identified by its agent path. The agent path must contain the destination agent's node name, application name, capability name, and the name of the agent itself.

```
// …

if(cmdAccessor.getCommand() instanceof MyCommand)
{
	ICommand myCommand = new MyCommand();
	AgentPath agentPath = new AgentPath(
		"nodeName",
		"myApplication",
		"myCapability",
		"myAgentName");
	IAgentProxy agent = cmdAccessor.getAgent(agentPath);
	agent.accept(myCommand);
}

// …
```

Figure 2-14: Obtaining an agent proxy using an agent path

The agent proxy's `accept` message verifies whether the user has supplied a valid agent path. The node stores in its local cluster image the agent paths to existing agents in the cluster. It knows about them as every node that creates or removes an agent sends a notification about the event to all other nodes in the cluster. When accepting a command the agent proxy looks up in the node's cluster image whether the user-supplied agent path exists. The exception `NoSuchAgentException` is thrown if it this is not the case.

If the agent path is valid the agent proxy checks whether the application name of the sending agent and the recipient agent are identical. If this condition is not met a protection violation has been detected, as agents must not communicate across application boundaries using commands (they may do so with the use of undirected events on a publish-subscribe basis), and the exception `IllegalAgentAccessException` is thrown. The system agents and the supreme agent are allowed to send commands across application boundaries which is required to implement core functionality efficiently. But application-defined agents are forced to use events. Figure 2-15 on page 31 shows how a command is sent to the agent itself that executes the current command using the message `getCurrentAgent`. The required try-catch-blocks to handle these exceptions have been omitted from the sample code for sake of brevity.

The `CommandAccessor` provides several convenience methods for obtaining an agent proxy that are delegate methods of class `AbstractApplication`. These methods fill in the application name, capability name, and agent name depending on which method was called into the agent path.

```
// …

if(cmdAccessor.getCommand() instanceof MyCommand)
{
      ICommand myCommand = new MyCommand();
      IAgentProxy agent = cmdAccessor.getCurrentAgent();
      agent.accept(myCommand);
}

// …
```

Figure 2-15: Sending a command to the agent itself

Multi Agent Proxies

If the same command has to be sent to several agents at once the `MultiAgentProxy` iterates over all agents to send the command to them and frees the user from doing so herself. In Figure 2-16 the command is sent to all agents in the cluster with the same agent path as the current agent.

```
// …

if(cmdAccessor.getCommand() instanceof MyCommand)
{
      ICommand myCommand = new MyCommand();
      IAgentProxy agent = cmdAccessor. getAllForeignAgents();
      agent.accept(myCommand);
}

// …
```

Figure 2-16: Using a MultiAgentProxy

The MultiAgentProxy implements the `IAgentProxy` interface like the `AgentProxy`. It clones a command before sending it to the destination agent. This makes sure that in simulated mode, where all nodes run in the same Java virtual machine, and when commands are sent to agents with the same node (and therefore live on the same Java virtual machine using the same heap space) each recipient agent works on a copy of the original just as in distributed mode or when sending a command to an agent on a different node (where the command is necessarily copied due to the marshalling process). Without cloning the command, each recipient agent living in the same heap space would receive a pointer to the same command that is also being processed by the other recipient agents resulting in command state data to be changed without synchronization.

Installing a Callback Handler

If an agent expects a value to be returned from the destination agent it can pass on a callback handler to the agent proxy's `accept` method as shown in Figure 2-17 on the next page.

```
1   // …
2
3   if(cmdAccessor.getCommand() instanceof MyCommand)
4   {
5         ICommand myCommand = new MyCommand();
6         IAgentProxy agent = cmdAccessor.getAgent(“nodeName”);
7         ICallbackHandler handler = new MyCallbackHandler();
8         agent.accept(myCommand, handler);
9   }
10
11  // …
```

Figure 2-17: Installing a callback handler

After the callback handler has been passed on the thread continues execution. The callback handler will be invoked when the reply of the destination agent has arrived. Figure 2-18 shows how to define a callback handler by implementing the interface `ICallbackHandler` which requires the method `handle` to be defined.

```
public class MyCallbackHandler implements ICallbackHandler
{
      // …

      public void handle(Object callbackParameter)
      {
            // process result
      }

      // …
}
```

Figure 2-18: Handling the callback

2.2.3.3 Sending Commands to Agents: Implementation

The previous section described the steps the user has to take to send a command from an agent to another one where agent proxies were used to hide the complexity of the underlying mechanism. The following explains what happens within the agent proxy to send the command to the destination agent.

2.2.3.3.1 General Mechanism

This section describes the mechanism to send a command across the network from one agent to another. The description explains the steps that need to be carried out in Janet.CAS to send a valid command envelope to the destination agent’s node agent dispatcher. It does not explain the concept of RMI or inner workings of it.

Command Envelope

When a command is sent from an agent to another agent, and later on is eventually sent back, the system keeps a history of the visited agents and travel times. Bookkeeping travel times is needed for performance measurements. After a command has arrived at an agent it needs to have a reference to the recipient agent as an entry point to access the agent's application, object space and the node itself in case a system command is executed. Adding the required attributes to hold the references to these objects to an abstract superclass of the command class would result in the user not being free to choose the superclass of its command. For this reason, the interface ICommand is defined that must be implemented by all commands. The needed attributes are defined in another class that also carries the command from agent to agent which is class `CommandEnvelope`.

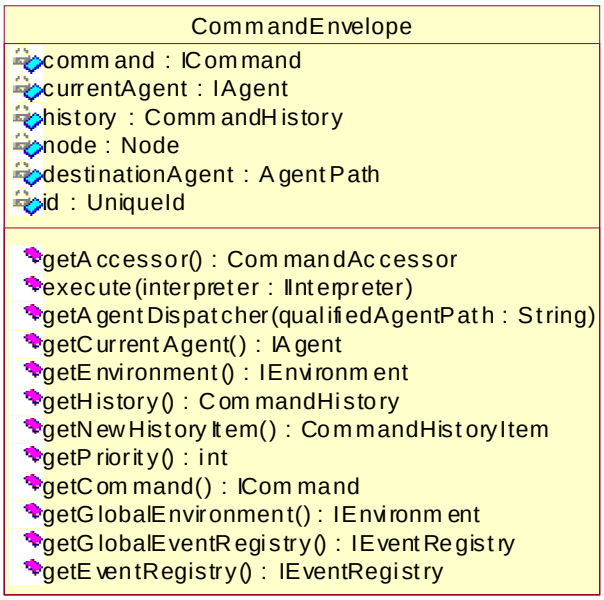

Figure 2-19: CommandEnvelope basic class description

Using the Agent Dispatcher to send a Command

After the agent proxy has created the command envelope it adds bookkeeping information to it (e.g., the send time), clears variables storing objects that must not be serialized (like the current agent or the node object). It then sends the `accept` message to the destination agent's agent dispatcher with the command envelope as the parameter which results in the command envelope to be physically sent across the network to the workstation hosting the destination node. The agent dispatcher is a reference to the RMI server object agent dispatcher of the destination agent's node. The agent proxy obtained a reference to the agent dispatcher when it was instantiated from the node's cluster image that holds the RMI server object agent dispatchers of all other nodes, which were added to it during the node startup procedure. To get a reference to the RMI server object agent dispatcher the agent proxy needs to provide the destination agent's node name.

2.2.3.3.2 Extensions for Callbacks

To invoke callback handlers, class `CommandEnvelope` is extended by a specialized command envelope. The abstract class `CommandResponseEnvelope` is introduced as a subclass of `CommandEnvelope` that takes care of sending the command envelope back with some return value to the sending agent after the interpreter, invoked by the destination agent to execute the command, has finished execution.

When the agent proxy accepts a command for which a callback handler has been supplied, it instantiates class `CommandCallbackEnvelope`, which is a subclass of `CommandResponseEnvelope`, instead of class `CommandEnvelope` as in the general case when no callback handler is supplied. It places the callback handler in the agent's application object space and stores the callback handler's application object space lookup key in the attribute `responseId`. The class hierarchy for class `CommandCallbackEnvelope` with most important attributes and methods is displayed in Figure 2-20.

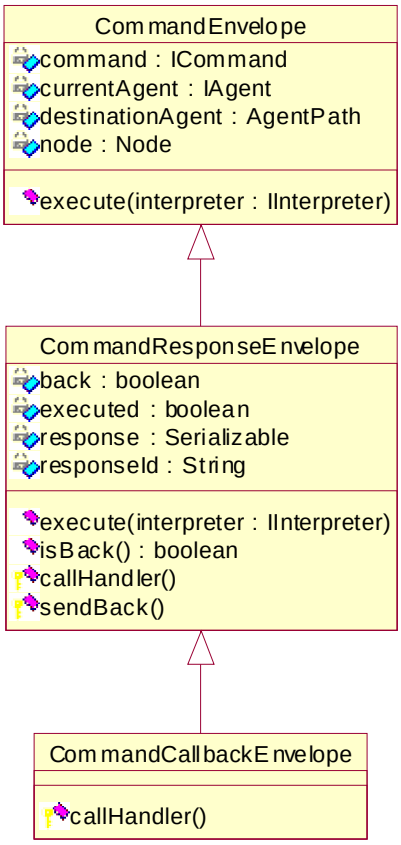

Figure 2-20: CommandCallbackEnvelope class hierarchy

The main extension in class `CommandResponseEnvelope` is to redefine the inherited execute method.

```
1    public abstract class CommandResponseEnvelope
2    extends CommandEnvelope
3    {
4          // …
5          public void execute(IInterpreter interpreter)
6          {
7                if (!executed)
8                {
9                      super.execute(interpreter);
10                     executed = true;
11                     sendBack();
12               }
13               else
14               {
15                     callHandler();
16               }
17         }
18         // …
19   }
```

Figure 2-21: Redefined execute method for class CommandResponseEnvelope

Figure 2-21 shows the `CommandResponseEnvelope's execute` method. If the `Command-ResponseEnvelope's` command has not been executed so far, the inherited `execute` method from class `CommandEnvelope` is called (line 9). The `CommandResponseEnvelope` then marks the command as having been executed (line 10) and sends the command envelope back by calling `sendBack` (line 11). When the command envelope has arrived back at the sending agent it is executed and the method `callHandler` is called (line 15). The method `callHandler` is declared abstract in class `CommandResponseEnvelope`.

```
public class CommandCallbackEnvelope
extends CommandResponseEnvelope implements Serializable
{
      // …
      protected void callHandler()
      {
            IObjectSpace env = getCurrentAgent().getObjectSpace();
            ICallbackHandler handler =
                  (ICallbackHandler) env.remove(responseId);
            handler.handle(response);
      }
      // …
}
```

Figure 2-22: Invoking the callback handler

It is defined in class `CommandCallbackEnvelope` as displayed in Figure 2-22. The callback handler stored in the sending agent's object space before the command was sent to the destina-

tion agent is taken from the object space and the callback handler is called passing on the response.

2.2.3.4 Convenience Facility: Synchronous Command Sends

All commands sends in Janet are asynchronous following the agent-oriented paradigm. In some situations the application logic requires that an agent needs to wait till some other agent has finished executing a command it had sent to the other agent before it can continue. In Janet.CAS this is for example the case during the startup-process where the system agents has to wait till it has received an acknowledgement from all other nodes in the cluster. Using asynchronous commands makes sure that the application cannot get stuck because of commands creating a deadlock situation. But in some situations it is convenient to use a synchronous command, as this would simplify application logic considerably. Janet.CAS provides a facility for the user that blocks the current thread till the response of the other agent has arrived and then unblocks it. It is left to the responsibility of the user to use this facility only in cases where it is justified not to compromise the agent-oriented paradigm by not using asynchronous commands.

2.2.3.4.1 User Interface

This section describes the user interface for using synchronous commands to receive an acknowledgement by the destination and to receive a reply synchronously. The next section explains the details of the inner workings of the facility to send synchronous commands.

Waiting for Acknowledgement

The sample code in Figure 2-23 shows how to send a command to an agent that requires an acknowledgement by the recipient agent that is sent back after the recipient agent has executed the command.

```
    // …
 1  if(cmdAccessor.getCommand() instanceof MyCommand)
 2  {
 3        ICommand myCommand = new MyCommand();
 4        IAgentProxy agent = cmdAccessor.getAgent("nodeName");
 5        Acknowledgement ack = new Acknowledgement();
 6        agent.accept(myCommand, ack);
 7
 8        try
 9        {
10              long timeOutPeriodInMillis = 2000;
11              ack.acquire(timeOutPeriodInMillis);
12        }
13        catch (TimeoutException e)
14        {
15              // handle timeout
16              return;
          }
    }
    // …
```

Figure 2-23: Waiting for an acknowledgement

From the sample code in Figure 2-23 on the previous page it can be seen that the user interface is on principle the same than when sending a command asynchronously. The only difference to the agent proxy's `accept` method is that an acknowledgement object has to be passed on (line 8). After the command has been sent away the current thread has to be blocked till the acknowledgment has arrived (line 13). If no timeout period is specified the sending thread is possibly blocked forever. A `TimeoutException` is thrown if the acknowledgement has not arrived before the timeout period has expired. When a command is sent to a `MultiAgentProxy` and an acknowledgement is requested the `MultiAgentProxy` waits till the acknowledgements from all destination agents have arrived.

Waiting for a Reply

The user interface for waiting for a synchronous reply from the destination agent is on principle the same than when waiting for an acknowledgement. As shown in Figure 2-24 a future result object is passed on instead of an acknowledgement object to the agent proxy's `accept` method (line 8). The result sent back from the destination agent to the sending agent has to be asked from the result object (line 13 + 14) that blocks the current thread until the reply has arrived.

```
1   // …
2
3   if(cmdAccessor.getCommand() instanceof MyCommand)
4   {
5         ICommand myCommand = new MyCommand();
6         IAgentProxy agent = cmdAccessor.getAgent("nodeName");
7         FutureResult futureResult = new FutureResult();
8         agent.accept(myCommand, futureResult);
9
10        try
11        {
12              long timeOutPeriodInMillis = 2000;
13              Object result =
14                    futureResult.getResult(timeOutPeriodInMillis);
15        }
16        catch (TimeoutException e)
17        {
18              // handle timeout
19              return;
20        }
21  }
22
23  // …
```

Figure 2-24: Waiting for a reply

If no timeout period is specified the sending thread is blocked possibly forever. A `TimeoutException` is thrown if the reply has not arrived before the timeout period has expired.

2.2.3.4.2 Implementation

The idea of a `CommandResponseEnvelope` to invoke a callback handler, installed by an agent before sending a command to another agent, was already introduced in section “2.2.3.3.2

Extensions for Callbacks". The `CommandResponseEnvelope` is sent back from the destination agent after executing the command. Upon receipt the `CommandResponseEnvelope's execute` method retrieves the callback handler from the agent's object space and passes on the callback value carried with it from the responding agent when invoking the callback handler.

Deadlock Problem due to Synchronicity

The same approach can be used to carry a reply value back synchronously from an agent to another. In addition, the thread running the sending agent has to be blocked till the reply has arrived. Waiting for an acknowledgment can be implemented using the same approach without having to pass on a reply value. This approach works well for implementing asynchronous callbacks. In case of synchronous replies or acknowledgments it has to be extended to prevent the deadlock from happening that would occur as the thread of the sending agent is still blocked at the time the response command arrives. Before the sending agent can execute the response command, which would unblock the agent's thread, it needs to finish execution of the current command. Because the agent schedulers execute one command till completion till they execute the next one and the current command is blocked waiting for the response command, the response command will never execute and the agent runs into a deadlock.

Solution

There is no solution than can work by adding the response command to the waiting agent's scheduler queue. One solution would be to let every agent have a shadow agent with its own scheduler that handles response commands. While this approach seems conceptually clean the result would be a duplication of the number of agents in a node which would be inefficient. This suggests that the solution would be to have a single agent to handle response commands. For this reason, an additional system agent is created that serves no other purpose than executing response commands. Since such a response agent is conceptually not important it has not been mentioned so far. It would also be possible to let every application have its response agent. For the time being, the simpler approach of having a single response agent for an entire node is considered sufficient and left as such until proven not to be sufficient. The response agent runs with system scheduler priority to minimize waiting times till a response command can be executed.

Blocking the calling thread is done using class `Latch` from Doug Lea's `util.concurrent` class library that contains several common classes for thread synchronization and inter-process communication. All synchronization in Janet is done using synchronization classes from this library, which is described in [LEA99].

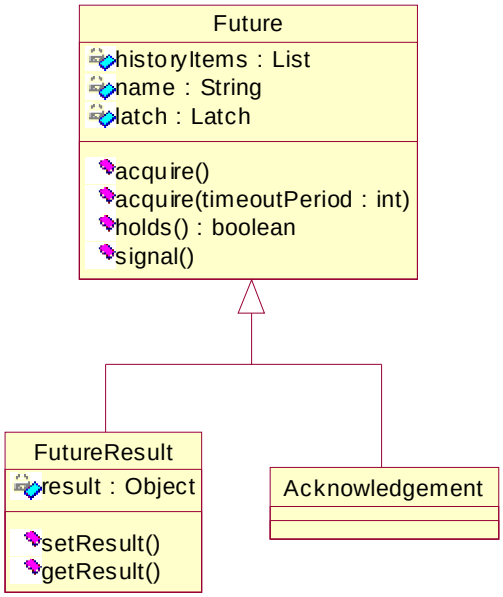

Figure 2-25: Future objects to block calling threads

2.2.4 Object Spaces

The idea of object spaces is to supply agents with a store where they can insert objects that need to be present permanently and must not go out of scope after an interpreter has finished execution. Object spaces can also be used as a convenient way to share information between agents.

2.2.4.1 Overview

There are object spaces on three levels: application-level, node-level, and cluster-level. All object spaces allow agents to exchange objects or store objects that need to remain alive after a command has finished execution. All object spaces implement the same interface and are synchronized.

- Application Object Space: Agents that belong to the same application and node have access to the application object space, which can be obtained from the agent's application object.

- Node Object Space: Agents that belong to the same node, but not necessarily to the same application, can access the node object space, which can be obtained from the agent's node object or its accessor object.

- Cluster Object Space: All agents in the cluster can access the cluster object space independently from the node they reside on or the application they live in. This object space is a RMI server object, which any agent can access directly using the object space's interface without sending commands. The number of cluster object spaces in the cluster is arbitrary. For cluster object spaces to be visible to agents, they must be defined in the node descriptor. The node descriptor defines a node's statically defined applications with their capabili-

ties and agents. It is read at node startup time. Node descriptors are presented in detail for the driving applications presented in this chapter.

```
<clusterObjectSpaces>
  <clusterObjectSpace name="sharedSpace1"
      hostame="myWorkstation1" port="1099" />
  <clusterObjectSpace name="sharedSpace2"
      hostname="myWorkstation2" port="1099" />
</clusterObjectSpaces>
```

Figure 2-26: Defining cluster object spaces in the node descriptor file

Figure 2-26 shows an excerpt from a node's descriptor file that defines a cluster object space named "sharedSpace1" and "sharedSpace2" that reside on the workstations "myWorkstation1" and "myWorkstation2". The RMI registry, to which they are bound to, is connected to port 1099. When a node starts up, it checks whether it resides on any workstation listed in the `clusterObjectSpaces` section of the node descriptor. If so, it creates one and binds it with the local RMI registry, or looks it up in case it was already bound by some other node on the same workstation that had started up before.

2.2.4.2 Message-Passing vs. Shared Memory

In distributed computing there are two computing models that are based on message-passing and shared memory. Discussing which model is the better one is an arduous task that yields no benefits for this work. In most cases, the decision, which model is the better choice, depends mostly on the given situation (requirements, hardware setup, etc.). Both models have their advantages and disadvantages:

- Message-Passing

+ Controlled execution: no race conditions, protection
+ Explicit control makes performance issues clear
- Difficult to program, especially for irregular, dynamic programs

- Shared Memory

+ Easier to program, graceful migration path, hence attractive
+ Works well on moderate-scale tightly-coupled systems
- Race conditions, synchronization hazards, fault intolerance

Janet is clearly based on the message-passing model where commands take over the role of messages. Other systems, like JavaSpaces, are clearly based on the shared memory model. Janet's cluster object space can be used to a limited extend as a shared memory space in the sense of the shared memory model. However, this would obstruct the intention in which the system was designed and is not recommended. In any event, the cluster object space is by no means that comfortable and rich in functionality as shared memory spaces provided by JavaSpaces or other shared memory systems. Janet's cluster object space intentionally provides no way to register callbacks for events that happen inside the object space. Object spaces in Janet are intended to be used as spaces to store data that needs to survive after a certain action. They

can also be used to exchange information between agents without having to exchange commands to obtain this knowledge when cooperating agents know that the information is present in the object space. For example, if an agent knows that some other agent periodically provides some information to the public by inserting it into the object space, it can obtain this information directly from the shared object space without having to pay for the overhead inherent to message-passing.

2.2.4.3 Interface

The object space interface `org.objectscape.janet.cas.spaces.IObjectSpace` in Janet resembles the interface for an associative container: objects can be stored and retrieved from the object space using a lookup key associated with the object. Being able to store and retrieve objects is not flexible enough in case an agent needs to attach some specific information to an existing object inserted by some other agent. The object space interface therefore allows the user to attach objects to objects already existing in the object space or detach objects from them using attacher and detacher objects. These objects must implement the interfaces `IAttacher` or `IDetacher` in `org.objectscape.janet.cas.spaces` displayed in simplified form in Figure 2-27 and Figure 2-28.

```
public interface IAttacher
{
	public void attach(Object attachment, Object object);
}
```

Figure 2-27: Simplified IAttacher interface

```
public interface IDetacher
{
	public Object detach(Object object);
}
```

Figure 2-28: Simplified IDetacher interface

```
// …
ISerializableObjectSpace env1 =
	node1.getClusterObjectSpace("sharedSpace");

ISerializableObjectSpace env2 =
		node2.getClusterObjectSpace ("sharedSpace");

String key = TimeUtility.now();	// return the current time as a string
env1.put(key, new Vector());
String attachment = "foo";
env2.attach(key, attachment, new ListAttacher());
String detachment = (String) env1.detach(key, new ListDetacher());
// …
```

Figure 2-29: Using IAttacher and IDetacher objects

The code sample in Figure 2-29 shows how to use attacher and detacher objects with a cluster object space to add an object to a `Vector` and remove the first object from the `Vector` using a `ListAttacher` and a `ListDetacher` object that implement `IAttacher` and `IDetacher`. The variables `attachment` and `detachment` end up holding the same value.

Attacher and detacher objects can also be installed in the object space for every object that exists in the object space so that they are always used when `attach(String key, Object object)` or `Object detach(Object object)` in `IObjectSpace` are called. This gives the inserting agents control over what other agents can do with the objects they inserted. When using the cluster object space the interface defines that only instances of `Serializable` may be stored in the object space in contrast to the application object space and the node object space where instances of `Object` may be used as well.

2.2.5 Event Registries

Analogously to object spaces, there are event registries on three levels: application-level, node-level, and cluster-level. The application-level event registry allows agents of the same application to be notified about events. Using the event registry on node-level agents of different applications residing on the same node may notify each other about event occurrences. Finally, the cluster-level event registry allows agents of different applications on different nodes to communicate through events.

Fairness: Who pays for the Execution of an Event Handler?

When the handler of a signaled event is executed the event registry has to make sure that the agent that benefits from the execution of the handler pays for the CPU cost of executing it. The interface for registering an event handler therefore requires that an agent is specified that executes the event handler. After an event was signaled the event registry wraps the event handler with the event parameters received by the signal into a command and sends it to the specified agent.

2.2.5.1 Executing Event Handlers

The event registry uses the system command `ExecuteEventHandlerCommand` as a command wrapper for the event handler. Instead of using user-level agent proxies, the event registry creates the command envelope itself and plugs the `ExecuteEventHandlerInterpreter` in. When the `ExecuteEventHandlerCommand` is executed the interpreter associated with the command will not be looked up from the agent's capability but taken from the command envelope. This is a departure from the concept where an agent chooses the interpreter for executing a command himself. The reason this is done in this case, is to free the user from having to define the `ExecuteEventHandlerInterpreter` in every capability of every application she has defined. To predefine which interpreter is to be chosen for the execution of a command is only permitted on system-level. On application-level the user has no way of doing this as applications do not allow access to the node object, from which the respective agent dispatcher can be obtained to send a command envelope to an agent. The user is forced to use agent proxies instead.

As explained, executing an event handler results in a command being invoked of which the associated interpreter executes the handler in the end. Agents execute commands sequentially.

The idea of events is that events interrupt the program and notifies it about the event. The `ExecuteEventHandlerCommand` is executed with system priority, which means that it overtakes all application-level commands in the agents command queue (the user has no way to assign the system priority to an application-level command). Nevertheless, the `ExecuteEventHandlerCommand` will only execute after the currently running command has finished execution, or after other commands with system priority that might have been inserted into the queue before. If any waiting time till the `ExecuteEventHandlerCommand` is executed cannot be accepted for application-dependent reasons, the user may define a special agent for handling events or handling a specific event to which no other commands are sent.

2.2.5.2 Interface

The event registries of all three levels share the same interface. Obtaining a reference to an event registry is specific for each level. To register for an event the application that defines the executed interpreter has to be specified as well as an agent of this application, beside some other parameters. The agent will execute the `ExecuteEventHandlerCommand` that invokes the event handler. Figure 2-30 shows the registration, signaling, and deregistration of an event using an application-level event registry.

```
public class MyInterpreter implements IInterpreter
{
      // …
      public void execute(CommandAccessor cmdAccessor)
      {
 1     ILocalEventRegistry eventRegistry =
 2           cmdAccessor.getApplication().getEventRegistry();
 3     ApplicationAccessor app =
 4           cmdAccessor.getApplication().getAccessor();
 5     AgentPath agentPath =
 6           app.getLocalAgentPath("MyCapName", "MyAgentName");
 7     EventHandlerEnvelope item =
 8           new EventHandlerEnvelope(new MyHandler(), agentPath);
 9     HandlerList list = new HandlerList();
10     list.add(item);
11
12     eventRegistry.register(MyParams.EVENT_NAME, list, app);
13     assert(eventRegistry.getHandlerCount(MyParams.EVENT_NAME) == 1);
14
15     IEventParams params = new MyParams();
16     Event event = new Event(MyParams.EVENT_NAME, params);
17     eventRegistry.occurred(event);
18
19     eventRegistry.deregister(MyParams.EVENT_NAME, list);
20     assert(eventRegistry.getHandlerCount(MyParams.EVENT_NAME) == 0);
      }
      // …
}
```

Figure 2-30: Event registry partial interface

In line 1 + 2 the application event registry of the application that defines the executed interpreter is retrieved. Line 5 + 6 define an agent path of an agent with capability name `"MyCapName"` and agent name `"MyAgentName"`. Since the agent path is obtained from the application, node name and application name are set by the `getLocalAgentPath` method as appropri-

ate for the application. The event handler defined in line 7 + 8 needs to know which agent will execute the handler. The agent path is therefore passed on to the `EventHandlerEnvelope` constructor. The event handlers are installed in line 12. When the registration method is invoked, it re-inserts node name and application name into the agent paths of the handlers to make sure that the user cannot chisel by specifying an agent path of an agent on a different node or a different application. The event is signaled in line 17 and deregistered in line 19.

```
public class MyInterpreter implements IInterpreter
{
	// …
	public void execute(CommandAccessor cmdAccessor)
	{
		ILocalEventRegistry eventRegistry =
			cmdAccessor.getEventRegistry();
		// …
	}
	// …
}
```

Figure 2-31: Obtaining the node event registry

As shown in Figure 2-30 the application event registry is obtained from the application. The node registry is obtained from the command accessor, which provides a convenience method for that purpose, as the user cannot access the node object, as shown in Figure 2-31.

2.2.5.3 Cluster Event Registry

The cluster event registries of a cluster must be reachable by every node in the cluster. The cluster event registry could therefore be designed as a RMI server object in the same way as the cluster object space. Another possibility would be to use a special node to hold the cluster event registry. This more elaborated approach would provide greater flexibility and extensibility, for example, if more advanced features such as persistence or transactions had to be added. Since the implementation of such advanced features is beyond the scope of this work, the less effortful approach has been chosen, which is sufficient. Abandoning this approach and implementing the cluster event registry as a node later on would not result in a loss of much work.

Local Cluster Event Registries and the Cluster Event Registry

Every node has a local cluster event registry, where applications of the node register and deregister events, which are propagated by the local cluster event registry to the cluster event registry itself. When an event is signaled, the event handler registered in the local cluster event registry is invoked first. Thereafter, the signal is propagated to the cluster event registry. The cluster event registry in turn passes the signal on to all other local cluster event registries on all other nodes that have described for the event.

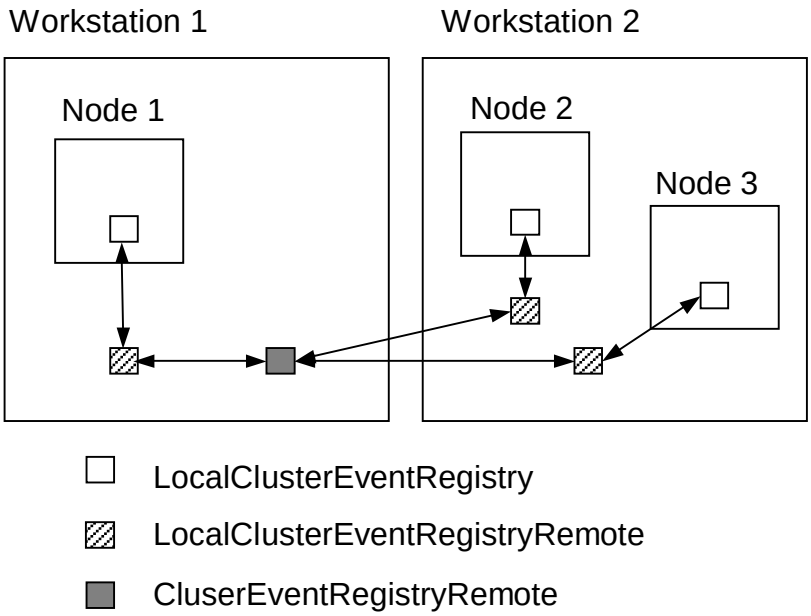

Figure 2-32: Cluster event registry with local cluster event registries

The sequence of actions when a cluster-wide registered event is signaled is display in Figure 2-32. The LocalClusterEventRegistryRemote RMI server object is needed for the Cluster-EventRegistryRemote to be able to pass an event on to a local cluster registry.

Node Descriptor Definition

For cluster event registries to be visible to agents, they must be defined in the node descriptor. The definition of cluster event registries is analogous to the definition of cluster object spaces. A sample cluster event registry definition from a node descriptor file is displayed in Figure 2-33.

```
<clusterEventRegistries>
   <clusterEventRegistry name="sharedEventRegistry1"
      hostname="myWorkstation1" port="1099" />
   <clusterEventRegistry name="sharedEventRegistry2"
      hostname="myWorkstation2" port="1099" />
 </clusterEventRegistries>
```

Figure 2-33: Defining cluster event registries in the node descriptor file

When the last node is shut down on a workstation where the cluster event registry resides the cluster event registry is also shut down. RMI, for security reasons, only permits an RMI server object to be unbound on the workstation where it is registered. The cluster event registry can therefore not be unbound from a remote workstation. The user needs to take caution when shutting down nodes. The node on the workstation where the cluster event registry resides must be shut down last. It is recommended to add the definition of a cluster event registry to the central's node descriptor as well.

When the central is started up first, the cluster event registry is bound with the local RMI registry on the same workstation as the central. Since the central has to be shut down last, no caution needs to be taken in which sequence to shut down nodes.

2.3 Driving Application: Fibonacci Numbers

It is useful when developing a system that serves as an application platform to develop a sample application, which serves as an example to show the user how to use the application platform. Another reason to develop a sample application is that by stepwise developing the sample application the application platform itself grows through the development process as new requirements become evident that were not clear to begin with. The sample application can also be used to validate architecture, conceptual design, and implementation of the application platform.

2.3.1 Fibonacci Numbers

Fibonacci numbers are calculated recursively. Calculation of large Fibonacci numbers therefore can take relatively long time, which is the reason that the calculation of these numbers is sometimes used to get a rough performance estimate of a computer. As a simple driving example for Janet.CAS an application is developed for the distributed calculation of Fibonacci numbers. From one Fibonacci agent commands are sent to all other Fibonacci agents on all other nodes to calculate a Fibonacci number. The sending agent calculates a Fibonacci number as well and waits till all results have returned. Thereafter, all results are displayed. The application is solely based on Janet.CAS and does not make use so far of Janet.ADÉ. This means that the recipient agents to calculate Fibonacci numbers are selected by the sending agent explicitly.

An agent-oriented system like Janet is not well suited for distributed number crunching. Compared to less flexible distributed applications architectures where peer-to-peer connections may be hard-wired, agents induce several additional indirections (such as dynamic agent lookup, use of schedulers, command queues, commands and interpreters), which only cause unnecessary overhead when calculation speed is the only important criteria. An agent-oriented system like Janet is well suited to solve complex problems where agents with their autonomy and ability to solve problems themselves, or part of them in conjunction with other agents, can be used to reduce complexity. Nevertheless, the CAS.Fibonacci sample remains useful since it only serves to explain how to use the most important features of the Janet.CAS layer. In addition, it is very useful to make performance measurements. It becomes possible to compare how much time it takes to calculate the same Fibonacci number on a single workstation n times and how much time it takes when n workstation in the cluster with one node each calculate the same Fibonacci number once. Later on, when the example is extended to serve as a driving application for Janet.ADÉ, a running Fibonacci command can be preempted and evicted from a node to level out workload imbalances. Because large Fibonacci numbers take several seconds to be calculated there is sufficient time available to provoke a load change that makes command preemption necessary. Since Fibonacci numbers are calculated recursively it is simple to interrupt the command, save its context, and resume it after arrival at the new node. When the system requires the Fibonacci command to suspend execution it stores the current state after the last iteration, tells the system that it is ready for migration, and after arrival at the new node resumes execution after the last iteration.

This sample application makes use of most features of Janet.CAS. When the Fibonacci commands are sent to all nodes in a round-trip fashion and finally return with the results most features of Janet.CAS have been made use of and are therefore validated and tested. Event notification is needed as well in the end when the results finally arrive and the calling thread has to be unblocked to resume execution. The CAS.Fibonacci sample does not make use of the cluster object space nor the cluster event registry. These features have been validated and tested separately.

2.3.2 Defining the Fibonacci Application

A Janet cluster consists of one central node, which is simply called “the central”, and one or more nodes. The different behavior of the central and the nodes is defined by specifying a system application appropriate for the role the node is meant to fulfill.

System Application

Unlike user-level applications, the system application has a fix structure: it must have a capability named `CORE` and it always has a single supreme agent. The `CORE` capability required to be present in the system application makes sure that the user can only change the behavior of a node, but she cannot change a node’s internal structure and its underlying design such as the number of supreme agents, which always must be one. The node’s internal structure represents fundamental design decisions the user must not change. Therefore, the definition of the system application in a node’s descriptor file is predefined to some extend. The user cannot alter the predefined part of structure. Doing so would result in a node descriptor parse exception to be thrown at node startup time. On the contrary, for a user-level application the user is free to define an arbitrary number of capabilities with an arbitrary number of agents that may also be defined or undefined programmatically at runtime. The role of a node (central or node) is defined by the interpreters listed in the core capability of the node’s system application. This means that there is no difference in the static class structure between a central and a node. Defining different behavior is confined to the interpreters. Interpreters, which are grouped in a capability, collectively define a capability’s functionality. Any permanent node objects must be installed in the system application’s object space. As a central needs different permanent node objects compared to a node (it needs to store different kind of cluster information), the interpreters of the central’s core capability are responsible for installing them in the system application’s object space of their node. In the same way, the interpreters of a node’s core capability carry the same responsibility. The interpreters of a capability must know the type of the permanent objects they use. They are responsible to cast their permanent objects back to their actual type when they are retrieved from an object space as instances of class `Object`.

Figure 2-34 on the next page shows the central’s main permanent node object, the CentralNodeAnchor, which was installed by one of the central’s core interpreters into the system application’s object space. A node’s main permanent object, the NodeAnchor, was installed in a node’s object space analogously.

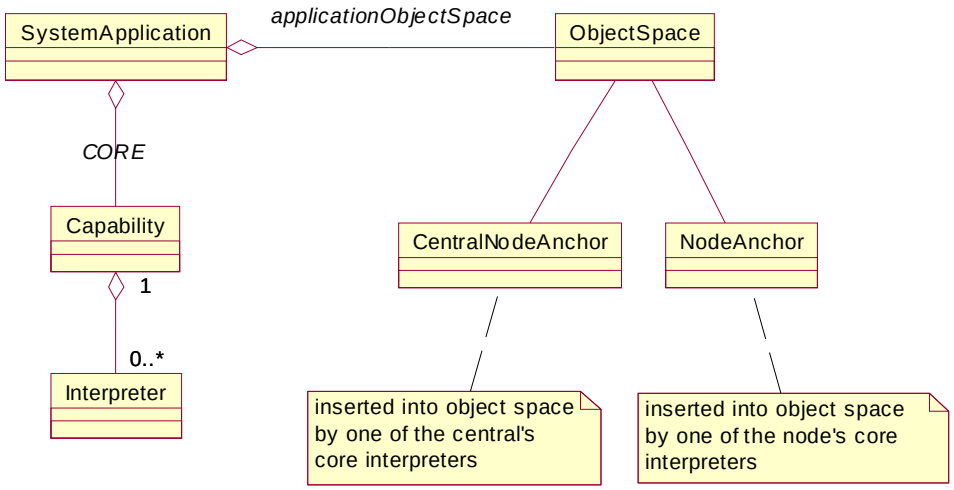

Figure 2-34: A node's core interpreters to install permanent node objects

Defining the Core Capability

To define a node's system application with its core capability the node descriptor has to list the required interpreters that define a node's role. Figure 2-35 displays a basic node descriptor as a skeleton with an empty list of core interpreters.

```
<?xml version="1.0" encoding="ISO-8859-1" ?>
<!-- node definition for central -->
<node version="0.1" showGUI="true" exitVMOnNodeShutdown="true">
    <registry centralHostname="myWorkstation" centralPort="1099"
      localPort="1099" />
   <applications>
    <systemApplication>
      <capabilities>
        <capability name="CORE">
          <interpreters>
            <!-- list all interpreters of the system application – see Figure 2-36 -->
          </interpreters>
        </capability>
      </capabilities>
    </systemApplication>
   </applications>
 </node>
```

Figure 2-35: Skeleton of a node descriptor file

Figure 2-36 lists all the interpreters of the system application's core capability omitted in Figure 2-35. The package paths are truncated to avoid line breaks. For a node to be able to start up, the fully qualified class names of the interpreters have to be provided so that the class loader can load the interpreter classes and instantiate them. The core capability of the central and a node list the same interpreters as shown in Figure 2-36. The interpreters that are rede-

fined for the special behavior of the central have a package path that ends with “central”. Those that need no redefinition end with the default package name “node”.

```
<interpreter>...central.NodeStartedInterpreter</interpreter>
<interpreter>...central.RegisterNodeInterpreter</interpreter>
<interpreter>...central.DeregisterNodeInterpreter</interpreter>
<interpreter>...node.DeregisterNodeFinalInterpreter</interpreter>
<interpreter>...node.RegisterApplicationInterpreter</interpreter>
<interpreter>...node.DeregisterApplicationInterpreter</interpreter>
<interpreter>...central.NodeShutdownRequestInterpreter</interpreter>
```

Figure 2-36: A node’s core interpreters as listed in the node descriptor

CAS_FIBONACCI Application

The main part of the node descriptor is the section that defines a node’s applications. A node’s applications consist of the system application, which has already been introduced, and applications defined by the user. User-level applications may also be defined programmatically after the node has started up. On the contrary, the system application can only be defined in the node descriptor.

The Fibonacci application is defined as a user-level application in the node descriptor. Its description is shown in Figure 2-37. It is a very simple application named `CAS_FIBONACCI` (application names must not contain dots) that consists of a single capability named `CORE`, which is served by a single agent named `CALCULATOR` and defines two interpreters.

```
<application name="CAS_FIBONACCI">
  <capabilities>
    <capability name="CORE">
      <agents>
          <agent name="CALCULATOR" executeWhenStarted="
            org.objectscape.janet...FibonacciStartViewCommand"
            />
        </agents>
      <interpreters>
          <interpreter>
              org.objectscape.janet...FibonacciStartViewInterpreter
          </interpreter>
          <interpreter>
              org.objectscape.janet...FibonacciInterpreter
          </interpreter>
        </interpreters>
      </capability>
    </capabilities>
  </application>
```

Figure 2-37: Definition of the CAS_FIBONACCI application

After the node has started up, the `FibonacciStartViewCommand` specified by the `executeWhenStarted` attribute is executed, which invokes the `FibonacciStartViewInterpreter` that starts the sample's user interface. The interpreter `FibonacciInterpreter` calculates the Fibonacci number and sends the result back to the requesting agent. The full package path of commands and interpreters has been omitted in Figure 2-37 for sake of readability. The full package path is `org.objectscape.janet.cas.demo.fibonacci`.

Figure 2-38 shows how an application is defined programmatically and registered with the central (try-catch-blocks are omitted for brevity).

```
String pathToNodeDescriptor = "./nodes/fibonacci";
NodeAccessor node = NodeStarter.start(pathToNodeDescriptor);
Application app = new Application("CAS_FIBONACCI");
Capability cap = new Capability(app, "CORE", "CALCULATOR");
cap.add(new FibonacciInterpreter());
node.registerApplication(app);
```

Figure 2-38: Registering an application programmatically

After registration (last line in Figure 2-38) the application is known by all nodes in the cluster with all its capabilities and agents. From now on, any agent of the same application on any node in the cluster can communicate with the agents of the newly registered application by sending commands or by signaling events. The user is responsible that the same capabilities of an application are defined the same way on every node. However, not every node may need an application's full set of capabilities. Nevertheless, on all nodes with the same application, a capability must be defined the same way as on another node with the same capability.

2.3.3 Node Startup

At node startup the `NodeStarter` creates the node with all its subobjects and parses the node descriptor. After that the node's applications are created and registered within the cluster. All interpreters defined in application capabilities are loaded with the use of the Java class loader. Every interpreter knows which command it interprets which allows the respective scheduler to dispatch a command to an interpreter.

At the end of the startup process the node's system view is displayed on the screen (the node can be run headless by setting the attribute `showGUI` in the node descriptor to false). For every node the applications tab of the system view shows all applications registered by every node in the cluster. Figure 2-39 displays the node main view application tab of the node "AARHUS-2" on a workstation named "AARHUS". As the application tag shows, the cluster consists of three nodes that all reside on the workstation "AARHUS" (the central is not displayed as the user should not use it to define applications). The three nodes are named "AARHUS-0", "AARHUS-1", and "AARHUS-2" following the Janet node naming convention (which cannot be changed by the user as Janet needs to make sure that a node name is unique within the cluster). All nodes define the application `CAS_FIBONACCI` with the capability `CORE` and one agent named `CALCULATOR`. For the node "AARHUS-2" itself the system application and the interpreters of the capabilities are listed as well.

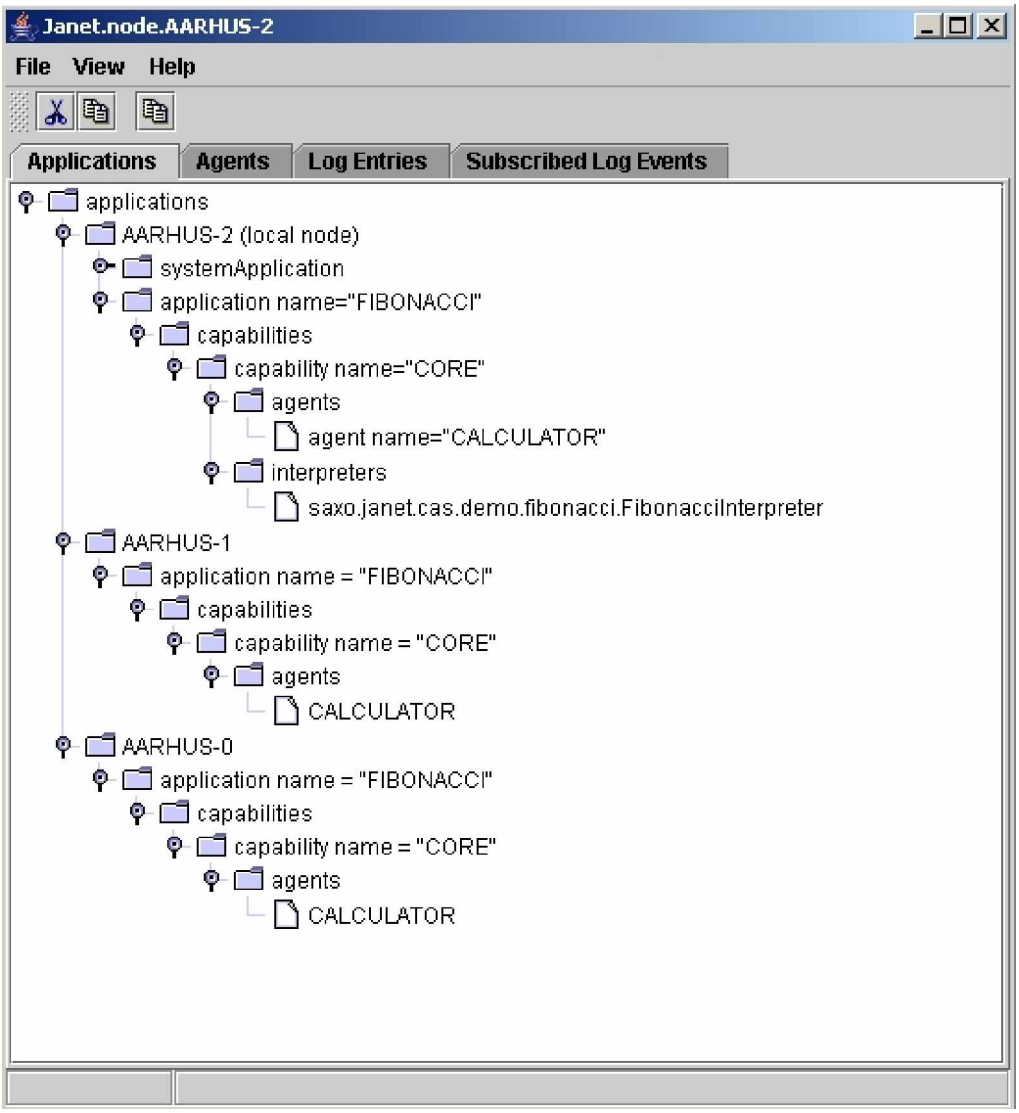

Figure 2-39: Applications tab of the node main view

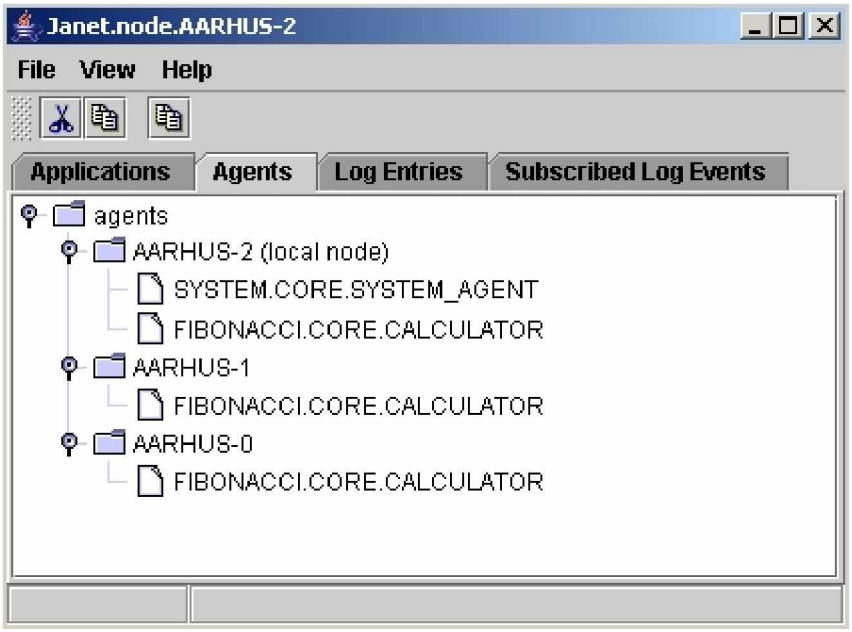

Figure 2-40: Agent tab of the node main view

The agent tab of the node main view displayed in Figure 2-40 shows all nodes in the cluster as defined above with the agents they define. For the node “AARHUS-2” itself the system agent is listed as well.

After node startup all agents are waiting for input. Nothing will happen until some agent sends a command to another agent. Sending a command can, of course, be done programmatically. For convenience, the node descriptor allows to define a command for every agent, which is sent to the agent after its application has been registered.

```
<agents>
    <agent name="Calculator" executeWhenStarted="
      org.objectscape.janet.cas.demo.fibonacci.StartFibonacciCom
      mand">
 </agents>
```

Figure 2-41: Defining an agent's initial command

Figure 2-41 shows the definition of the `Fibonacci.Core.Calculator` agent, for which the command `StartFibonacciCommand` has been defined. When node startup has completed, the `StartFibonacciCommand` is sent to the `Fibonacci.Core.Calculator` agent. The `StartFibonacciCommand` has been defined in such a way that it retrieves all the existing `Fibonacci.Core.Calculator` agents from the other nodes in the cluster from its application (which defines an interface for the user for doing this) and sends all of them a `FibonacciCommand`. All agents that receive the `FibonacciCommand` start calculating a Fibonacci number (their capabilities define the same interpreter). The sending agent waits till all calculated Fibonacci numbers have been sent back and displays them on the console.

2.3.4 Implementing Commands and Interpreters

After the Fibonacci application has been defined in the node descriptor the commands and interpreters of the `Fibonacci.Core` capability have to be implemented.

Implementing the FibonacciCommand

Commands are typically easy to implement since they simply serve to carry parameters of a command from agent to agent. Figure 2-42 shows the class skeleton of the `FibonacciCommand`. A command must implement the interface `ICommand`. The interface `Serializable` must be implemented as well for the command to be serializable when passed from one agent to another using RMI. The class attribute `input` is used to store which Fibonacci number is to be calculated.

```
import java.io.Serializable;
import org.objectscape.janet.cas.scheduling.ICommand;

public class FibonacciCommand implements ICommand, Serializable
{
	public static final String QualifiedName =
		"org.objectscape.cas.demo.fibonacci.FibonacciCommand";

	protected int input = -1;

	public FibonacciCommand(int input)
	{
		super();
		this.input = input;
	}

	public int getInput()
	{
		return input;
	}

	// other required methods of interface ICommand omitted
}
```

Figure 2-42: FibonacciCommand class skeleton

The `ICommand` interface requires several additional methods to be implemented to return the qualified name of the command, the command's priority, how to clone the command, and what display string to use for the command when displayed in a logger. The definitions of these required methods are displayed in Figure 2-43.

```
public String getQualifiedName()
{
	return QualifiedName;
}
```

```
public int getPriority()
{
	return ICommand.ApplicationMaxPriority;
}

public String toLogString()
{
	return "FibonacciCommand"; //$NON-NLS-1$
}

public Object clone() throws CloneNotSupportedException
{
	FibonacciCommand cmd = (FibonacciCommand) super.clone();
	return cmd;
}
```

Figure 2-43: Implementing the ICommand interface for the FibonacciCommand

It has to be noted that the highest priority of a user-defined application command cannot be higher than `ICommand.ApplicationMaxPriority`. If the user specifies a higher priority, the command envelope carrying the command from agent to agent will set back the command's priority to `ICommand.ApplicationMaxPriority` if it is sent to a non-system agent (that is a user-defined application agent). To prevent ambiguities, the qualified command name has to be the fully qualified command name or some other unique id. A command has to be cloned when it is sent to several local agents (which is necessarily the case in simulated mode when several nodes run in the same Java VM) so that every agent receives a command object of which it can change values without affecting other agents. For this reason, a command has to implement the `clone` method from class `Object`.

Implementing the FibonacciInterpreter

An interpreter must implement the interface IInterpreter, which only requires two methods to be implemented: IInterpreter.execute and IInterpreter.`commandNames`. The implementation of the `FibonacciInterpreter` class is relatively simple. It is displayed in Figure 2-44 below. It displays the full implementation of the `FibonacciInterpreter` (only the `calculate` method is simplified for brevity).

```
import org.objectscape.janet.cas.scheduling.CommandAccessor;
import org.objectscape.janet.cas.scheduling.IInterpreter;
import org.objectscape.commons.util.exception.InvalidMessageException;


public class FibonacciInterpreter implements IInterpreter
{

	public FibonacciInterpreter()
	{
		super();
	}

	public void execute(CommandAccessor cmdAccessor)
	{
		if (cmdAccessor.getCommand() instanceof FibonacciCommand)
```

```
            {
                  FibonacciCommand command = (FibonacciCommand)
                                    cmdAccessor.getCommand();
                  try
                  {
                        BigInteger fibonacciNumber =
                              calculate(command.getInput());
                        cmdAccessor.setReply(fibonacciNumber);
                  }
                  catch (InvalidMessageException e)
                  {
                        cmdAccessor.log(e);
                  }
            }
      }

      protected BigInteger calculate (int nthFibonacciNumber)
      {
            // code omitted for brevity
      }

      public StringList commandNames()
      {
            return new StringList(FibonacciCommand.QualifiedName);
      }
}
```

Figure 2-44: Implementation of the FibonacciInterpreter class

2.3.5 Sending Fibonacci Commands

After the command and interpreter for calculating Fibonacci numbers have been implemented the `StartFibonacciCommand` remains to be implemented (see Figure 2-41) to distribute `FibonacciCommands` to agents in the cluster that have the `Fibonacci.Core` capability. The implementation of the `StartFibonacciCommand` is analoguous to the implementation of the `FibonacciCommand` and therefore not explained. The implementation of the `StartFibonacci-Interpreter` is of more interest. This interpreter has to get hold of all agents in the cluster that have the `Fibonacci.Core` capability and send them a `FibonacciCommand`. The `StartFi-bonacciInterpreter` installs callback handlers that are invoked when the calculation results are returned from the `Fibonacci.Core` agents and print the results to the console.

```
   public void execute(CommandAccessor cmdAccessor)
   {
2
3        int nthFibonacci = 50000;
4        long startTime = System.currentTimeMillis();
5        NodeAccessor node = cmdAccessor.getNodeAccessor();
6        LoggerAccessor logger = node.getLogAccessor();
         HistoryTotalsCreator totalsCreator = new HistoryTotalsCreator(
7              agents.size(), nthFibonacci, logger, startTime);
8
9        FibonacciCallbackHandler handler =
               new FibonacciCallbackHandler(logger, totalsCreator);
         IAgentProxy agents = cmdAccessor.getApplication().
```

```
10              getAllAgents(cmdAccessor.getLocalAgentPath());
11        FibonacciCommand cmd = new
12              FibonacciCommand(nthFibonacci), handler);
13
14        agents.accept(cmd, handler);
    }
```

Figure 2-45: Execute method of the StartFibonacciInterpreter

The scheduler of an agent invokes the `execute` method of an interpreter in response to a received command. The `execute` method of the StartFibonacciInterpreter is displayed in Figure 2-45. Taking all the work into account the StartFibonacciInterpreter has to do, its `execute` method looks relatively simple. This is mostly because most of the work is done by two system convenience methods:

- `getAllAgents` (line 11): This method in class `Application` retrieves a list with all agents in the cluster that belong to the same application as the application the `getAllAgents` method was sent to. `cmdAccessor.getLocalAgentPath` in line 11 returns the local agent path of the agent that executes the currently executed interpreter which is `Fibonacci.Core.Calculator`. This local agent path is passed on as a parameter to `getAllAgents`, so that this method knows it has to retrieve all agents in the cluster with the same local agent path on their node. This information is retrieved from the node's anchor cluster image. The `getAllAgents` method returns an instance of class `MultiAgentProxy` (described in section 2.2.3.2: "Sending Commands to Agents: User Interface").

- The `MultiAgentProxy` implements the `IAgentProxy` interface so that the user does not need to be concerned about how to deal with a `MultiAgentProxy`. The user will simply treat the `MultiAgentProxy` the same way as an `IAgentProxy` (using the `accept` message as in line 14). The `MultiAgentProxy` makes sure that a command sent to it, is propagated to all `IAgentProxies` it contains.

After the `MultiAgentProxy` has sent all commands to the destination agents, the thread continues execution. Execution of the `StartFibonacciInterpreter's execute` method has finished and the scheduler will execute the next command in its command queue if there is any. When the calculated Fibonacci numbers have returned the callback handlers created in line 8 + 9 will be invoked. The callback mechanism has been explained in section 2.2.3.3.2: "

Extensions for Callbacks". The `MultiAgentProxy` makes sure that for every `IAgentProxy` it contains a separate callback handler is installed.

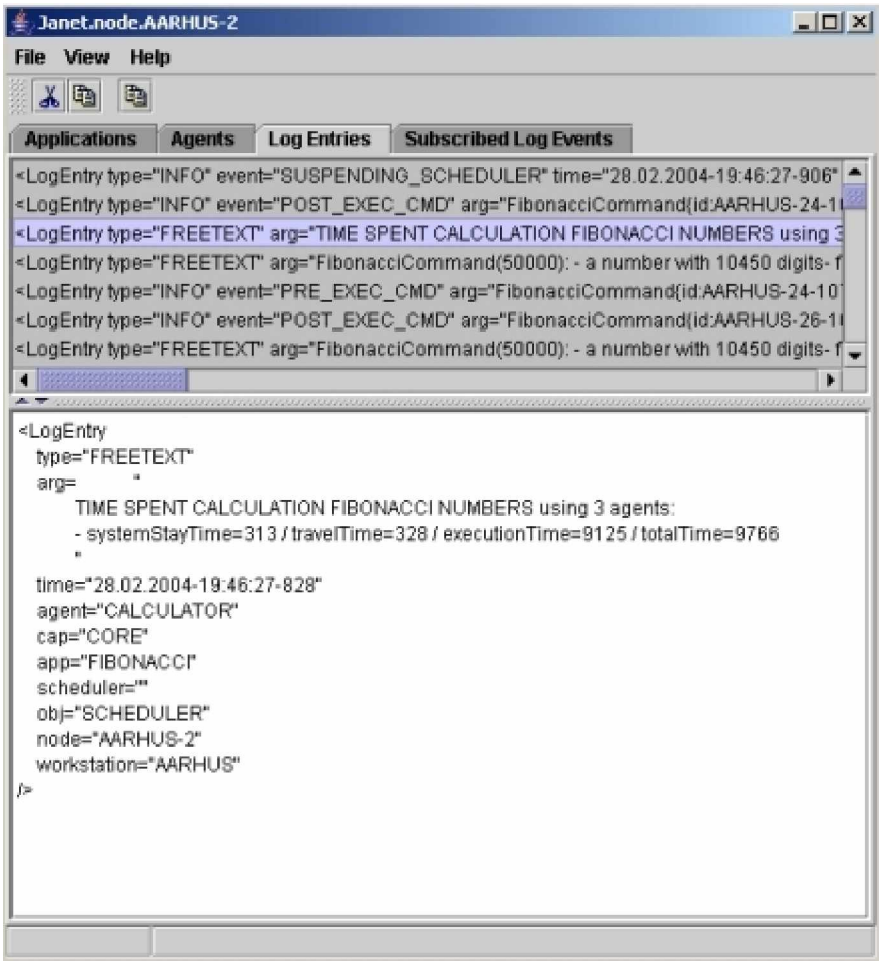

Figure 2-46: Results displayed in log entries tab

When the last calculated Fibonacci number has arrived, the callback handler displays the results in the node's main view log entries tab. The `Logger` used to display log messages is explained in further detail in chapter 2.4: "Driving Application: Remote Logger".

2.4 Driving Application: Remote Logger

Every node has a logger that displays log messages in the node's main view log entries tab. This logger has not been described so far as it is not conceptually important. The remote logger listens to log messages sent to this logger and displays the log messages in a window. The log messages displayed have been sent from all nodes in the cluster that have subscribed to the remote logger service. The remote logger was implemented as a Janet.CAS application. It could also have been implemented using existing logging tools for Java such as log4j. The former approach was chosen to use the remote logger as a tool to validate concepts of Janet.CAS such as the concept of a node, of which the system behavior can be changed according to the role

the node is intended to fulfill, or defining user-level applications in order to add new functionality.

Implementing the remote logger as a node of its own, it could be implemented as a system facility being served by the system agent or as a user-defined application being served by an application agent. Remote logging is not a core facility that is needed to implement a node. Propagating log messages to a remote logger agent produces CPU load the system agent should not have to carry, as it needs to remain available to fulfill tasks critical for running the node. For that reason, the remote logger is not be provided by the system. It is implemented as a user-defined application. This means that the agents of the remote logger facility run at application priority. Heavy logging activity can therefore neither bog down the system agent (which runs at higher priority than the application agents) nor can it cause starvation of other applications, since the arbitrator makes sure that every application obtains the same time slice.

2.4.1 Consumer and Producer Capability

For the remote logger a capability is needed that accepts remote log messages and displays them in a window for the user to see. This capability is called the `Consumer` capability. It needs one agent, which is called the `Logger` agent. The agent path to the consumer logger agent is therefore: `Remote_Logger.Consumer.Logger`. One node is defined with the `Remote_Logger.Consumer` capability as the sole user-defined application capability. This node takes the entire load to display remotely received log messages. It can be run as the sole node on a workstation so that it does not use up resources of other nodes. It is also possible to start up several nodes with a `Remote_Logger.Consumer` capability.

```
<application name="REMOTE_LOGGER">
  <capabilities>
    <capability name="CONSUMER">
      <agents>
          <agent name="LOGGER" executeWhenStarted=
            "org.objectscape.janet.cas.logger.commands.
            StartViewCommand" />
        </agents>
      <interpreters>
          <interpreter>
              org.objectscape.janet.cas.logger.interpreters.
              DisplayLogEntryInterpreter
          </interpreter>
          <interpreter>
             org.objectscape.janet.cas.logger.interpreters.
             StartViewInterpreter
          </interpreter>
        </interpreters>
      </capability>
    </capabilities>
  </application>
```

Figure 2-47: Definition of the remote logger consumer capability

As showed in Figure 2-47 the consumer capability defines two interpreters:

- `StartViewInterpreter`: Executed after the node has started up. This interpreter starts up the window to display remotely received log messages. It then sends the `InstallLoggerCommand` to all nodes in the cluster with the remote logger producer capability (introduced below). When the node shuts down the `UnInstallLoggerCommand` is sent to all these nodes.

- `DisplayLogEntryInterpreter`: Displays all the log messages received from another node through the `DisplayLogEntryCommand` in a window.

All nodes of which the log messages are to be displayed by the `Remote_Logger.Consumer.Logger` agent, define a different capability. This capability is called the `Producer` capability since the node it belongs to "produces" log messages. The agent path to the producer logger agent is: `Remote_Logger.Producer.Logger`. This agent installs a listener that listens to log messages sent to the node's logger and passes them on the consumer agent. When the consumer node shuts down, the listener is uninstalled.

```
<application name="REMOTE_LOGGER">
  <capabilities>
    <capability name="PRODUCER">
      <agents>
          <agent name="LOGGER" />
       </agents>
      <interpreters>
        <interpreter>
         org.objectscape.janet.cas.logger.interpreters.
        InstallLoggerInterpreter
        </interpreter>
        <interpreter>
         org.objectscape.janet.cas.logger.interpreters.
         UnInstallLoggerInterpreter
        </interpreter>
       </interpreters>
     </capability>
   </capabilities>
 </application>
```

Figure 2-48: Definition of the remote logger producer capability

The definition of the producer capability is displayed in Figure 2-48. It defines two interpreters:

- `InstallLoggerInterpreter`: Installs a listener in the logger. The listener passes the log messages sent to the logger on to the `Remote_Logger.Consumer.Logger` agent.
- `UnInstallLoggerInterpreter`: Uninstalls the listener.

2.4.2 Starting up a Consumer Node

When a consumer node starts up, the StartViewCommand, defined in the Logger agent's `executeWhenStarted` attribute, is executed. It starts the consumer window to display log messages and sends an `InstallLoggerCommand` to every producer node in the cluster. This scenario is displayed in Figure 2-49.

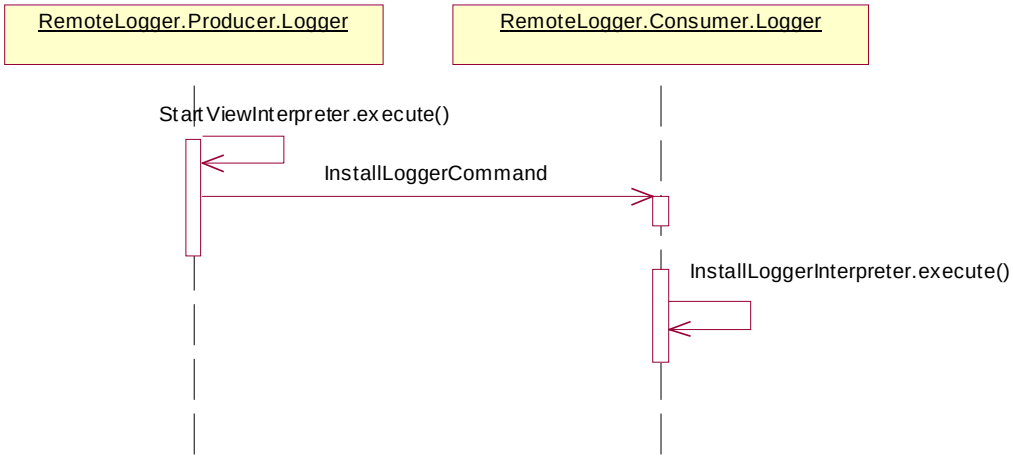

Figure 2-49: Starting up nodes with remote logger capabilities

The consumer agent knows from its node's cluster image which nodes in the cluster have the producer capability. When a producer node starts up and a consumer node is already present, the consumer node needs to receive some kind of notification that a new producer node exists. At startup the consumer node registers for the `FOREIGN_APPLICATION_REGISTERED` event by installing its own `ForeignApplicationRegisteredHandler`. Whenever a node starts up, it tells all other nodes in the cluster about the applications and agents it has. Analogously, when a new application is registered, the hosting node informs all other nodes about the new application and its agents as well. A node that receives such a notification, signals the `FOREIGN_APPLICATION_REGISTERED` event. The consumer agent's `ForeignApplicationRegisteredHandler` is invoked and the consumer agent sends the `InstallLoggerCommand` to the newly started up node.

2.4.3 Starting up a Producer Node

After a producer node has started up it receives the `InstallLoggerCommand` from every consumer node in the cluster. A producer node need not be concerned about looking up a consumer node and registering with it. When it shuts down it does not need to tell the consumer node about it, either. It will simply cease to send log message to the consumer agent for display. When the `InstallLoggerCommand` is executed the log listener is installed in the node's logger. From that moment on, the log listener receives a notification each time a log message is

sent to the logger and passes the log message on the consumer agent enclosed in `DisplayLogEntryCommand`.

Installing the Log Listener Using An Event

The logger is a system object that may be used by user-defined applications for logging as well. An application that not only uses the logger for logging, but also listens to log messages sent to the logger is able to track down what actions agents of other applications are carrying out. This would infringe the protection of the system application and of the user-defined applications. For this reason, the logger has no public interface to install a log listener. The installation of a log listener therefore has to be done with the use of an event (events have been introduced in section 2.1.4). The installation of the log listener is only initiated by the `InstallLoggerInterpreter`, which signals an event that makes the system install the log listener.

In the `exportedEvents` section of the system application, the user has to define which handler is invoked in case the `EVENT_ADD_LOG_LISTENER` is signaled. The respective section of a producer's node descriptor is shown in Figure 2-50. Since the event is defined for the system application, the system agent will run the event handler, which has the privilege to install a log listener. The node descriptor is under control of the workstation owner. The workstation owner has therefore full control over what should happen when the `EVENT_ADD_LOG_LISTENER` event is signaled as she can define the handler to be invoked in response to the event. The default system handlers can be defined or user-defined ones. If the `exportedEvents` section does not contain an entry for the `EVENT_ADD_LOG_LISTENER` event, nothing will happen when the event is signaled. The handlers are either installed programmatically or by extending the node descriptor file. The default remote logger event handlers simply add or remove a listener to the logger.

```
<!—lines omitted >
<systemApplication>
  <exportedEvents>
      <event name="EVENT_ADD_LOG_LISTENER"
        handler="org.objectscape.commons.util.logging.
          AddLogListenerHandler" />
      <event name="EVENT_REMOVE_LOG_LISTENER"
        handler="org.objectscape.commons.util.logging.
          RemoveLogListenerHandler" />
    </exportedEvents>
<!—lines omitted >
</systemApplication>
<!—lines omitted >
```

Figure 2-50: Extract from node descriptor file to install event handlers

Figure 2-50 shows an extract from a node descriptor file that defines event handlers to add and remove log listeners. The default handlers installed are `org.objectscape.commons.util.logging.AddLogListenerHandler` and `org.objectscape.commons.util.logging.RemoveLogListenerHandler`.

2.4.4 Shutting down a Consumer Node

When the consumer node shuts down, it tells all producer agents to disconnect themselves from their node logger, which results in no more log messages being passed on to the consumer agent. The consumer agent sends the `UnInstallLoggerCommand` to all producer nodes. The `UnInstallLoggerInterpreters` uninstalls the log listener using the `EVENT_REMOVE_LOG_LISTENER` event.

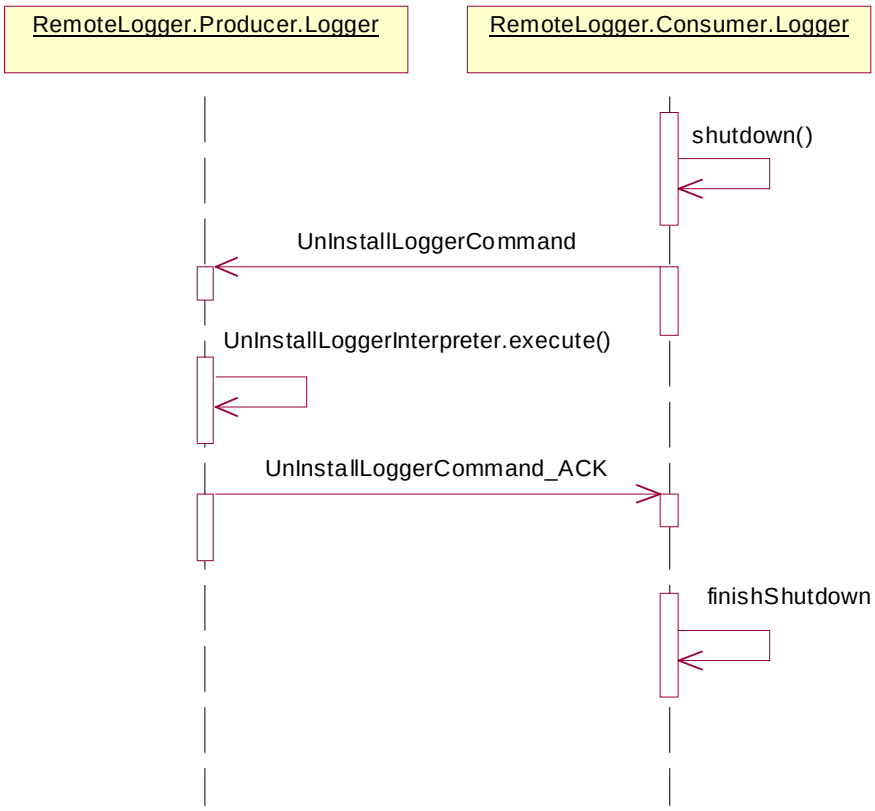

Figure 2-51: Shutting down a consumer node

The consumer node waits till all producer nodes have finished the log listener uninstallation process and then shuts down the node itself, which is shown in Figure 2-51.

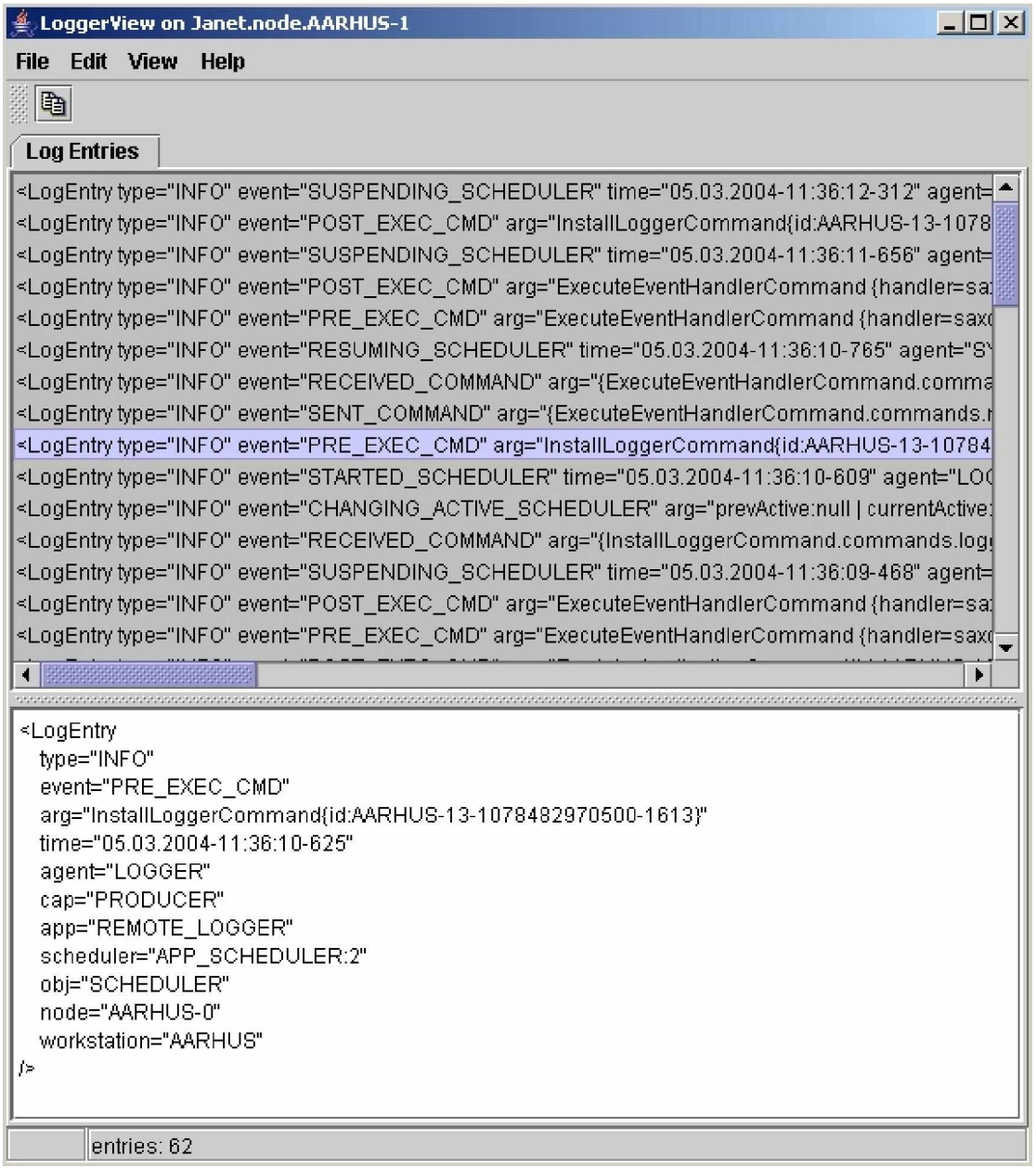

Figure 2-52: Consumer agent log view

Figure 2-52 shows the consumer log view that displays all log messages received from producer nodes. The selected log entry shows a log message from the node AARHUS-0, which indicates that the `InstallLoggerCommand` is about to be executed by the `Remote_Logger.Producer.Logger` agent.

2.5 Measurements

The CAS.Fibonacci sample application already presented can be used to measure Janet.CAS system performance. The `CommandEnvelope`, after being sent away to another agent and upon arrival at the destination agent, measures the time that has passed by. These durations can be used to measure command travel times. In the following measurements are taken with more

and more nodes being part of the cluster to see how command travel times are affected when the cluster size grows.

2.5.1 Overview

General Measurement Scenario

The following measurements are based on a scenario where Fibonacci commands are distributed evenly in the cluster. For each new measurement the cluster size is augmented by one node. A Fibonacci agent on one node in the cluster sends a Fibonacci command to itself and to all other Fibonacci agents in the cluster where every workstation in the cluster hosts one node with one Fibonacci agent. Every Fibonacci agent calculates the same Fibonacci number, which is the 50,000th Fibonacci number, and sends the result back to the initially sending agent. To reduce the effect of outliers the calculations are repeated ten times for every cluster size. Maximum, minimum, and average values refer to the maximum, minimum, and average value of ten measurements for a cluster with a given size. All measurements measure overall time.

Setup

All workstations that are used to form a cluster are setup as follows: Pentium III, 512 MB, 1 GHz, SuSE Linux 8.2. Newtork: 100 Mbit/s Ethernet switched.

Garbage Collection

All measurements are time overall measurements that also include time spent on garbage collection. The Java VM option –verbose:gc prints various garbage collection statistics to the console. This is a sample output:

```
[GC 325407K->83000K(776768K), 0.2300771 secs]
[GC 325816K->83372K(776768K), 0.2454258 secs]
[Full GC 267628K->83769K(776768K), 1.8479984 secs]
```

The statistical output is useful to determine whether the garbage collector has become a performance bottleneck for an application. If this is the case, it can be used to verify whether the tuning of the garbage collector shows the expected results. However, the garbage collector statistics is not provided in a way that it can be processed automatically to calculate overall time spent without garbage collection. The time spent on garbage collection is therefore not separated out but included in the measurements.

2.5.2 Measuring Total Time

The total time a Fibonacci commands consumes during its lifetime with more and more nodes being added to the cluster is supposed to give some impression about how well Janet.CAS scales with growing cluster size.

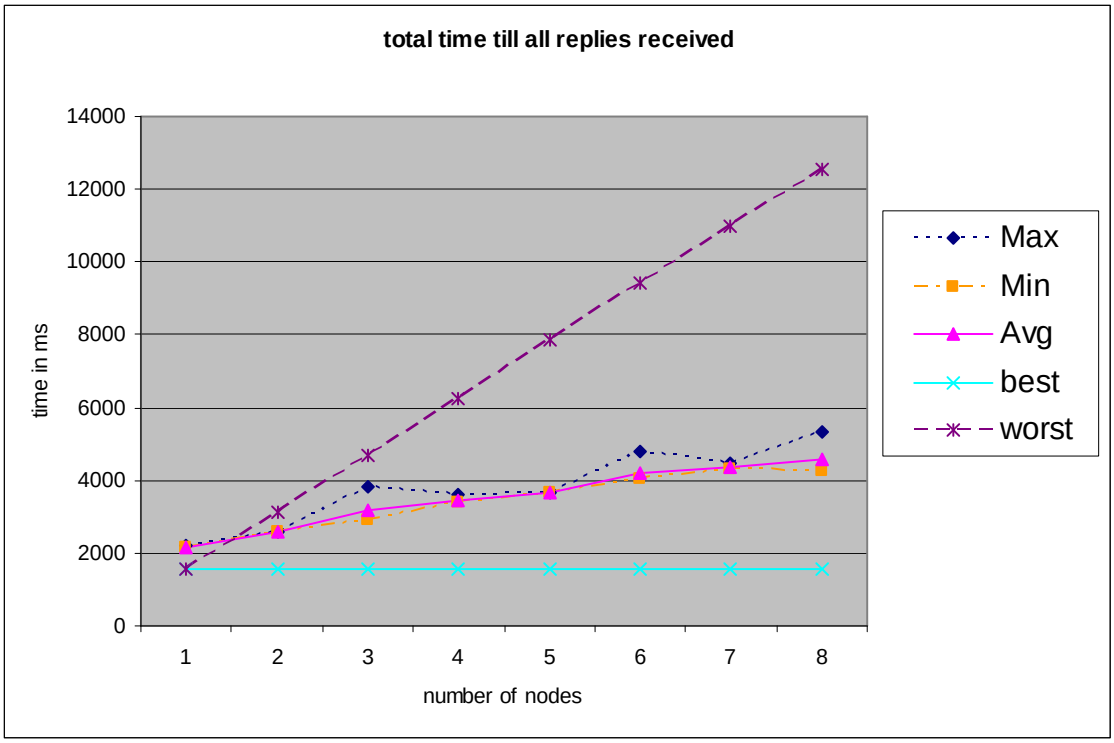

Figure 2-53: Total time till received replies from all nodes

Figure 2-53 shows the total time to calculate Fibonacci commands distributed evenly in the cluster. The total time is measured from the time on the Fibonacci commands where sent away till all replies have arrived.

The *lower horizontal line* shows the time required to calculate the Fibonacci number without the overhead caused by Janet.CAS. A most simple program not using Janet.CAS was written that enters a loop to calculate the Fibonacci number, prints the time spent for calculation to the console and exits. In the ideal case where there is no overhead caused by the cluster software or network the time to calculate n Fibonacci numbers is the same as for calculating one Fibonacci number. The horizontal line represents this ideal case.

The *steepest line* represents the worst case where there is no distributed calculation and calculating n Fibonacci numbers takes n times as much as when calculating it once. This line was obtained by multiplying the time for calculating the Fibonacci number without Janet.CAS by the number of nodes.

The lines for maximum, minimum, and average are in between the lines for the two extreme situations described above. The line with triangular symbols for the average time shows close to linear growth. The line that displays averages is very close to the one for the minimums where the line for maximums is in some points relatively far away from the line for averages. This shows that total time till a Fibonacci command has returned to its sending agent can vary considerably.

2.5.3 Janet.CAS Measuring Interface

When a command is sent from an agent to another agent, Janet.CAS does some bookkeeping to measure the time the command spends during various phases of its life time:

- travel time: the time spent after the command was sent away till it was received by the destination node's agent dispatcher. This is the time consumed by the middleware and the network to transport the command physically to another process.

- execution time: the time the commands spends for the execution of its interpreter.

- system stay time: all the time the command does not spend on traveling from agent to agent and executing its interpreter. This is the time spent after the command was created till it was sent away plus the time spent after reception by the destination node's agent dispatcher till the command was executed. In case the command is sent back to the sending agent with a result the system stay time for sending the command back is added.

- total time: sum of travel time, execution time, and system stay time.

Janet.CAS provides an interface for the user to query travel time, execution time, system stay time, and total time. Figure 2-54 shows a simplified code sample to obtain statistical information from a command.

```
// …

IAgentProxy agent = getMyAgent();
FutureResult futureResult = new FutureResult();
agent.accept(new FibonacciCommand(50000), futureResult);
BigInteger result = (BigInteger) future.getResult();

ICommandHistorySummary summary = new CommandHistorySummary();
future.createHistorySummary(summary);

System.out.println(summary.getSystemStayTime());
System.out.println(summary.getTravelTime());
System.out.println(summary.getExecutionTime());
System.out.println(summary.getTotalTime());

// …
```

Figure 2-54: Interface to obtain statistical command information

After the result has arrived the user can query statistical command information from the `FutureResult` object by supplying her implementation of the `ICommandHistorySummary` interface. If supplied to several commands the `ICommandHistorySummary` object contains the totals of all the measured durations. The interface remains the same when using an `Acknowledge` object instead of a `FutureResult` object or when using a callback handler. For the measurements presented in this chapter callback handlers were used instead of `FutureResult` objects.

2.5.4 Measuring Command Travel Times

It can be expected that the time a command spends within the Janet system and the time spent for executing a command remains for the most part constant. However, the more nodes are in the cluster the more commands are sent through the network and the network load increases.

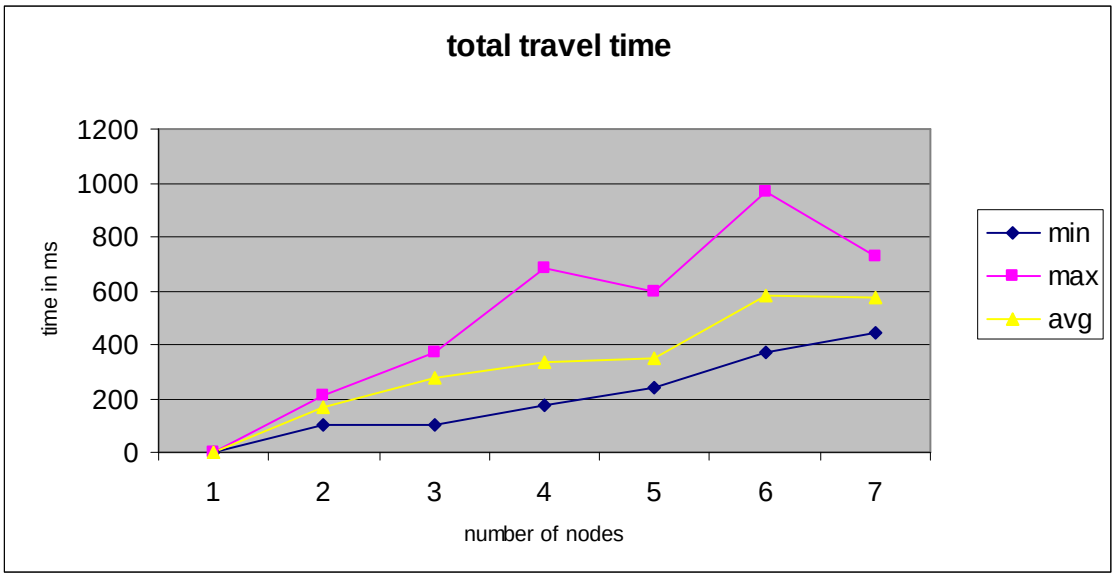

Figure 2-55: Depiction of command travel times

Figure 2-55 shows travel times for the Fibonacci command from 1 to 7 nodes. If only a single node is present, the command is sent to an agent that lives in the single node itself. In this case, sending the command to the agent becomes a simple message send without serialization. As the figure shows, for a single node travel time falls below the smallest unit of measure, which is 1 millisecond. Travel times increase the more nodes exist in the cluster. It can be seen from the figure that the growth of travel times remains linear. It is noteworthy that maximum travel times vary in a relatively large range. If the number of nodes in the cluster is relatively small, the maximum travel time can be up to twice as much as the average travel time.

2.5.5 Measuring Command Execution Times

The execution time of a Fibonacci command is for the general measurement scenario not particularly interesting. Since every node executes only one command at a time and nodes do not share CPUs it can be expected that execution time remains mostly constant.

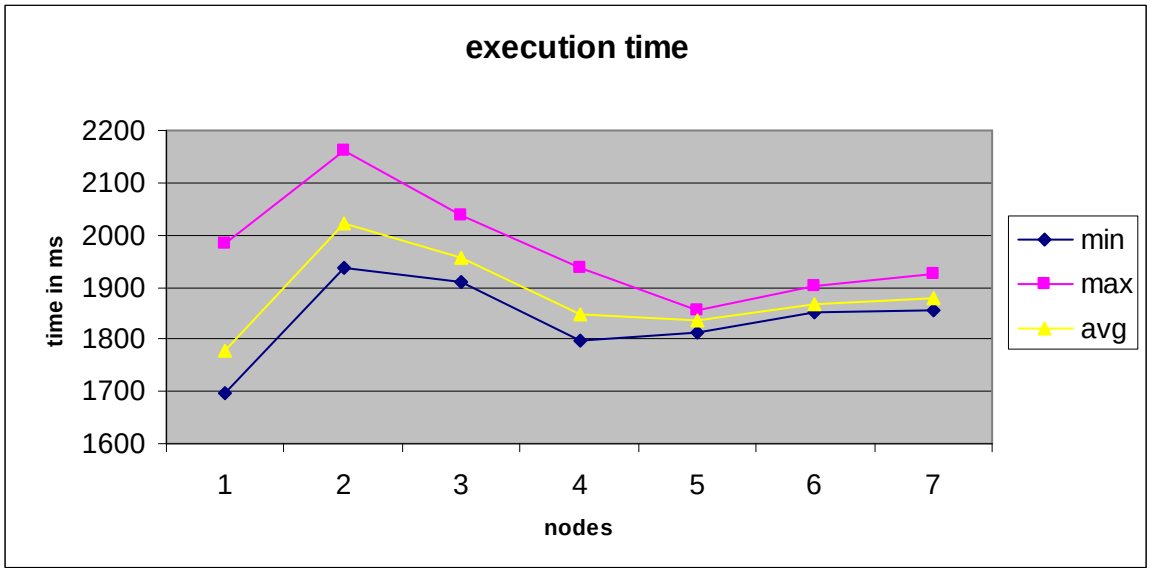

Figure 2-56: Total execution times

Figure 2-56 displays total execution time of commands in clusters varying in size from 1 to 7 nodes. The curves for minimum, average, and maximum execution time are relatively close together indicating that outliers have no significant effect.

2.5.6 Comparing Average Values

In Figure 2-57 the curves for the averages of travel times, system stay times, and total execution time have been depicted in one diagram.

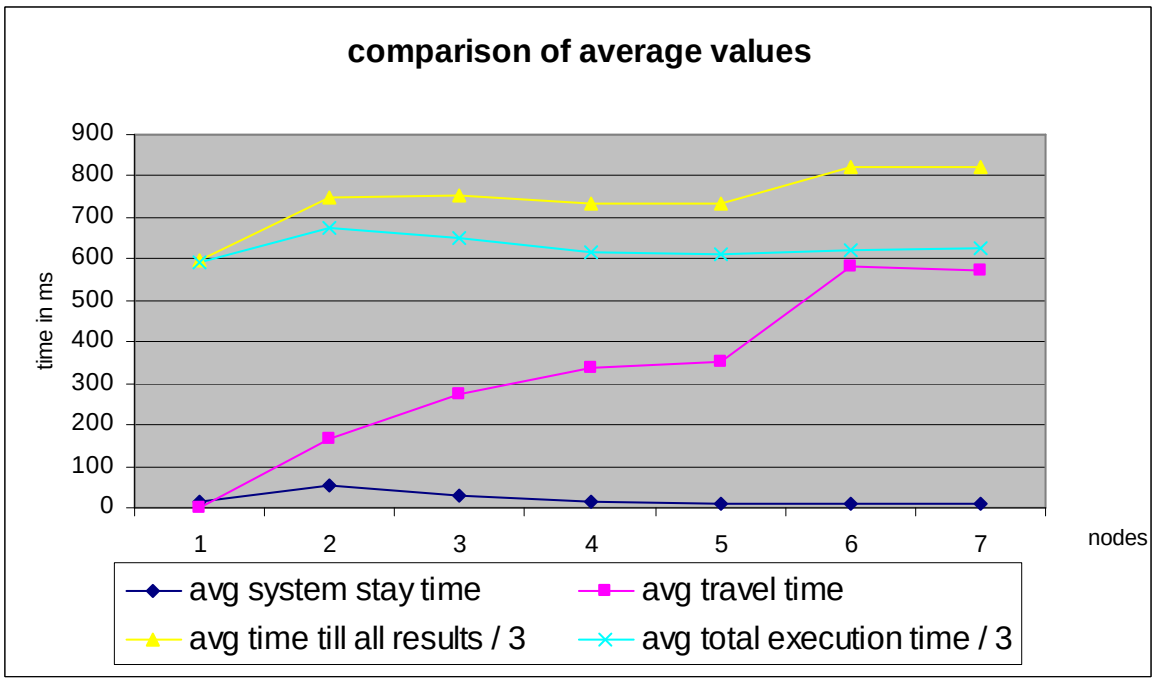

Figure 2-57: Comparison of different curves for averages

The averages for total execution time and the time till all results have been received by the agent sending out Fibonacci commands have been divided by 3 to make them better fit into the figure. The figure shows that average system stay time is relatively low whereas average travel time is high. This indicates that command travel time is the most important time consumer. Since travel times keep growing with the number of nodes in the cluster, travel time is the most important factor for potentially limiting cluster scalability. Average total execution time remains mostly constant, which was expected as for the given general measurement scenario workload for every workstation in the cluster remains the same when the size of the cluster grows.

Average travel time increases sharply from 5 nodes to 6 nodes. It is interesting to see that the curve for the average time till all results have arrived increases sharply at this point as well. It seems to be mostly in parallel with the curve for average travel time with the difference that it does not increase that strong. This confirms the presumption that command travel time is the most important factor in overall response time. The slower increase can be explained by the average total execution time and the average system stay time decreasing slightly with the number of nodes in the cluster rising, which lowers the increase of the overall total.

3 Janet.ADÉ

Janet.ADÉ (**A**utomatic **D**istributed **E**xecution) is the layer that implements workload balancing in Janet. It makes use of the cooperative agent system provided by Janet.CAS to make agents evict commands to less loaded nodes. Janet.ADÉ defines two new command interfaces: `IWorkLoadSharingCommand and IWorkLoadBalancingCommand`. The system applies workload sharing if the user defines a command that implements the former command interface which results in the system sending the command to the least loaded node for execution where it resides till execution has completed. In the following, commands that implement this interface are called workload sharing commands. If the user defines a command that implements the latter interface, workload balancing applies. In this case, the command is added to the scheduler queue of the agent it was sent to. If the node hosting this agent is overloaded, the command may be suspended, sent to some other less loaded node, and then be restarted. Such a command is called a workload balancing command in the following. Both kinds of commands are called workload-aware commands. Contrary to workload balancing commands, workload sharing commands cannot be suspended after they have been started. However, they may be evicted as well as long as they remain waiting in an agent's scheduler queue.

Workload-aware commands in Janet.ADÉ are intended for the implementation of long running tasks, for which the overhead caused by workload determination and command eviction can be justified in order to balance overall workload in the cluster. For short running tasks the ICommand interface of Janet.CAS is intended to be used.

3.1 Conceptual Design

This section explains the conceptual design of Janet.ADÉ. It describes the roles of the nodes defined to accomplish workload balancing, the balancing algorithm that is used, how it has been developed and what the considerations have been to choose such an algorithm.

3.1.1 Load Determination

There are several methods to choose a node to migrate commands to. The most import ones are: Random, Threshold, Shortest Queue, and Broadcast and Bidding. Random delivers significantly better results than without load balancing. Threshold and Shortest Queue deliver even better results. Broadcast and Bidding results in significantly increased network traffic which is especially a problem in Janet since commands in Janet take more time as remote procedure calls in distributed operating systems. Commands in Janet are sent to agents. Then they are added to a scheduler, which processes the command after all previous ones have been processed. Furthermore, dispatch of command and interpreter by the scheduler is dynamic. For this reason, Broadcast and Bidding is considered too costly for Janet and is not further investigated as an option.

Shortest Queue and Queue Size Categories

The Shortest Queue method is especially interesting for workload balancing in Janet. In Janet commands sent to agents are added to a scheduler queue from which they are executed one after the other. Counting the number of queues with their number of commands returns a measure for the load of the system that is simple to obtain and conceptually consistent with the

agent-scheduler-queue paradigm used in Janet, which makes the Shortest Queue method an obvious candidate method to determine a node's load in Janet. The time a command has to wait till it is processed is another measure that can be used to determine a node's load. However, the drawback of the Shortest Queue method is that a node needs to inform a central node about the total size of its queues whenever it changes, which causes more overhead than when using the Threshold method. As already mentioned, commands sends in Janet are relatively costly, which means that an approach resulting in heavy message traffic should be avoided. To address this problem the Shortest Queue method is extended by introducing queue size categories (QSC) where the user can define several categories of queue numbers and queue sizes. For example, for queue size category 0 (QSC0) all command queues are empty and there are no executing commands (the node is idle). For queue size category 1 (QSC1) there is only 1 executing workload-aware command in all of the node's scheduler queues. For queue size category 2 (QSC2) there is at least 1 executing command and at least 3 waiting commands. A node only informs a central node about queue size changes in case it changes state from one QSC to another. Using this approach, the Shortest Queue method can be used for workload determination while keeping the message traffic between nodes and a central balancing node low. Another advantage of queue size categories is that they can be defined individually for every node. The QSC definition for a node that resides on a workstation with considerable more CPU power than other workstations in the cluster can be set up in such a way that queue size categories contain a larger number of executing commands and waiting commands than in the QSC definition of nodes on less powerful workstations.

3.1.2 Distribution Algorithm

As shown by Mirchandaney et al. [MTS89] a symmetric distribution algorithm, which is a combination of sender-initiated and receiver-initiated algorithm, performs better than either single algorithm. In the receiver-initiated approach, an underloaded node requests commands from a heavily loaded node. A node in Janet would therefore have to retrieve heavily loaded nodes from some load data store and request commands from it. It makes sense to have a central load data store to minimize the number of notifications across the network about changes of queue size categories (as described earlier, broadcasts in Janet are costly and should be avoided). The question is whether the central data store should remain a passive store or whether it should be able to carry out actions to assist in the load balancing process. The result of a central data store that remains a passive object is a distributed algorithm, rather than a centralized one. The more "intelligence" is given to it, the more centralized the distribution algorithm becomes. The number of commands exchanged between agents to balance workload increases if nodes have to interact with an additional central data store agent. In the worst case, all communication between nodes goes through the central data store agent, which means that the number of commands exchanged in the cluster doubles compared to direct node-to-node communication. For efficiency reasons, the number of exchanged commands is to be kept at a minimum, which means that the central data store agent receives most of the intelligence or functionality to carry out workload balancing. A centralized approach with a central workload balancer has been chosen to minimize command traffic.

Cost of Command Janet Sends

This paragraph tries to provide a short explanation why command sends in Janet are relatively costly and why high command traffic in Janet is likely to cause a performance problem. Command sends in Janet are more costly than RPC calls used in several distributed operating systems. Java RMI, which is used in Janet for communication between distributed agents, relies

on RPC calls as well. However, Java RMI is a high-level RPC-based layer to provide location transparency for objects. Many more RPC calls are sent on the socket layer to make a distributed object communicate with another one seaminglessly than when making a single RPC call in a distributed operating system. In addition, sending a command in Janet from one agent to another involves additional steps beyond transmitting the command using Java RMI. After being accepted by the recipient agent dispatcher the destination agent has to be looked up from the agent dispatcher's agent table. The command is then sent to the agent, which places it in its scheduler's command queue where it waits till all previous commands in the queue have been executed. As it can be seen, command sends in Janet are relatively costly and several times more costly than RPC calls in a distributed operating system. This is an important fact that has to be taken into consideration when developing a conceptual design for workload balancing.

3.1.3 Executor-Observer-Distributor Triad

The executor-observer-distributor triad defines three roles for objects being involved in the process of workload sharing and workload balancing. The executor is an object that is responsible for executing workload-aware commands. The observer observes a workstation's CPU load. More precisely, it observes the CPU load of processes that do not belong to Janet nodes on a particular workstation. If the owner of the workstation reclaims the workstation for purposes other than executing commands using Janet, the observer will observe that the CPU load of non-Janet processes increases. It will then notify one or more distributor objects about the event, which will decide on actions to be taken. If other less loaded nodes exist in the cluster, workload-aware commands will be evicted from all nodes residing on the affected workstation to less loaded nodes on other workstations.

The three kinds of objects of the executor-observer-distributor triad described so far have only been defined in terms of general roles or responsibilities. These roles are likely to be defined in other workload balancing systems as well. No statement has been made whether these kinds of objects can be seen as kinds of nodes or agents, whether there is one or several distributors, etc. The next step consists of the development of the conceptual design, which needs to provide answers to a multitude of questions: Should workload distribution be decentralized as in MOSIX or should it be centralized? Should there be a single distributor object, node, or agent, or should there be several ones? In case the non-Janet CPU load increases, should the observer tell all nodes on the same workstation to evict all commands or should this responsibility be assigned to the distributor? Should an executor send an evicted command to the distributor, which passes it on to the least nodded node, or should it send it directly to some other less loaded agent? There are several questions of this kind for which a conceptual solution is developed in the following.

3.1.3.1 Distributor

It is important to keep the number of commands low that are exchanged to do workload balancing. This is already the reason for the introduction of queue size categories. If there were more than a single distributor in the cluster, all changes of nodes queue size categories would have to be propagated to all distributors in the cluster. Given the high costs of command sends in Janet such a solution would be considered suboptimal. Janet.ADÉ therefore defines a single distributor node that may define several agents. Whenever a nodes QSC changes, the distributor is informed about the state. In MOSIX state change notification is sent to a random number of nodes in order to reduce message traffic. Such an approach is thinkable for Janet.ADÉ as well. Another idea would be to have a small number of distributors, to which executors send

QSC change notifications in alternating order. The solution chosen so far with a single central distributor represents an initial approach or implementation step, which leaves room for enhancements after this implementation step has been completed.

Load Administrator Agent

There is a special agent that is solely responsible for processing QSC changes, which is called the load administrator agent. Defining a special agent for this purpose makes sure that QSC changes are being taken care of immediately. If a distributor's agent queue were filled with a lot of commands that serve a different purpose than taking care of QSC changes, the QSC change notifications might not be handled in time. In the worst case, a command is not evicted to the currently least loaded agent, because the latest queue size change notifications with the most recent status information needed to determine the least loaded node are located in the command queue behind the eviction request itself and can therefore not be considered in time.

3.1.3.2 Observer

The observer is defined as a single node on a workstation that only serves the purpose of watching a workstation's CPU load of non-Janet processes. In case the workstation owner reclaims the workstation for other purposes than executing Janet commands, the observer notifies the distributor about the CPU load change if a certain threshold value is exceeded (it does so in the opposite case as well when CPU load drops down from above the threshold value to a level below it). The distributor will then decide where workload-aware commands from these nodes will be sent to for further execution. The indirection of going through the distributor could be saved if the observer told all nodes on the workstation directly to evict all commands. During the further development of the conceptual design it will become evident that saving this indirection does not result in significantly reduced response time to CPU load changes and only further complicates the workload balancing process.

3.1.3.3 Executor

An executor is any node that defines the required capabilities of Janet.ADÉ to enable workload balancing. When these capabilities are defined for a node, Janet.ADÉ will make use of that node to balance the cluster's workload. A node may benefit from its commands being executed at different sites, which loads some other workstation CPU or may be used by other nodes for the execution of their commands. Workload-aware commands being sent to agents on nodes that have not these capabilities defined will be treated as commands of the Janet.CAS layer that cannot be seen by the workload distribution facility of Janet.ADÉ and therefore do not take part in the workload balancing process. An observer or a distributor could be used as an executor as well. However, it is recommended not to use these kinds of nodes as executors in addition to their special roles since the additional load would result in reduced response time to workload changes in the cluster.

3.1.4 Leveling Out Workload Imbalances

Whenever the QSC of an executor node changes it notifies the distributor about the new QSC. The distributor is therefore able to construct an image of the workload of nodes in the cluster.

Workstation	Node	NodeQSC	WorkstationQSC	Product
1	1	1	1 x 2	2
1	2	2	1 x 2	2
2	3	1	1 x 3	3
2	4	3	1 x 3	3
3	5	2	2 x 2	4
3	6	2	2 x 2	4

Figure 3-1: Cluster Queue Size Category Table

The table displayed in Figure 3-1 lists all 6 nodes in a cluster with 3 workstations with their QSC. Workstation 1 is the least loaded workstation with a node QSC product of 2. From this workstation node 1 is the least loaded one with the lowest QSC, which should be chosen when determining the least loaded node to assign a workload-aware command to.

Number of workload-aware commands per capability

It needs to be taken into account, that a command can only be sent to an agent that has the capability required to execute the command. This might not necessarily be the case for node 1 of the table in Figure 3-1. For this reason, whenever an executor's QSC changes, it sends a table of capability paths to the distributor with the number of workload-aware commands that were sent to agents with the capability identified by the capability path (a string consisting of the application name of the application the capability is defined in, which is unique, and the capability's name). The table contains two entries for a list with waiting and executing workload-aware commands by capability path and kind of workload-aware command (sharing or balancing). It is not possible to send information about the queue length of every agent that has received workload-aware commands, as the number of agents being hosted by a node may be very large. Frequent transmission of large amount of QSC data from executors to the distributor would cause a high a load. On the contrary, the number of capabilities of a node can be expected to remain comparatively small.

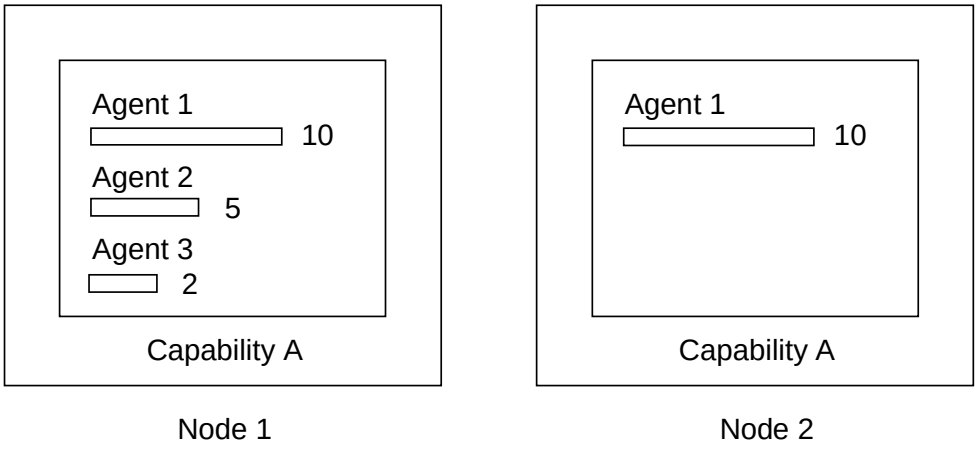

Figure 3-2: Command distribution within capabilities

Figure 3-2 on the previous page shows the same capability A, which exists on the nodes 1 and 2. On node 1, there are 3 agents that have the capability A. On node 1, agent 1 has 10 commands in its queue, agent 2 has 5 and agent 3 has 2. The total number of commands for capability A on node 1 is 17. For node 2 the total number is 10. The distributor knows the total number of workload-aware commands per capability and node. This total number is called the capability queue size (CQS). Whenever an agent is created on a node, through registration of an application that defines certain agents from the beginning or through dynamic creation of an agent at runtime, all nodes in the cluster are notified about the event. The distributor therefore knows about all the agents on all nodes as all other nodes and about their agent paths, which contains the capability name and the name of the agent's application. In the example in Figure 3-2 the distributor knows that the number of commands per agent for capability A is 17 / 3 for node 1 and 10 / 1 for node 2. Assuming that commands are to be moved from node 1 to node 2 to distribute workload more evenly, from which agent's queue should commands be taken? Will moving commands from one node to another in this example in the end result in an improvement?

Node	NodeQSC	CQS
node1	5	25
node2	4	10
node3	4	14
node4	6	30

Figure 3-3: Leveling out commands between nodes

There is another problem that is difficult to solve when leveling out commands between nodes. Figure 3-3 shows a table with the QSC for several nodes and their capability queue sizes (CQS). As the table in Figure 3-3 shows, the nodes 2 and 3 are less loaded than the other nodes. To level out commands between nodes, commands could be moved from the heaviest loaded node 4 to the least loaded nodes 1 and 2. The question is how many commands should be transferred. After a certain amount of commands has been transferred, the receiver node's QSC will rise. The transfer then has to be stopped. After how many received commands will QSC start to rise? The distributor has no way to tell as the QSC definition is individual for every node and is not sent to it at startup. If this information were available the calculations to determine the point where the QSC changes are not necessarily simple and may be costly. It is possible that during the process of transferring commands from one node to another a load imbalance occurs, incurred by new workload-aware commands being created, new executors being started or shut down, or by the workstation owner starting non-Janet processes. The transfer of commands would then have to be canceled.

3.1.5 Workload Balancing

The problems described so far make it clear that leveling out load imbalances can only be carried out as an iterative process where a single command is evicted instead of several commands in a row. "Spontaneous" changes in the cluster's workload balance can then not occur during the eviction of several commands at a time of which the agent to migrate to was determined before the last workload change. The newly changed workload balance situation can be taken into account when deciding which command on which node and of which capability to evict

next to which agent. Furthermore, it seems obvious that leveling out commands between nodes that are all already loaded with a certain amount of commands is not simple. The approach taken in Janet is therefore to use a receiver-based approach, where nodes that are about to run empty ask for commands from heavier loaded nodes. Using this approach, there is no need to perform difficult actions to level out workload between nodes. Whenever the distributor realises through received QSC change notifications that a node has fallen onto a certain low QSC level, it transfers one command from a node that is heavier loaded or has a longer capability queue size. The user is advised to define only those commands as workload-aware commands that take several seconds to execute and load a workstation's CPU heavily. If workload-aware commands are defined in such a way, a node will be fully busy even when executing a single command so that there is no urgency to keep a node's capability queue filled with many commands.

By default, QSC0 is defined as a load situation where a node has zero workload-aware commands (is idle). QSC1 is defined by default as a load situation with a single executing command. The distributor will transfer a command to a node that drops onto QSC1. The user has to be aware of this fact when adapting a node's queue size categories.

Adjusting Waiting Queues and Balancing Executing Commands

The receiver-based approach described above results in waiting queues of different queues not to be leveled out. In Figure 3-4 the number of agents per capability on the two nodes 1 and 2 is the same, but the size of the waiting queues is different. In this situation the waiting queue on node 2 is likely to run empty in less time than on node 1 where the waiting queue is longer. Once the waiting queue size on node 2 has dropped to 1, node 2 will notify the distributor that is has fallen onto QSC1. The distributor will then evict one command from node 1, provided its waiting queue is still longer than on node 2, and migrate it to node 2. This process will continue until both waiting queues have run empty. Workload distribution in this scenario is optimal since both nodes constantly remain busy. The different size of the waiting queue is not relevant since both nodes only have a single agent that can only execute one command at a time.

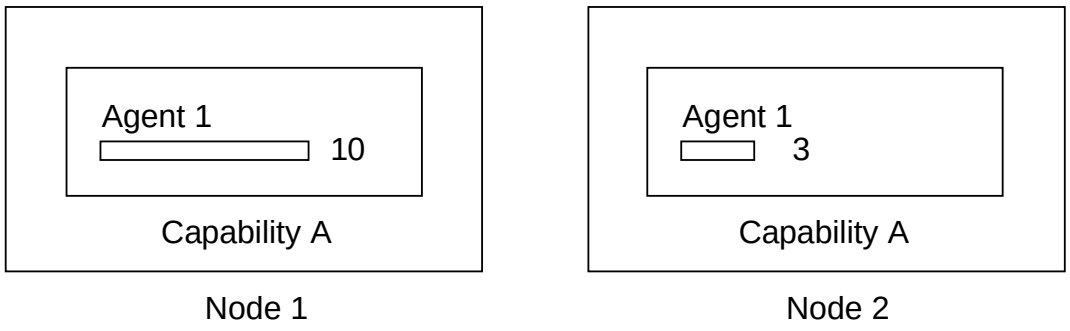

Figure 3-4: Waiting queues of different length

The situation is different when the number of executing commands on different nodes differs. In the situation in Figure 3-5 node 1 has 3 executing commands (each executing command is symbolized by a black filled rectangle) whereas node 2 has 1 executing command.

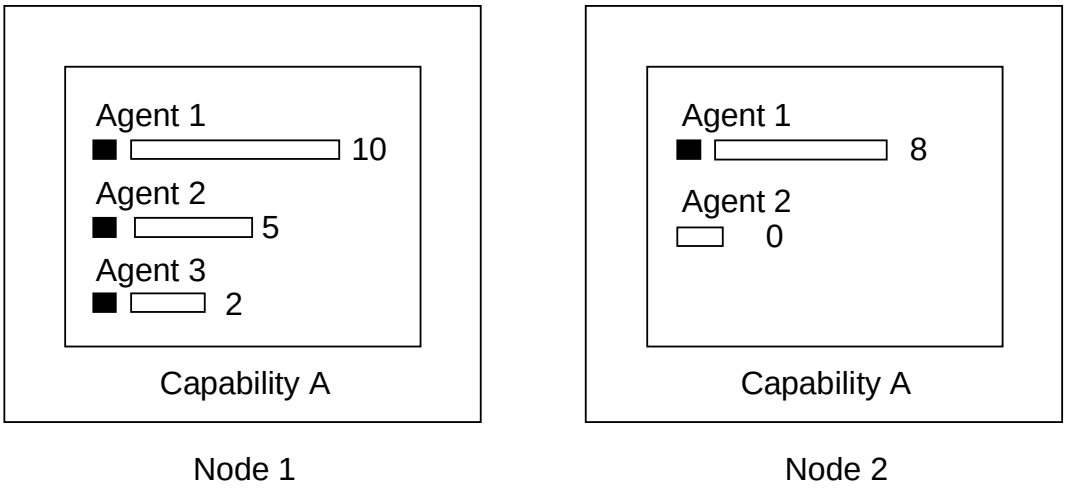

Figure 3-5: Several executing commands

The situation in Figure 3-5 shows an imbalance. A situation with an equal number of executing commands on both nodes would result in a more even workload distribution. Since agent 2 on node 2 is idle, evicting an executing command from node 1 and migrating it to node 2 would remove the imbalance. The workload balancing algorithm presented so far will not do anything about changing the imbalance in the situation in Figure 3-5. With every QSC change notification the distributor receives information about the number of executing commands per capability. It will evict commands and transfer them to nodes with fewer executing commands if possible. Several criteria have to be fulfilled for a node to receive an evicted executing command:

- The node needs to have the required capability to execute a command evicted from some other node.
- The node must not be in the process of a full eviction.
- The node needs to have a lower QSC than the overloaded node. The QSC of other nodes on the same workstation must be considered as well.
- The node needs to have an idle agent (with an empty waiting queue and no executing command) that has the required capability.

From the nodes that fulfill these criteria, the node with the lowest number of executing commands is chosen. If there are several nodes that all have the same lowest number of executing commands the one with the lowest QSC is chosen.

One Node Overloaded, All Other Nodes on QSC0

There is a special case where the receiver-initiated approach does not offer a solution, which means that it has to be handled specifically. In this special case workload balancing commands are sent to a single agent and all other nodes are on QSC0. The recipient agent's waiting queue will start to grow as a result. If all other nodes are on QSC0, no QSC change notification will be sent to the distributor to make it migrate commands from the overloaded node to the nodes

with QSC0. For that reason, whenever a node raises in QSC level above QSC1, the distributor checks whether there is any node on QSC0 to migrate a command to.

3.1.5.1 Full Eviction

When the observer realises that the CPU load of non-Janet processes on a workstation has risen above a certain threshold value all workload-aware commands are evicted from all nodes on the workstation. For the time that this load value remains above the threshold value the nodes on the workstation will not receive any commands from the distributor. When the threshold value is exceeded the observer sends a notification to the distributor. The distributor determines whether any nodes are available to which commands could be transferred to. If any node is available it first locks all nodes on the workstation with the exceeded CPU load threshold value so that they receive no evicted commands. The distributor then sends a command to all executors on the workstation, which start evicting all executing and waiting workload-aware commands. These commands are sent to the distributor, which decides for every command to which agent to pass it on to. It is possible that due to workload changes in the cluster no more nodes are available to transfer evicted commands to. The distributor then sends a cancel eviction command to the nodes evicting commands.

Canceling Full Eviction

Commands in Janet run to completion. Canceling a command that is evicting commands therefore requires the introduction of some additional mechanism. The command that carries out full eviction is the `ReduceLoadCommand`. It is sent from the distributor to the executor's system agent, which runs at highest priority. This makes sure that the `ReduceLoadCommand` is executed immediately. The `ReduceLoadCommand` places a token in the executor's application space and sends the `InterruptibleReduceLoadCommand` to the executor's special executor agent which is managed by the system arbitrator and therefore runs at a higher priority than all application schedulers managed by the application arbitrator. The scheduler thread executing the `InterruptibleReduceLoadCommand` therefore interrupts all lower prioritized scheduler threads that run application-level agents and can any time be interrupted by the thread that runs the system scheduler. This is required in case full eviction has to be canceled. In this case, the `CancelReduceLoadCommand` is sent to the executor's system agent, which will result in the lower prioritized thread running the `InterruptibleReduceLoadCommand` to be suspended and the `CancelReduceLoadCommand` to be executed immediately. The `CancelReduceLoadCommand` removes the token placed by the `ReduceLoadCommand` in the executor's application space. The `InterruptibleReduceLoadCommand` that checks for the existence of this token after every eviction of a command will no longer find it and cancel its operation.

Carrying Out Full Eviction

The purpose of full eviction is to lower the CPU load immediately caused by the processes running the Java virtual machines that run Janet. This task cannot be accomplished if the application agent's schedulers continue to run. Whenever an executing command was suspended and evicted the agent's scheduler takes in the next command from the queue and starts executing it which results in the CPU load to remain high. Clearing waiting workload-aware commands from the scheduler's queue first is no alternative solution in case the number of waiting commands is high. The approach is therefore to stop all application schedulers, suspend all executing workload balancing commands and remove all workload-aware commands from the scheduler's queue. After all workload-aware commands of a scheduler's queue have been

evicted the scheduler is started again. More precisely, instead of stopping and starting a scheduler, an additional semaphore that controls access to the scheduler's queue is closed so that the scheduler has to wait and cannot pick the next command from the queue until the semaphore is opened again. This approach is less effortful and more efficient than starting and stopping a scheduler.

3.1.5.2 Partial Eviction

The term partial eviction refers to the case where an executor node is about to run idle and a command from some other heavier loaded node is transferred to it. In case of partial eviction, contrary to full eviction where simply all workload-aware commands of a node are evicted, a command has to be determined that is transferred to the executor node that is about to run empty. The command queue for eviction is selected using the following criteria:

- Select all workstations that are available for eviction: CPU load threshold for the workstation not exceeded.

- From all available nodes select the ones that have the required capabilities, capability queue size greater than zero, and QSC2 or greater. For all matching nodes on the same workstations create the product of node queue size categories to determine the heaviest loaded workstation.

- From the heaviest loaded workstation select the node with the greatest QSC. Select the capability with the largest number of workload-aware commands. If two or more nodes have the same overall QSC, select the node with the longest capability queue.

After the distributor has selected the node and capability queue to evict a command from, it sends the command `EvictCommand`, that knows from which capability queue to pick a waiting command or suspend an executing command and to which agent to pass it on. The distributor has no knowledge which agent that has the respective capability has the longest scheduler queue. For this reason, the longest scheduler queue is determined by the `EvictCommand` at the executors site.

3.1.6 Workload Sharing

When a workload sharing command is sent to an agent, it is not immediately executed as it would be the case for commands of the Janet.CAS layer but passed on to some agent on the distributor node. This agent is called the sharing distributor agent, which serves for the sole purpose of assigning workload sharing commands to agents that are less loaded. The reason for this special agent to deal with workload sharing commands to exist is that workload sharing commands are different than workload balancing commands in the way that they remain on the node they have initially been assigned to until they have finished execution. Using a special agent for workload sharing makes sure that the distribution process of workload sharing commands does not interfere with the workload balancing tasks and can be treated as a separate part.

The sharing distributor agent has to decide which agent in the cluster a workload sharing command is to be sent to. For that purpose, the sharing distributor agent has to determine the least loaded agent in the cluster. This is the opposite of what the balancing distributor agent has to

do to accomplish workload balancing. The process of determining the least loaded agent is very similar to determining the heaviest loaded one. The steps remain essentially the same except for selecting least loaded workstations, least loaded nodes, and shortest queues instead of selecting the heaviest loaded ones, and longest queues as in case of partial eviction:

- Select all workstations that are available: CPU load threshold for the workstation not exceeded.

- From all available nodes select the ones that have the required capabilities. For all matching nodes on the same workstations create the product of node queue size categories to determine the least loaded workstation.

- From the least loaded workstation select the node with the smallest QSC. Select the capability with the smallest number of workload-aware commands. If two or more nodes have the same overall QSC, select the node with the shortest capability queue.

3.2 Detailed Design and Implementation

This section describes the detailed design and implementation of the three kinds of nodes of the executor-observer-distributor triad.

3.2.1 Executor

The executor is the part in the executor-observer-distributor triad that needs to expose an interface for the user to execute workload-aware commands. It is more illustrative to start detailed design and implementation with a presentation of the user interface.

3.2.1.1 User Interface Extensions

Agent Extensions

The `ICommand` interface for commands from Janet.CAS is extended for workload sharing commands and workload balancing commands.

```
public interface IWorkLoadSharingCommand extends ICommand
{
}

public interface IWorkLoadBalancingCommand extends ICommand
{
}
```

Figure 3-6: Interface for workload-aware commands

As Figure 3-6 shows, both interfaces, `IWorkLoadSharingCommand` and `IWorkLoadBalancingCommand`, are empty. The idea is to make use of method parameter polymorphism in Java. When a workload-aware command implementing either interface is sent to an agent proxy using the `accept` selector the respective method is invoked at runtime.

The additional `accept` method of the `IAgentProxy` are displayed in Figure 3-7 on the next page. Class `AgentProxy`, which implements the `IAgentProxy` interface, implements the additional `accept` selectors suitable for each kind of workload-aware command. The selector `accept(IWorkLoadSharingCommand command)` is implemented in such a way that the workload sharing command is sent to the distributor's sharing distributor agent. If this agent cannot by found, a warning is displayed. The command is then casted to the `ICommand` interface and sent to the receiver agent again, which results in the command to be executed by the recipient agent as a common command of the Janet.CAS layer that cannot be evicted. The other selector `accept(IWorkLoadBalancingCommand command)` is implemented in such a way that the `AgentProxy` checks whether the distributor's balancing distributor agent exists.

```
public interface IAgentProxy
{
      // already described accept selectors omitted

      public void accept(IWorkLoadSharingCommand command)
      throws RemoteException, InvalidCommandException;

      public void accept(IWorkLoadBalancingCommand command)
      throws RemoteException, InvalidCommandException;
}
```

Figure 3-7: IAgentProxy interface extensions

If this is not the case a warning is displayed and the workload balancing command is sent to the destination agent represented by the agent proxy. As mentioned earlier, workload balancing commands are only evicted on demand. For this reason, contrary to workload sharing commands, they are not sent to the distributor for distribution to the least loaded applicable agent.

Additional Abstract Interpreters and Interpreter Suspension

There is no additional kind of interpreter needed for the execution of workload sharing commands since this additional kind of command runs to completion in the same way as common commands in Janet.CAS. As workload balancing commands may be interrupted another kind of abstract interpreter is required that permits interruption by another party.

```
public interface IWorkLoadBalancingInterpreter extends IInterpreter
{
      public void suspend(ISuspensionHandler suspensionHandler);
      public Object clone() throws CloneNotSupportedException;
}
```

Figure 3-8: Workload balancing interpreter interface

Figure 3-8 shows the interface of the abstract workload balancing interpreter that must be implemented for the execution of user-defined workload balancing commands. The interface defines in addition to the extended `IInterpreter` interface a suspend method. This method is called when an executing workload balancing command has to be evicted. The suspension handler passed on as a parameter has to be signaled upon suspension of the interpreter. A user

implementing any workload balancing command must implement the suspend method. If this is not the case, Janet.ADÉ has no way to interrupt an executing command and the command will run to completion without being evicted. After suspension, the command carrying out the eviction will then finally evict the command. A common solution to make an interpreter suspendable is to set a flag to suspended in case the suspend method was sent. The interpreter checks the suspended flag periodically. When it detects that this flag has been set to true, it saves permanent information in the command object received through the command accessor, exits the interpreter's execute method and signals the suspension handler.

Every interpreter is instantiated by Janet.CAS once (either at startup time after parsing the node descriptor or when an application is registered programmatically) and then stored in a lookup table that is used to dispatch commands to interpreters. If a user-defined flag like some suspend flag is changed, its value will remain changed (set to suspended) for all subsequent executions of this interpreter, which would result in the execution of the interpreter to suspend immediately whenever the associated command is executed. For this reason, Janet.ADÉ clones a workload balancing interpreter before every execution. The `IWorkLoadBalancingInterpreter` displayed in Figure 3-8 therefore requires the clone method inherited from class `Object` to be implemented for any workload balancing command.

Additional Agent Extensions

The `IAgentProxy` interface defines for the additional `accept` methods the respective methods to install callback handlers and to send command synchronously as well. Implementing these methods does not require an extension of the existing mechanisms, which rely on a reply command to unblock a waiting thread or on invoking a callback handler. The last entry in the command envelope's history contains the origin agent path to which the command has to be sent after completion. Visiting several nodes will result in the command envelope's history to grow beyond the size of two entries. Nevertheless, the existing mechanisms will continue to work as designed since the last entry in the command envelope's history remains the agent path to the origin agent.

3.2.1.2 Command Tracking

The executor has to keep track of workload-aware commands that have been received. It needs to know into which queues they have been inserted so that it knows from which queues that have to be removed in case of eviction. The executor needs to do some bookkeeping as well, so that it knows which workload-aware commands require which capability to execute and how many commands there are per capability. This information is required to deduct the current QSC.

The `AgentDispatcher` had to be extended to signal a synchronous event whenever a command has been received. This is the only extension that had to be made in the Janet.CAS layer to implement the executor. All other functionality has been implemented with the use of another kind of command envelope that exposes the interface of a command to the existing `CommandEnvelope` while assisting the executor in doing its bookkeeping whenever a user-defined command is about to execute or has finished execution.

The `ExecutorAnchor` is the anchor object of the executor. It stores the bookkeeping information and keeps track of the current QSC. The class diagram of the `ExecutorAnchor` and related classes are displayed in Figure 3-9 on the next page.

Command Arrival

When the `AgentDispatcher` receives a command it signals the respective event, to which the `ExecutorAnchor` has subscribed to. The event handler `CommandArrivedHandler`, the `ExecutorAnchor` has registered to handle the event, notifies the `ExecutorAnchor` about the command arrival in case it is a workload-aware command and sends either the message `workloadSharingCommandArrived` or `workloadBalancingCommandArrived` as appropriate. The `ExecutorAnchor` inserts the command envelope of the command in the respective lists for waiting commands and increments the respective waiting command counters.

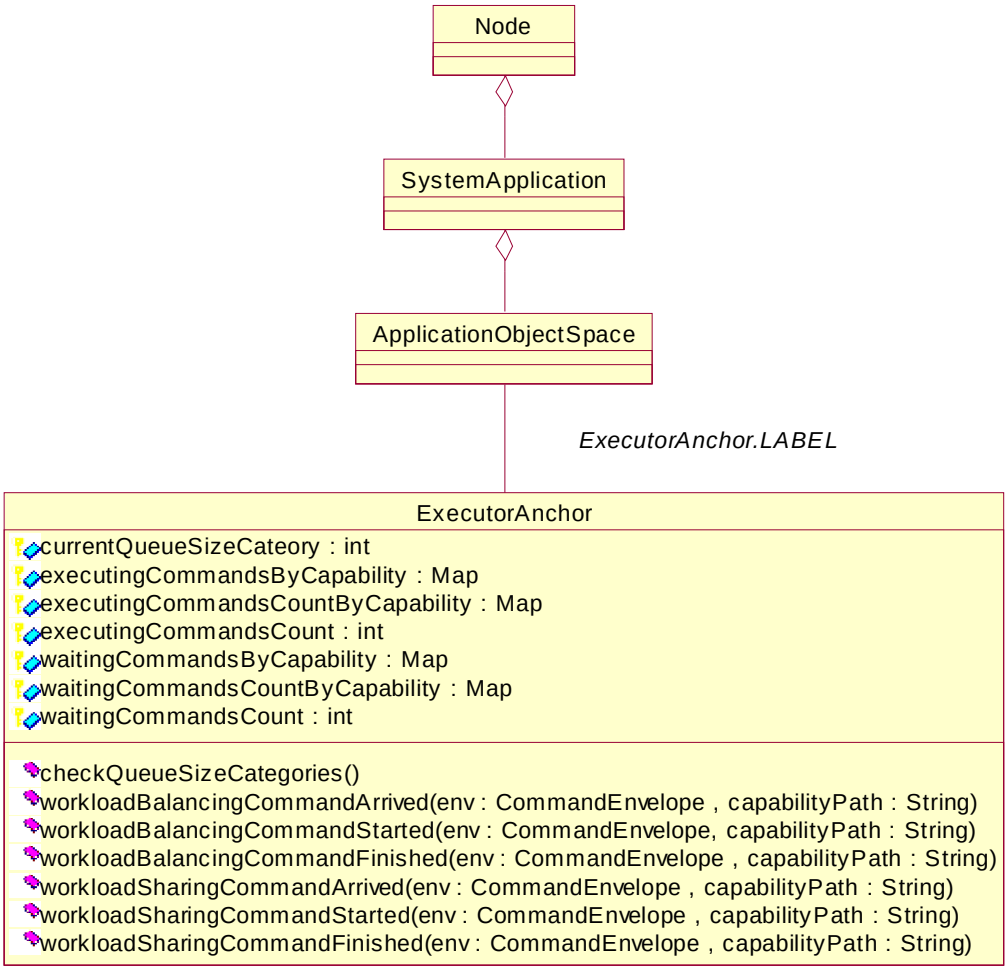

Figure 3-9: ExecutorAnchor class diagram

The message sequence that takes place upon command arrival is displayed in Figure 3-10 on the next page.

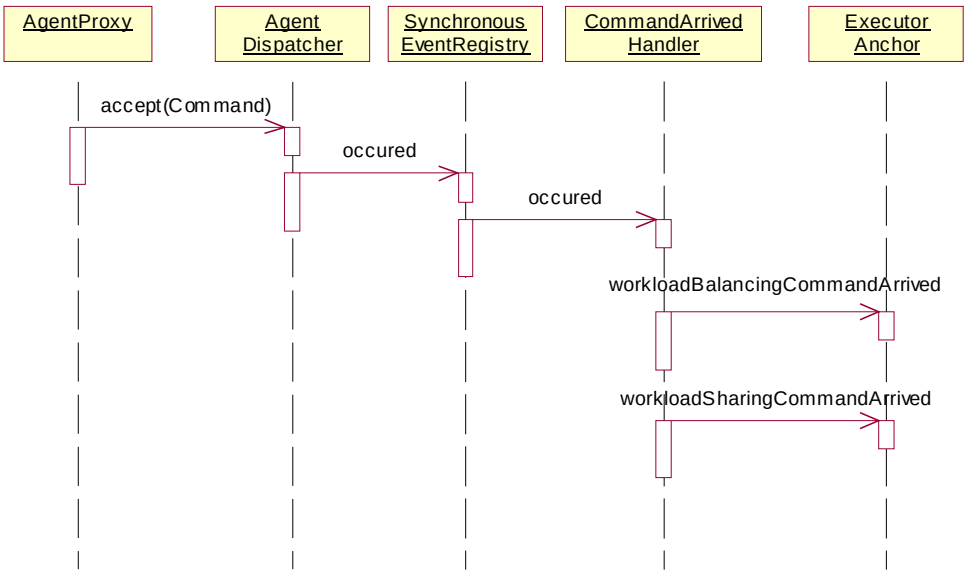

Figure 3-10: Command arrival message sequence

Executing Workload-Aware Commands

When a workload-aware command is sent to an agent proxy, the agent proxy inserts the command into a special command. There is a special command for either kind of workload-aware command: `ExecuteWorkloadSharingCommand` and `ExecuteWorkloadBalancingCommand`. An agent's command scheduler executes either special command as applicable. Both special commands notify the `ExecutorAnchor` when they are about to execute the user-defined command they contain and when they have finished executing it, which enables the `ExecutorAnchor` to keep track of the state of workload-aware commands. Whenever a workload-aware command has arrived, is about to start execution, or has finished execution, the `ExecutorAnchor's checkQueueSizeCategories` method is called, which makes the `ExecutorAnchor` check whether the QSC has changed due to the command state changes. If this is the case, the distributor is notified. The message sequence to execute a workload-aware command is displayed in brief in Figure 3-11.

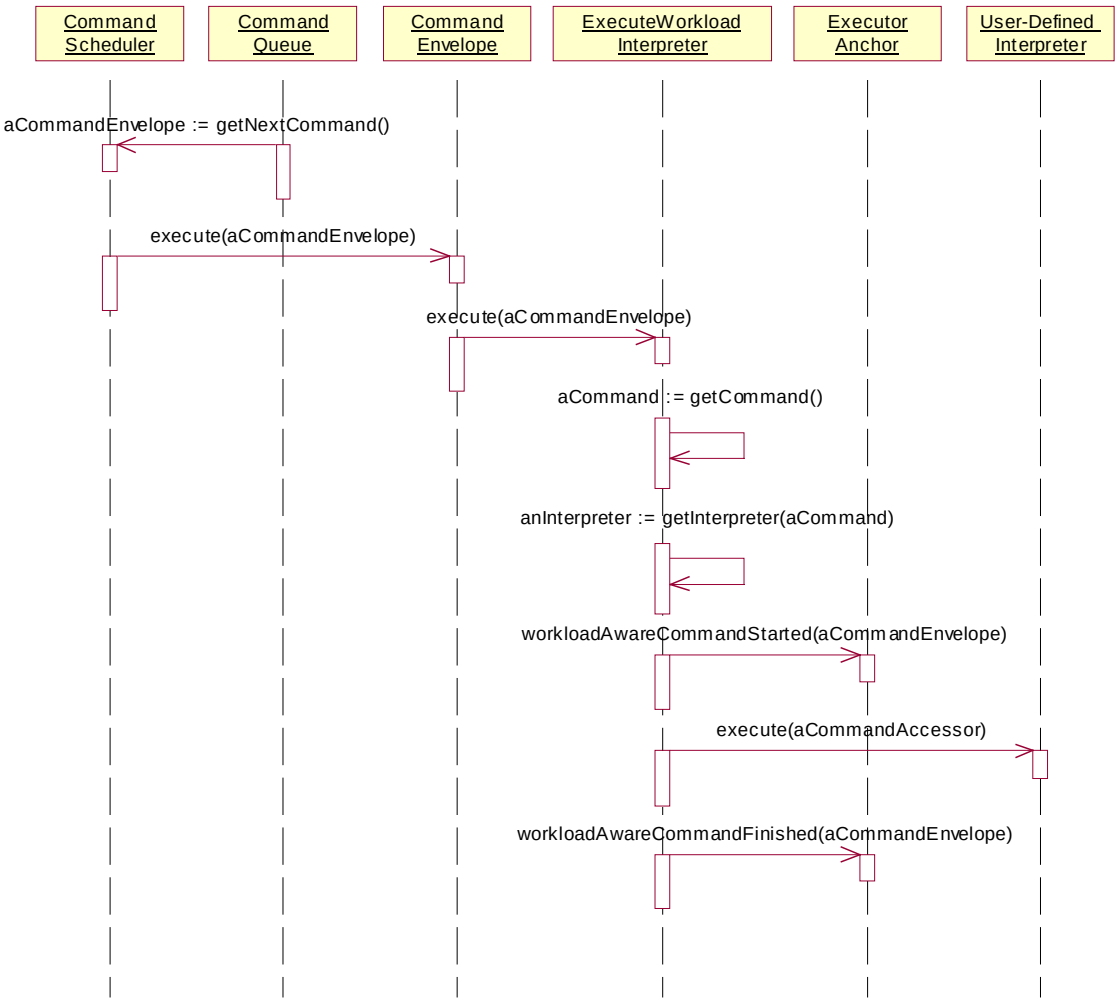

Figure 3-11: Executing an ExecuteWorkloadInterpreter

A command is always executed by an interpreter. The interpreters for the two special commands are named `ExecuteWorkloadSharingInterpreter` and `ExecuteWorkloadBalancingInterpreter`. The interpreter for the user-defined command carried by the special commands may be defined in any user-defined capability. For the interpreters of the special commands to be executable, they have to be added to the respective user-defined capability. To free the user from having to define these interpreters in a capability whenever she has to define an interpreter of a workload-aware command, the agent proxy inserts the respective required interpreter into the command envelope, carrying the user-defined command, before the command is sent to the destination agent. If the command envelope's attribute that holds the interpreter to be used for the execution of a command is not set to null, the scheduler will not look up the interpreter for the command dynamically but use the already specified interpreter. Preventing dynamic interpreter lookup is a compromise for the sake of making the definition of workload-aware command interpreters as simple as possible for the user. There is no way for the user to prevent dynamic interpreter lookup since the respective inner node classes provide no such interface.

3.2.1.3 Executor Descriptor

To define an executor node a node's system application has to be extended. Commands that need to be executed by the supreme agent, that uses the supreme scheduler, have to be defined as part of system applications' CORE capability. For the executor this is the case for the commands `ReduceLoadInterpreter` and `CancelReduceLoadInterpreter`. The `ReduceLoadInterpreter` must be executed immediately to make sure partial or full eviction is carried out without delay. The `CancelReduceLoadInterpreter` to be able to cancel a full eviction must be executed with highest priority as well.

```
<systemApplication>
  <capabilities>
    <capability name="CORE">
      <interpreters>
        <!-- interpreters defined by Janet.CAS omitted -->
        <interpreter>
          org.objectscape.janet.ade.executor.interpreters.
          ReduceLoadInterpreter
        </interpreter>
        <interpreter>
          org.objectscape.janet.ade.executor.interpreters.
          CancelReduceLoadInterpreter
        </interpreter>
      </interpreters>
    </capability>
  </capabilities>
</systemApplication>
```

Figure 3-12: System application's additional interpreters of the CORE capability

Figure 3-12 displays the system application's `CORE` capability extended with the respective interpreters. The remaining commands executed by the executor's agents need to run with system priority. For that reason they are defined as part of an additional system capability so that they will be executed by system agents that use system schedulers. The additional System capability is named `ADE_EXECUTOR`. Its definition is displayed in Figure 3-13.

```
<systemApplication>
  <capabilities>
      <capability name="CORE">
        <!-- interpreters omitted for brevity -->
      </capability>
      <capability name="ADE_EXECUTOR" descriptor="executorDescriptor.xml">
        <agents>
          <agent name="EXECUTOR" executeWhenStarted=
          "org.objectscape.janet.ade.commands.StartCommand" />
        </agents>
        <interpreters>
          <interpreter>
            org.objectscape.janet.ade.executor.interpreters.
            StartInterpreter
```

```
            </interpreter>
            <interpreter>
               org.objectscape.janet.ade.executor.interpreters.
               InterruptibleReduceLoadInterpreter
            </interpreter>
          </interpreters>
        </capability>
  </capabilities>
</systemApplication>
```

Figure 3-13: Executor's main system capability

The `ADE_EXECUTOR` capability defines the `EXECUTOR` agent, which carries out full and partial eviction using the `InterruptibleReduceLoadInterpreter`. The executor's QSCs are defined in the descriptor of the `ADE_EXECUTOR` capability, which in Figure 3-13 is stored in the file `executorDescriptor.xml`.

```
<executor>
    <observerInterval delay="2000" period="2000" />
    <queueSizeCategories>
      <queueSizeCategory name="0" maxWaitingCommands="0"
        maxExecutingCommands="0" />
      <queueSizeCategory name="1" maxWaitingCommands="0"
        maxExecutingCommands="1" />
      <queueSizeCategory name="2" maxWaitingCommands="3"
        maxExecutingCommands="1" />
      <queueSizeCategory name="3" maxWaitingCommands="20"
        maxExecutingCommands="1" />
      <queueSizeCategory name="4" maxWaitingCommands="10"
        maxExecutingCommands="3" />
    </queueSizeCategories>
  </executor>
```

Figure 3-14: Executor capability descriptor defining queue size categories

A definition of QSCs is shown in Figure 3-14. QSCs are numbered in ascending order; every QSC defines a `maxWaitingCommands` and a `maxExecutingCommands` attribute. When determining the current QSC the executor iterates over the QSC definitions in descending order and checks whether both criteria are met. If it is met the current iterator's QSC name is returned. Otherwise, the iterator moves on to next lower QSC.

3.2.1.4 Command Eviction

During full eviction it is not necessary to identify specific commands in specific queues since simply all waiting and executing commands are moved to the distributor. In case of partial eviction, the evicting command needs to know precisely from which queue of which capability to pick a command for eviction. Partial eviction is therefore the more demanding eviction process, which is covered in more detail than full eviction.

After the ReduceLoadCommand has been accepted by the supreme agent, it sends the InterruptibleReduceLoadCommand to the EXECUTOR agent. The EXECUTOR agent invokes the InterruptibleReduceLoadInterpreter, which retrieves an eviction assignment from its command. The eviction assignment was inserted by the distributor into the ReduceLoadCommand. It defines whether a waiting or executing command has to be evicted, from which capability, and to which agent to transfer the evicted command.

Evicting A Waiting Command

When evicting a waiting command there is no need to suspend it since execution has not started. The waiting command is removed from the queue it is waiting in and transferred to the destination agent. If the waiting queue has run empty after the eviction assignment was sent to the executor, the InterruptibleReduceLoadInterpreter has nothing to do and terminates. Otherwise, the agent with the capability specified by the eviction assignment with the longest queue has to be retrieved. All agents with the required capability are obtained from the node's local node image. Since the IAgentProxy defines a size method that returns the agent's current queue size, the agent with the longest waiting queue can be detected effortlessly. The ExecutorAnchor stores waiting commands by their command envelope. The command envelope knows the queue its command is waiting in. The command envelope can therefore be asked to remove its command from its waiting queue. After removal the command is sent to the destination agent. If any monitor node is present in the cluster, it receives a notification that a command has been evicted on a specific node so that the user can follow command movements of commands by watching command counts being incremented and decremented.

After the eviction a QSC change notification is sent to the distributor with the current queue size information even if the QSC has not changed so that the distributor has an accurate picture that includes the recent load adjustment.

Evicting An Executing Command

When an executing command is evicted the eviction process remains essentially the same. The only difference is that the executing command has to be asked to suspend execution. The EXECUTOR agent does so by passing on a suspension handler. The EXECUTOR agent does therefore not remain waiting till the command has finally been suspended. Only after the suspension handler has been signaled the EXECUTOR agent moves the suspended command on to the destination agent. Any monitor node, if present in the cluster, is notified as well. The mechanism to evict a command is described in section 3.3.1 on the basis of the driving ADÉ.Fibonacci application. In case several executing agents with required capability exist, the command executed by the agent with the longest waiting queue is chosen for eviction.

3.2.2 Observer

The observer observes a workstation's CPU load periodically to detect whether the workstation has been retracted for purposes other than executing Janet commands. The observer capability is named ADE_LOAD_OBSERVER and is defined as a capability of the system application. The observer's agent named OBSERVER therefore runs with second highest priority, which makes sure that the observer agent can only be interrupted by the supreme agent. The observer's capability definition is displayed in Figure 3-15.

```
<systemApplication>
```

```
<capabilities>
  <!-- CORE capability omitted for brevity -->
  <capability name="CORE">
  <capability name="ADE_LOAD_OBSERVER"
      descriptor="observerDescriptor.xml">
    <agents>
      <agent name="OBSERVER" executeWhenStarted=
        "org.objectscape.janet.ade.commands.StartCommand" />
    </agents>
    <interpreters>
      <interpreter>
        org.objectscape.janet.ade.observer.simulation.interpreters.
        StartInterpreter
      </interpreter>
      <interpreter>
        org.objectscape.janet.ade.observer.simulation.interpreters.
        ObserveWorkstationLoadInterpreter
    </interpreter>
    </interpreters>
  </capability>
  <capabilities>
</systemApplication>
```

Figure 3-15: Simplified observer descriptor definition

The user can change several settings that are defined in the capability descriptor file of the observer's capability (in the descriptor in Figure 3-15 named `observerDescriptor.xml`). The capability descriptor is displayed in Figure 3-16.

```
<observer>
    <interval periodInMillis="2000" />
    <loadChange significantWhenExceedingPercentage="10"/>
 </observer>
```

Figure 3-16: Observer capability descriptor

The user can change the interval period after which the observer checks the current CPU load (`periodInMillis`) and how strong a CPU change needs to be to be considered significant (`significantWhenExceedingPercentage`).

3.2.2.1 Simulated Observer

The `ADE_LOAD_OBSERVER` capability defines two interpreters. The `StartInterpreter` is executed after the node has finished the start-up process, which starts the observer's graphical user interface. The `ObserveWorkstationLoadInterpreter` reads the CPU load periodically to detect load changes and notifies the distributor in case of significant change. Both interpreters are defined in the `org.objectscape.janet.ade.observer.simulation` package since the observer in its current state is a simulation that does not read the CPU load from the host operating system but reads a user-defined value (`CPU-LOAD All Others` slider in Figure 3-17). The use of a simulation makes it possible to make the system react to load changes that are

difficult to create in an unsimulated environment. Using a simulation is a necessity to create an environment where implementation and test can be carried out in a simple and straightforward way.

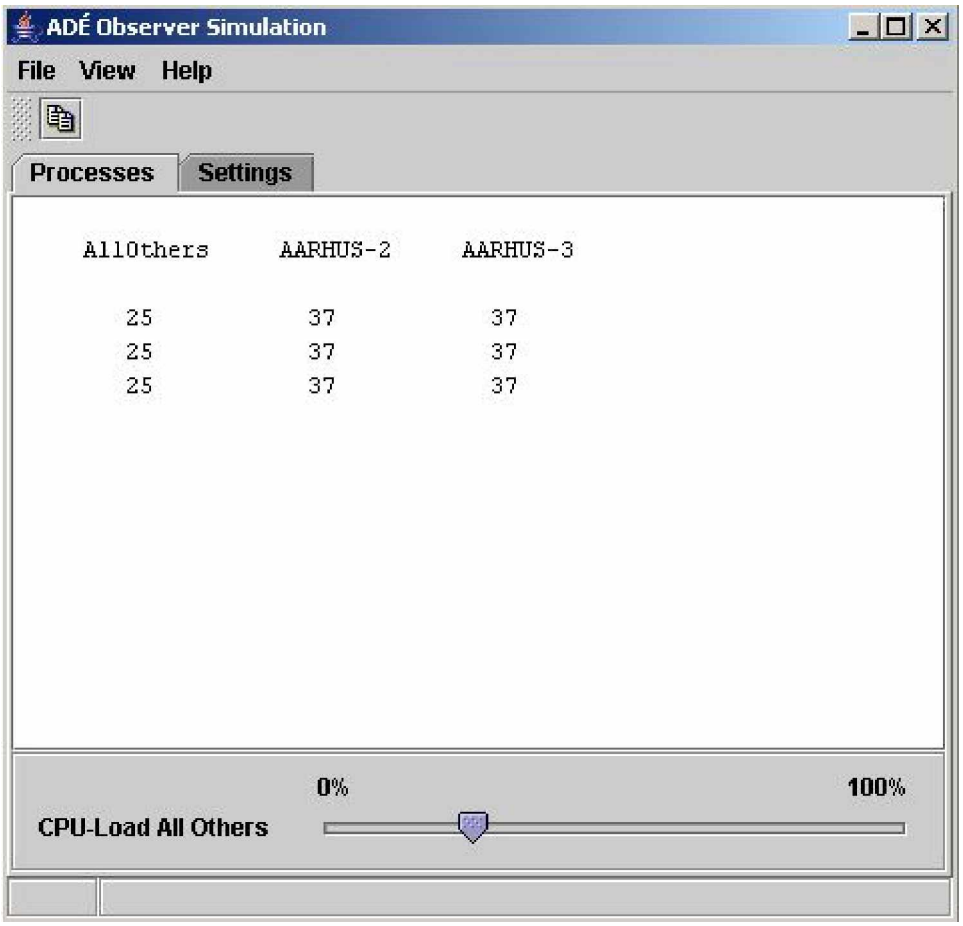

Figure 3-17: Observer's main view processes tab

The observer's main view processes tab displayed in Figure 3-17 displays the value of the simulated CPU load (`AllOthers`) and the CPU load caused by the two executors hosted by the node AARHUS-2 and AARHUS-3, which is derived from the executors QSC. Every executor writes the current QSC into a file following the naming pattern `nodeName.Executor.info`. The simulated observer reads in the current QSC from file for every executor and displays it in the processes tab. In order to implement and test in simulated mode using a single machine, the observer's main view settings tab, displayed in Figure 3-18, allows the user to specify which nodes the observer should assume to be on the same workstation. Clicking the "`Look for local Janet nodes`" button forces the simulated observer to look again for all `nodeName.Executor.info` files in case new executor nodes have been started up meanwhile.

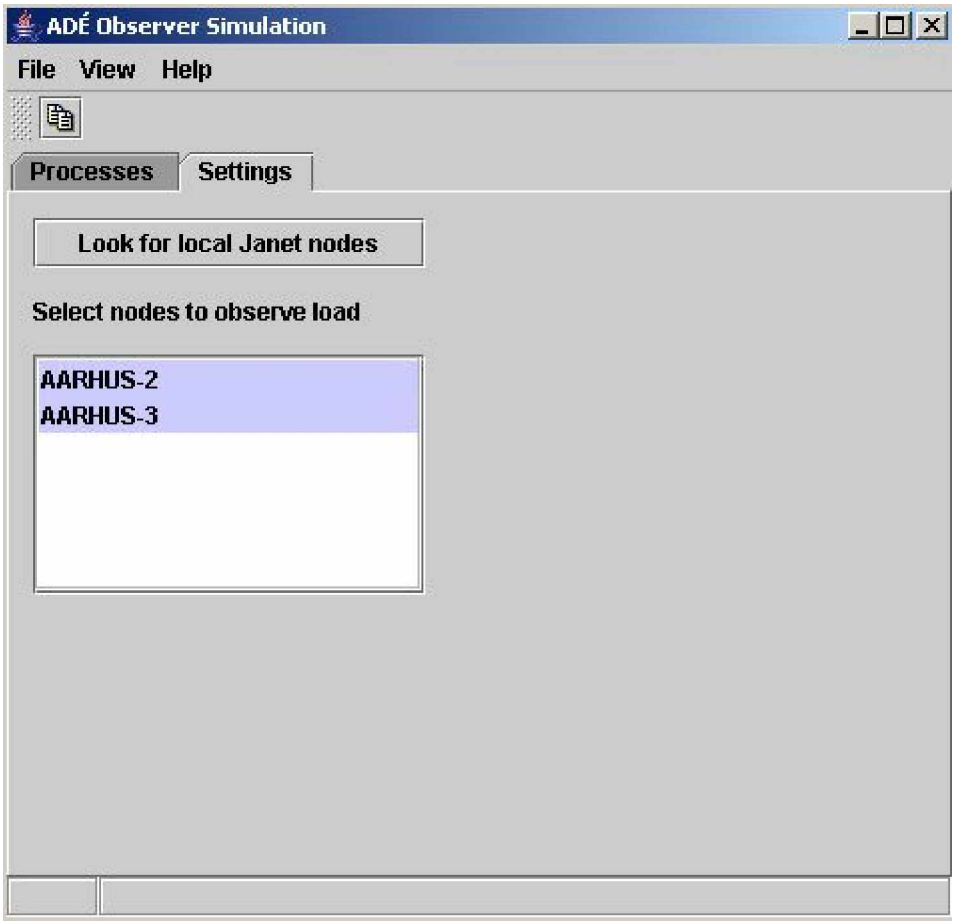

Figure 3-18: Observer's main view settings tab

3.2.3 Distributor

The distributor is the central authority that decides whether commands have to be evicted to level out workload imbalances and decides where commands are evicted and where they are transferred.

The explanation of the distributor's descriptor is a good starting point to describe the distributor's constitution. As mentioned in the conceptual description of the distributor three agents are defined that run as system schedulers with second highest priority. All agents run with the same priority to make sure that one cannot cause starvation of the others. If the `BALANCING_DISTRIBUTOR` agent, that makes the eviction decisions, ran at higher priority than the others, the `LOAD_ADMINISTRATOR` agent might be blocked for a while and could not update the distributor's load image. This would result in the `BALANCING_DISTRIBUTOR` agent making eviction decisions not based on most recent information. Similarly, if the `LOAD_ADMINISTRATOR` agent ran at higher priority, the `BALANCING_DISTRIBUTOR` agent could be blocked not being able to make eviction decision for the distributor to be responsive to workload changes. To make sure that the distributor is not obstructed it is recommended not to define additional system capabilities for a distributor node. If the `LOAD_ADMINISTRATOR` agent

seems to be much more busy than the other agents, adjusting the nodes' QSCs should be considered.

```
<systemApplication>
  <capabilities>
    <!-- CORE capability omitted for brevity -->
    <capability name="ADE_LOAD_DISTRIBUTOR" descrip-
        tor="distributorDescriptor.xml">
      <agents>
        <agent name="BALANCING_DISTRIBUTOR" execute-
          WhenStarted=
          "org.objectscape.janet.ade.commands.StartCommand"
              />
        <agent name="SHARING_DISTRIBUTOR" />
        <agent name="LOAD_ADMINISTRATOR" />
      </agents>
      <interpreters>
        <interpreter>
          org.objectscape.janet.ade.distributor.interpreters.
          StartInterpreter
        </interpreter>
        <interpreter>
          org.objectscape.janet.ade.distributor.interpreters.
          WorkloadDistributionInterpreter
        </interpreter>
        <interpreter>
          org.objectscape.janet.ade.distributor.interpreters.
          ProcessQSCChangedInterpreter
        </interpreter>
        <interpreter>
          org.objectscape.janet.ade.distributor.interpreters.
          ProcessCPULoadChangedInterpreter
        </interpreter>
        <interpreter>
          org.objectscape.janet.ade.distributor.interpreters.
          NotifyQSCChangedInterpreter
        </interpreter>
        <interpreter>
          org.objectscape.janet.ade.distributor.interpreters.
          NotifyCPULoadChangedInterpreter
        </interpreter>
        <interpreter>
          org.objectscape.janet.ade.distributor.interpreters.
          ObserverStateChangedInterpreter
        </interpreter>
      </interpreters>
    </capability>
  </capabilities>
</systemApplication>
```

Figure 3-19: Distributor descriptor

The distributor's description displayed in Figure 3-19 defines several interpreters. The `WorkloadDistributionInterpreter` carries out initial placement of a workload sharing command and places workload-aware commands received through full eviction. The two notification commands `NotifyQSCChangedCommand` and `NotifyCPULoadChangedCommand` notify the distributor about changed conditions concerning the QSC of an executor in the former case and the changed CPU load detected by an observer in the latter case. Both notification commands update the distributors internal cluster load image. If they detect an imbalance, they create the respective commands that take action to remove the imbalance and send them to the `BALANCING_DISTRIBUTOR` agent: `ProcessQSCChangedCommand` and `ProcessCPULoadChangedCommand`. Only sending these commands in case an imbalance was detected reduces the `BALANCING_DISTRIBUTOR` agent's load and improves responsiveness. The `ProcessQSCChangedInterpreter` tries to level out imbalances in the number of executing commands and feeds an executor with commands in case it runs into QSC1. The `ProcessCPULoadChangedCommand` carries out full eviction or cancels it. `ObserverStateChangedInterpreter` is used to inform the distributor that an executor has been connected to an observer or has been disconnect from an observer.

Displaying Cluster Load Information

The distributor displays in values tab of its node main view the current workload information it has. This information can be used to reproduce eviction decisions.

3.3 Driving Application: Fibonacci Numbers Revisited

The Fibonacci sample application developed as a driving application for Janet.CAS is extended with new functionality from Janet.ADÉ. The driving application is called ADÉ.Fibonacci. Firstly, A Fibonacci workload sharing command is implemented that is transparently placed at a lightly loaded node by the distributor. Secondly, a Fibonacci workload balancing command is implemented that will be evicted from the agent it was initially sent to if required to balance load.

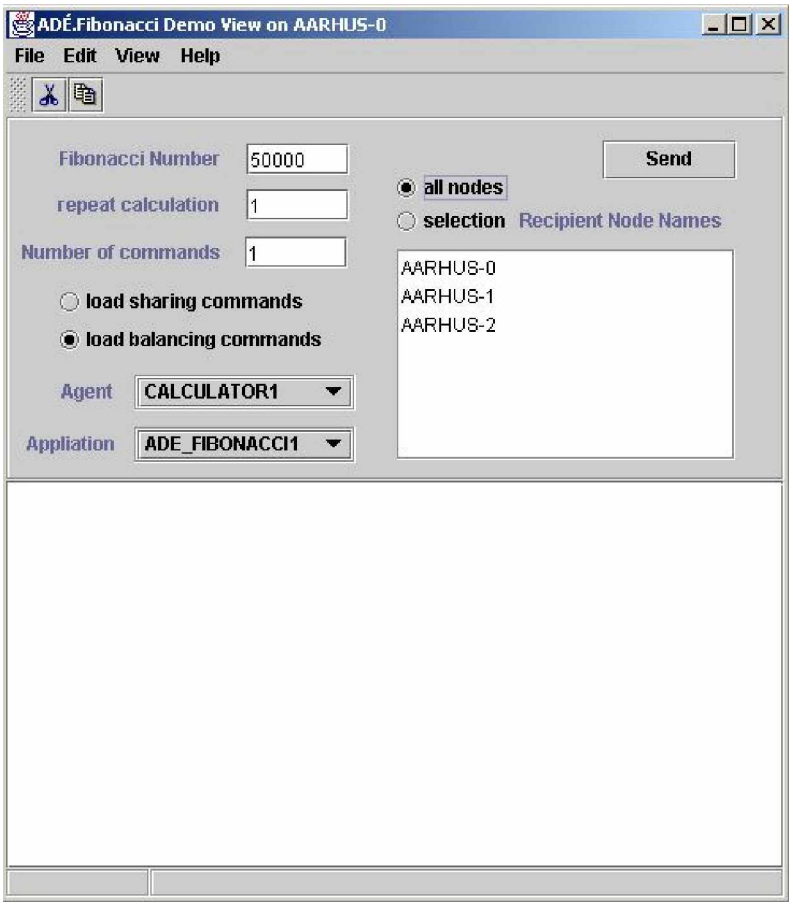

Figure 3-20: ADÉ.Fibonacci test console

A console is provided to the user with which the user can create various workload scenarios and observe how the system responds in order to level out workload imbalances. The console is displayed in Figure 3-20 on the previous page The user can define what Fibonacci number has to be calculated by the commands. In Figure 3-20 the 50,000th Fibonacci number will be calculated once, 1 workload balancing command is sent to all nodes in the cluster that have the application `ADE_FIBONACCI1`. A Fibonacci command can be told to repeat calculation of the Fibonacci number several times by setting the value in the entry field `repeat calculation` accordingly. By entering a value greater 1 the user can make sure that the node receiving the command will be fully loaded for many seconds. This makes it often easier to create specific workload scenarios. It is possible to send commands to all nodes in the cluster with the application selected in the `Application` combo box or to specific nodes that were selected in the `Recipient Agent Names` list box. The `Application` combo box contains the names of three ADÉ.Fibonacci applications named `ADE_FIBONACC1`, `ADE_FIBONACC2`, and `ADE_FIBONACC3` defined in the ADÉ.Fibonacci application description. All these applications are defined in the same way as ADÉ.Fibonacci applications. By having more than one application it is possible to create scenarios where the system is under load by different applications (these applications have the same definition but different names and are therefore regarded by the distributor as being different applications). The `Agent` combo box allows specifying to which agent commands are sent. Since every ADÉ.Fibonacci application defines more than 1 agent it is possible to create scenarios, where several agents with the same capability are executing commands in-

stead of only 1. The `Recipient Node Name` lets the user specify the node of where the recipient agent resides. The number of commands that are sent at once can be specified in the `Number of commands` entry field. For example, when using this feature to send more than one workload sharing command the user can observe on which nodes the distributor places them.

Janet.CAS offers a monitor application that serves as a cluster-wide visible blackboard. Nodes, by default, send status information to the monitor in case it is present in the cluster. Using the monitor the user can follow how workload-aware commands travel.

3.3.1 Defining Commands and Interpreters

As for every Janet application command-interpreter pairs have to be defined. For the ADÉ.Fibonacci driving application a Fibonacci workload sharing command and a Fibonacci workload balancing command have to be implemented.

3.3.1.1 Defining Commands

Implementing the commands only consists of defining the required attribute to store input data. A class diagram in displayed in. The full implementation is not displayed here as of little interest. The commands can be found in the package `org.objectscape.janet.ade.demo.fibonacci` named `FibonacciSharingCommand` and `FibonacciBalancingCommand`.

Figure 3-21 on the next page shows the class hierarchy of the Fibonacci commands defined for ADÈ.Fibonacci. Common attributes of both kinds of Fibonacci workload command classes are defined in the abstract class `FibonacciCommand`. Class `FibonacciBalancingCommand` has additional attributes in order to save the current execution state at the time the associated interpreter was suspended for eviction.

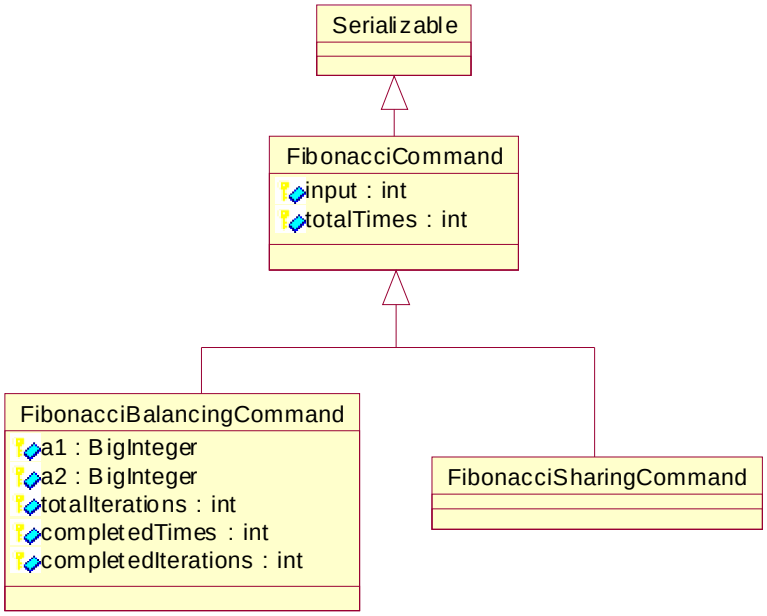

Figure 3-21: Fibonacci workload commands class hierarchy

3.3.1.2 Defining Interpreters

The `FibonacciSharingInterpreter` is defined in the same way as the `FibonacciInterpreter` developed for CAS.Fibonacci, but its `commandNames` method specifies the qualified name of the `FibonacciSharingCommand`. For the `FibonacciBalancingInterpreter` an additional effort is needed to make it suspendable.

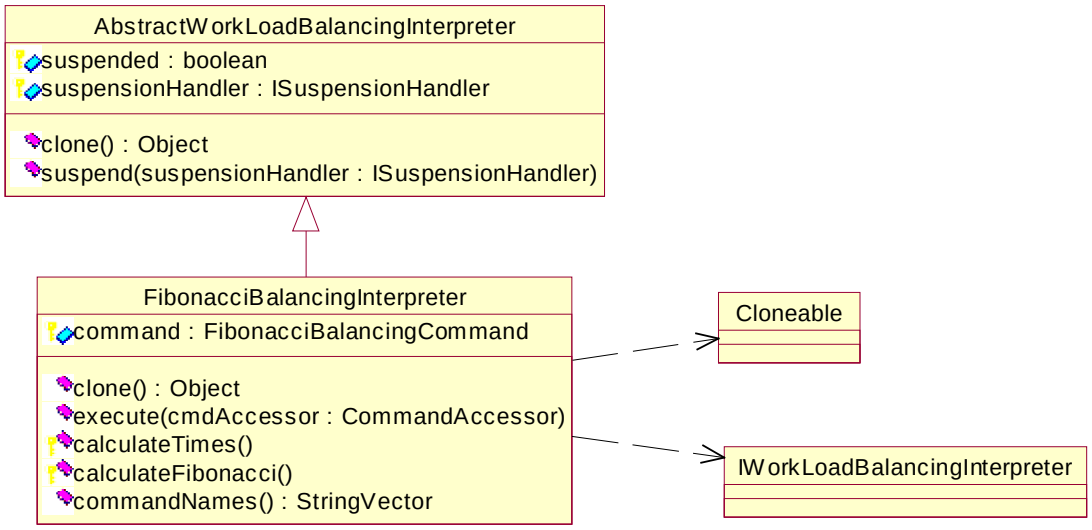

Figure 3-22: Class hierarchy of the FibonacciBalancingInterpreter

Janet.ADÉ defines an abstract workload balancing interpreter named `AbstractWorkLoadBalancingInterpreter` that is subclassed by the `FibonacciBalancingInterpreter`. The abstract class defines common attributes needed for every workload balancing command. If it is not used it is important to define the `suspend` attribute in the user's workload interpreter class as volatile. If it is not declared volatile the Java compiler might create a cache to store the value of the attribute in, which results in some other thread not to see the changed value but still the cached one. Alternatively, the `suspend` attribute can be protected by a synchronized block, which has a higher cost.

The `FibonacciBalancingInterpreter` class must implement the methods defined in the `IWorkLoadBalancingInterpreter` and be cloneable. Its class hierarchy is displayed in Figure 3-22. The execute method it needs to define is in this case simple as can be seen in Figure 3-23.

```
public void execute(CommandAccessor cmdAccessor)
{
      if (cmdAccessor.getCommand() instanceof FibonacciBalancingCommand)
      {
            command = (FibonacciBalancingCommand) cmdAccessor.getCommand();
            calculateTimes();
            handleResult(cmdAccessor);
      }
}
```

Figure 3-23: FibonacciBalancingInterpreter execute method

It stores its command in the `command` attribute and starts the calculation. The calculation methods are of more interest.

```
    protected void calculateTimes()
    {
1         int completedTimes = command.getCompletedTimes();
2         int totalTimes = command.getTotalTimes();
3
4         for (int i = completedTimes; i < totalTimes; i++) {
5           if(!suspended) {
6                 calculateFibonacci();
7                 if(!suspended) {
8                       command.setCompletedTimes(i + 1);
9                       command.setCompletedIterations(0);
10                }
11          }
12          else
13          {
14                break;
            }
        }
    }
```

Figure 3-24: FibonacciBalancingInterpreter calculateTimes method

The `execute` method calls the `calculateTimes` method displayed in Figure 3-24. If the user specified in the ADÉ.Fibonacci console that the Fibonacci number should be calculated n times, the `calculateTimes` method calls the `calculateFibonacci` method n times as long as the interpreter has not been suspended.

```
    protected BigInteger calculateFibonacci()
    {
1         int nthFibonacciNumber = command.getTotalIterations();
2         if (nthFibonacciNumber < 3)
3           return BigInteger.ZERO;
4
5         BigInteger a1 = command.getA1();
6         BigInteger a2 = command.getA2();
7         BigInteger an = BigInteger.ZERO;
8         int completedIterations = command.getCompletedIterations();
9
10        for (int i = completedIterations; i < nthFibonacciNumber; i++)
11        {
```

```
12                if(suspended)
13                {
14                      command.setA1(a1);
15                      command.setA2(a2);
16                      break;
17                }
18                else
19                {
20                      an = a1.add(a2);
21                      a1 = a2;
22                      a2 = an;
23                      command.setCompletedIterations(i + 1);
24                }
25          }
26          return an;
```

Figure 3-25: FibonacciBalancingInterpreter calculateFibonacci method

The `calculateFibonacci` method displayed in Figure 3-25 calculates the Fibonacci number itself. It checks after every iteration whether the interpreter has been asked to suspend execution (line 12). If so, the previous and current Fibonacci numbers, `a1` and `a2`, are stored in the command object (line 14 + 15) and execution of the method terminates, which causes the `calculateTimes` method to store its context-dependent information in the command as well (line 11 + 12 in Figure 3-24) before terminating. When a command is about to be evicted its suspend method is called first. The `suspend` method for the FibonacciBalancingInterpreter is inherited from class `AbstractWorkLoadBalancingInterpreter`. It stores the `suspensionHandler` passed on as a parameter in the class' `suspensionHandler` attribute and sets the `suspend` attribute to true, which results in the calculation of the Fibonacci number to terminate and the `handleResult` method to be called (see Figure 3-23).

```
    protected void handleResult(CommandAccessor cmdAccessor)
    {
1         if(suspended)
2         {
3               suspensionHandler.suspended();
4         }
5         else
6         {
7               cmdAccessor.setReply(command.getAn());
          }
    }
```

Figure 3-26: Notify the suspension handler about the suspension

The implementation of the `handleResult` method is shown in Figure 3-26. If the calculation has finished without the interpreter having been suspended before, the thread of execution jumps to line 7, where the calculated Fibonacci number is sent back to the agent sending the command (try-catch-block omitted for brevity). The calculation result will be handed over to the callback handler, installed by the agent when sending the command, and the handler will be invoked. If the interpreter has been suspended, the `suspensionHandler` passed on as a method parameter of the `suspend` method is notified that suspension has finished (line 3). Thereafter, the `suspensionHandler` will evict the command.

3.3.2 Assembling The Application

After commands and interpreters have been defined the application definition of ADÉ.Fibonacci has to be assembled and added to the executor's node descriptor (which has been presented in section 3.2.1.3).

```
<application name="ADE_FIBONACCI1">
  <capabilities>
    <capability name="CORE">
      <agents>
          <agent name="CALCULATOR1" executeWhenStarted=
            "org.objectscape.janet.ade.demo.fibonacci.StartViewCommand" />
        </agents>
      <interpreters>
          <interpreter>
            org.objectscape.janet.ade.demo.fibonacci.StartViewInterpreter
          </interpreter>
          <interpreter>
            org.objectscape.janet.ade.demo.fibonacci.
            FibonacciBalancingInterpreter
          </interpreter>
          <interpreter>
            org.objectscape.janet.ade.demo.fibonacci.FibonacciSharingInterpreter
         </interpreter>
       </interpreters>
    </capability>
  </capabilities>
</application>
```

Figure 3-27: ADÉ.Fibonacci application description

The definition of the ADÉ.Fibonacci application, that has to be added to the executor's node descriptor, is displayed in Figure 3-27. For ADÉ.Fibonacci 1 agent is defined named `CALCULATOR1`. After the application has been registered the `StartViewCommand` specified by the agent's `executeWhenStarted` attribute is sent to the agent, which executes the `StartViewInterpreter`. The `StartViewInterpreter` displays the test console on the screen. The interpreters `FibonacciBalancingInterpreter and FibonacciSharingInterpreter` have to be added to the capability for the capability's agent to be able to respond to Fibonacci workload sharing and workload balancing commands.

4 Extensions for Janet

This chapter describes several ideas for further extensions for Janet. Potential extensions are Janet.DIC to distribute code in Janet (dynamically supplying nodes with applications and capabilities through the network) and Janet.VOS (evicting large objects to nodes with more available memory).

4.1 Janet.DIC

Janet.DIC (**Di**stributed **C**ode) is the idea of an extension to Janet that allows nodes to be equipped with applications their capabilities remotely through the network. Transferring a capability includes the transfer of the interpreters they define together with the interpreters' byte code that is contained in the interpreters' class files. At the target node, the byte code has to be loaded into program space with the use of the Java class loader.

Using Janet.DIC nodes could be configured dynamically, which would be helpful when configuring nodes at distant locations that are hard to reach. There would be no need to shut down and start up a node to read in additional interpreter class files previously not existing on the node's workstation. The number of interpreters that have to be present on a node's workstation can be minimized. Interpreters could be installed dynamically on a node in case of an agent with a capability previously not present at that node has to be sent to that node. With such a feature it would be possible to use Janet as an agent platform to implement mobile agents or to implement a platform that offers similar functionality as a mobile agent platform without having to accept some of the drawbacks of mobile agents.

4.1.1 Mobile Agents vs. Mobile Applications

Because of Java's ability to distribute code many mobile agent platforms have been developed in Java. Mobile agents are one way to migrate an agent from one platform to another. The advantage of mobile agents is that they can also be started on a minimally equipped destination system as they carry the executable code they need with them. They are therefore not dependent on heavyweight agent platforms and can migrate to low footprint devices such as handhelds, PDAs, mobile phones, etc.

Instead of using mobile agents the approach in Janet.DIC could be to use Janet.CAS as a lightweight agent platform with a small footprint and send a command with applications and their capabilities to a node where these applications are needed. When interpreted by the recipient the command installs the applications and asks the system to start their associated agents. Mobile agents are a special kind of agents that only have an advantage in a special setting - and are therefore not universal - where the destination machine does contain the mobile agent's executable code and environment.

Janet.CAS, on the contrary, is a general-purpose agent platform that together with Janet.DIC can basically offer the same functionality as mobile agents. However, Janet.CAS and Janet.DIC would have to be installed and running on every node, which would cost a certain amount of disk and heap space. A workstation that can accept a mobile agent needs to have a minimal kernel of some mobile agent platform installed so that a mobile agent after arrival can

be started. Since Janet.CAS is a lightweight agent platform the space required by Janet.CAS is probably not higher compared to the minimal mobile agent platform kernel of a real-world mobile agent platform such as SeMoA. Additionally, when an agent in Janet has to migrate between nodes in a cluster it does not need to carry its entire executable code with it as a mobile agent. If it already has visited a node earlier the application it needs is already installed and needs not be sent to that node another time. Many of the security problems of mobile agents arise from agent and code traveling together. It might be worth investigating whether several security problems of mobile agents could be solved easier or could be solved at all if code and agent travel separately.

4.1.2 Security

Security is an important concern with regard to distributed code. The standard approach in Java is to use signed applets. Similarly, for Janet.DIC some kind of signed applications could be introduced to authenticate origin and destination of distributed code.

4.2 Janet.VOS

Distributed operating systems such as MOSIX support memory ushering: if a node runs low on memory, objects can be evicted and be moved to some other node. The idea of Janet.VOS (**V**irtual **O**bject **S**pace) is to implement memory ushering for Janet as well. It has to be taken into account that a disk drive, used by an operating system's virtual memory system, can swap out objects much faster than it is possible to transfer them through a network – even when the network is a high-speed network. There seems to be no way that Janet.VOS could compete directly with a disk drive as a swap medium. Janet.VOS would therefore need to have a concept that offers advantages an operating system's virtual memory system could not provide. For example, when available memory becomes low, instead of evicting commands, it could evict agents together with all the permanent objects they need to other nodes. A system offering such functionality could react in a very flexible way to changing amounts of available memory. After an agent was evicted, it does not have to be transferred back to the node it was evicted from in case it needs to be accessed in the way that memory pages need to be read in from disk if accessed after having been swapped out. Since agents in Janet are distributed from the beginning, an evicted agent could remain on the node it was migrated to when accessed after eviction. A fair amount of the functionality to evict agents would be provided by Janet.DIC. Janet.VOS, beyond the functionality provided by Janet.DIC, would have to observe the amount of available memory on every node, would have to decide which node to evict an agent to, and initiate the agent eviction process. An agent could also be evicted by some user-defined criteria, other than a node's available memory running low. The considerations described in this section concerning Janet.VOS are not final and more of a brainstorming nature. They are described to display potential extensions of Janet.

5 Summary and Conclusions

A platform for distributed cooperative agents in Java has been developed. The platform offers distributed event notification and distributed object spaces. It provides an interface for users to plug in their custom applications that make use of the agent platform. Applications consist of capabilities that are assigned to agents and constitute their behavior. Instead of invoking methods on agents, an alternative paradigm is used where agents communicate through the asynchronous exchange of commands to which they respond with the execution of an interpreter they have chosen autonomously. Interpreters to be executed are scheduled by an agent's scheduler that executes interpreters sequentially. Agents with the same capability are able to communicate directly through commands and may be distributed over several nodes. A node provides the platform's runtime environment, which serves as a habitat for agents residing on a workstation. There is no restriction to the number of nodes per workstation.

The workload distribution layer is completely separated from the agent platform. It allows to level out load imbalances by evicting commands from overloaded agents to lightly loaded agents on other nodes. Since interpreters are inserted into scheduler queues, detecting lightly loaded agents using the ShortestQueue algorithm is straightforward. Initial placement of commands is provided in order to offer workload sharing of commands to the user as well as migration of started commands to offer workload balancing. The user has to assist the balancing system by implementing commands eligible for workload balancing in such a way that the system can suspend them before migration. With this slight sacrifice in transparency workload balancing could be implemented for Java without having to modify the Java virtual machine to provide transparent thread migration.

Summing up, the concept used by the developed system represents an interesting compromise between workload distribution systems on system-level that cannot be tailored to an application's specific requirements and systems that leave load distribution completely to the programmer. The system offers an interesting combination of an agent platform and a workload balancing system. It can be used as a workload balancing system only, as an agent platform only, or as an agent-oriented system that can balance the workload of agent's.

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Appendix A: Abbreviations

General Abbreviations

ACL	Agent Communication Language
LFS	Log-Structured File System
MOSIX	Multicomputer OS for UNIX
NFS	Network File System

Abbreviations Janet

ADÉ	Automatic Distributed Execution
DIC	Distributed Code
CAS	Cooperative Agent System
QSC	Queue Size Category
CQS	Category Queue Size

Appendix B: Links

Systems

Aglets	http://www.trl.ibm.com/aglets/
Amoeba	http://www.cs.vu.nl/pub/amoeba/
CORBA	http://www.corba.org/
FIPA	http://www.fipa.org/
GigaSpaces	http://www.gigaspaces.com/
Intamission	http://www.intamission.com/
JACK	http://www.agent-software.com/
JADE	http://sharon.cselt.it/projects/jade/
JavaSpaces	http://www.javasoft.com/products/javaspaces/
JESSICA	http://www.srg.csis.hku.hk/jessica.htm
JMS	http://java.sun.com/products/jms/
JPower	http://www.jpower.org/
JUnit	http://www.junit.org/
Linda	http://www.cs.yale.edu/Linda/linda.html
MOSIX	http://www.mosix.org/
OMG	http://www.omg.org/
Outrigger	http://wwws.sun.com/software/jini/
OWL	http://www.w3.org/2001/sw/WebOnt/
Plurix	http://www.plurix.de/
RMI	http://java.sun.com/products/jdk/rmi/
SeMoA	http://www.semoa.org/
SOAP	http://www.w3.org/TR/SOAP/
Sprite	http://www.cs.berkeley.edu/projects/sprite/sprite.html
W3C	http://www.w3c.org
XML-RPC	http://www.xml-rpc.org/

Other

Agent FAQ	http://www.ee.mcgill.ca/~belmarc/agent_faq.html