

TRANSACTIONS



Scalaris:

Users and Developers Guide

Version 0.5.0+svn

October 29, 2012

Copyright 2007-2012 Zuse Institute Berlin and onScale solutions.

Licensed under the Apache License, Version 2.0 (the "License"); you may not use this file except in compliance with the License. You may obtain a copy of the License at

<http://www.apache.org/licenses/LICENSE-2.0>

Unless required by applicable law or agreed to in writing, software distributed under the License is distributed on an "AS IS" BASIS, WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied. See the License for the specific language governing permissions and limitations under the License.

Contents

I. Users Guide	5
1. Introduction	6
1.1. Brewer's CAP Theorem	6
1.2. Scientific Background	7
2. Download and Installation	8
2.1. Requirements	8
2.2. Download	8
2.2.1. Development Branch	8
2.2.2. Releases	8
2.3. Build	9
2.3.1. Linux	9
2.3.2. Windows	9
2.3.3. Java-API	9
2.3.4. Python-API	10
2.3.5. Ruby-API	10
2.4. Installation	10
3. Setting up Scalaris	12
3.1. Runtime Configuration	12
3.1.1. Logging	12
3.2. Running Scalaris	13
3.2.1. Running on a local machine	13
3.2.2. Running distributed	13
3.3. Custom startup using <code>scalarisctl</code>	14
4. Using the system	15
4.1. Application Programming Interfaces (APIs)	15
4.1.1. Supported Types	16
4.1.2. Supported Operations	17
4.1.3. JSON API	24
4.1.4. Java API	28
4.2. Command Line Interfaces	29
4.2.1. Java command line interface	29
4.2.2. Python command line interface	30
4.2.3. Ruby command line interface	30
5. Testing the system	31
5.1. Erlang unit tests	31
5.2. Java unit tests	31
5.3. Python unit tests	32

5.4. Interoperability Tests	34
6. Troubleshooting	35
6.1. Network	35
6.2. Miscellaneous	35
 II. Developers Guide	 36
7. General Hints	37
7.1. Coding Guidelines	37
7.2. Testing Your Modifications and Extensions	37
7.3. Help with Digging into the System	37
8. System Infrastructure	38
8.1. Groups of Processes	38
8.2. The Communication Layer <code>comm</code>	38
8.3. The <code>gen_component</code>	38
8.3.1. A basic <code>gen_component</code> including a message handler	39
8.3.2. How to start a <code>gen_component</code> ?	40
8.3.3. When does a <code>gen_component</code> terminate?	41
8.3.4. How to determine whether a process is a <code>gen_component</code> ?	41
8.3.5. What happens when unexpected events / messages arrive?	41
8.3.6. What if my message handler generates an exception or crashes the process?	41
8.3.7. Changing message handlers and implementing state dependent message re- sponsiveness as a state-machine	42
8.3.8. Handling several messages atomically	42
8.3.9. Halting and pausing a <code>gen_component</code>	43
8.3.10. Integration with <code>pid_groups</code> : Redirecting messages to other <code>gen_components</code>	43
8.3.11. Replying to ping messages	43
8.3.12. The debugging interface of <code>gen_component</code> : Breakpoints and step-wise exe- cution	43
8.3.13. Future use and planned extensions for <code>gen_component</code>	46
8.4. The Process' Database (<code>pdb</code>)	46
8.5. Failure Detectors (<code>fd</code>)	46
8.6. Monitoring Statistics (<code>monitor</code> , <code>rrd</code>)	46
8.7. Writing Unittests	48
8.7.1. Plain unittests	48
8.7.2. Randomized Testing using <code>tester.erl</code>	48
9. Basic Structured Overlay	49
9.1. Ring Maintenance	49
9.2. T-Man	49
9.3. Routing Tables	49
9.3.1. The routing table process (<code>rt_loop</code>)	53
9.3.2. Simple routing table (<code>rt_simple</code>)	54
9.3.3. Chord routing table (<code>rt_chord</code>)	58
9.4. Local Datastore	62
9.5. Cyclon	62
9.6. Vivaldi Coordinates	62
9.7. Estimated Global Information (Gossiping)	62

9.8. Load Balancing	62
9.9. Broadcast Trees	62
10. Transactions in Scalaris	63
10.1. The Paxos Module	63
10.2. Transactions using Paxos Commit	63
10.3. Applying the Tx-Modules to replicated DHTs	63
11. How a node joins the system	64
11.1. Supervisor-tree of a Scalaris node	65
11.2. Starting the sup_dht_node supervisor and general processes of a node	66
11.3. Starting the sup_dht_node_core supervisor with a peer and some paxos processes . .	66
11.4. Initializing a dht_node-process	67
11.5. Actually joining the ring	67
11.5.1. A single node joining an empty ring	68
11.5.2. A single node joining an existing (non-empty) ring	68
12. Directory Structure of the Source Code	77
13. Java API	78

Part I.

Users Guide

1. Introduction

Scalaris is a scalable, transactional, distributed key-value store based on the peer-to-peer principle. It can be used to build scalable Web 2.0 services. The concept of Scalaris is quite simple: Its architecture consists of three layers.

It provides self-management and scalability by replicating services and data among peers. Without system interruption it scales from a few PCs to thousands of servers. Servers can be added or removed on the fly without any service downtime.



Scalaris takes care of:

- Fail-over
- Data distribution
- Replication
- Strong consistency
- Transactions

The Scalaris project was initiated by Zuse Institute Berlin and onScale solutions and was partly funded by the EU projects Selfman and XtreamOS. Additional information (papers, videos) can be found at <http://www.zib.de/CSR/Projects/scalaris> and <http://www.onscale.de/scalarix.html>.

1.1. Brewer's CAP Theorem

In distributed computing there exists the so called CAP theorem. It basically says that there are three desirable properties for distributed systems but one can only have any two of them.

Strict Consistency. Any read operation has to return the result of the latest write operation on the same data item.

Availability. Items can be read and modified at any time.

Partition Tolerance. The network on which the service is running may split into several partitions which cannot communicate with each other. Later on the networks may re-join again.

For example, a service is hosted on one machine in Seattle and one machine in Berlin. This service is partition tolerant if it can tolerate that all Internet connections over the Atlantic (and Pacific) are interrupted for a few hours and then get repaired.

The goal of Scalaris is to provide strict consistency and partition tolerance. We are willing to sacrifice availability to make sure that the stored data is always consistent. I.e. when you are running Scalaris with a replication degree of 4 and the network splits into two partitions, one partition with three replicas and one partition with one replica, you will be able to continue to use the service only in the larger partition. All requests in the smaller partition will time out until the two networks merge again. Note, most other key-value stores tend to sacrifice consistency.

1.2. Scientific Background

Basics. The general structure of Scalaris is modelled after Chord. The Chord paper [4] describes the ring structure, the routing algorithms, and basic ring maintenance.

The main routines of our Chord node are in `src/dht_node.erl` and the join protocol is implemented in `src/dht_node_join.erl` (see also Chap. 11 on page 64). Our implementation of the routing algorithms is described in more detail in Sect. 9.3 on page 49 and the actual implementation is in `src/rt_chord.erl`.

Transactions. The most interesting part is probably the transaction algorithms. The most current description of the algorithms and background is in [6].

The implementation consists of the paxos algorithm in `src/paxos` and the transaction algorithms itself in `src/transactions` (see also Chap. 10 on page 63).

Ring Maintenance. We changed the ring maintenance algorithm in Scalaris. It is not the standard Chord one, but a variation of T-Man [5]. It is supposed to fix the ring structure faster. In some situations, the standard Chord algorithm is not able to fix the ring structure while T-Man can still fix it. For node sampling, our implementation relies on Cyclon [7].

The T-Man implementation can be found in `src/rm_tman.erl` and the Cyclon implementation in `src/cyclon`.

Vivaldi Coordinates. For some experiments, we implemented so called Vivaldi coordinates [2]. They can be used to estimate the network latency between arbitrary nodes.

The implementation can be found in `src/vivaldi.erl`.

Gossiping. For some algorithms, we use estimates of global information. These estimates are aggregated with the help of gossiping techniques [8].

The implementation can be found in `src/gossip.erl`.

2. Download and Installation

2.1. Requirements

For building and running Scalaris, some third-party software is required which is not included in the Scalaris sources:

- Erlang R13B01 or newer
- OpenSSL (required by Erlang's crypto module)
- GNU-like Make and autoconf (not required on Windows)

To build the Java API (and its command-line client) the following programs are also required:

- Java Development Kit 6
- Apache Ant

Before building the Java API, make sure that JAVA_HOME and ANT_HOME are set. JAVA_HOME has to point to a JDK installation, and ANT_HOME has to point to an Ant installation.

To build the Python API (and its command-line client) the following programs are also required:

- Python \geq 2.6

2.2. Download

The sources can be obtained from <http://code.google.com/p/scalaris>. RPM and DEB packages are available from <http://download.opensuse.org/repositories/home:/scalaris/> for various Linux distributions.

2.2.1. Development Branch

You find the latest development version in the svn repository:

```
# Non-members may check out a read-only working copy anonymously over HTTP.  
svn checkout http://scalaris.googlecode.com/svn/trunk/ scalaris-read-only
```

2.2.2. Releases

Releases can be found under the 'Download' tab on the web-page.

2.3. Build

2.3.1. Linux

Scalaris uses autoconf for configuring the build environment and GNU Make for building the code.

```
%> ./configure
%> make
%> make docs
```

For more details read README in the main Scalaris checkout directory.

2.3.2. Windows

We are currently not supporting Scalaris on Windows. However, we have two small .bat files for building and running Scalaris nodes. It seems to work but we make no guarantees.

- Install Erlang
<http://www.erlang.org/download.html>
- Install OpenSSL (for crypto module)
<http://www.slproweb.com/products/Win32OpenSSL.html>
- Checkout Scalaris code from SVN
- adapt the path to your Erlang installation in build.bat
- start a cmd.exe
- go to the Scalaris directory
- run build.bat in the cmd window
- check that there were no errors during the compilation; warnings are fine
- go to the bin sub-directory
- adapt the path to your Erlang installation in firstnode.bat, joining_node.bat
- run firstnode.bat or one of the other start scripts in the cmd window

build.bat will generate a Emakefile if there is none yet. If you have Erlang < R13B04, you will need to adapt the Emakefile. There will be empty lines in the first three blocks ending with “}”.: add the following to these lines and try to compile again. It should work now.

```
, {d, type_forward_declarations_are_not_allowed}
, {d, forward_or_recursive_types_are_not_allowed}
```

For the most recent description please see the FAQ at <http://code.google.com/p/scalaris/wiki/FAQ>.

2.3.3. Java-API

The following commands will build the Java API for Scalaris:

```
%> make java
```

This will build `scalaris.jar`, which is the library for accessing the overlay network. Optionally, the documentation can be build:

```
%> cd java-api
%> ant doc
```

2.3.4. Python-API

The Python API for Python 2.* (at least 2.6) is located in the `python-api` directory. Files for Python 3.* can be created using `2to3` from the files in `python-api`. The following command will use `2to3` to convert the modules and place them in `python3-api`.

```
%> make python3
```

Both versions of python will compile required modules on demand when executing the scripts for the first time. However, pre-compiled modules can be created with:

```
%> make python
%> make python3
```

2.3.5. Ruby-API

The Ruby API for Ruby ≥ 1.8 is located in the `ruby-api` directory. Compilation is not necessary.

2.4. Installation

For simple tests, you do not need to install Scalaris. You can run it directly from the source directory. Note: `make install` will install Scalaris into `/usr/local` and place `scalarisctl` into `/usr/local/bin`, by default. But it is more convenient to build an RPM and install it. On openSUSE, for example, do the following:

```
export SCALARIS_SVN=http://scalaris.googlecode.com/svn/trunk
for package in main bindings; do
  mkdir -p ${package}
  cd ${package}
  svn export ${SCALARIS_SVN}/contrib/packages/${package}/checkout.sh
  ./checkout.sh
  cp * /usr/src/packages/SOURCES/
  rpmbuild -ba scalaris*.spec
  cd ..
done
```

If any additional packages are required in order to build an RPM, `rpmbuild` will print an error.

Your source and binary RPMs will be generated in `/usr/src/packages/SRPMS` and `RPMS`.

We build RPM and DEB packages for all tagged Scalaris versions as well as snapshots of svn trunk and provide them using the Open Build Service. The latest stable version is available at <http://download.opensuse.org/repositories/home:/scalaris/>. The latest svn snapshot as well as archives of previous versions are available in their respective folders below <http://download.opensuse.org/repositories/home:/scalaris/>. Packages are available for

- Fedora 16, 17,

- Mandriva 2010, 2010.1, 2011,
- openSUSE 11.4, 12.1, Factory, Tumbleweed
- SLE 10, 11, 11SP1, 11SP2,
- CentOS 5.5, 6.2,
- RHEL 5.5, 6,
- Debian 5.0, 6.0 and
- Ubuntu 10.04, 10.10, 11.04, 11.10, 12.04.

An up-to-date list of available repositories can be found at https://code.google.com/p/scalaris/wiki/FAQ#Prebuild_packages.

For those distributions which provide a recent-enough Erlang version, we build the packages using their Erlang package and recommend using the same version that came with the distribution. In this case we do not provide Erlang packages in our repository.

Exceptions are made for openSUSE-based and RHEL-based distributions as well as Debian 5.0:

- For openSUSE, we provide the package from the `devel:languages:erlang` repository.
- For RHEL-based distributions (CentOS 5, RHEL 5, RHEL 6) we included the Erlang package from the EPEL repository of RHEL 6.
- For Debian 5.0 we included the Erlang package of Ubuntu 11.04.

3. Setting up Scalaris

Description is based on SVN revision r1810.

3.1. Runtime Configuration

Scalaris reads two configuration files from the working directory: `bin/scalaris.cfg` (mandatory) and `bin/scalaris.local.cfg` (optional). The former defines default settings and is included in the release. The latter can be created by the user to alter settings. A sample file is provided as `bin/scalaris.local.cfg.example`. To run Scalaris distributed over several nodes, each node requires a `bin/scalaris.local.cfg`:

File `scalaris.local.cfg`:

```
%% userdevguide-begin local_cfg:distributed
% Insert the appropriate IP-addresses for your setup
% as comma separated integers:
% IP Address, Port, and label of the boot server
{mgmt_server, {{127,0,0,1}, 14194, mgmt_server}}.

% IP Address, Port, and label of a node which is already in the system
{known_hosts, [{{127,0,0,1}, 14195, service_per_vm}]}.
%% userdevguide-end local_cfg:distributed
```

A Scalaris deployment can have a management server and several nodes. The management-server is optional and provides a global view on all nodes of a Scalaris deployment which contact this server, i.e. have its address specified in the `mgmt_server` configuration setting.

In this example, the `mgmt_server`'s location is defined as an IP address plus a TCP port and its Erlang-internal process name. If the deployment should not use a management server, replace the setting with an invalid address, e.g. ' null '.

3.1.1. Logging

Scalaris uses the `log4erl` library (see `contrib/log4erl`) for logging status information and error messages. The log level can be configured in `bin/scalaris.cfg` for both the stdout and file logger. The default value is `warn`; only warnings, errors and severe problems are logged.

```
%% @doc Loglevel: debug < info < warn < error < fatal < none
{log_level, warn}.
{log_level_file, warn}.
```

In some cases, it might be necessary to get more complete logging information, e.g. for debugging. In Chapter 11 on page 64, we are explaining the startup process of Scalaris nodes in more detail, here the `info` level provides more detailed information.

```
%% @doc Loglevel: debug < info < warn < error < fatal < none
{log_level, info}.
```

```
{log_level_file, info}.
```

3.2. Running Scalaris

As mentioned above, Scalaris consists of:

- management servers and
- regular nodes

The management server will maintain a list of nodes participating in the system. A regular node is either the first node in a system or joins an existing system deployment.

3.2.1. Running on a local machine

Open at least two shells. In the first, inside the Scalaris directory, start the first node (`firstnode.bat` on Windows):

```
%> ./bin/firstnode.sh
```

This will start a new Scalaris deployment with a single node, including a management server. On success <http://localhost:8000> should point to the management interface page of the management server. The main page will show you the number of nodes currently in the system. A first Scalaris node should have started and the number should show 1 node. The main page will also allow you to store and retrieve key-value pairs but should not be used by applications to access Scalaris. See Section 4.1 on page 15 for application APIs.

In a second shell, you can now start a second Scalaris node. This will be a ‘regular node’:

```
%> ./bin/joining_node.sh
```

The second node will read the configuration file and use this information to contact a number of known nodes (set by the `known_hosts` configuration setting) and join the ring. It will also register itself with the management server. The number of nodes on the web page should have increased to two by now.

Optionally, a third and fourth node can be started on the same machine. In a third shell:

```
%> ./bin/joining_node.sh 2
```

In a fourth shell:

```
%> ./bin/joining_node.sh 3
```

This will add two further nodes to the deployment. The `./bin/joining_node.sh` script accepts a number as its parameter which will be added to the started node’s name, i.e. 1 will lead to a node named `node1`. The web pages at <http://localhost:8000> should show the additional nodes.

3.2.2. Running distributed

Scalaris can be installed on other machines in the same way as described in Section 2.4 on page 10. In the default configuration, nodes will look for the management server on 127.0.0.1 on port

14195. You should create a `scalaris.local.cfg` pointing to the node running the management server. You should also add a list of known nodes.

File `scalaris.local.cfg`:

```
1 % Insert the appropriate IP-addresses for your setup
2 % as comma separated integers:
3 % IP Address, Port, and label of the boot server
4 {mgmt_server, [{127,0,0,1}, 14194, mgmt_server]}.
5
6 % IP Address, Port, and label of a node which is already in the system
7 {known_hosts, [{127,0,0,1}, 14195, service_per_vm]}.
```

If you are starting the management server using `firstnode.sh`, it will listen on port 14195 and you have to change the port and the IP address in the configuration file. Otherwise the other nodes will not find the management server. Calling `./bin/joining_node.sh` on a remote machine will start the node and automatically contact the configured management server.

3.3. Custom startup using `scalarisctl`

On linux you can also use the `scalarisctl` script to start a management server and ‘regular’ nodes directly.

```
%> ./bin/sclarisctl -h
```

```
usage: scalarisctl [options] [services] <cmd>
options:
  -h          - print this help message
  -d          - daemonize
  --screen    - if daemonized, put an interactive session into screen
  -e <params> - pass additional parameters to erl
  -f          - first node (to start a new Scalaris instead of joining one) (not with -q)
  -q          - elect first node from known hosts (not with -f)
  -n <name>   - Erlang process name (default 'node')
  -c <cookie> - Erlang cookie to use (for distributed Erlang) (default 'chocolate chip cookie')
  -p <port>   - TCP port for the Scalaris node
  -y <port>   - TCP port for the built-in webserver
  -k <key>    - join at the given key
  -v          - verbose
  --dist-erl-port <port>
                - (single) port distributed erlang listens on
  --nodes-per-vm <number>
                - number of Scalaris nodes to start inside the VM

services:
  -m          - global Scalaris management server
  -s          - Scalaris node (see also -f)

commands:
  checkinstallation
                - test installation
  start       - start services (see -m and -s)
  stop        - stop a scalaris process defined by its name (see -n)
  restart     - restart a scalaris process by its name (see -n)

  list        - list locally running Erlang VMs
  debug       - connect to a running node via an Erlang shell
```

4. Using the system

Description is based on SVN revision r1936.

Scalaris can be used with one of the provided command line interfaces or by using one of the APIs in a custom program. The following sections will describe the APIs in general, each API in more detail and the use of our command line interfaces.

4.1. Application Programming Interfaces (APIs)

Currently we offer the following APIs:

- an *Erlang API* running on the node Scalaris is run
(functions can be called using remote connections with distributed Erlang)
- a *Java API* using Erlang's JInterface library
(connections are established using distributed Erlang)
- a generic *JSON API*
(offered by an integrated HTTP server running on each Scalaris node)
- a *Python API* for Python ≥ 2.6 using JSON to talk to Scalaris.
- a *Ruby API* for Ruby ≥ 1.8 using JSON to talk to Scalaris.

Each API contains methods for accessing functions from the three layers Scalaris is composed of. Table 4.1 shows the modules and classes of Erlang, Java, Python and Ruby and their mapping to these layers. Details about the supported operations and how to access them in each of the APIs are provided in Section 4.1.2 on page 17. A more detailed discussion about the generic JSON API including examples of JSON calls is shown in Section 4.1.3 on page 24.

	Erlang module	Java class in de.zib.scalariz	JSON file in <URL>/api/	Python / Ruby class in module scalaris
Transaction Layer	api_tx	Transaction, TransactionSingleOp	tx.yaws	Transaction, TransactionSingleOp
	api_pubsub	PubSub	pubsub.yaws	PubSub
Replication Layer	api_rdht	ReplicatedDHT	rdht.yaws	ReplicatedDHT
P2P Layer	api_dht			
	api_dht_raw		dht_raw.yaws	
	api_vm	ScalarisVM		
	api_monitor	Monitor	monitor.yaws	

Table 4.1.: Layered API structure

	Erlang	Java	JSON	Python	Ruby
boolean	<code>boolean()</code>	<code>bool</code> , <code>Boolean</code>	<code>true</code> , <code>false</code>	<code>True</code> , <code>False</code>	<code>true</code> , <code>false</code>
integer	<code>integer()</code>	<code>int</code> , <code>Integer</code> <code>long</code> , <code>Long</code> <code>BigInteger</code>	<code>int</code>	<code>int</code>	<code>Fixnum</code> , <code>Bignum</code>
float	<code>float()</code>	<code>double</code> , <code>Double</code>	<code>int frac</code> <code>int exp</code> <code>int frac exp</code>	<code>float</code>	<code>Float</code>
string	<code>string()</code>	<code>String</code>	<code>string</code>	<code>str</code>	<code>String</code>
binary	<code>binary()</code>	<code>byte[]</code>	<code>string</code> (base64-encoded)	<code>bytearray</code>	<code>String</code>
list(type)	<code>[type()]</code>	<code>List<Object></code>	<code>array</code>	<code>list</code>	<code>Array</code>
JSON	<code>json_obj()</code> *	<code>Map<String, Object></code>	<code>object</code>	<code>dict</code>	<code>Hash</code>
custom	<code>any()</code>	<code>OtpErlangObject</code>	<code>/</code>	<code>/</code>	<code>/</code>

*
`json_obj() :: {struct, [Key::atom() | string(), Value::json_val()]}`
`json_val() :: string() | number() | json_obj() | {array, [any()]} | true | false | null`

Table 4.2.: Types supported by the Sclaris APIs

4.1.1. Supported Types

Different programming languages have different types. In order for our APIs to be compatible with each other, only a subset of the available types is officially supported.

Keys are always strings. In order to avoid problems with different encodings on different systems, we suggest to only use ASCII characters.

For *values* we distinguish between *native*, *composite* and *custom* types.

Native types are

- boolean values
- integer numbers
- floating point numbers
- strings and
- binary objects (a number of bytes).

Composite types are

- lists of native types (*except binary objects!*)
- JavaScript Object Notation (JSON)¹

Custom types include any Erlang term not covered by the previous types. Special care needs to be taken using custom types as they may not be accessible through every API or may be misinterpreted by an API. The use of them is discouraged.

Table 4.2 shows the mapping of supported types to the language-specific types of each API.

¹see <http://json.org/>

4.1.2. Supported Operations

Most operations are available to all APIs, but some (especially convenience methods) are API- or language-specific. The following paragraphs provide a brief overview of what is available to which API. For a full reference, see the documentation of the specific API.

Transaction Layer

Read Reads the value stored at a given key using quorum read.

```
Erlang    api_tx:read(Key)
Java:     TransactionSingleOp.read(Key)
JSON:     tx.yaws/read(Key)
Python:   TransactionSingleOp.read(Key)
Ruby:     TransactionSingleOp.read(Key)
```

Write Writes a value to a given key.

```
Erlang    api_tx:write(Key, Value)
Java:     TransactionSingleOp.write(Key, Value)
JSON:     tx.yaws/write(Key, Value)
Python:   TransactionSingleOp.write(Key, Value)
Ruby:     TransactionSingleOp.write(Key, Value)
```

“Add to” & “Delete from” List Operations For the list stored at a given key, first add all elements from a given list, then remove all elements from a second given list.

```
Erlang    api_tx:add_del_on_list(Key, ToAddList, ToRemoveList)
Java:     TransactionSingleOp.addDelOnList(Key, ToAddList, ToRemoveList)
JSON:     tx.yaws/add_del_on_list(Key, ToAddList, ToRemoveList)
Python:   TransactionSingleOp.add_del_on_list(Key, ToAddList, ToRemoveList)
Ruby:     TransactionSingleOp.add_del_on_list(Key, ToAddList, ToRemoveList)
```

Add to a number Adds a given number to the number stored at a given key.

```
Erlang    api_tx:add_on_nr(Key, ToAddNumber)
Java:     TransactionSingleOp.addOnNr(Key, ToAddNumber)
JSON:     tx.yaws/add_on_nr(Key, ToAddList, ToAddNumber)
Python:   TransactionSingleOp.add_on_nr(Key, ToAddNumber)
Ruby:     TransactionSingleOp.add_on_nr(Key, ToAddNumber)
```

Atomic Test and Set Writes the given (new) value to a key if the current value is equal to the given old value.

```
Erlang    api_tx:test_and_set(Key, OldValue, NewValue)
Java:     TransactionSingleOp.testAndSet(Key, OldValue, NewValue)
JSON:     tx.yaws/add_on_nr(Key, OldValue, NewValue)
Python:   TransactionSingleOp.test_and_set(Key, OldValue, NewValue)
Ruby:     TransactionSingleOp.test_and_set(Key, OldValue, NewValue)
```

Bulk Operations Executes multiple requests, i.e. operations, where each of them will be committed.

Collecting requests and executing all of them in a single call yields better performance than executing all on their own.

```
Erlang    api_tx:req_list_commit_each(RequestList)
Java:     TransactionSingleOp.req_list(RequestList)
JSON:     tx.yaws/req_list_commit_each(RequestList)
Python:   TransactionSingleOp.req_list(RequestList)
Ruby:     TransactionSingleOp.req_list(RequestList)
```

Transaction Layer (with TLog)

Read (with TLog) Reads the value stored at a given key using quorum read as an additional part of a previous transaction or for starting a new one (*no auto-commit!*).

```
Erlang    api_tx:read(TLog, Key)
Java:     Transaction.read(Key)
JSON:     n/a - use req_list
Python:   Transaction.read(Key)
Ruby:     Transaction.read(Key)
```

Write (with TLog) Writes a value to a given key as an additional part of a previous transaction or for starting a new one (*no auto-commit!*).

```
Erlang    api_tx:write(TLog, Key, Value)
Java:     Transaction.write(Key, Value)
JSON:     n/a - use req_list
Python:   Transaction.write(Key, Value)
Ruby:     Transaction.write(Key, Value)
```

“Add to” & “Delete from” List Operations (with TLog) For the list stored at a given key, first add all elements from a given list, then remove all elements from a second given list as an additional part of a previous transaction or for starting a new one (*no auto-commit!*).

```
Erlang    api_tx:add_del_on_list(TLog, Key, ToAddList, ToRemoveList)
Java:     Transaction.addDelOnList(Key, ToAddList, ToRemoveList)
JSON:     n/a - use req_list
Python:   Transaction.add_del_on_list(Key, ToAddList, ToRemoveList)
Ruby:     Transaction.add_del_on_list(Key, ToAddList, ToRemoveList)
```

Add to a number (with TLog) Adds a given number to the number stored at a given key as an additional part of a previous transaction or for starting a new one (*no auto-commit!*).

```
Erlang    api_tx:add_on_nr(TLog, Key, ToAddNumber)
Java:     Transaction.addOnNr(Key, ToAddNumber)
JSON:     n/a - use req_list
Python:   Transaction.add_on_nr(Key, ToAddNumber)
Ruby:     Transaction.add_on_nr(Key, ToAddNumber)
```

Atomic Test and Set (with TLog) Writes the given (new) value to a key if the current value is equal to the given old value as an additional part of a previous transaction or for starting a new one (*no auto-commit!*).

```
Erlang  api_tx:test_and_set(TLog, Key, OldValue, NewValue)
Java:    Transaction.testAndSet(Key, OldValue, NewValue)
JSON:    tx.yaws/test_and_set(Key, OldValue, NewValue)
Python:  Transaction.test_and_set(Key, OldValue, NewValue)
Ruby:    Transaction.test_and_set(Key, OldValue, NewValue)
```

Bulk Operations (with TLog) Executes multiple requests, i.e. operations, as an additional part of a previous transaction or for starting a new one (*no auto-commit!*). Only one commit request is allowed per call!

Collecting requests and executing all of them in a single call yields better performance than executing all on their own.

```
Erlang  api_tx:req_list(RequestList), api_tx:req_list(TLog, RequestList)
Java:    Transaction.req_list(RequestList)
JSON:    tx.yaws/req_list(RequestList), req_list(TLog, RequestList)
Python:  Transaction.req_list(RequestList)
Ruby:    Transaction.req_list(RequestList)
```

Transaction Layer (Pub/Sub)

Scalaris implements a simple Publish/Subscribe system. Subscribers can subscribe URLs for some topic. If an event is published to that topic, a JSON-RPC is sent to that URL, i.e. a JSON object of the following form:

```
{
  "method": "notify",
  "params": [<topic>, <content>],
  "id"     : <number>
}
```

Publish Publishes an event under a given topic.

```
Erlang  api_pubsub:publish(Topic, Content)
Java:    PubSub.publish(Topic, Content)
JSON:    pubsub.yaws/publish(Topic, Content)
Python:  PubSub.publish(Topic, Content)
Ruby:    PubSub.publish(Topic, Content)
```

Subscribe Subscribes a URL for a topic.

```
Erlang  api_pubsub:subscribe(Topic, URL)
Java:    PubSub.subscribe(Topic, URL)
JSON:    pubsub.yaws/subscribe(Topic, URL)
Python:  PubSub.subscribe(Topic, URL)
Ruby:    PubSub.subscribe(Topic, URL)
```

Unsubscribe Subscribes a URL from a topic.

```
Erlang  api_pubsub:unsubscribe(Topic, URL)
Java:   PubSub.unsubscribe(Topic, URL)
JSON:   pubsub.yaws/unsubscribe(Topic, URL)
Python: PubSub.unsubscribe(Topic, URL)
Ruby:   PubSub.unsubscribe(Topic, URL)
```

Get Subscribers Gets a list of subscribed URLs for a given topic.

```
Erlang  api_pubsub:get_subscribers(Topic)
Java:   PubSub.getSubscribers(Topic)
JSON:   pubsub.yaws/get_subscribers(Topic)
Python: PubSub.get_subscribers(Topic)
Ruby:   PubSub.get_subscribers(Topic)
```

Replication Layer

Delete Tries to delete a value at a given key.

Warning: This can only be done outside the transaction layer and is thus not absolutely safe. Refer to the following thread on the mailing list: http://groups.google.com/group/scalaris/browse_thread/thread/ff1d9237e218799.

```
Erlang  api_rdht:delete(Key), api_rdht:delete(Key, Timeout)
Java:   ReplicatedDHT.delete(Key), ReplicatedDHT.delete(Key, Timeout)
JSON:   rdht.yaws/delete(Key), rdht.yaws/delete(Key, Timeout)
Python: ReplicatedDHT.delete(Key), ReplicatedDHT.delete(Key, Timeout)
Ruby:   ReplicatedDHT.delete(Key), ReplicatedDHT.delete(Key, Timeout)
```

Get Replica Keys Gets the (hashed) keys used for the replicas of a given (user) key (ref. Section [P2P Layer](#)).

```
Erlang  api_rdht:get_replica_keys(Key)
Java:   n/a
JSON:   n/a
Python: n/a
Ruby:   n/a
```

P2P Layer

Hash Key Generates the hash of a given (user) key.

```
Erlang  api_dht:hash_key(Key)
Java:   n/a
JSON:   n/a
Python: n/a
Ruby:   n/a
```

Get Replica Keys Gets the (hashed) keys used for the replicas of a given (hashed) key.

Erlang `api_dht_raw:get_replica_keys(HashedKey)`
Java: `n/a`
JSON: `n/a`
Python: `n/a`
Ruby: `n/a`

Range Read Reads all Key-Value pairs in a given range of (hashed) keys.

Erlang `api_dht_raw:range_read(StartHashedKey, EndHashedKey)`
Java: `n/a`
JSON: `dht_raw.yaws/range_read(StartHashedKey, EndHashedKey)`
Python: `n/a`
Ruby: `n/a`

P2P Layer (VM Management)

Get Scalaris Version Gets the version of Scalaris running in the requested Erlang VM.

Erlang `api_vm:get_version()`
Java: `ScalarisVM.getVersion()`
JSON: `n/a`
Python: `n/a`
Ruby: `n/a`

Get Node Info Gets various information about the requested Erlang VM and the running Scalaris code, e.g. Scalaris version, erlang version, memory use, uptime.

Erlang `api_vm:get_info()`
Java: `ScalarisVM.getInfo()`
JSON: `n/a`
Python: `n/a`
Ruby: `n/a`

Get Information about Different VMs Get connection info about other Erlang VMs running Scalaris nodes. Note: This info is provided by the cyclon service built into Scalaris.

Erlang `api_vm:get_other_vms(MaxVMs)`
Java: `ScalarisVM.getOtherVMs(MaxVMs)`
JSON: `n/a`
Python: `n/a`
Ruby: `n/a`

Get Number of Scalaris Nodes in the VM Gets the number of Scalaris nodes running inside the Erlang VM.

Erlang `api_vm:number_of_nodes()`
Java: `ScalarisVM.getNumberOfNodes()`
JSON: `n/a`
Python: `n/a`
Ruby: `n/a`

Get Scalaris Nodes Gets a list of Scalaris nodes running inside the Erlang VM.

```
Erlang    api_vm:get_nodes()
Java:     ScalarisVM.getNodes()
JSON:     n/a
Python:   n/a
Ruby:     n/a
```

Add Scalaris Nodes Starts additional Scalaris nodes inside the Erlang VM.

```
Erlang    api_vm:add_nodes(Number)
Java:     ScalarisVM.addNodes(Number)
JSON:     n/a
Python:   n/a
Ruby:     n/a
```

Shutdown Scalaris Nodes Gracefully kill some Scalaris nodes inside the Erlang VM. This will first move the data from the nodes to other nodes and then shut them down.

```
Erlang    api_vm:shutdown_node(Name),
           api_vm:shutdown_nodes(Count), api_vm:shutdown_nodes_by_name(Names)
Java:     ScalarisVM.shutdownNode(Name),
           ScalarisVM.shutdownNodes(Number), ScalarisVM.shutdownNodesByName(Names)
JSON:     n/a
Python:   n/a
Ruby:     n/a
```

Kill Scalaris Nodes Immediately kills some Scalaris nodes inside the Erlang VM.

```
Erlang    api_vm:kill_node(Name),
           api_vm:kill_nodes(Count), api_vm:kill_nodes_by_name(Names)
Java:     ScalarisVM.killNode(Name),
           ScalarisVM.killNodes(Number), ScalarisVM.killNodesByName(Names)
JSON:     n/a
Python:   n/a
Ruby:     n/a
```

Shutdown the Erlang VM Gracefully shuts down all Scalaris nodes in the Erlang VM and then exits.

```
Erlang    api_vm:shutdown_vm()
Java:     ScalarisVM.shutdownVM()
JSON:     n/a
Python:   n/a
Ruby:     n/a
```

Kill the Erlang VM Immediately kills all Scalaris nodes in the Erlang VM and then exits.

Erlang `api_vm:kill_vm()`
Java: `ScalarisVM.killVM()`
JSON: `n/a`
Python: `n/a`
Ruby: `n/a`

P2P Layer (Monitoring)

Get Node Info Gets some information about the node, e.g. Scalaris version, Erlang version, number of Scalaris nodes in the VM.

Erlang `api_monitor:get_node_info()`
Java: `Monitor.getNodeInfo()`
JSON: `monitor.yaws/get_node_info()`
Python: `n/a`
Ruby: `n/a`

Get Node Performance Gets some performance information about the node, e.g. the average latency and standard deviation of transactional operations.

Erlang `api_monitor:get_node_performance()`
Java: `Monitor.getNodePerformance()`
JSON: `monitor.yaws/get_node_performance()`
Python: `n/a`
Ruby: `n/a`

Get Service Info Gets some information about the whole Scalaris ring (may be estimated if no management server is used). Includes the overall load and the total number of nodes in the ring.

Erlang `api_monitor:get_service_info()`
Java: `Monitor.getServiceInfo()`
JSON: `monitor.yaws/get_service_info()`
Python: `n/a`
Ruby: `n/a`

Get Service Performance Gets some performance information about the whole Scalaris ring, e.g. the average latency and standard deviation of transactional operations. Both are aggregated and may be estimates.

Erlang `api_monitor:get_service_performance()`
Java: `Monitor.getServicePerformance()`
JSON: `monitor.yaws/get_service_performance()`
Python: `n/a`
Ruby: `n/a`

Convenience Methods / Classes

Connection Pool Implements a thread-safe pool of connections to Scalaris instances. Can be instantiated with a fixed maximum number of connections. Connections are either taken from a

pool of available connections or are created on demand. If finished, a connection can be put back into the pool.

Erlang	n/a
Java:	ConnectionPool
JSON:	n/a
Python:	ConnectionPool
Ruby:	n/a

Connection Policies Defines policies on how to select a node to connect to from a set of possible nodes and whether and how to automatically re-connect.

Erlang	n/a
Java:	ConnectionPolicy
JSON:	n/a
Python:	n/a
Ruby:	n/a

4.1.3. JSON API

Scalaris supports a JSON API for transactions. To minimize the necessary round trips between a client and Scalaris, it uses request lists, which contain all requests that can be done in parallel. The request list is then send to a Scalaris node with a POST message. The result contains a list of the results of the requests and - in case of a transaction - a TransLog. To add further requests to the transaction, the TransLog and another list of requests may be send to Scalaris. This process may be repeated as often as necessary. To finish the transaction, the request list can contain a 'commit' request as the last element, which triggers the validation phase of the transaction processing. Request lists are also supported for single read/write operations, i.e. every single operation is committed on its own.

The JSON-API can be accessed via the Scalaris-Web-Server running on port 8000 by default and pages under <URL>/api/. For backwards-compatibility the page <URL>/jsonrpc.yaws provides some functions otherwise provided by the different pages under <URL>/api/ but beware that this may be removed in future. Other examples include <http://localhost:8000/api/tx.yaws>. See Table 4.1 on page 15 for a mapping of the layers to the different pages. Requests are issued by sending a JSON object with header "Content-type"="application/json" to this URL. The result will then be returned as a JSON object with the same content type. The following table shows how both objects look like:

Request

```
{
  "jsonrpc": "2.0",
  "method": "<method>",
  "params": [<params>],
  "id": <number>
}
```

Result

```
{
  "result" : <result_object>,
  "id"      : <number>
}
```

The id in the request can be an arbitrary number which identifies the request and is returned in the result. The following operations (shown as <method>(<params>)) are currently supported (the given result is the <result_object> mentioned above):

generic, e.g. for testing - <URL>/api/*.yaws

- nop(Value) - no operation, result:

```
"ok"
```

single operations, e.g. read/write - <URL>/api/tx.yaws:

- req_list_commit_each(<req_list_ce>) - commit each request in the list, result:

```
{["status": "ok"} or {"status": "ok", "value": <json_value>} or  
 {"status": "fail", "reason": "timeout" or "abort" or "not_found" or  
   "not_a_list" or "not_a_number"} or  
 {"status": "fail", "reason": "key_changed", "value": <json_value>}]}
```

- read(<key>) - read the value at key, result:

```
{"status": "ok", "value": <json_value>} or  
{"status": "fail", "reason": "timeout" or "not_found"}
```

- write(<key>, <json_value>) - write value (inside json_value) to key, result:

```
{"status": "ok"} or  
{"status": "fail", "reason": "timeout" or "abort"}
```

- add_del_on_list(<key>, ToAdd, ToRemove) - adding to / removing from a list (for the list at key adds all values in the ToAdd list and then removes all values in the ToRemove list; if there is no value at key, uses an empty list - both value lists are [<value>]), result:

```
{"status": "ok"} or  
{"status": "fail", "reason": "timeout" or "abort" or "not_a_list"}
```

- add_on_nr(<key>, <value>) - adding to a number (adds value to the number at key - both values must be numbers), result:

```
{"status": "ok"} or  
{"status": "fail", "reason": "timeout" or "abort" or "not_a_number"}
```

- test_and_set(<key>, OldValue, NewValue) - atomic test-and-set (write NewValue to key if the current value is OldValue - both values are <json_value>), result:

```
{"status": "ok"} or  
{"status": "fail", "reason": "timeout" or "abort" or "not_found"} or  
{"status": "fail", "reason": "key_changed", "value": <json_value>}
```

transactions - <URL>/api/tx.yaws:

- req_list(<req_list>) - process a list of requests, result:

```
{"tlog": <tlog>,  
 "results": [{"status": "ok"} or {"status": "ok", "value": <json_value>} or  
 {"status": "fail", "reason": "timeout" or "abort" or "not_found" or  
   "not_a_list" or "not_a_number"} or  
 {"status": "fail", "reason": "key_changed", "value": <json_value>}]}
```

- req_list(<tlog>, <req_list>) - process a list of requests with a previous translog, result:

```
{"tlog": <tlog>,  
 "results": [{"status": "ok"} or {"status": "ok", "value": <json_value>} or
```

```

{"status": "fail", "reason": "timeout" or "abort" or "not_found" or
                             "not_a_list" or "not_a_number"} or
{"status": "fail", "reason": "key_changed", "value": <json_value>}}

```

replication layer functions - <URL>/api/rdht.yaws:

- delete(<key>) - delete the value at key, default timeout 2s, result:

```

{"ok": <number>, "results": ["ok" or "locks_set" or "undef"]} or
{"failure": "timeout", "ok": <number>, "results": ["ok" or "locks_set" or "undef"]}

```

- delete(<key>, Timeout) - delete the value at key with a timeout of Timeout Milliseconds, result:

```

{"ok": <number>, "results": ["ok" or "locks_set" or "undef"]} or
{"failure": "timeout", "ok": <number>, "results": ["ok" or "locks_set" or "undef"]}

```

raw DHT functions - <URL>/api/dht_raw.yaws:

- range_read(From, To) - read a range of (raw) keys, result:

```

{"status": "ok" or "timeout",
 "value": [{"key": <key>, "value": <json_value>, "version": <version>}]}

```

publish/subscribe - <URL>/api/pubsub.yaws:

- publish(Topic, Content) - publish Content to Topic (<key>), result:

```

{"status": "ok"}

```

- subscribe(Topic, URL) - subscribe URL to Topic (<key>), result:

```

{"status": "ok"} or
{"status": "fail", "reason": "timeout" or "abort"}

```

- unsubscribe(Topic, URL) - unsubscribe URL from Topic (<key>), result:

```

{"status": "ok"} or
{"status": "fail", "reason": "timeout" or "abort" or "not_found"}

```

- get_subscribers(Topic) - get subscribers of Topic (<key>), result:

```

[<urls>]

```

monitor - <URL>/api/monitor.yaws:

- get_node_info() - gets some information about the node, result:

```

{"status": "ok" or "timeout",
 "value": [{"scalaris_version": <version_string>,
            "erlang_version": <version_string>,
            "dht_nodes": <number>}]}

```

- get_node_performance() - gets some performance information about the node, result:

```

{"status": "ok" or "timeout",
 "value": [{"latency_avg": <perf_data>, "latency_stddev": <perf_data>}]}

```

- `get_service_info()` - gets some information about the Scalaris ring, result:

```
{ "status": "ok" or "timeout",
  "value": [ { "total_load": <number>, "nodes": <number> } ] }
```

- `get_service_performance()` - gets some performance information about the Scalaris ring, result:

```
{ "status": "ok" or "timeout",
  "value": [ { "latency_avg": <perf_data>, "latency_stddev": <perf_data> } ] }
```

Note:

```
<json_value> = { "type": "as_is" or "as_bin", "value": <value> }
<operation> = { "read": <key> } or { "write", { <key>: <json_value> } } or
               { "add_del_on_list": { "key": <key>, "add": [ <value> ], "del": [ <value> ] } } or
               { "add_on_nr": { <key>: <value> } } or
               { "test_and_set": { "key": <key>, "old": <json_value>, "new": <json_value> } }
<req_list_ce> = [ <operation> ]
<req_list> = [ <operation> or { "commit", _ } ]
<perf_data> = { <number>: <perf_val>, ... }
```

The <value> inside <json_value> is either a base64-encoded string representing a binary object (type = "as_bin") or the value itself (type = "as_is").

JSON-Example

The following example illustrates the message flow:

Client

Make a transaction, that sets two keys →

```
{ "jsonrpc": "2.0",
  "method": "req_list",
  "params": [
    [ { "write": { "keyA": { "type": "as_is", "value": "valueA" } } },
      { "write": { "keyB": { "type": "as_is", "value": "valueB" } } },
      { "commit": "" } ]
  ],
  "id": 0
}
```

Scalaris node

←

Scalaris sends results back

```
{ "error": null,
  "result": {
    "results": [ { "status": "ok" }, { "status": "ok" }, { "status": "ok" } ],
    "tlog": <TLOG> // this is the translog for further operations!
  },
  "id": 0
}
```

In a second transaction: Read the two keys →

```
{ "jsonrpc": "2.0",
  "method": "req_list",
  "params": [
    [ { "read": "keyA" },
      { "read": "keyB" } ]
  ],
  "id": 0
}
```

←

Scalaris sends results back

```
{
  "error": null,
  "result": {
    "results": [
      { "status": "ok", "value": { "type": "as_is", "value": "valueA" } },
      { "status": "ok", "value": { "type": "as_is", "value": "valueB" } }
    ],
    "tlog": <TLOG>
  },
  "id": 0
}
```

Calculate something with the read values →
 and make further requests, here a write
 and the commit for the whole transaction. Also include the latest translog we

```
{
  "jsonrpc": "2.0",
  "method": "req_list",
  "params": [
    <TLOG>,
    [ { "write": { "keyA": { "type": "as_is", "value": "valueA2" } } },
      { "commit": "" } ]
  ],
  "id": 0
}
```

←

Scalaris sends results back

```
{
  "error": null,
  "result": {
    "results": [ { "status": "ok" }, { "status": "ok" } ],
    "tlog": <TLOG>
  },
  "id": 0
}
```

Examples of how to use the JSON API are the Python and Ruby API which use JSON to communicate with Scalaris.

4.1.4. Java API

The `scalaris.jar` provides a Java command line client as well as a library for Java programs to access Scalaris. The library provides several classes:

- `TransactionSingleOp` provides methods for reading and writing values.
- `Transaction` provides methods for reading and writing values in transactions.
- `PubSub` provides methods for a simple topic-based pub/sub implementation on top of Scalaris.
- `ReplicatedDHT` provides low-level methods for accessing the replicated DHT of Scalaris.

For details regarding the API we refer the reader to the Javadoc:

```
%> cd java-api
%> ant doc
%> firefox doc/index.html
```

4.2. Command Line Interfaces

4.2.1. Java command line interface

As mentioned above, the `scalaris.jar` file contains a small command line interface client. For convenience, we provide a wrapper script called `scalaris` which sets up the Java environment:

```
%> ./java-api/scalaris --noconfig --help
```

```
../java-api/scalaris [script options] [options]
Script Options:
  --help, -h          print this message and scalaris help
  --noconfig          suppress sourcing of config files in $HOME/.scalaris/
                      and ${prefix}/etc/scalaris/
  --execdebug        print scalaris exec line generated by this
                      launch script
  --noerl            do not ask erlang for its (local) host name

usage: scalaris [Options]
  -h,--help          print this message
  -v,--verbose       print verbose information,
                      e.g. the properties read
                      gets the local host's name as
                      known to Java (for debugging
                      purposes)
  -b,--minibench <[ops]> <[tpn]> <[benchs]> run selected mini
                      benchmark(s) [1|...|18|all]
                      (default: all benchmarks, 500
                      operations, 10 threads per
                      Scalaris node)
  -r,--read <key>    read an item
  -w,--write <key> <value> write an item
  --test-and-set <key> <old> <new> atomic test and set, i.e.
                      write <key> to <new> if the
                      current value is <old>
  -d,--delete <key> <[timeout]> delete an item (default
                      timeout: 2000ms)
                      WARNING: This function can
                      lead to inconsistent data
                      (e.g. deleted items can
                      re-appear). Also when
                      re-creating an item the
                      version before the delete can
                      re-appear.
  -p,--publish <topic> <message> publish a new message for the
                      given topic
  -s,--subscribe <topic> <url> subscribe to a topic
  -u,--unsubscribe <topic> <url> unsubscribe from a topic
  -g,--getsubscribers <topic> get subscribers of a topic
  -jmx,--jmxservice <node> starts a service exposing
                      Scalaris monitoring values
                      via JMX
```

read, write, delete and similar operations can be used to read, write and delete from/to the overlay, respectively. `getsubscribers`, `publish`, and `subscribe` are the PubSub functions. The others provide debugging and testing functionality.

```
%> ./java-api/scalaris -write foo bar
write(foo, bar)
%> ./java-api/scalaris -read foo
read(foo) == bar
```

Per default, the `scalaris` script tries to connect to a management server at `localhost`. You can change the node it connects to (and further connection properties) by adapting the values defined

in java-api/scalaris.properties.

4.2.2. Python command line interface

```
%> ./python-api/scalaris_client.py --help
```

```
usage: ../python-api/scalaris_client.py [Options]
-r,--read <key>
                        read an item
-w,--write <key> <value>
                        write an item
--test-and-set <key> <old_value> <new_value>
                        atomic test and set, i.e. write <key> to
                        <new_value> if the current value is <old_value>
-d,--delete <key> [<timeout>]
                        delete an item (default timeout: 2000ms)
                        WARNING: This function can lead to inconsistent
                        data (e.g. deleted items can re-appear).
                        Also if an item is re-created, the version
                        before the delete can re-appear.
-p,--publish <topic> <message>
                        publish a new message for the given topic
-s,--subscribe <topic> <url>
                        subscribe to a topic
-g,--getsubscribers <topic>
                        get subscribers of a topic
-u,--unsubscribe <topic> <url>
                        unsubscribe from a topic
-h,--help
                        print this message
-b,--minibench [<ops> [<threads_per_node> [<benchmarks>]]]
                        run selected mini benchmark(s)
                        [1|...|9|all] (default: all benchmarks, 500
                        operations each, 10 threads per Scalaris node)
```

4.2.3. Ruby command line interface

```
%> ../ruby-api/scalaris_client.rb --help
```

```
Usage: scalaris_client [options]
-r, --read KEY          read key KEY
-w, --write KEY,VALUE   write key KEY to VALUE
--test-and-set KEY,OLDVALUE,NEWVALUE
                        write key KEY to NEWVALUE if the current value is OLDVALUE
--add-del-on-list KEY,TOADD,TOREMOVE
                        add and remove elements from the value at key KEY
--add-on-nr KEY,VALUE   add VALUE to the value at key KEY
-h, --help             Show this message
```

5. Testing the system

Description is based on SVN revision r1618.

5.1. Erlang unit tests

There are some unit tests in the `test` directory which test `Scalaris` itself (the Erlang code). You can call them by running `make test` in the main directory. The results are stored in a local `index.html` file.

The tests are implemented with the `common-test` package from the Erlang system. For running the tests we rely on `run_test`, which is part of the `common-test` package, but (on `erlang < R14`) is not installed by default. `configure` will check whether `run_test` is available. If it is not installed, it will show a warning and a short description of how to install the missing file.

Note: for the unit tests, we are setting up and shutting down several overlay networks. During the shut down phase, the runtime environment will print extensive error messages. These error messages do not indicate that tests failed! Running the complete test suite takes about 10-20 minutes, depending on your machine.

If the test suite is interrupted before finishing, the results may not have been linked into the `index.html` file. They are however stored in the `ct_run.ct@...` directory.

5.2. Java unit tests

The Java unit tests can be run by executing `make java-test` in the main directory. This will start a `Scalaris` node with the default ports and test all Java functions part of the Java API. A typical run will look like the following:

```
%> make java-test
[...]
tools.test:
[junit] Running de.zib.tools.PropertyLoaderTest
[junit] Testsuite: de.zib.tools.PropertyLoaderTest
[junit] Tests run: 3, Failures: 0, Errors: 0, Time elapsed: 0.113 sec
[junit] Tests run: 3, Failures: 0, Errors: 0, Time elapsed: 0.113 sec
[junit]
[junit] ----- Standard Output -----
[junit] Working Directory = <scalarisdir>/java-api/classes
[junit] -----
[...]
scalaris.test:
[junit] Running de.zib.scalaris.ConnectionTest
[junit] Testsuite: de.zib.scalaris.ConnectionTest
[junit] Tests run: 7, Failures: 0, Errors: 0, Time elapsed: 0.366 sec
[junit] Tests run: 7, Failures: 0, Errors: 0, Time elapsed: 0.366 sec
[junit]
[junit] Running de.zib.scalaris.DefaultConnectionPolicyTest
[junit] Testsuite: de.zib.scalaris.DefaultConnectionPolicyTest
[junit] Tests run: 12, Failures: 0, Errors: 0, Time elapsed: 0.314 sec
```

```

[junit] Tests run: 12, Failures: 0, Errors: 0, Time elapsed: 0.314 sec
[junit]
[junit] Running de.zib.scalariz.PeerNodeTest
[junit] Testsuite: de.zib.scalariz.PeerNodeTest
[junit] Tests run: 5, Failures: 0, Errors: 0, Time elapsed: 0.077 sec
[junit] Tests run: 5, Failures: 0, Errors: 0, Time elapsed: 0.077 sec
[junit]
[junit] Running de.zib.scalariz.PubSubTest
[junit] Testsuite: de.zib.scalariz.PubSubTest
[junit] Tests run: 33, Failures: 0, Errors: 0, Time elapsed: 4.105 sec
[junit] Tests run: 33, Failures: 0, Errors: 0, Time elapsed: 4.105 sec
[junit]
[junit] ----- Standard Error -----
[junit] 2011-03-25 15:07:04.412: INFO::jetty-7.3.0.v20110203
[junit] 2011-03-25 15:07:04.558: INFO::Started SelectChannelConnector@127.0.0.1:59235
[junit] 2011-03-25 15:07:05.632: INFO::jetty-7.3.0.v20110203
[junit] 2011-03-25 15:07:05.635: INFO::Started SelectChannelConnector@127.0.0.1:41335
[junit] 2011-03-25 15:07:05.635: INFO::jetty-7.3.0.v20110203
[junit] 2011-03-25 15:07:05.643: INFO::Started SelectChannelConnector@127.0.0.1:38552
[junit] 2011-03-25 15:07:05.643: INFO::jetty-7.3.0.v20110203
[junit] 2011-03-25 15:07:05.646: INFO::Started SelectChannelConnector@127.0.0.1:34704
[junit] 2011-03-25 15:07:06.864: INFO::jetty-7.3.0.v20110203
[junit] 2011-03-25 15:07:06.864: INFO::Started SelectChannelConnector@127.0.0.1:57898
[junit] 2011-03-25 15:07:06.864: INFO::jetty-7.3.0.v20110203
[junit] 2011-03-25 15:07:06.865: INFO::Started SelectChannelConnector@127.0.0.1:47949
[junit] 2011-03-25 15:07:06.865: INFO::jetty-7.3.0.v20110203
[junit] 2011-03-25 15:07:06.866: INFO::Started SelectChannelConnector@127.0.0.1:53886
[junit] 2011-03-25 15:07:07.090: INFO::jetty-7.3.0.v20110203
[junit] 2011-03-25 15:07:07.093: INFO::Started SelectChannelConnector@127.0.0.1:33141
[junit] 2011-03-25 15:07:07.094: INFO::jetty-7.3.0.v20110203
[junit] 2011-03-25 15:07:07.096: INFO::Started SelectChannelConnector@127.0.0.1:39119
[junit] 2011-03-25 15:07:07.096: INFO::jetty-7.3.0.v20110203
[junit] 2011-03-25 15:07:07.097: INFO::Started SelectChannelConnector@127.0.0.1:41603
[junit] -----
[junit] Running de.zib.scalariz.ReplicatedDHTTest
[junit] Testsuite: de.zib.scalariz.ReplicatedDHTTest
[junit] Tests run: 6, Failures: 0, Errors: 0, Time elapsed: 0.732 sec
[junit] Tests run: 6, Failures: 0, Errors: 0, Time elapsed: 0.732 sec
[junit]
[junit] Running de.zib.scalariz.TransactionSingleOpTest
[junit] Testsuite: de.zib.scalariz.TransactionSingleOpTest
[junit] Tests run: 28, Failures: 0, Errors: 0, Time elapsed: 0.632 sec
[junit] Tests run: 28, Failures: 0, Errors: 0, Time elapsed: 0.632 sec
[junit]
[junit] Running de.zib.scalariz.TransactionTest
[junit] Testsuite: de.zib.scalariz.TransactionTest
[junit] Tests run: 18, Failures: 0, Errors: 0, Time elapsed: 0.782 sec
[junit] Tests run: 18, Failures: 0, Errors: 0, Time elapsed: 0.782 sec
[junit]

test:

BUILD SUCCESSFUL
Total time: 10 seconds
'jtest_boot@csr-pc9.zib.de'

```

5.3. Python unit tests

The Python unit tests can be run by executing `make python-test` in the main directory. This will start a Scalaris node with the default ports and test all Python functions part of the Python API. A typical run will look like the following:

```

%> make python-test
[...]
testDoubleClose (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testRead_NotConnected (TransactionSingleOpTest.TestTransactionSingleOp) ... ok

```



```

testRead_NotFound (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testTestAndSetList1 (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testTestAndSetList2 (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testTestAndSetList_NotConnected (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testTestAndSetList_NotFound (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testTestAndSetString1 (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testTestAndSetString2 (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testTestAndSetString_NotConnected (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testTestAndSetString_NotFound (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testTransactionSingleOp1 (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testTransactionSingleOp2 (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testWriteList1 (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testWriteList2 (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testWriteList_NotConnected (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testWriteString1 (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testWriteString2 (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testWriteString_NotConnected (TransactionSingleOpTest.TestTransactionSingleOp) ... ok
testAbort_Empty (TransactionTest.TestTransaction) ... ok
testAbort_NotConnected (TransactionTest.TestTransaction) ... ok
testCommit_Empty (TransactionTest.TestTransaction) ... ok
testCommit_NotConnected (TransactionTest.TestTransaction) ... ok
testDoubleClose (TransactionTest.TestTransaction) ... ok
testRead_NotConnected (TransactionTest.TestTransaction) ... ok
testRead_NotFound (TransactionTest.TestTransaction) ... ok
testTransaction1 (TransactionTest.TestTransaction) ... ok
testTransaction3 (TransactionTest.TestTransaction) ... ok
testWriteList1 (TransactionTest.TestTransaction) ... ok
testWriteString (TransactionTest.TestTransaction) ... ok
testWriteString_NotConnected (TransactionTest.TestTransaction) ... ok
testWriteString_NotFound (TransactionTest.TestTransaction) ... ok
testDelete1 (ReplicatedDHTTest.TestReplicatedDHT) ... ok
testDelete2 (ReplicatedDHTTest.TestReplicatedDHT) ... ok
testDelete_notExistingKey (ReplicatedDHTTest.TestReplicatedDHT) ... ok
testDoubleClose (ReplicatedDHTTest.TestReplicatedDHT) ... ok
testReplicatedDHT1 (ReplicatedDHTTest.TestReplicatedDHT) ... ok
testReplicatedDHT2 (ReplicatedDHTTest.TestReplicatedDHT) ... ok
testDoubleClose (PubSubTest.TestPubSub) ... ok
testGetSubscribersOtp_NotConnected (PubSubTest.TestPubSub) ... ok
testGetSubscribers_NotExistingTopic (PubSubTest.TestPubSub) ... ok
testPubSub1 (PubSubTest.TestPubSub) ... ok
testPubSub2 (PubSubTest.TestPubSub) ... ok
testPublish1 (PubSubTest.TestPubSub) ... ok
testPublish2 (PubSubTest.TestPubSub) ... ok
testPublish_NotConnected (PubSubTest.TestPubSub) ... ok
testSubscribe1 (PubSubTest.TestPubSub) ... ok
testSubscribe2 (PubSubTest.TestPubSub) ... ok
testSubscribe_NotConnected (PubSubTest.TestPubSub) ... ok
testSubscription1 (PubSubTest.TestPubSub) ... ok
testSubscription2 (PubSubTest.TestPubSub) ... ok
testSubscription3 (PubSubTest.TestPubSub) ... ok
testSubscription4 (PubSubTest.TestPubSub) ... ok
testUnsubscribe1 (PubSubTest.TestPubSub) ... ok
testUnsubscribe2 (PubSubTest.TestPubSub) ... ok
testUnsubscribe_NotConnected (PubSubTest.TestPubSub) ... ok
testUnsubscribe_NotExistingTopic (PubSubTest.TestPubSub) ... ok
testUnsubscribe_NotExistingUrl (PubSubTest.TestPubSub) ... ok

```

```

-----
Ran 58 tests in 12.317s

```

```

OK

```

```

'jtest_boot@csr-pc9.zib.de'

```

5.4. Interoperability Tests

In order to check whether the common types described in Section 4.1 on page 15 are fully supported by the APIs and yield to the appropriate types in another API, we implemented some interoperability tests. They can be run by executing `make interop-test` in the main directory. This will start a Scalaris node with the default ports, write test data using both the Java and the Python APIs and let each API read the data it wrote itself as well as the data the other API read. On success it will print

```
%> make interop-test
[...]  
all tests successful
```

6. Troubleshooting

Description is based on SVN revision r1618.

6.1. Network

Scalaris uses a couple of TCP ports for communication. It does not use UDP at the moment.

	HTTP Server	Inter-node communication
default (see bin/scalaris.cfg)	8000	14195–14198
first node (bin/firstnode.sh)	8000	14195
joining node 1 (bin/joining_node.sh)	8001	14196
other joining nodes (bin/joining_node.sh <ID>)	8000 + <ID>	14195 + <ID>
standalone mgmt server (bin/mgmt-server.sh)	7999	14194

Please make sure that at least 14195 and 14196 are not blocked by firewalls in order to be able to start at least one first and one joining node on each machine..

6.2. Miscellaneous

For up-to-date information about frequently asked questions and troubleshooting, please refer to our FAQs at <https://code.google.com/p/scalaris/wiki/FAQ> and our mailing list at <http://groups.google.com/group/scalaris>.

Part II.

Developers Guide

7. General Hints

7.1. Coding Guidelines

- Keep the code short
- Use `gen_component` to implement additional processes
- Don't use `receive` by yourself (Exception: to implement single threaded user API calls (`cs_api`, `yaws_calls`, etc))
- Don't use `erlang:now/0`, `erlang:send_after/3`, `receive after` etc. in performance critical code, consider using `msg_delay` instead.
- Don't use `timer:tc/3` as it catches exceptions. Use `util:tc/3` instead.

7.2. Testing Your Modifications and Extensions

- Run the testsuites using `make test`
- Run the java api test using `make java-test` (Scalaris output will be printed if a test fails; if you want to see it during the tests, start a `bin/firstnode.sh` and run the tests by `cd java; ant test`)
- Run the Ruby client by starting Scalaris and running `cd contrib; ./jsonrpc.rb`

7.3. Help with Digging into the System

- use `ets:i/0,1` to get details on the local state of some processes
- consider changing `pdb.erl` to use `ets` instead of `erlang:put/get`
- Have a look at `strace -f -p PID` of beam process
- Get message statistics via the Web-interface
- enable/disable tracing for certain modules
- Use `etop` and look at the total memory size and atoms generated
- send processes `sleep` or `kill` messages to test certain behaviour (see `gen_component.erl`)
- use `mgmt_server:number_of_nodes(). flush()`.
- use `admin_checkring(). flush()`.

8. System Infrastructure

8.1. Groups of Processes

- What is it? How to distinguish from Erlangs internal named processes?
- Joining a process group
- Why do we do this... (managing several independent nodes inside a single Erlang VM for testing)

8.2. The Communication Layer `comm`

- in general
- format of messages (tuples)
- use messages with cookies (server and client side)
- What is a message tag?

8.3. The `gen_component`

Description is based on SVN revision r2675.

The generic component model implemented by `gen_component` allows to add some common functionality to all the components that build up the Scalaris system. It supports:

event-handlers: message handling with a similar syntax as used in [3].

FIFO order of messages: components cannot be inadvertently locked as we do not use selective receive statements in the code.

sleep and halt: for testing components can sleep or be halted.

debugging, breakpoints, stepwise execution: to debug components execution can be steered via breakpoints, step-wise execution and continuation based on arriving events and user defined component state conditions.

basic profiling,

state dependent message handlers: depending on its state, different message handlers can be used and switched during runtime. Thereby a kind of state-machine based message handling is supported.

prepared for `pid_groups`: allows to send events to named processes inside the same group as the actual component itself (`send_to_group_member`) when just holding a reference to any group member, and

unit-testing of event-handlers: as message handling is separated from the main loop of the component, the handling of individual messages and thereby performed state manipulation can easily be tested in unit-tests by directly calling message handlers.

In Scalaris all Erlang processes should be implemented as `gen_component`. The only exception are functions interfacing to the client, where a transition from asynchronous to synchronous request handling is necessary and that are executed in the context of a client's process or a process that behaves as a proxy for a client (`cs_api`).

8.3.1. A basic `gen_component` including a message handler

To implement a `gen_component`, the component has to provide the `gen_component` behaviour:

File `gen_component.erl`:

```

118 -ifdef(have_callback_support).
119 -callback init(Args::term()) -> user_state().
120 -else.
121 -spec behaviour_info(atom()) -> [{atom(), arity()}] | undefined.
122 behaviour_info(callbacks) ->
123     [
124         {init, 1} %% initialize component
125         %% note: can use arbitrary on-handler, but by default on/2 is used:
126         %% {on, 2} %% handle a single message
127         %% on(Msg, UserState) -> NewUserState | unknown_event | kill
128     ];
129 behaviour_info(_Other) -> undefined.
130 -endif.

```

This is illustrated by the following example:

File `msg_delay.erl`:

```

70 %% initialize: return initial state.
71 -spec init([]) -> state().
72 init([]) ->
73     MyGroup = pid_groups:my_groupname(),
74     ?TRACE("msg_delay:init for pid group ~p~n", [MyGroup]),
75     TimeTable = pdb:new(MyGroup ++ "_msg_delay", [set, protected, named_table]),
76     %% use random table name provided by ets to *not* generate an atom
77     %% TimeTable = pdb:new(?MODULE, [set, private]),
78     comm:send_local(self(), {msg_delay_periodic}),
79     _State = {TimeTable, _Round = 0}.
80
81 -spec on(message(), state()) -> state().
82 on({msg_delay_req, Seconds, Dest, Msg} = _FullMsg,
83     {TimeTable, Counter} = State) ->
84     ?TRACE("msg_delay:on(~.0p, ~.0p)~n", [_FullMsg, State]),
85     Future = trunc(Counter + Seconds),
86     EMsg = case erlang:get(trace_mpath) of
87         undefined -> Msg;
88         PState -> trace_mpath:epidemic_reply_msg(PState, comm:this(), Dest, Msg)
89     end,
90     case pdb:get(Future, TimeTable) of
91         undefined ->
92             pdb:set({Future, [{Dest, EMsg}]}, TimeTable);
93         {_, MsgQueue} ->
94             pdb:set({Future, [{Dest, EMsg} | MsgQueue]}, TimeTable)
95     end,
96     State;
97
98 %% periodic trigger
99 on({msg_delay_periodic} = Trigger, {TimeTable, Counter} = _State) ->
100     ?TRACE("msg_delay:on(~.0p, ~.0p)~n", [Trigger, State]),
101     _ = case pdb:take(Counter, TimeTable) of
102         undefined -> ok;
103         {_, MsgQueue} ->
104             _ = [ case Msg of
105                 {'$gen_component', trace_mpath, PState, _From, _To, OrigMsg} ->
106                     Restore = erlang:get(trace_mpath),

```

```

107             trace_mpath:start(PState),
108             comm:send_local(Dest, OrigMsg),
109             erlang:put(trace_mpath, Restore);
110         _ -> comm:send_local(Dest, Msg)
111     end || {Dest, Msg} <- MsgQueue ]
112 end,
113 ETrigger =
114     case erlang:get(trace_mpath) of
115         undefined -> Trigger;
116         PState -> trace_mpath:epidemic_reply_msg(PState, comm:this(), comm:this(), Trigger)
117     end,
118 comm:send_local_after(1000, self(), ETrigger),
119 {TimeTable, Counter + 1};
120
121 on({web_debug_info, Requestor}, {TimeTable, Counter} = State) ->
122     KeyValueList =
123         [{"queued messages (in 0-10s, messages):", ""} |
124         [begin
125             Future = trunc(Counter + Seconds),
126             Queue = case pdb:get(Future, TimeTable) of
127                 undefined -> none;
128                 {_, Q} -> Q
129             end,
130             {webhelpers:safe_html_string("~p", [Seconds]),
131              webhelpers:safe_html_string("~p", [Queue])}
132         end || Seconds <- lists:seq(0, 10)]],
133     comm:send_local(Requestor, {web_debug_info_reply, KeyValueList}),
134     State.

```

`your_gen_component:init/1` is called during start-up of a `gen_component` and should return the initial state to be used for this `gen_component`. Later, the current state of the component can be retrieved using `gen_component:get_state/1`.

To react on messages / events, a message handler is used. The default message handler is given to `gen_component:start_link/3` or `gen_component:start_link/4` as well as `gen_component:start/3`, `gen_component:start/4` or `gen_component:start/5`. It can be changed by calling `gen_component:-change_handler/2` (see Section 8.3.7). When an event / message for the component arrives, this handler is called with the event itself and the current state of the component. In the handler, the state of the component may be adjusted depending upon the event. The handler itself may trigger new events / messages for itself or other components and has finally to return the updated state of the component or the atoms `unknown_event` or `kill`. It must neither call `receive` nor `timer:sleep/1` nor `erlang:exit/1`.

8.3.2. How to start a `gen_component`?

A `gen_component` can be started using one of:

```
gen_component:start(Module, Args, GenCOptions = [])
```

```
gen_component:start_link(Module, Args, GenCOptions = [])
```

Module: the name of the module your component is implemented in

Args: List of parameters passed to `Module:init/1` for initialization

GenCOptions: optional parameter. List of options for `gen_component`

`{pid_groups_join_as, ProcessGroup, ProcessName}`: registers the new process with the given process group (also called `instanceid`) and name using `pid_groups`.

`{erlang_register, ProcessName}`: registers the process as a named Erlang process.

`wait_for_init`: wait for `Module:init/1` to return before returning to the caller.

These functions are compatible to the Erlang/OTP supervisors. They spawn a new process for the component which itself calls `Module:init/1` with the given `Args` to initialize the component.

`Module:init/1` should return the initial state for your component. For each message sent to this component, the default message handler `Module:on(Message, State)` will be called, which should react on the message and return the updated state of your component.

`gen_component:start()` and `gen_component:start_link()` return the pid of the spawned process as `{ok, Pid}`.

8.3.3. When does a `gen_component` terminate?

A `gen_component` can be stopped using:

`gen_component:kill(Pid)` or by returning `kill` from the current message handler.

8.3.4. How to determine whether a process is a `gen_component`?

A `gen_component` can be detected by:

`gen_component:is_gen_component(Pid)`, which returns a boolean.

8.3.5. What happens when unexpected events / messages arrive?

Your message handler (default is `your_gen_component:on/2`) should return `unknown_event` in the final clause (`your_gen_component:on(_, _)`). `gen_component` then will nicely report on the unhandled message, the component's name, its state and currently active message handler, as shown in the following example:

```
# bin/boot.sh
[...]
(boot@localhost)10> pid_groups ! {no_message}.
{no_message}
[error] unknown message: {no_message} in Module: pid_groups and
handler on in State null
(boot@localhost)11>
```

The `pid_groups` (see Section 8.1) is a `gen_component` which registers itself as named Erlang process with the `gen_component` option `erlang_register` and therefore can be addressed by its name in the Erlang shell. We send it a `{no_message}` and `gen_component` reports on the unhandled message. The `pid_groups` module itself continues to run and waits for further messages.

8.3.6. What if my message handler generates an exception or crashes the process?

`gen_component` catches exceptions generated by message handlers and reports them with a stack trace, the message, that generated the exception, and the current state of the component.

If a message handler terminates the process via `erlang:exit/1`, this is out of the responsibility scope of `gen_component`. As usual in Erlang, all linked processes will be informed. If for example `gen_component:start_link/2` or `/3` was used for starting the `gen_component`, the spawning process will be informed, which may be an Erlang supervisor process taking further actions.

8.3.7. Changing message handlers and implementing state dependent message responsiveness as a state-machine

Sometimes it is beneficial to handle messages depending on the state of a component. One possibility to express this is implementing different clauses depending on the state variable, another is introducing case clauses inside message handlers to distinguish between current states. Both approaches may become tedious, error prone, and may result in confusing source code.

Sometimes the use of several different message handlers for different states of the component leads to clearer arranged code, especially if the set of handled messages changes from state to state. For example, if we have a component with an initialization phase and a production phase afterwards, we can handle in the first message handler messages relevant during the initialization phase and simply queue all other requests for later processing using a common default clause.

When initialization is done, we handle the queued user requests and switch to the message handler for the production phase. The message handler for the initialization phase does not need to know about messages occurring during production phase and the message handler for the production phase does not need to care about messages used during initialization. Both handlers can be made independent and may be extended later on without any adjustments to the other.

One can also use this scheme to implement complex state-machines by changing the message handler from state to state.

To switch the message handler `gen_component:change_handler(State, new_handler)` is called as the last operation after a message in the active message handler was handled, so that the return value of `gen_component:change_handler/2` is propagated to `gen_component`. The new handler is given as an atom, which is the name of the 2-ary function in your component module to be called.

Starting with non-default message handler.

It is also possible to change the message handler right from the start in your `your_gen_component:init/1` to avoid the default message handler `your_gen_component:on/2`. Just create your initial state as usual and call `gen_component:change_handler(State, my_handler)` as the final call in your `your_gen_component:init/1`. We prepared `gen_component:change_handler/2` to return `State` itself, so this will work properly.

8.3.8. Handling several messages atomically

The message handler is called for each message separately. Such a single call is atomic, i.e. the component does not perform any other action until the called message handler finishes. Sometimes, it is necessary to execute two or more calls to the message handler atomically (without other interleaving messages). For example if a message A contains another message B as payload, it may be necessary to handle A and B directly one after the other without interference of other messages. So, after handling A you want to call your message handler with B.

In most cases, you could just do so by calculating the new state as result of handling message A first and then calling the message handler with message B and the new state by yourself.

It is safer to use `gen_component:post_op(2)` in such cases: When *B* contains a special message, which is usually handled by the `gen_component` module itself (like `send_to_group_member`, `kill`, `sleep`), the direct call to the message handler would not achieve the expected result. By calling `gen_component:post_op(NewState, B)` to return the new state after handling message A, message

B will be handled directly after the current message A.

8.3.9. Halting and pausing a `gen_component`

Using `gen_component:kill(Pid)` and `gen_component:sleep(Pid, Time)` components can be terminated or paused.

8.3.10. Integration with `pid_groups`: Redirecting messages to other `gen_components`

Each `gen_component` by itself is prepared to support `comm:send_to_group_member/3` which forwards messages inside a group of processes registered via `pid_groups` (see Section 8.1) by their name. So, if you hold a `Pid` of one member of a process group, you can send messages to other members of this group, if you know their registered Erlang name. You do not necessarily have to know their individual `Pid`.

In consequence, no `gen_component` can individually handle messages of the form `{send_to_group_member, _, _}` as such messages are consumed by `gen_component` itself.

8.3.11. Replying to ping messages

Each `gen_component` replies automatically to `{ping, Pid}` requests with a `{pong}` send to the given `Pid`. Such messages are generated, for example, by `vivaldi_latency` which is used by our `vivaldi` module.

In consequence, no `gen_component` can individually handle messages of the form: `{ping, _}` as such messages are consumed by `gen_component` itself.

8.3.12. The debugging interface of `gen_component`: Breakpoints and step-wise execution

We equipped `gen_component` with a debugging interface, which especially is beneficial, when testing the interplay between several `gen_components`. It supports breakpoints (bp) which can pause the `gen_component` depending on the arriving messages or depending on user defined conditions. If a breakpoint is reached, the execution can be continued step-wise (message by message) or until the next breakpoint is reached.

We use it in our unit tests to steer protocol interleavings and to perform tests using random protocol interleavings between several processes (see `paxos_SUITE`). It allows also to reproduce given protocol interleavings for better testing.

Managing breakpoints.

Breakpoints are managed by the following functions:

`gen_component:bp_set(Pid, MsgTag, BPName)`: For the component running under `Pid` a breakpoint `BPName` is set. It is reached, when a message with a message tag `MsgTag` is next to be handled by the component (See `comm:get_msg_tag/1` and Section 8.2 for more information on message tags). The `BPName` is used as a reference for this breakpoint, for example to delete it later.

`gen_component:bp_set_cond(Pid, Cond, BPName)`: The same as `gen_component:bp_set/3` but a user defined condition implemented in `{Module, Function, Params = 2}` = `Cond` is checked by calling `Module:Function(Message, State)` to decide whether a breakpoint is reached or not. `Message` is the next message to be handled by the component and `State` is the current state of the component. `Module:Function/2` should return a boolean.

`gen_component:bp_del(Pid, BPName)`: The breakpoint `BPName` is deleted. If the component is in this breakpoint, it will not be released by this call. This has to be done separately by `gen_component:bp_cont/1`. But the deleted breakpoint will no longer be considered for newly entering a breakpoint.

`gen_component:bp_barrier(Pid)`: Delay all further handling of breakpoint requests until a breakpoint is actually entered.

Note, that the following call sequence may not catch the breakpoint at all, as during the sleep the component not necessarily consumes a ping message and the set breakpoint 'sample_bp' may already be deleted before a ping message arrives.

```
gen_component:bp_set(Pid, ping, sample_bp),
timer:sleep(10),
gen_component:bp_del(Pid, sample_bp),
gen_component:bp_cont(Pid).
```

To overcome this, `gen_component:bp_barrier/1` can be used:

```
gen_component:bp_set(Pid, ping, sample_bp),
gen_component:bp_barrier(Pid),
%% After the bp_barrier request, following breakpoint requests
%% will not be handled before a breakpoint is actually entered.
%% The gen_component itself is still active and handles messages as usual
%% until it enters a breakpoint.
gen_component:bp_del(Pid, sample_bp),
% Delete the breakpoint after it was entered once (ensured by bp_barrier).
% Release the gen_component from the breakpoint and continue.
gen_component:bp_cont(Pid).
```

None of the calls in the sample listing above is blocking. It just schedules all the operations, including the `bp_barrier`, for the `gen_component` and immediately finishes. The actual events of entering and continuing the breakpoint in the `gen_component` happens independently later on, when the next ping message arrives.

Managing execution.

The execution of a `gen_component` can be managed by the following functions:

`gen_component:bp_step(Pid)`: This is the only blocking breakpoint function. It waits until the `gen_component` is in a breakpoint and has handled a single message. It returns the module, the active message handler, and the handled message as a tuple `{Module, On, Message}`. This function does not actually finish the breakpoint, but just lets a single message pass through. For further messages, no breakpoint condition has to be valid, the original breakpoint is still active. To leave a breakpoint, use `gen_component:bp_cont/1`.

`gen_component:bp_cont(Pid)`: Leaves a breakpoint. `gen_component` runs as usual until the next breakpoint is reached.

If no further breakpoints should be entered after continuation, you should delete the registered breakpoint using `gen_component:bp_del/2` before continuing the execution with `gen_component:-`

bp_cont/1. To ensure, that the breakpoint is entered at least once, gen_component:bp_barrier/1 should be used before deleting the breakpoint (see the example above). Otherwise it could happen, that the delete request arrives at your gen_component before it was actually triggered. The following continuation request would then unintentional apply to an unrelated breakpoint that may be entered later on.

gen_component:runnable(Pid): Returns whether a gen_component has messages to handle and is runnable. If you know, that a gen_component is in a breakpoint, you can use this to check, whether a gen_component:bp_step/1 or gen_component:bp_cont/1 is applicable to the component.

Tracing handled messages – getting a message interleaving protocol.

We use the debugging interface of gen_component to test protocols with random interleaving. First we start all the components involved, set breakpoints on the initialization messages for a new Paxos consensus and then start a single Paxos instance on all of them. The outcome of the Paxos consensus is a learner_decide message. So, in paxos_SUITE:step_until_decide/3 we look for runnable processes and select randomly one of them to perform a single step until the protocol finishes with a decision.

File paxos_SUITE.erl:

```

237 -spec prop_rnd_interleave(1..4, 4..16, {pos_integer(), pos_integer(), pos_integer()})
238     -> true.
239 prop_rnd_interleave(NumProposers, NumAcceptors, Seed) ->
240     ct:pal("Called with: paxos_SUITE:prop_rnd_interleave(~p, ~p, ~p).~n",
241         [NumProposers, NumAcceptors, Seed]),
242     Majority = NumAcceptors div 2 + 1,
243     {Proposers, Acceptors, Learners} =
244         make(NumProposers, NumAcceptors, 1, "rnd_interleave"),
245     %% set bp on all processes
246     _ = [ gen_component:bp_set(comm:make_local(X), proposer_initialize, bp)
247         || X <- Proposers ],
248     _ = [ gen_component:bp_set(comm:make_local(X), acceptor_initialize, bp)
249         || X <- Acceptors ],
250     _ = [ gen_component:bp_set(comm:make_local(X), learner_initialize, bp)
251         || X <- Learners ],
252     %% start paxos instances
253     _ = [ proposer:start_paxosid(X, paxidrndinterl, Acceptors,
254         proposal, Majority, NumProposers, Y)
255         || {X,Y} <- lists:zip(Proposers, lists:seq(1, NumProposers)) ],
256     _ = [ acceptor:start_paxosid(X, paxidrndinterl, Learners)
257         || X <- Acceptors ],
258     _ = [ learner:start_paxosid(X, paxidrndinterl, Majority,
259         comm:this(), cpaxidrndinterl)
260         || X <- Learners ],
261     %% randomly step through protocol
262     OldSeed = random:seed(Seed),
263     Steps = step_until_decide(Proposers ++ Acceptors ++ Learners, cpaxidrndinterl, 0),
264     ct:pal("Needed ~p steps~n", [Steps]),
265     _ = case OldSeed of
266         undefined -> ok;
267         _ -> random:seed(OldSeed)
268     end,
269     _ = [ gen_component:kill(comm:make_local(X))
270         || X <- lists:flatten([Proposers, Acceptors, Learners]) ],
271     true.
272
273 step_until_decide(Processes, PaxId, SumSteps) ->
274     %% io:format("Step ~p~n", [SumSteps]),
275     Runnable = [ X || X <- Processes, gen_component:runnable(comm:make_local(X)) ],
276     case Runnable of
277     [] ->
278         ct:pal("No runnable processes of ~p~n", [length(Processes)]),

```

```

279         timer:sleep(5), step_until_decide(Processes, PaxId, SumSteps);
280     - ->
281         Num = random:uniform(length(Runnable)),
282         _ = gen_component:bp_step(comm:make_local(lists:nth(Num, Runnable))),
283         receive
284             {learner_decide, cpaxidrndinterl, _, _Res} = _Any ->
285                 %% io:format("Received ~p~n", [_Any]),
286                 SumSteps
287         after 0 -> step_until_decide(Processes, PaxId, SumSteps + 1)
288         end
289     end.

```

To get a message interleaving protocol, we either can output the results of each `gen_component:bp_step/1` call together with the `Pid` we selected for stepping, or alter the definition of the macro `TRACE_BP_STEPS` in `gen_component`, when we execute all `gen_components` locally in the same Erlang virtual machine.

File `gen_component.erl`:

```

39 %-define(TRACE_BP_STEPS(X,Y), io:format(X,Y)).      %% output on console
40 %-define(TRACE_BP_STEPS(X,Y), ct:pal(X,Y)).        %% output even if called by unittest
41 %-define(TRACE_BP_STEPS(X,Y), io:format(user,X,Y)). %% clean output even if called by unittest
42 -define(TRACE_BP_STEPS(X,Y), ok).

```

8.3.13. Future use and planned extensions for `gen_component`

`gen_component` could be further extended. For example it could support hot-code upgrade or could be used to implement algorithms that have to be run across several components of Scalaris like snapshot algorithms or similar extensions.

8.4. The Process' Database (pdb)

- How to use it and how to switch from `erlang:put/set` to `ets` and implied limitations.

8.5. Failure Detectors (fd)

- uses Erlang monitors locally
- is independent of component load
- uses heartbeats between Erlang virtual machines
- uses a single proxy heartbeat server per Erlang virtual machine, which itself uses Erlang monitors to monitor locally
- uses dynamic timeouts to implement an eventually perfect failure detector.

8.6. Monitoring Statistics (monitor, rrd)

Description is based on SVN revision r2546.

The `monitor` module offers several methods to gather meaningful statistics using the `rrd()` data type defined in `rrd`.

`rrd()` records work with time slots, i.e. a fixed slot length is given at creation and items which should be inserted will be either put into the current slot, or a new slot will be created. Each data item thus needs a time stamp associated with it. It must not be a real time, but can also be a virtual time stamp.

The `rrd` module thus offers two different APIs: one with transparent time handling, e.g. `rrd:create/3`, `rrd:add_now/2`, and one with manual time handling, e.g. `rrd:create/4`, `rrd:add/3`.

To allow different evaluations of the stored data, the following types of data are supported:

- **gauge**: only stores the newest value of a time slot, e.g. for thermometers,
- **counter**: sums up all values inside a time slot,
- **timing**: records time spans and stores values to easily calculate e.g. the sum, the standard deviation, the number of events, the min and max,
- **timing_with_hist**: similar to **timing** but also records a more detailed (approximated) histogram of the data,
- **event**: records each event (including its time stamp) inside a time slot in a list (this should be rarely used as the amount of data stored may be very big).

The `monitor` offers functions to conveniently store and retrieve such values. It is also started as a process in each `dht_node` and `basic_services` group as well as inside each `clients_group`. This process ultimately stores the whole `rrd()` structure. There are three paradigms how values can be stored:

1. Values are gathered in the process that is generating the values. Inside this process, the `rrd()` is stored in the erlang dictionary. Whenever a new time slot is started, the values will be reported to the monitor process of the gathering process' group.
2. Values are gathered in the process that is generating the values. Inside this process, the `rrd()` is handled manually. After changing the `rrd()`, a manual check for reporting needs to be issued using `monitor:check_report/4`.
3. Values are immediately send to the monitor process where it undergoes the same procedures until it is finally stored and available to other processes. This is especially useful if the process generating the values does not live long or does not regularly create new data, e.g. the client.

The following example illustrates the first mode, i.e. gathering data in the generating process. It has been taken from the `cyclon` module which uses a counter data type:

```
% initialise the monitor with an empty rrd() using a 60s monitoring interval
monitor:proc_set_value(?MODULE, 'shuffle', rrd:create(60 * 1000000, 3, counter)),
% update the value by adding one
monitor:proc_set_value(?MODULE, 'shuffle', fun(Old) -> rrd:add_now(1, Old) end),
% check regularly whether to report the data to the monitor:
monitor:proc_check_timeslot(?MODULE, 'shuffle')
```

The first two parameters of `monitor:proc_set_value/3` define the name of a monitored value, the module's name and a unique key. The second can be either an `rrd()` or an update fun. The `monitor:proc_check_timeslot/3` function can be used if your module does not regularly create new data. In this case, the monitor process would not have the latest data for others to retrieve. This function forces a check and creates the new time slot if needed (thus reporting the data).

This is how forwarding works (taken from `api_tx`):

```
monitor:client_monitor_set_value(
  ?MODULE, 'req_list',
  fun(Old) ->
```

```
Old2 = case Old of
    % 10s monitoring interval, only keep newest in the client process
    undefined -> rrd:create(10 * 1000000, 1, {timing, ms});
    _ -> Old
end,
rrd:add_now(TimeInUs / 1000, Old2)
end),
```

As in this case there is no safe way of initialising the value, it is more useful to provide an update fun to `monitor:client_monitor_set_value/3`. This function is only useful for the client processes as it reports to the monitor in the `clients_group` (recall that client processes do not belong to any group). All other processes should use `monitor:monitor_set_value/3` with the same semantics.

8.7. Writing Unittests

8.7.1. Plain unittests

8.7.2. Randomized Testing using `tester.erl`

9. Basic Structured Overlay

9.1. Ring Maintenance

9.2. T-Man

9.3. Routing Tables

Description is based on SVN revision r4005.

Each node of the ring can perform searches in the overlay.

A search is done by a lookup in the overlay, but there are several other demands for communication between peers. Scalaris provides a general interface to route a message to the (other) peer, which is currently responsible for a given key.

File `api_dht_raw.erl`:

```
34 -spec unreliable_lookup(Key::?RT:key(), Msg::comm:message()) -> ok.
35 unreliable_lookup(Key, Msg) ->
36     comm:send_local(pid_groups:find_a(dht_node),
37         {?lookup_aux, Key, 0, Msg}).
38
39 -spec unreliable_get_key(Key::?RT:key()) -> ok.
40 unreliable_get_key(Key) ->
41     unreliable_lookup(Key, {?get_key, comm:this(), Key}).
42
43 -spec unreliable_get_key(CollectorPid::comm:mypid(),
44     ReqId::{rdht_req_id, pos_integer()},
45     Key::?RT:key()) -> ok.
46 unreliable_get_key(CollectorPid, ReqId, Key) ->
47     unreliable_lookup(Key, {?get_key, CollectorPid, ReqId, Key}).
```

The message `Msg` could be a `get_key` which retrieves content from the responsible node or a `get_node` message, which returns a pointer to the node.

All currently supported messages are listed in the file `dht_node.erl`.

The message routing is implemented in `dht_node_lookup.erl`

File `dht_node_lookup.erl`:

```
28 %% @doc Find the node responsible for Key and send him the message Msg.
29 -spec lookup_aux(State::dht_node_state:state(), Key::intervals:key(),
30     Hops::non_neg_integer(), Msg::comm:message()) -> ok.
31 lookup_aux(State, Key, Hops, Msg) ->
32     Neighbors = dht_node_state:get(State, neighbors),
33     WrappedMsg = ?RT:wrap_message(Msg, Hops),
34     case intervals:in(Key, nodelist:succ_range(Neighbors)) of
35     true -> % found node -> terminate
36         P = node:pidX(nodelist:succ(Neighbors)),
37         comm:send(P, {?lookup_fin, Key, Hops + 1, WrappedMsg}, [{shepherd, self()}]);
38     _ ->
39         P = ?RT:next_hop(State, Key),
```

```

40         comm:send(P, {?lookup_aux, Key, Hops + 1, WrappedMsg}, [{shepherd, self()}])
41     end.
42
43 %% @doc Find the node responsible for Key and send him the message Msg.
44 -spec lookup_fin(State::dht_node_state:state(), Key::intervals:key(),
45               Hops::non_neg_integer(), Msg::comm:message()) -> dht_node_state:state().
46 lookup_fin(State, Key, Hops, Msg) ->
47     MsgFwd = dht_node_state:get(State, msg_fwd),
48     FwdList = [P || {I, P} <- MsgFwd, intervals:in(Key, I)],
49     case FwdList of
50         [] ->
51             case dht_node_state:is_db_responsible(Key, State) of
52                 true ->
53                     comm:send_local(dht_node_state:get(State, monitor_proc),
54                                   {lookup_hops, Hops}),
55                     Unwrap = ?RT:unwrap_message(Msg, State),
56                     gen_component:post_op(State, Unwrap);
57                 false ->
58                     % it is possible that we received the message due to a
59                     % forward while sliding and before the other node removed
60                     % the forward -> do not warn then
61                     SlidePred = dht_node_state:get(State, slide_pred),
62                     SlideSucc = dht_node_state:get(State, slide_succ),
63                     Neighbors = dht_node_state:get(State, neighbors),
64                     case ((SlidePred /= null andalso
65                           slide_op:get_sendORreceive(SlidePred) == 'send' andalso
66                           intervals:in(Key, slide_op:get_interval(SlidePred)))
67                        or
68                           (SlideSucc /= null andalso
69                            slide_op:get_sendORreceive(SlideSucc) == 'send' andalso
70                            intervals:in(Key, slide_op:get_interval(SlideSucc)))
71                        or
72                           intervals:in(Key, nodelist:succ_range(Neighbors))) of
73                         true -> ok;
74                         false ->
75                             DBRange = dht_node_state:get(State, db_range),
76                             DBRange2 = [begin
77                                     case intervals:is_continuous(Interval) of
78                                         true -> {intervals:get_bounds(Interval), Id};
79                                         _ -> {Interval, Id}
80                                     end
81                                 end || {Interval, Id} <- DBRange],
82                             log:log(warn,
83                                     "[ ~.0p ] Routing is damaged!! Trying again...~n myrange:~p~n
84                                     db_range:~p~n msgfwd:~p~n Key:~p",
85                                     [self(), intervals:get_bounds(nodelist:node_range(Neighbors)),
86                                      DBRange2, MsgFwd, Key])
86                             end,
87                             lookup_aux(State, Key, Hops, Msg),
88                             State
89                         end;
90         [Pid] -> comm:send(Pid, {?lookup_fin, Key, Hops + 1, Msg}),
91                 State
92     end.

```

Each node is responsible for a certain key interval. The function `intervals:in/2` is used to decide, whether the key is between the current node and its successor. If that is the case, the final step is delivers a `lookup_fin` message to the local node. Otherwise, the message is forwarded to the next nearest known peer (listed in the routing table) determined by `?RT:next_hop/2`.

`rt_beh.erl` is a generic interface for routing tables. It can be compared to interfaces in Java. In Erlang interfaces can be defined using a so called ‘behaviour’. The files `rt_simple` and `rt_chord` implement the behaviour ‘`rt_beh`’.

The macro `?RT` is used to select the current implementation of routing tables. It is defined in `include/scalaris.hrl`.

File scalaris.hrl:

```
28 %%The RT macro determines which kind of routingtable is used. Uncomment the
29 %%one that is desired.
30
31 %%Standard Chord routingtable
32 -define(RT, rt_chord).
33 % first valid key:
34 -define(MINUS_INFINITY, 0).
35 -define(MINUS_INFINITY_TYPE, 0).
36 % first invalid key:
37 -define(PLUS_INFINITY, 16#10000000000000000000000000000000).
38 -define(PLUS_INFINITY_TYPE, 16#10000000000000000000000000000000).
39
40 %%Simple routingtable
41 %-define(RT, rt_simple).
```

The functions, that have to be implemented for a routing mechanism are defined in the following file:

File rt_beh.erl:

```
28 -ifdef(have_callback_support).
29 -include("scalaris.hrl").
30 -include("client_types.hrl").
31 -type rt() :: term().
32 -type external_rt() :: term().
33 -type key() :: term().
34
35 -callback empty_ext(nodelist:neighborhood()) -> external_rt().
36 -callback init(nodelist:neighborhood()) -> rt().
37 -callback hash_key(client_key()) -> key().
38 -callback get_random_node_id() -> key().
39 -callback next_hop(dht_node_state:state(), key()) -> comm:mypid().
40
41 -callback init_stabilize(nodelist:neighborhood(), rt()) -> rt().
42 -callback update(OldRT::rt(), OldNeighbors::nodelist:neighborhood(),
43                 NewNeighbors::nodelist:neighborhood())
44     -> {trigger_rebuild, rt()} | {ok, rt()}.
45 -callback filter_dead_node(rt(), comm:mypid()) -> rt().
46
47 -callback to_pid_list(rt()) -> [comm:mypid()].
48 -callback get_size(rt() | external_rt()) -> non_neg_integer().
49 -callback get_replica_keys(key()) -> [key()].
50
51 -callback n() -> number().
52 -callback get_range(Begin::key(), End::key() | ?PLUS_INFINITY_TYPE) -> number().
53 -callback get_split_key(Begin::key(), End::key() | ?PLUS_INFINITY_TYPE, SplitFraction::{Num::0..100, Den::1..100}) -> key().
54
55 -callback dump(RT::rt()) -> KeyValueTypeList::[{Index::string(), Node::string()}].
56
57 -callback to_list(dht_node_state:state()) -> nodelist:snodelist().
58 -callback export_rt_to_dht_node(rt(), Neighbors::nodelist:neighborhood()) -> external_rt().
59 -callback handle_custom_message(comm:message(), rt_loop:state_active()) -> rt_loop:state_active() | undefined.
60
61 -callback check(OldRT::rt(), NewRT::rt(), Neighbors::nodelist:neighborhood(),
62                 ReportToFD::boolean()) -> ok.
63 -callback check(OldRT::rt(), NewRT::rt(), OldNeighbors::nodelist:neighborhood(),
64                 NewNeighbors::nodelist:neighborhood(), ReportToFD::boolean()) -> ok.
65
66 -callback check_config() -> boolean().
67 -callback wrap_message(Msg::comm:message(), Hops::non_neg_integer()) -> comm:message().
68 -callback unwrap_message(Msg::comm:message(), State::dht_node_state:state()) ->
69     comm:message().
70
71 -else.
72 -spec behaviour_info(atom()) -> [{atom(), arity()}] | undefined.
73 behaviour_info(callbacks) ->
74     [
75         % create a default routing table
```

```

76     {empty_ext, 1},
77     % initialize a routing table
78     {init, 1},
79     % mapping: key space -> identifier space
80     {hash_key, 1}, {get_random_node_id, 0},
81     % routing
82     {next_hop, 2},
83     % trigger for new stabilization round
84     {init_stabilize, 2},
85     % adapt RT to changed neighborhood
86     {update, 3},
87     % dead nodes filtering
88     {filter_dead_node, 2},
89     % statistics
90     {to_pid_list, 1}, {get_size, 1},
91     % gets all (replicated) keys for a given (hashed) key
92     % (for symmetric replication)
93     {get_replica_keys, 1},
94     % address space size, range and split key
95     % (may all throw 'throw:not_supported' if unsupported by the RT)
96     {n, 0}, {get_range, 2}, {get_split_key, 3},
97     % for debugging and web interface
98     {dump, 1},
99     % for bulkowner
100    {to_list, 1},
101    % convert from internal representation to version for dht_node
102    {export_rt_to_dht_node, 2},
103    % handle messages specific to a certain routing-table implementation
104    {handle_custom_message, 2},
105    % common methods
106    {check, 4}, {check, 5},
107    {check_config, 0},
108    % wrap and unwrap lookup messages
109    {wrap_message, 2},
110    {unwrap_message, 2}
111 ];
112 behaviour_info(_Other) ->
113     undefined.
114 -endif.

```

empty/1 gets a successor and generates an empty routing table for use inside the routing table implementation. The data structure of the routing table is undefined. It can be a list, a tree, a matrix ...

empty_ext/1 similarly creates an empty external routing table for use by the dht_node. This process might not need all the information a routing table implementation requires and can thus work with less data.

hash_key/1 gets a key and maps it into the overlay's identifier space.

get_random_node_id/0 returns a random node id from the overlay's identifier space. This is used for example when a new node joins the system.

next_hop/2 gets a dht_node's state (including the external routing table representation) and a key and returns the node, that should be contacted next when searching for the key, i.e. the known node nearest to the id.

init_stabilize/2 is called periodically to rebuild the routing table. The parameters are the identifier of the node, its successor and the old (internal) routing table state. This method may send messages to the routing_table process which need to be handled by the handle_custom_message/handler since they are implementation-specific.

update/7 is called when the node's ID, predecessor and/or successor changes. It updates the (internal) routing table with the (new) information.

filter_dead_node/2 is called by the failure detector and tells the routing table about dead nodes. This function gets the (internal) routing table and a node to remove from it. A new routing table state is returned.

to_pid_list/1 get the PIDs of all (internal) routing table entries.
get_size/1 get the (internal or external) routing table's size.
get_replica_keys/1 Returns for a given (hashed) Key the (hashed) keys of its replicas. This used for implementing symmetric replication.
n/0 gets the number of available keys. An implementation may throw `throw:not_supported` if the operation is unsupported by the routing table.
dump/1 dump the (internal) routing table state for debugging, e.g. by using the web interface. Returns a list of `{Index, Node_as_String}` tuples which may just as well be empty.
to_list/1 convert the (external) representation of the routing table inside a given `dht_node_state` to a sorted list of known nodes from the routing table, i.e. first=succ, second=next known node on the ring, ... This is used by bulk-operations to create a broadcast tree.
export_rt_to_dht_node/2 convert the internal routing table state to an external state. Gets the internal state and the node's neighborhood for doing so.
handle_custom_message/2 handle messages specific to the routing table implementation. `rt_loop` will forward unknown messages to this function.
check/5, check/6 check for routing table changes and send an updated (external) routing table to the `dht_node` process.
check_config/0 check that all required configuration parameters exist and satisfy certain restrictions.
wrap_message/1 wraps a message send via a `dht_node_lookup:lookup_aux/4`.
unwrap_message/2 unwraps a message send via `dht_node_lookup:lookup_aux/4` previously wrapped by `wrap_message/1`.

9.3.1. The routing table process (rt_loop)

The `rt_loop` module implements the process for all routing tables. It processes messages and calls the appropriate methods in the specific routing table implementations.

File `rt_loop.erl`:

```
40 -opaque(state_active() :: {Neighbors :: nodelist:neighborhood(),
41                               RTState    :: ?RT:rt(),
42                               TriggerState :: trigger:state()}).
43 -type(state_inactive() :: {inactive,
44                               MessageQueue::msg_queue:msg_queue(),
45                               TriggerState::trigger:state()}).
46 %% -type(state() :: state_active() | state_inactive()).
```

If initialized, the node's id, its predecessor, successor and the routing table state of the selected implementation (the macro `RT` refers to).

File `rt_loop.erl`:

```
154 on_active({trigger_rt}, {Neighbors, OldRT, TriggerState}) ->
155     % start periodic stabilization
156     % log:log(debug, "[ RT ] stabilize"),
157     NewRT = ?RT:init_stabilize(Neighbors, OldRT),
158     ?RT:check(OldRT, NewRT, Neighbors, true),
159     % trigger next stabilization
160     NewTriggerState = trigger:next(TriggerState),
161     new_state(Neighbors, NewRT, NewTriggerState);
```

Periodically (see `routingtable_trigger` and `pointer_base_stabilization_interval` config parameters) a trigger message is sent to the `rt_loop` process that starts the periodic stabilization implemented by each routing table.

File `rt_loop.erl`:

```
138 % update routing table with changed ID, pred and/or succ
139 on_active({update_rt, OldNeighbors, NewNeighbors}, {_Neighbors, OldRT, TriggerState}) ->
140     case ?RT:update(OldRT, OldNeighbors, NewNeighbors) of
141     {trigger_rebuild, NewRT} ->
142         % trigger immediate rebuild
143         NewTriggerState = trigger:now(TriggerState),
144         ?RT:check(OldRT, NewRT, OldNeighbors, NewNeighbors, true),
145         new_state(NewNeighbors, NewRT, NewTriggerState)
146     ;
147     {ok, NewRT} ->
148         ?RT:check(OldRT, NewRT, OldNeighbors, NewNeighbors, true),
149         new_state(NewNeighbors, NewRT, TriggerState)
150     end;
```

Every time a node's neighborhood changes, the `dht_node` sends an `update_rt` message to the routing table which will call `?RT:update/7` that decides whether the routing table should be rebuilt. If so, it will stop any waiting trigger and schedule an immediate (periodic) stabilization.

9.3.2. Simple routing table (`rt_simple`)

One implementation of a routing table is the `rt_simple`, which routes via the successor. Note that this is inefficient as it needs a linear number of hops to reach its goal. A more robust implementation, would use a successor list. This implementation is also not very efficient in the presence of churn.

Data types

First, the data structure of the routing table is defined:

File `rt_simple.erl`:

```
26 -type key_t() :: 0..16#FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF. % 128 bit numbers
27 -type rt_t() :: Succ::node:node_type().
28 -type external_rt_t() :: Succ::node:node_type().
29 -type custom_message() :: none().
```

The routing table only consists of a node (the successor). Keys in the overlay are identified by integers ≥ 0 .

A simple `rm_beh` behaviour

File `rt_simple.erl`:

```
41 %% @doc Creates an "empty" routing table containing the successor.
42 -spec empty(nodelist:neighborhood()) -> rt().
43 empty(Neighbors) -> nodelist:succ(Neighbors).
```

File `rt_simple.erl`:

```
226 -spec empty_ext(nodelist:neighborhood()) -> external_rt().
227 empty_ext(Neighbors) -> empty(Neighbors).
```

The empty routing table (internal or external) consists of the successor.

File `rt_simple.erl`:

Keys are hashed using MD5 and have a length of 128 bits.

File `rt_simple.erl`:

```
63 %% @doc Generates a random node id, i.e. a random 128-bit number.
64 -spec get_random_node_id() -> key().
65 get_random_node_id() ->
66     case config:read(key_creator) of
67         random -> hash_key_(randoms:getRandomString());
68         random_with_bit_mask ->
69             {Mask1, Mask2} = config:read(key_creator_bitmask),
70             (hash_key_(randoms:getRandomString()) band Mask2) bor Mask1
71     end.
```

Random node id generation uses the helpers provided by the `randoms` module.

File `rt_simple.erl`:

```
231 %% @doc Returns the next hop to contact for a lookup.
232 -spec next_hop(dht_node_state:state(), key()) -> comm:mypid().
233 next_hop(State, _Key) -> node:pidX(dht_node_state:get(State, succ)).
```

Next hop is always the successor.

File `rt_simple.erl`:

```
79 %% @doc Triggered by a new stabilization round, renews the routing table.
80 -spec init_stabilize(nodelist:neighborhood(), rt()) -> rt().
81 init_stabilize(Neighbors, _RT) -> empty(Neighbors).
```

`init_stabilize/2` resets its routing table to the current successor.

File `rt_simple.erl`:

```
85 %% @doc Updates the routing table due to a changed node ID, pred and/or succ.
86 -spec update(OldRT::rt(), OldNeighbors::nodelist:neighborhood(),
87             NewNeighbors::nodelist:neighborhood()) -> {ok, rt()}.
88 update(_OldRT, _OldNeighbors, NewNeighbors) ->
89     {ok, nodelist:succ(NewNeighbors)}.
```

`update/7` updates the routing table with the new successor.

File `rt_simple.erl`:

```
93 %% @doc Removes dead nodes from the routing table (rely on periodic
94 %%     stabilization here).
95 -spec filter_dead_node(rt(), comm:mypid()) -> rt().
96 filter_dead_node(RT, _DeadPid) -> RT.
```

`filter_dead_node/2` does nothing, as only the successor is listed in the routing table and that is reset periodically in `init_stabilize/2`.

File `rt_simple.erl`:

```
100 %% @doc Returns the pids of the routing table entries.
101 -spec to_pid_list(rt()) -> [comm:mypid()].
102 to_pid_list(Succ) -> [node:pidX(Succ)].
```

`to_pid_list/1` returns the pid of the successor.

File `rt_simple.erl`:

```
106 %% @doc Returns the size of the routing table.
107 -spec get_size(rt() | external_rt()) -> non_neg_integer().
108 get_size(_RT) -> 1.
```

The size of the routing table is always 1.

File `rt_simple.erl`:

```
150 %% @doc Returns the replicas of the given key.
151 -spec get_replica_keys(key()) -> [key()].
152 get_replica_keys(Key) ->
153     [Key,
154      Key bxor 16#40000000000000000000000000000000,
155      Key bxor 16#80000000000000000000000000000000,
156      Key bxor 16#C0000000000000000000000000000000
157     ].
```

This `get_replica_keys/1` implements symmetric replication.

File `rt_simple.erl`:

```
112 %% @doc Returns the size of the address space.
113 -spec n() -> integer().
114 n() -> n_().
115 %% @doc Helper for n/0 to make dialyzer happy with internal use of n/0.
116 -spec n_() -> 16#10000000000000000000000000000000.
117 n_() -> 16#FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF + 1.
```

There are 2^{128} available keys.

File `rt_simple.erl`:

```
161 %% @doc Dumps the RT state for output in the web interface.
162 -spec dump(RT::rt()) -> KeyValueType::[{Index::string(), Node::string()}].
163 dump(Succ) -> [{"0", webhelpers:safe_html_string("~p", [Succ])}].
```

`dump/1` lists the successor.

File `rt_simple.erl`:

```
244 %% @doc Converts the (external) representation of the routing table to a list
245 %%      in the order of the fingers, i.e. first=succ, second=shortest finger,
246 %%      third=next longer finger,...
247 -spec to_list(dht_node_state:state()) -> nodelist:nodelist().
248 to_list(State) -> [dht_node_state:get(State, succ)].
```

`to_list/1` lists the successor from the external routing table state.

File `rt_simple.erl`:

```
237 %% @doc Converts the internal RT to the external RT used by the dht_node. Both
238 %%      are the same here.
239 -spec export_rt_to_dht_node(rt(), Neighbors::nodelist:neighborhood()) -> external_rt().
240 export_rt_to_dht_node(RT, _Neighbors) -> RT.
```

`export_rt_to_dht_node/2` states that the external routing table is the same as the internal table.

File `rt_simple.erl`:

```
183 %% @doc There are no custom messages here.
184 -spec handle_custom_message
185       (custom_message() | any(), rt_loop:state_active()) -> unknown_event.
186 handle_custom_message(_Message, _State) -> unknown_event.
```


Custom messages could be send from a routing table process on one node to the routing table process on another node and are independent from any other implementation.

File `rt_simple.hrl`:

```

190 %% @doc Notifies the dht_node and failure detector if the routing table changed.
191 %%     Provided for convenience (see check/5).
192 -spec check(OldRT::rt(), NewRT::rt(), Neighbors::nodelist:neighborhood(),
193           ReportToFD::boolean()) -> ok.
194 check(OldRT, NewRT, Neighbors, ReportToFD) ->
195     check(OldRT, NewRT, Neighbors, Neighbors, ReportToFD).
196
197 %% @doc Notifies the dht_node if the (external) routing table changed.
198 %%     Also updates the failure detector if ReportToFD is set.
199 %%     Note: the external routing table only changes the internal RT has
200 %%     changed.
201 -spec check(OldRT::rt(), NewRT::rt(), OldNeighbors::nodelist:neighborhood(),
202           NewNeighbors::nodelist:neighborhood(), ReportToFD::boolean()) -> ok.
203 check(OldRT, NewRT, _OldNeighbors, NewNeighbors, ReportToFD) ->
204     case OldRT == NewRT of
205     true -> ok;
206     _ ->
207         Pid = pid_groups:get_my(dht_node),
208         RT_ext = export_rt_to_dht_node(NewRT, NewNeighbors),
209         comm:send_local(Pid, {rt_update, RT_ext}),
210         % update failure detector:
211         case ReportToFD of
212         true ->
213             NewPids = to_pid_list(NewRT),
214             OldPids = to_pid_list(OldRT),
215             fd:update_subscriptions(OldPids, NewPids);
216         _ -> ok
217         end
218     end.

```

Checks whether the routing table changed and in this case sends the `dht_node` an updated (external) routing table state. Optionally the failure detector is updated. This may not be necessary, e.g. if `check` is called after a crashed node has been reported by the failure detector (the failure detector already unsubscribes the node in this case).

File `rt_simple.hrl`:

```

190 %% @doc Notifies the dht_node and failure detector if the routing table changed.
191 %%     Provided for convenience (see check/5).
192 -spec check(OldRT::rt(), NewRT::rt(), Neighbors::nodelist:neighborhood(),
193           ReportToFD::boolean()) -> ok.
194 check(OldRT, NewRT, Neighbors, ReportToFD) ->
195     check(OldRT, NewRT, Neighbors, Neighbors, ReportToFD).
196
197 %% @doc Notifies the dht_node if the (external) routing table changed.
198 %%     Also updates the failure detector if ReportToFD is set.
199 %%     Note: the external routing table only changes the internal RT has
200 %%     changed.
201 -spec check(OldRT::rt(), NewRT::rt(), OldNeighbors::nodelist:neighborhood(),
202           NewNeighbors::nodelist:neighborhood(), ReportToFD::boolean()) -> ok.
203 check(OldRT, NewRT, _OldNeighbors, NewNeighbors, ReportToFD) ->
204     case OldRT == NewRT of
205     true -> ok;
206     _ ->
207         Pid = pid_groups:get_my(dht_node),
208         RT_ext = export_rt_to_dht_node(NewRT, NewNeighbors),
209         comm:send_local(Pid, {rt_update, RT_ext}),
210         % update failure detector:
211         case ReportToFD of
212         true ->
213             NewPids = to_pid_list(NewRT),
214             OldPids = to_pid_list(OldRT),
215             fd:update_subscriptions(OldPids, NewPids);

```

```

216         - -> ok
217     end
218 end.

```

File `rt_simple.erl`:

```

252 %% @doc Wrap lookup messages. This is a noop in rt_simple.
253 -spec wrap_message(Msg::comm:message(), Hops::non_neg_integer()) -> comm:message().
254 wrap_message(Msg, _Hops) -> Msg.

```

Wraps a message send via `dht_node_lookup:lookup/4` if needed. This routing algorithm does not need callbacks when finishing the lookup, so it does not need to wrap the message.

File `rt_simple.erl`:

```

258 %% @doc Unwrap lookup messages. This is a noop in rt_simple.
259 -spec unwrap_message(Msg::comm:message(), State::dht_node_state:state()) -> comm:message().
260 unwrap_message(Msg, _State) -> Msg.

```

Unwraps a message previously wrapped with `rt_simple:wrap_message/1`. As that function does not wrap messages, `rt_simple:unwrap_message/2` doesn't have to do anything as well.

9.3.3. Chord routing table (`rt_chord`)

The file `rt_chord.erl` implements Chord's routing.

Data types

File `rt_chord.erl`:

```

26 -type key_t() :: 0..16#FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF. % 128 bit numbers
27 -type rt_t() :: gb_tree().
28 -type external_rt_t() :: gb_tree().
29 -type index() :: {pos_integer(), non_neg_integer()}.
30 -type custom_message() ::
31     {rt_get_node, Source_PID::comm:mypid(), Index::index()} |
32     {rt_get_node_response, Index::index(), Node::node:node_type()}.

```

The routing table is a `gb_tree`. Identifiers in the ring are integers. Note that in Erlang integer can be of arbitrary precision. For Chord, the identifiers are in $[0, 2^{128})$, i.e. 128-bit strings.

The `rm_beh` behaviour for Chord (excerpt)

File `rt_chord.erl`:

```

46 %% @doc Creates an empty routing table.
47 -spec empty(nodelist:neighborhood()) -> rt().
48 empty(_Neighbors) -> gb_trees:empty().

```

File `rt_chord.erl`:

```

304 -spec empty_ext(nodelist:neighborhood()) -> external_rt().
305 empty_ext(_Neighbors) -> gb_trees:empty().

```

empty/1 returns an empty gb_tree, same for empty_ext/1.

rt_chord:hash_key/1, rt_chord:get_random_node_id/0, rt_chord:get_replica_keys/1 and rt_chord:-n/0 are implemented like their counterparts in rt_simple.erl.

File rt_chord.erl:

```
309 %% @doc Returns the next hop to contact for a lookup.
310 %%     If the routing table has less entries than the rt_size_use_neighbors
311 %%     config parameter, the neighborhood is also searched in order to find a
312 %%     proper next hop.
313 %%     Note, that this code will be called from the dht_node process and
314 %%     it will thus have an external_rt!
315 -spec next_hop(dht_node_state:state(), key()) -> comm:mypid().
316 next_hop(State, Id) ->
317     Neighbors = dht_node_state:get(State, neighbors),
318     case intervals:in(Id, nodelist:succ_range(Neighbors)) of
319     true -> node:pidX(nodelist:succ(Neighbors));
320     _ ->
321         % check routing table:
322         RT = dht_node_state:get(State, rt),
323         RTSize = get_size(RT),
324         NodeRT = case util:gb_trees_largest_smaller_than(Id, RT) of
325             {value, _Key, N} ->
326                 N;
327             nil when RTSize == 0 ->
328                 nodelist:succ(Neighbors);
329             nil -> % forward to largest finger
330                 {_Key, N} = gb_trees:largest(RT),
331                 N
332         end,
333         FinalNode =
334             case RTSize < config:read(rt_size_use_neighbors) of
335             false -> NodeRT;
336             _ ->
337                 % check neighborhood:
338                 nodelist:largest_smaller_than(Neighbors, Id, NodeRT)
339             end,
340         node:pidX(FinalNode)
341     end.
```

If the (external) routing table contains at least one item, the next hop is retrieved from the gb_tree. It will be the node with the largest id that is smaller than the id we are looking for. If the routing table is empty, the successor is chosen. However, if we haven't found the key in our routing table, the next hop will be our largest finger, i.e. entry.

File rt_chord.erl:

```
83 %% @doc Starts the stabilization routine.
84 -spec init_stabilize(nodelist:neighborhood(), rt()) -> rt().
85 init_stabilize(Neighbors, RT) ->
86     % calculate the longest finger
87     Id = nodelist:nodeid(Neighbors),
88     Key = calculateKey(Id, first_index()),
89     % trigger a lookup for Key
90     api_dht_raw:unreliable_lookup(Key, {send_to_group_member, routing_table,
91                                         {rt_get_node, comm:this(), first_index()}}),
92     RT.
```

The routing table stabilization is triggered for the first index and then runs asynchronously, as we do not want to block the rt_loop to perform other request while recalculating the routing table.

We have to find the node responsible for the calculated finger and therefore perform a lookup for the node with a rt_get_node message, including a reference to ourselves as the reply-to address and the index to be set.

The lookup performs an overlay routing by passing the message until the responsible node is found. There, the message is delivered to the routing_table process. The remote node sends the requested information back directly. It includes a reference to itself in a rt_get_node_response message. Both messages are handled by rt_chord:handle_custom_message/2:

File rt_chord.erl:

```

244 %% @doc Chord reacts on 'rt_get_node_response' messages in response to its
245 %%      'rt_get_node' messages.
246 -spec handle_custom_message(custom_message(), rt_loop:state_active()) ->
247                                     rt_loop:state_active() | unknown_event.
248 handle_custom_message({rt_get_node, Source_PID, Index}, State) ->
249     MyNode = nodelist:node(rt_loop:get_neighb(State)),
250     comm:send(Source_PID, {rt_get_node_response, Index, MyNode}, ?SEND_OPTIONS),
251     State;
252 handle_custom_message({rt_get_node_response, Index, Node}, State) ->
253     OldRT = rt_loop:get_rt(State),
254     Neighbors = rt_loop:get_neighb(State),
255     NewRT = stabilize(Neighbors, OldRT, Index, Node),
256     check(OldRT, NewRT, rt_loop:get_neighb(State), true),
257     rt_loop:set_rt(State, NewRT);
258 handle_custom_message(_Message, _State) ->
259     unknown_event.

```

File rt_chord.erl:

```

167 %% @doc Updates one entry in the routing table and triggers the next update.
168 -spec stabilize(Neighbors::nodelist:neighborhood(), OldRT::rt(),
169               Index::index(), Node::node:node_type()) -> NewRT::rt().
170 stabilize(Neighbors, RT, Index, Node) ->
171     MyId = nodelist:nodeid(Neighbors),
172     Succ = nodelist:succ(Neighbors),
173     case (node:id(Succ) /= node:id(Node)) % reached succ?
174     andalso (not intervals:in(           % there should be nothing shorter
175               node:id(Node),             % than succ
176               nodelist:succ_range(Neighbors))) of
177     true ->
178         NewRT = gb_trees:enter(Index, Node, RT),
179         NextKey = calculateKey(MyId, next_index(Index)),
180         CurrentKey = calculateKey(MyId, Index),
181         case CurrentKey /= NextKey of
182         true ->
183             Msg = {rt_get_node, comm:this(), next_index(Index)},
184             api_dht_raw:unreliable_lookup(
185                 NextKey, {send_to_group_member, routing_table, Msg});
186         _ -> ok
187         end,
188         NewRT;
189     _ -> RT
190     end.

```

stabilize/5 assigns the received routing table entry and triggers the routing table stabilization for the the next shorter entry using the same mechanisms as described above.

If the shortest finger is the successor, then filling the routing table is stopped, as no further new entries would occur. It is not necessary, that Index reaches 1 to make that happen. If less than 2^{128} nodes participate in the system, it may happen earlier.

File rt_chord.erl:

```

194 %% @doc Updates the routing table due to a changed node ID, pred and/or succ.
195 -spec update(OldRT::rt(), OldNeighbors::nodelist:neighborhood(),
196             NewNeighbors::nodelist:neighborhood()) -> {trigger_rebuild, rt()}.
197 update(_OldRT, _OldNeighbors, NewNeighbors) ->
198     % to be on the safe side ...
199     {trigger_rebuild, empty(NewNeighbors)}.

```

Tells the `rt_loop` process to rebuild the routing table starting with an empty (internal) routing table state.

File `rt_chord.erl`:

```
96 %% @doc Removes dead nodes from the routing table.
97 -spec filter_dead_node(rt(), comm:mypid()) -> rt().
98 filter_dead_node(RT, DeadPid) ->
99     DeadIndices = [Index || {Index, Node} <- gb_trees:to_list(RT),
100                          node:same_process(Node, DeadPid)],
101     lists:foldl(fun(Index, Tree) -> gb_trees:delete(Index, Tree) end,
102                RT, DeadIndices).
```

`filter_dead_node` removes dead entries from the `gb_tree`.

File `rt_chord.erl`:

```
345 -spec export_rt_to_dht_node(rt(), Neighbors::nodelist:neighborhood()) -> external_rt().
346 export_rt_to_dht_node(RT, Neighbors) ->
347     Id = nodelist:nodeid(Neighbors),
348     Pred = nodelist:pred(Neighbors),
349     Succ = nodelist:succ(Neighbors),
350     Tree = gb_trees:enter(node:id(Succ), Succ,
351                          gb_trees:enter(node:id(Pred), Pred, gb_trees:empty())),
352     util:gb_trees_foldl(fun (_K, V, Acc) ->
353                          % only store the ring id and the according node structure
354                          case node:id(V) == Id of
355                              true -> Acc;
356                              false -> gb_trees:enter(node:id(V), V, Acc)
357                          end
358                      end, Tree, RT).
```

`export_rt_to_dht_node` converts the internal `gb_tree` structure based on indices into the external representation optimised for look-ups, i.e. a `gb_tree` with node ids and the nodes themselves.

File `rt_chord.hrl`:

```
263 %% @doc Notifies the dht_node and failure detector if the routing table changed.
264 %% Provided for convenience (see check/5).
265 -spec check(OldRT::rt(), NewRT::rt(), Neighbors::nodelist:neighborhood(),
266           ReportToFD::boolean()) -> ok.
267 check(OldRT, NewRT, Neighbors, ReportToFD) ->
268     check(OldRT, NewRT, Neighbors, Neighbors, ReportToFD).
269
270 %% @doc Notifies the dht_node if the (external) routing table changed.
271 %% Also updates the failure detector if ReportToFD is set.
272 %% Note: the external routing table also changes if the Pred or Succ
273 %% change.
274 -spec check(OldRT::rt(), NewRT::rt(), OldNeighbors::nodelist:neighborhood(),
275           NewNeighbors::nodelist:neighborhood(), ReportToFD::boolean()) -> ok.
276 check(OldRT, NewRT, OldNeighbors, NewNeighbors, ReportToFD) ->
277     case OldRT == NewRT andalso
278         nodelist:pred(OldNeighbors) == nodelist:pred(NewNeighbors) andalso
279         nodelist:succ(OldNeighbors) == nodelist:succ(NewNeighbors) of
280     true -> ok;
281     _ ->
282         Pid = pid_groups:get_my(dht_node),
283         RT_ext = export_rt_to_dht_node(NewRT, NewNeighbors),
284         case Pid of
285             failed -> ok;
286             _ -> comm:send_local(Pid, {rt_update, RT_ext})
287         end,
288         % update failure detector:
289         case ReportToFD of
290             true ->
291                 NewPids = to_pid_list(NewRT),
292                 OldPids = to_pid_list(OldRT),
293                 fd:update_subscriptions(OldPids, NewPids);
```

```
294         - -> ok
295     end
296 end.
```

Checks whether the routing table changed and in this case sends the `dht_node` an updated (external) routing table state. Optionally the failure detector is updated. This may not be necessary, e.g. if `check` is called after a crashed node has been reported by the failure detector (the failure detector already unsubscribes the node in this case).

File `rt_chord.erl`:

```
372 %% @doc Wrap lookup messages. This is a noop in Chord.
373 -spec wrap_message(Msg::comm:message(), Hops::non_neg_integer()) -> comm:message().
374 wrap_message(Msg, _Hops) -> Msg.
```

Wraps a message send via `dht_node_lookup:lookup/4` if needed. This routing algorithm does not need callbacks when finishing the lookup, so it does not need to wrap the message.

File `rt_chord.erl`:

```
378 %% @doc Unwrap lookup messages. This is a noop in Chord.
379 -spec unwrap_message(Msg::comm:message(), State::dht_node_state:state()) -> comm:message().
380 unwrap_message(Msg, _State) -> Msg.
```

Unwraps a message previously wrapped with `rt_chord:wrap_message/1`. As that function does not wrap messages, `rt_chord:unwrap_message/2` doesn't have to do anything as well.

9.4. Local Datastore

9.5. Cyclon

9.6. Vivaldi Coordinates

9.7. Estimated Global Information (Gossiping)

9.8. Load Balancing

9.9. Broadcast Trees

10. Transactions in Scalaris

10.1. The Paxos Module

10.2. Transactions using Paxos Commit

10.3. Applying the Tx-Modules to replicated DHTs

Introduces transaction processing on top of a Overlay

11. How a node joins the system

Description is based on SVN revision r1370.

After starting a new Scalaris-System as described in Section 3.2.1 on page 13, ten additional local nodes can be started by typing `api_vm:add_nodes(10)` in the Erlang-Shell that is opened during startup¹.

```
scalaris> ./bin/firstnode.sh
[...]  
(firstnode@csr-pc9)1> api_vm:add_nodes(10)
```

In the following we will trace what this function does in order to add additional nodes to the system. The function `api_vm:add_nodes(pos_integer())` is defined as follows.

File `api_vm.erl`:

```
65 %% @doc Adds Number Scalaris nodes to this VM.  
66 -spec add_nodes(non_neg_integer()) -> {[pid_groups:groupname()], [{error, term()}]}.  
67 add_nodes(Number) when is_integer(Number) andalso Number >= 0 ->  
68     Result = {Ok, _Failed} = admin:add_nodes(Number),  
69     % at least wait for the successful nodes to have joined, i.e. left the join phases  
70     util:wait_for(  
71         fun() ->  
72             DhtModule = config:read(dht_node),  
73             NotReady = [Name || Name <- Ok,  
74                 not DhtModule:is_alive(  
75                     gen_component:get_state(  
76                         pid_groups:pid_of(Name, dht_node)))]],  
77             [] == NotReady  
78         end),  
79     Result.
```

It uses the `admin:add_nodes/1` function to actually add the given number of nodes and then waits for all nodes to successfully complete their join phases.

File `admin.erl`:

```
45 % @doc add new Scalaris nodes on the local node  
46 -spec add_node_at_id(?RT:key()) -> pid_groups:groupname() | {error, term()}.  
47 add_node_at_id(Id) ->  
48     add_node([{{dht_node, id}, Id}, {skip_psv_lb}]).  
49  
50 -spec add_node([tuple()]) -> pid_groups:groupname() | {error, term()}.  
51 add_node(Options) ->  
52     DhtNodeId = randoms:getRandomString(),  
53     Group = pid_groups:new("dht_node_"),  
54     Desc = util:sup_supervisor_desc(  
55         DhtNodeId, config:read(dht_node_sup), start_link,  
56         [{Group,  
57             [{my_sup_dht_node_id, DhtNodeId} | Options]]]),  
58     Sup = erlang:whereis(main_sup),  
59     case sup:start_sup_as_child([" +"], Sup, Desc) of  
60         {ok, _Child, Group} -> Group;  
61         {error, already_present} -> add_node(Options); % try again, different Id
```

¹Increase the log level to info to get more detailed startup logs. See Section 3.1.1 on page 12

When new nodes are started using `admin:add_node/1`, only new `sup_dht_node` supervisors are started.

11.2. Starting the `sup_dht_node` supervisor and general processes of a node

Starting supervisors is a two step process: a call to `supervisor:start_link/2,3`, e.g. from a custom supervisor's own `start_link` method, will start the supervisor process. It will then call `Module:init/1` to find out about the restart strategy, maximum restart frequency and child processes. Note that `supervisor:start_link/2,3` will not return until `Module:init/1` has returned and all child processes have been started.

Let's have a look at `sup_dht_node:init/1`, the 'DHT node supervisor'.

File `sup_dht_node.erl`:

```
42 -spec init([pid_groups:groupname(), [tuple()]])
43       -> {ok, [{one_for_one, MaxRetries::pos_integer(),
44                 PeriodInSeconds::pos_integer()}, []]}.
45 init([DHTNodeGroup, _Options] = X) ->
46     pid_groups:join_as(DHTNodeGroup, ?MODULE),
47     mgmt_server:connect(),
48     supspec(X).
```

The return value of the `init/1` function specifies the child processes of the supervisor and how to start them. Here, we define a list of processes to be observed by a `one_for_one` supervisor. The processes are: `Monitor`, `Delayer`, `Reregister`, `DeadNodeCache`, `RingMaintenance`, `RoutingTable`, `Cyclon`, `Vivaldi`, `DC_Clustering`, `Gossip` and a `SupDHTNodeCore_AND` process in this order.

The term `{one_for_one, 10, 1}` specifies that the supervisor should try 10 times to restart each process before giving up. `one_for_one` supervision means, that if a single process stops, only that process is restarted. The other processes run independently.

When the `sup_dht_node:init/1` is finished the supervisor module starts all the defined processes by calling the functions that were defined in the returned list.

For a join of a new node, we are only interested in the starting of the `SupDHTNodeCore_AND` process here. At that point in time, all other defined processes are already started and running.

11.3. Starting the `sup_dht_node_core` supervisor with a peer and some paxos processes

Like any other supervisor the `sup_dht_node_core` supervisor calls its `sup_dht_node_core:init/1` function:

File `sup_dht_node_core.erl`:

```
41 -spec init([pid_groups:groupname(), Options::[tuple()]]) ->
42       {ok, [{one_for_all, MaxRetries::pos_integer(),
43                 PeriodInSeconds::pos_integer(),
44                 [ProcessDescr::supervisor:child_spec()]}]}.
45 init([DHTNodeGroup, _Options] = X) ->
46     pid_groups:join_as(DHTNodeGroup, ?MODULE),
47     supspec(X).
```

It defines five processes, that have to be observed using a `one_for_all`-supervisor, which means, that if one fails, all have to be restarted. The `dht_node` module implements the main component of a full Scalaris node which glues together all the other processes. Its `dht_node:start_link/2` function will get the following parameters: (a) the processes' group that is used with the `pid_groups` module and (b) a list of options for the `dht_node`. The process group name was calculated a bit earlier in the code. *Exercise: Try to find where.*

File `dht_node.erl`:

```
418 %% @doc spawns a scalaris node, called by the scalaris supervisor process
419 -spec start_link(pid_groups:groupname(), [tuple()]) -> {ok, pid()}.
420 start_link(DHTNodeGroup, Options) ->
421     gen_component:start_link(?MODULE, fun ?MODULE:on/2, Options,
422                               [{pid_groups_join_as, DHTNodeGroup, dht_node}, wait_for_init]).
```

Like many other modules, the `dht_node` module implements the `gen_component` behaviour. This behaviour was developed by us to enable us to write code which is similar in syntax and semantics to the examples in [3]. Similar to the supervisor behaviour, a module implementing this behaviour has to provide an `init/1` function, but here it is used to initialize the state of the component. This function is described in the next section.

Note: `?MODULE` is a predefined Erlang macro, which expands to the module name, the code belongs to (here: `dht_node`).

11.4. Initializing a `dht_node`-process

File `dht_node.erl`:

```
399 %% @doc joins this node in the ring and calls the main loop
400 -spec init(Options::[tuple()])
401     -> dht_node_state:state() |
402     {'$gen_component', [{on_handler, Handler::gen_component:handler()}], State::dht_node_join:
403 init(Options) ->
404     {my_sup_dht_node_id, MySupDhtNode} = lists:keyfind(my_sup_dht_node_id, 1, Options),
405     erlang:put(my_sup_dht_node_id, MySupDhtNode),
406     % get my ID (if set, otherwise chose a random ID):
407     Id = case lists:keyfind({dht_node, id}, 1, Options) of
408         {{dht_node, id}, IdX} -> IdX;
409         _ -> ?RT:get_random_node_id()
410     end,
411     case is_first(Options) of
412         true -> dht_node_join:join_as_first(Id, 0, Options);
413         _ -> dht_node_join:join_as_other(Id, 0, Options)
414     end.
```

The `gen_component` behaviour registers the `dht_node` in the process dictionary. Formerly, the process had to do this itself, but we moved this code into the behaviour. If an ID was given to `dht_node:init/1` function as a `{{dht_node, id}, KEY}` tuple, the given `Id` will be used. Otherwise a random key is generated. Depending on whether the node is the first inside a VM marked as first or not, the according function in `dht_node_join` is called. Also the pid of the node's supervisor is kept for future reference.

11.5. Actually joining the ring

After retrieving its identifier, the node starts the join protocol which processes the appropriate messages calling `dht_node_join:process_join_state(Message, State)`. On the existing node,

join messages will be processed by `dht_node_join:process_join_msg(Message, State)`.

11.5.1. A single node joining an empty ring

File `dht_node_join.erl`:

```
100 -spec join_as_first(Id::?RT:key(), IdVersion::non_neg_integer(), Options::[tuple()])
101     -> dht_node_state:state().
102 join_as_first(Id, IdVersion, _Options) ->
103     comm:init_and_wait_for_valid_pid(),
104     log:log(info, "[ Node ~w ] joining as first: (~.0p, ~.0p)",
105         [self(), Id, IdVersion]),
106     Me = node:new(comm:this(), Id, IdVersion),
107     % join complete, State is the first "State"
108     finish_join(Me, Me, Me, ?DB:new(), msg_queue:new()).
```

If the ring is empty, the joining node will be the only node in the ring and will thus be responsible for the whole key space. It will trigger all known nodes to initialize the comm layer and then finish the join. `dht_node_join:finish_join/5` just creates a new state for a Scalaris node consisting of the given parameters (the node as itself, its predecessor and successor, an empty database and the queued messages that arrived during the join). It then activates all dependent processes and creates a routing table from this information.

The `dht_node_state:state()` type is defined in

File `dht_node_state.erl`:

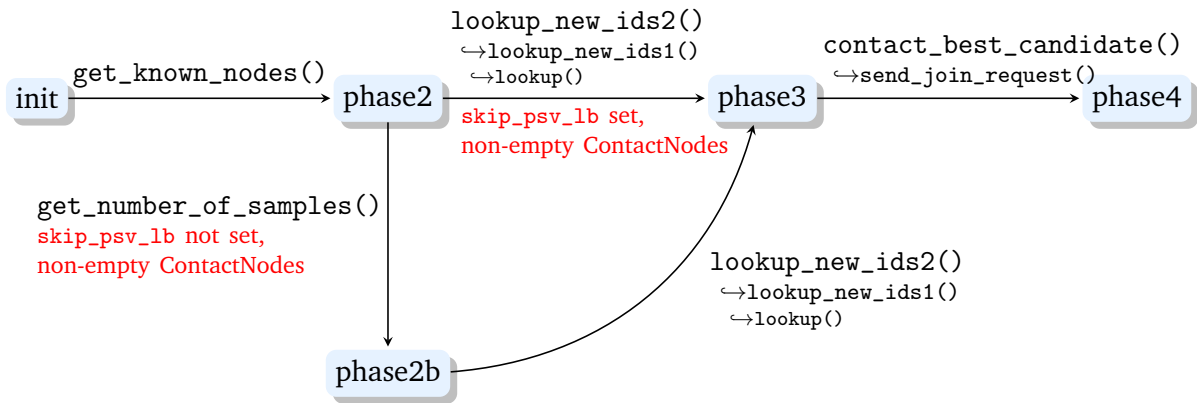
```
59 -record(state, {rt           = ?required(state, rt)           :: ?RT:external_rt(),
60                 rm_state    = ?required(state, rm_state)    :: rm_loop:state(),
61                 join_time   = ?required(state, join_time)   :: util:time(),
62                 db          = ?required(state, db)           :: ?DB:db(),
63                 tx_tp_db    = ?required(state, tx_tp_db)     :: any(),
64                 proposer    = ?required(state, proposer)    :: pid(),
65                 % slide with pred (must not overlap with 'slide with succ'):
66                 slide_pred  = null :: slide_op:slide_op() | null,
67                 % slide with succ (must not overlap with 'slide with pred'):
68                 slide_succ  = null :: slide_op:slide_op() | null,
69                 % additional range to respond to during a move:
70                 db_range    = [] :: [{intervals:interval(), slide_op:id()}],
71                 bulkowner_reply_timer = null :: null | reference(),
72                 bulkowner_reply_ids = [] :: [uid:global_uid()],
73                 monitor_proc = ?required(state, monitor_proc) :: pid(),
74                 prbr_kv_db  = ?required(state, prbr_state) :: prbr:state()
75             }).
76 -opaque state() :: #state{}.
```

11.5.2. A single node joining an existing (non-empty) ring

If a node joins an existing ring, its join protocol will step through the following four phases:

- **phase2** finding nodes to contact with the help of the configured `known_hosts`
- **phase2b** getting the number of Ids to sample (may be skipped)
- **phase3** lookup nodes responsible for all sampled Ids
- **phase4** joining a selected node and setting up item movements

The following figure shows a (non-exhaustive) overview of the transitions between the phases in the normal case. We will go through these step by step and discuss what happens if errors occur.



At first all nodes set in the known_hosts configuration parameter are contacted. Their responses are then handled in phase 2. In order to separate the join state from the ordinary dht_node state, the gen_component is instructed to use the dht_node:on_join/2 message handler which delegates every message to dht_node_join:process_join_state/2.

File dht_node_join.erl:

```

112 -spec join_as_other(Id::?RT:key(), IdVersion::non_neg_integer(), Options::[tuple()])
113       -> {'$gen_component', [{on_handler, Handler::gen_component:handler()}],
114         State::{join, phase2(), msg_queue:msg_queue()}}.
115 join_as_other(Id, IdVersion, Options) ->
116     comm:init_and_wait_for_valid_pid(),
117     log:log(info, "[ Node ~w ] joining, trying ID: (~.0p, ~.0p)",
118       [self(), Id, IdVersion]),
119     JoinUUID = uid:get_pids_uid(),
120     get_known_nodes(JoinUUID),
121     msg_delay:send_local(get_join_timeout() div 1000, self(),
122       {join, timeout, JoinUUID}),
123     gen_component:change_handler(
124       {join, {phase2, JoinUUID, Options, IdVersion, [], [Id], []},
125         msg_queue:new()}),
126     fun dht_node_join:process_join_state/2).

```

Phase 2 and 2b

Phase 2 collects all dht_node processes inside the contacted VMs. It therefore mainly processes get_dht_nodes_response messages and integrates all received nodes into the list of available connections. The next step depends on whether the {skip_psv_lb} option for skipping any passive load balancing algorithm has been given to the dht_node or not. If it is present, the node will only use the ID that has been initially passed to dht_node_join:join_as_other/3, issue a lookup for the responsible node and move to phase 3. Otherwise, the passive load balancing's lb_psv_*:-get_number_of_samples/1 method will be called asking for the number of IDs to sample. Its answer will be processed in phase 2b.

get_dht_nodes_response messages arriving in phase 2b or later will be processed anyway and received dht_node processes will be integrated into the connections. These phases' operations will not be interrupted and nothing else is changed though.

File dht_node_join.erl:

```

154 % in phase 2 add the nodes and do lookups with them / get number of samples
155 process_join_state({get_dht_nodes_response, Nodes} = _Msg,
156   {join, JoinState, QueuedMessages})
157   when element(1, JoinState) == phase2 ->
158     ?TRACE_JOIN1(_Msg, JoinState),
159     Connections = [{null, Node} || Node <- Nodes, Node /= comm:this()],

```

```

160     JoinState1 = add_connections(Connections, JoinState, back),
161     NewJoinState = phase2_next_step(JoinState1, Connections),
162     ?TRACE_JOIN_STATE(NewJoinState),
163     {join, NewJoinState, QueuedMessages};
164
165 % in all other phases, just add the provided nodes:
166 process_join_state({get_dht_nodes_response, Nodes} = _Msg,
167                   {join, JoinState, QueuedMessages})
168   when element(1, JoinState) =:= phase2b orelse
169     element(1, JoinState) =:= phase3 orelse
170     element(1, JoinState) =:= phase4 ->
171     ?TRACE_JOIN1(_Msg, JoinState),
172     Connections = [{null, Node} || Node <- Nodes, Node /= comm:this()],
173     JoinState1 = add_connections(Connections, JoinState, back),
174     ?TRACE_JOIN_STATE(JoinState1),
175     {join, JoinState1, QueuedMessages};

```

Phase 2b will handle `get_number_of_samples` messages from the passive load balance algorithm. Once received, new (unique) IDs will be sampled randomly so that the total number of join candidates (selected IDs together with fully processed candidates from further phases) is at least as high as the given number of samples. Afterwards, lookups will be created for all previous IDs as well as the new ones and the node will move to phase 3.

File `dht_node_join.erl`:

```

201 % note: although this message was send in phase2, also accept message in
202 % phase2, e.g. messages arriving from previous calls
203 process_join_state({join, get_number_of_samples, Samples, Conn} = _Msg,
204                   {join, JoinState, QueuedMessages})
205   when element(1, JoinState) =:= phase2 orelse
206     element(1, JoinState) =:= phase2b ->
207     ?TRACE_JOIN1(_Msg, JoinState),
208     % prefer node that send get_number_of_samples as first contact node
209     JoinState1 = reset_connection(Conn, JoinState),
210     % (re-)issue lookups for all existing IDs and
211     % create additional samples, if required
212     NewJoinState = lookup_new_ids2(Samples, JoinState1),
213     ?TRACE_JOIN_STATE(NewJoinState),
214     {join, NewJoinState, QueuedMessages};
215
216 % ignore message arriving in other phases:
217 process_join_state({join, get_number_of_samples, _Samples, Conn} = _Msg,
218                   {join, JoinState, QueuedMessages}) ->
219     ?TRACE_JOIN1(_Msg, JoinState),
220     NewJoinState = reset_connection(Conn, JoinState),
221     ?TRACE_JOIN_STATE(NewJoinState),
222     {join, NewJoinState, QueuedMessages};

```

Lookups will make `Scalaris` find the node currently responsible for a given ID and send a request to simulate a join to this node, i.e. a `get_candidate` message. Note that during such an operation, the joining node would become the existing node's predecessor. The simulation will be delegated to the passive load balance algorithm the joining node requested, as set by the `join_lb_psv` configuration parameter.

File `dht_node_join.erl`:

```

507 process_join_msg({join, get_candidate, Source_PID, Key, LbPsv, Conn} = _Msg, State) ->
508     ?TRACE1(_Msg, State),
509     LbPsv:create_join(State, Key, Source_PID, Conn);

```

Phase 3

The result of the simulation will be send in a `get_candidate_response` message and will be processed in phase 3 of the joining node. It will be integrated into the list of processed candidates. If there are no more IDs left to process, the best among them will be contacted. Otherwise further `get_candidate_response` messages will be awaited. Such messages will also be processed in the other phases where the candidate will be simply added to the list.

File `dht_node_join.erl`:

```
254 process_join_state({join, get_candidate_response, OrigJoinId, Candidate, Conn} = _Msg,
255                    {join, JoinState, QueuedMessages})
256   when element(1, JoinState) =:= phase3 ->
257     ?TRACE_JOIN1(_Msg, JoinState),
258     JoinState0 = reset_connection(Conn, JoinState),
259     JoinState1 = remove_join_id(OrigJoinId, JoinState0),
260     JoinState2 = integrate_candidate(Candidate, JoinState1, front),
261     NewJoinState =
262       case get_join_ids(JoinState2) of
263         [] -> % no more join ids to look up -> join with the best:
264           contact_best_candidate(JoinState2);
265         [_|_] -> % still some unprocessed join ids -> wait
266           JoinState2
267       end,
268     ?TRACE_JOIN_STATE(NewJoinState),
269     {join, NewJoinState, QueuedMessages};
270
271 % In phase 2 or 2b, also add the candidate but do not continue.
272 % In phase 4, add the candidate to the end of the candidates as they are sorted
273 % and the join with the first has already started (use this candidate as backup
274 % if the join fails). Do not start a new join.
275 process_join_state({join, get_candidate_response, OrigJoinId, Candidate, Conn} = _Msg,
276                    {join, JoinState, QueuedMessages})
277   when element(1, JoinState) =:= phase2 orelse
278     element(1, JoinState) =:= phase2b orelse
279     element(1, JoinState) =:= phase4 ->
280     ?TRACE_JOIN1(_Msg, JoinState),
281     JoinState0 = reset_connection(Conn, JoinState),
282     JoinState1 = remove_join_id(OrigJoinId, JoinState0),
283     JoinState2 = case get_phase(JoinState1) of
284       phase4 -> integrate_candidate(Candidate, JoinState1, back);
285       _ -> integrate_candidate(Candidate, JoinState1, front)
286     end,
287     ?TRACE_JOIN_STATE(JoinState2),
288     {join, JoinState2, QueuedMessages};
```

If `dht_node_join:contact_best_candidate/1` is called and candidates are available (there should be at this stage!), it will sort the candidates by using the passive load balance algorithm, send a `join_request` message and continue with phase 4.

File `dht_node_join.erl`:

```
801 %% @doc Contacts the best candidate among all stored candidates and sends a
802 %%      join_request (Timeouts = 0).
803 -spec contact_best_candidate(JoinState::phase_2_4())
804       -> phase2() | phase2b() | phase4().
805 contact_best_candidate(JoinState) ->
806   contact_best_candidate(JoinState, 0).
807 %% @doc Contacts the best candidate among all stored candidates and sends a
808 %%      join_request. Timeouts is the number of join_request_timeout messages
809 %%      previously received.
810 -spec contact_best_candidate(JoinState::phase_2_4(), Timeouts::non_neg_integer())
811       -> phase2() | phase2b() | phase4().
812 contact_best_candidate(JoinState, Timeouts) ->
813   JoinState1 = sort_candidates(JoinState),
814   send_join_request(JoinState1, Timeouts).
```


File dht_node_join.erl:

```
818 %% @doc Sends a join request to the first candidate. Timeouts is the number of
819 %%      join_request_timeout messages previously received.
820 %%      PreCond: the id has been set to the ID to join at and has been updated
821 %%              in JoinState.
822 -spec send_join_request(JoinState::phase_2_4(), Timeouts::non_neg_integer())
823     -> phase2() | phase2b() | phase4().
824 send_join_request(JoinState, Timeouts) ->
825     case get_candidates(JoinState) of
826     [] -> % no candidates -> start over (should not happen):
827         start_over(JoinState);
828     [BestCand | _] ->
829         Id = node_details:get(lb_op:get(BestCand, n1_new), new_key),
830         IdVersion = get_id_version(JoinState),
831         NewSucc = node_details:get(lb_op:get(BestCand, n1succ_new), node),
832         Me = node:new(comm:this(), Id, IdVersion),
833         CandId = lb_op:get(BestCand, id),
834         ?TRACE_SEND(node:pidX(NewSucc), {join, join_request, Me, CandId}),
835         comm:send(node:pidX(NewSucc), {join, join_request, Me, CandId}),
836         msg_delay:send_local(
837             get_join_request_timeout() div 1000, self(),
838             {join, join_request_timeout, Timeouts, CandId, get_join_uuid(JoinState)}),
839         set_phase(phase4, JoinState)
840     end.
```

The join_request message will be received by the existing node which will set up a slide operation with the new node. If it is not responsible for the key (anymore), it will deny the request and reply with a {join, join_response, not_responsible, Node} message. If it is responsible for the ID and is not participating in a slide with its current predecessor, it will set up a slide with the joining node:

File dht_node_join.erl:

```
513 process_join_msg({join, join_request, NewPred, CandId} = _Msg, State)
514     when (not is_atom(NewPred)) -> % avoid confusion with not_responsible message
515     ?TRACE1(_Msg, State),
516     TargetId = node:id(NewPred),
517     case dht_node_move:can_slide_pred(State, TargetId, {join, 'rcv'}) of
518     true ->
519         try
520             % TODO: implement step-wise join
521             MoveFullId = uid:get_global_uid(),
522             Neighbors = dht_node_state:get(State, neighbors),
523             fd:subscribe([node:pidX(NewPred)], {move, MoveFullId}),
524             SlideOp = slide_op:new_sending_slide_join(
525                 MoveFullId, NewPred, join, Neighbors),
526             SlideOp1 = slide_op:set_phase(SlideOp, wait_for_pred_update_join),
527             RMSubscrTag = {move, slide_op:get_id(SlideOp1)},
528             rm_loop:subscribe(self(), RMSubscrTag,
529                 fun(_OldN, NewN, _IsSlide) ->
530                     NewPred := nodelist:pred(NewN)
531                 end,
532                 fun dht_node_move:rm_notify_new_pred/4, 1),
533             State1 = dht_node_state:add_db_range(
534                 State, slide_op:get_interval(SlideOp1),
535                 slide_op:get_id(SlideOp1)),
536             MoveFullId = slide_op:get_id(SlideOp1),
537             MyOldPred = dht_node_state:get(State1, pred),
538             MyNode = dht_node_state:get(State1, node),
539             % no need to tell the ring maintenance -> the other node will trigger an update
540             % also this is better in case the other node dies during the join
541             %      rm_loop:notify_new_pred(comm:this(), NewPred),
542             Msg = {join, join_response, MyNode, MyOldPred, MoveFullId, CandId},
543             dht_node_move:send2(State1, SlideOp1, Msg)
544         catch throw: not_responsible ->
545             ?TRACE_SEND(node:pidX(NewPred),
546                 {join, join_response, not_responsible, CandId}),
547             comm:send(node:pidX(NewPred),
```



```

548             {join, join_response, not_responsible, CandId}},
549             State
550         end;
551     - ->
552     ?TRACE(" [ ~.Op ]~n ignoring join_request from ~.Op due to a running slide~n",
553           [self(), NewPred]),
554     State
555 end;

```

Phase 4

The joining node will receive the `join_response` message in phase 4 of the join protocol. If everything is ok, it will notify its ring maintenance process that it enters the ring, start all required processes and join the slide operation set up by the existing node in order to receive some of its data.

If the join candidate's node is not responsible for the candidate's ID anymore or the candidate's ID already exists, the next candidate is contacted until no further candidates are available and the join protocol starts over using `dht_node_join:start_over/1`.

Note that the `join_response` message will actually be processed in any phase. Therefore, if messages arrive late, the join can be processed immediately and the rest of the join protocol does not need to be executed again.

File `dht_node_join.erl`:

```

327 process_join_state({join, join_response, not_responsible, CandId} = _Msg,
328                   {join, JoinState, QueuedMessages} = State)
329   when element(1, JoinState) == phase4 ->
330     ?TRACE_JOIN1(_Msg, JoinState),
331     % the node we contacted is not responsible for the selected key anymore
332     % -> try the next candidate, if the message is related to the current candidate
333     case get_candidates(JoinState) of
334       [] -> % no candidates -> should not happen in phase4!
335         log:error(" [ Node ~w ] empty candidate list in join phase 4, "
336                 "starting over", [self()]),
337         NewJoinState = start_over(JoinState),
338         ?TRACE_JOIN_STATE(NewJoinState),
339         {join, NewJoinState, QueuedMessages};
340       [Candidate | _Rest] ->
341         case lb_op:get(Candidate, id) == CandId of
342           false -> State; % unrelated/old message
343           _ ->
344             log:log(info,
345                   "[ Node ~w ] node contacted for join is not responsible "
346                   "for the selected ID (anymore), trying next candidate",
347                   [self()]),
348             NewJoinState = try_next_candidate(JoinState),
349             ?TRACE_JOIN_STATE(NewJoinState),
350             {join, NewJoinState, QueuedMessages}
351         end
352     end;
353
354 % in other phases remove the candidate from the list (if it still exists):
355 process_join_state({join, join_response, not_responsible, CandId} = _Msg,
356                   {join, JoinState, QueuedMessages}) ->
357   ?TRACE_JOIN1(_Msg, JoinState),
358   {join, remove_candidate(CandId, JoinState), QueuedMessages};
359
360 % note: accept (delayed) join_response messages in any phase
361 process_join_state({join, join_response, Succ, Pred, MoveId, CandId} = _Msg,
362                   {join, JoinState, QueuedMessages} = State) ->
363   ?TRACE_JOIN1(_Msg, JoinState),
364   % only act on related messages, i.e. messages from the current candidate
365   Phase = get_phase(JoinState),

```

```

366 State1 = case get_candidates(JoinState) of
367   [] when Phase == phase4 -> % no candidates -> should not happen in phase4!
368     log:log(error, "[ Node ~w ] empty candidate list in join phase 4, "
369       "starting over", [self()]),
370     NewJoinState = start_over(JoinState),
371     ?TRACE_JOIN_STATE(NewJoinState),
372     {join, NewJoinState, QueuedMessages};
373   [] -> State; % in all other phases, ignore the delayed join_response
374     % if no candidates exist
375   [Candidate | _Rest] ->
376     CandidateNode = node_details:get(lb_op:get(Candidate, n1succ_new), node),
377     CandidateNodeSame = node:same_process(CandidateNode, Succ),
378     case lb_op:get(Candidate, id) == CandId of
379       false ->
380         log:log(warn, "[ Node ~w ] ignoring old or unrelated "
381           "join_response message", [self()]),
382         State; % ignore old/unrelated message
383       _ when not CandidateNodeSame ->
384         % id is correct but the node is not (should never happen!)
385         log:log(error, "[ Node ~w ] got join_response but the node "
386           "changed, trying next candidate", [self()]),
387         NewJoinState = try_next_candidate(JoinState),
388         ?TRACE_JOIN_STATE(NewJoinState),
389         {join, NewJoinState, QueuedMessages};
390       _ ->
391         MyId = node_details:get(lb_op:get(Candidate, n1_new), new_key),
392         MyIdVersion = get_id_version(JoinState),
393         case MyId == node:id(Succ) orelse MyId == node:id(Pred) of
394           true ->
395             log:log(warn, "[ Node ~w ] chosen ID already exists, "
396               "trying next candidate", [self()]),
397             % note: can not keep Id, even if skip_psv_lb is set
398             JoinState1 = remove_candidate_front(JoinState),
399             NewJoinState = contact_best_candidate(JoinState1),
400             ?TRACE_JOIN_STATE(NewJoinState),
401             {join, NewJoinState, QueuedMessages};
402           _ ->
403             ?TRACE("[ ~.0p ]~n joined MyId:~.0p, MyIdVersion:~.0p~n "
404               "Succ: ~.0p~n Pred: ~.0p~n",
405               [self(), MyId, MyIdVersion, Succ, Pred]),
406             Me = node:new(comm:this(), MyId, MyIdVersion),
407             log:log(info, "[ Node ~w ] joined between ~w and ~w",
408               [self(), Pred, Succ]),
409             rm_loop:notify_new_succ(node:pidX(Pred), Me),
410             rm_loop:notify_new_pred(node:pidX(Succ), Me),
411
412             finish_join_and_slide(Me, Pred, Succ, ?DB:new(),
413               QueuedMessages, MoveId)
414           end
415         end
416     end,
417     State1;

```

File dht_node_join.erl:

```

875 %% @doc Finishes the join and sends all queued messages.
876 -spec finish_join(Me::node:node_type(), Pred::node:node_type(),
877   Succ::node:node_type(), DB::?DB:db(),
878   QueuedMessages::msg_queue:msg_queue())
879   -> dht_node_state:state().
880 finish_join(Me, Pred, Succ, DB, QueuedMessages) ->
881   RMState = rm_loop:init(Me, Pred, Succ),
882   Neighbors = rm_loop:get_neighbors(RMState),
883   % wait for the ring maintenance to initialize and tell us its table ID
884   rt_loop:activate(Neighbors),
885   cyclon:activate(),
886   vivaldi:activate(),
887   dc_clustering:activate(),
888   gossip:activate(nodelist:node_range(Neighbors)),
889   dht_node_reregister:activate(),

```

```

890     msg_queue:send(QueuedMessages),
891     NewRT_ext = ?RT:empty_ext(Neighbors),
892     dht_node_state:new(NewRT_ext, RMState, DB).
893
894     %% @doc Finishes the join by setting up a slide operation to get the data from
895     %% the other node and sends all queued messages.
896     -spec finish_join_and_slide(Me::node:node_type(), Pred::node:node_type(),
897                               Succ::node:node_type(), DB::?DB:db(),
898                               QueuedMessages::msg_queue:msg_queue(), MoveId::slide_op:id())
899     -> {'$gen_component', [{on_handler, Handler::gen_component:handler()}],
900         State::dht_node_state:state()}.
901     finish_join_and_slide(Me, Pred, Succ, DB, QueuedMessages, MoveId) ->
902     State = finish_join(Me, Pred, Succ, DB, QueuedMessages),
903     fd:subscribe([node:pidX(Succ)], {move, MoveId}),
904     SlideOp = slide_op:new_receiving_slide_join(MoveId, Pred, Succ, node:id(Me), join),
905     SlideOp1 = slide_op:set_phase(SlideOp, wait_for_node_update),
906     SlideOp2 = slide_op:set_msg_fwd(SlideOp1, slide_op:get_interval(SlideOp1)),
907     State1 = dht_node_state:set_slide(State, succ, SlideOp2),
908     RMSubscrTag = {move, slide_op:get_id(SlideOp2)},
909     comm:send_local(self(), {move, node_update, RMSubscrTag}),
910     gen_component:change_handler(State1, fun dht_node:on/2).

```

The macro `?RT` maps to the configured routing algorithm. It is defined in `include/scalaris.hrl`. For further details on the routing see Chapter 9.3 on page 49.

Timeouts and other errors

The following table summarizes the timeout messages send during the join protocol on the joining node. It shows in which of the phases each of the messages is processed and describes (in short) what actions are taken. All of these messages are influenced by their respective config parameters, e.g. `join_timeout` parameter in the config files defines an overall timeout for the whole join operation. If it takes longer than `join_timeout` ms, a `{join, timeout}` will be send and processed as given in this table.

	known_hosts_ _timeout	get_number_of_ _samples_ _timeout	lookup_ _timeout	join_request_ _timeout	timeout
phase2	get known nodes from configured VMs	ignore	ignore	ignore	
phase2b	ignore	remove contact node, re-start join → phase 2 or 2b	ignore	ignore	
phase3	ignore	ignore	remove contact node, lookup remaining IDs → phase 2 or 3	ignore	
phase3b	ignore	ignore	ignore	ignore	re-start join → phase 2 or 2b
phase4	ignore	ignore	ignore	timeouts < 3? ² → contact candidate otherwise: remove candidate no candidates left? → phase 2 or 2b otherwise: → contact next one → phase 3b or 4	

On the existing node, there is only one timeout message which is part of the join protocol: the `join_response_timeout`. It will be send when a slide operation is set up and if the timeout hits before the next message exchange, it will increase the slide operation's number of timeouts. The slide will be aborted if at least `join_response_timeouts` timeouts have been received. This parameter is set in the config file.

Misc. (all phases)

Note that join-related messages arriving in other phases than those handling them will be ignored. Any other messages during a `dht_node`'s join will be queued and re-send when the join is complete.

²set by the `join_request_timeouts` config parameter

12. Directory Structure of the Source Code

The directory tree of Scalaris is structured as follows:

<code>bin</code>	contains shell scripts needed to work with Scalaris (e.g. start the management server, start a node, ...)
<code>contrib</code>	necessary third party packages (yaws and log4erl)
<code>doc</code>	generated Erlang documentation
<code>docroot</code>	root directory of the node's webserver
<code>ebin</code>	the compiled Erlang code (beam files)
<code>java-api</code>	a Java API to Scalaris
<code>log</code>	log files
<code>src</code>	contains the Scalaris source code
<code>test</code>	unit tests for Scalaris
<code>user-dev-guide</code>	contains the sources for this document

13. Java API

For the Java API documentation, we refer the reader to the documentation generated by javadoc or doxygen. The following commands create the documentation:

```
%> cd java-api  
%> ant doc  
%> doxygen
```

The documentation can then be found in `java-api/doc/index.html` (javadoc) and `java-api/doc-doxygen/html/index.html` (doxygen).

The API is divided into four classes:

- `de.zib.scalariz.Transaction` for (multiple) operations inside a transaction
- `de.zib.scalariz.TransactionSingleOp` for single transactional operations
- `de.zib.scalariz.ReplicatedDHT` for non-transactional (inconsistent) access to the replicated DHT items, e.g. deleting items
- `de.zib.scalariz.PubSub` for topic-based publish/subscribe operations

Bibliography

- [1] Joe Armstrong. *Programming Erlang: Software for a Concurrent World*. Pragmatic Programmers, ISBN: 978-1-9343560-0-5, July 2007
- [2] Frank Dabek, Russ Cox, Frans Kaashoek, Robert Morris. *Vivaldi: A Decentralized Network Coordinate System*. ACM SIGCOMM 2004.
- [3] Rachid Guerraoui and Luis Rodrigues. *Introduction to Reliable Distributed Programming*. Springer-Verlag, 2006.
- [4] Ion Stoica, Robert Morris, David Karger, M. Frans Kaashoek and Hari Balakrishnan. *Chord: A Scalable Peer-to-peer Lookup Service for Internet Applications*. ACM SIGCOMM 2001, San Deigo, CA, August 2001, pp. 149-160. http://pdos.csail.mit.edu/papers/chord:sigcomm01/chord_sigcomm.pdf
- [5] Márk Jelasity, Alberto Montresor, Ozalp Babaoglu. *T-Man: Gossip-based fast overlay topology construction*. Computer Networks (CN) 53(13):2321-2339, 2009.
- [6] F. Schintke, A. Reinefeld, S. Haridi, T. Schütt. *Enhanced Paxos Commit for Transactions on DHTs*. 10th IEEE/ACM Int. Conf. on Cluster, Cloud and Grid Computing, pp. 448-454, May 2010.
- [7] Spyros Voulgaris, Daniela Gavidia, Maarten van Steen. *CYCLON: Inexpensive Membership Management for Unstructured P2P Overlays*. J. Network Syst. Manage. 13(2): 2005.
- [8] Márk Jelasity, Alberto Montresor, Ozalp Babaoglu. *Gossip-based aggregation in large dynamic networks*. ACM Trans. Comput. Syst. 23(3), 219-252 (2005).

Index

?RT
 next_hop, 50
 update, 54

admin
 add_node, 65, 66
 add_nodes, 64, 65

api_tx, 47

api_vm
 add_nodes, 64

comm, 3, 38, 38
 get_msg_tag, 43
 send_to_group_member, 43

cs_api, 39

cyclon, 21, 47

dht_node, 52–54, 57, 62, 67, 69
 init, 67
 on_join, 69

dht_node_join, 67
 contact_best_candidate, 71, 71
 finish_join, 68, 74
 finish_join_and_slide, 74
 join_as_other, 69
 process_join_msg, 68
 process_join_state, 67, 69
 send_join_request, 72
 start_over, 73

dht_node_state
 state, 68

erlang
 exit, 40, 41
 now, 37
 send_after, 37

ets
 i, 37

fd, 46

gen_component, 3, 37, 38, 38–46
 bp_barrier, 44, 45
 bp_cont, 44, 45
 bp_del, 44
 bp_set, 43, 44
 bp_set_cond, 44
 bp_step, 44–46
 change_handler, 40, 42, 42
 get_state, 40
 is_gen_component, 41
 kill, 41, 43
 post_op, 42
 runnable, 45
 sleep, 43
 start, 40, 41
 start_link, 40, 41

intervals
 in, 50

lb_psv_*
 get_number_of_samples, 69

monitor, 46, 46, 47
 check_report, 47
 client_monitor_set_value, 48
 monitor_set_value, 48
 proc_check_timeslot, 47
 proc_set_value, 47

msg_delay, 37

paxos_SUITE, 43
 step_until_decide, 45

pdb, 46

pid_groups, 3, 38, 38, 40, 41, 43, 67

randoms, 55

rm_beh, 54, 58

routing_table, 60

rrd, 46, 46, 47
 add, 47
 add_now, 47
 create, 47

rt_beh, 49
 check, 53
 check_config, 53
 dump, 53

- empty, 52
- empty_ext, 52
- export_rt_to_dht_node, 53
- filter_dead_node, 52
- get_random_node_id, 52
- get_replica_keys, 53
- get_size, 53
- handle_custom_message, 53
- hash_key, 52
- init_stabilize, 52
- n, 53
- next_hop, 52
- to_list, 53
- to_pid_list, 52
- unwrap_message, 53
- update, 52
- wrap_message, 53
- rt_chord, 58
 - empty, 58
 - empty_ext, 58
 - export_rt_to_dht_node, 61
 - filter_dead_node, 61
 - get_random_node_id, 59
 - get_replica_keys, 59
 - handle_custom_message, 60, 60
 - hash_key, 59
 - init_stabilize, 59
 - n, 59
 - next_hop, 59
 - stabilize, 60
 - unwrap_message, 62
 - update, 60
 - wrap_message, 62
- rt_loop, 53, 53, 61
- rt_simple, 54
 - dump, 56
 - empty, 54
 - empty_ext, 54
 - export_rt_to_dht_node, 56
 - filter_dead_node, 55
 - get_random_node_id, 55
 - get_replica_keys, 56
 - get_size, 55
 - handle_custom_message, 56
 - hash_key, 54
 - init_stabilize, 55
 - n, 56
 - next_hop, 55
 - to_list, 56
 - to_pid_list, 55
 - unwrap_message, 58
 - update, 55
 - wrap_message, 58
- sup_dht_node
 - init, 66
 - start_link, 65
- sup_dht_node_core, 66
- sup_scalaris, 65
- supervisor
 - start_link, 66
- timer
 - sleep, 40
 - tc, 37
- util
 - tc, 37
- vivaldi, 43
- vivaldi_latency, 43
- your_gen_component
 - init, 40, 42
 - on, 41, 42