TRANSACTIONS

Scalaris:

Users and Developers Guide

Version 0.3.0 draft July 8, 2011

Contents

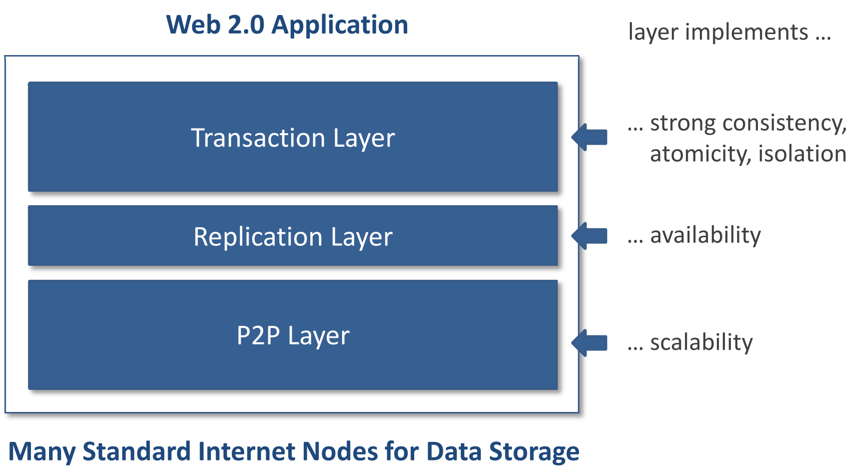
Part I.

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 XtreemOS. 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 51). Our implementation of the routing algorithms is described in more detail in Sect. 9.3 on page 39 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 50).

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`.

Gossipping. For some algorithms, we use estimates of global information. These estimates are aggregated with the help of gossipping 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 >= 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.

```
svn checkout http://scalaris.googlecode.com/svn/trunk/ scalaris-0.0.1
tar -cvjf scalaris-0.0.1.tar.bz2 scalaris-0.0.1 --exclude-vcs
cp scalaris-0.0.1.tar.bz2 /usr/src/packages/SOURCES/
rpmbuild -ba scalaris-0.0.1/contrib/scalaris.spec
```

Your source and binary RPMs will be generated in `/usr/src/packages/SRPMS` and `RPMS`. We build RPM and DEB packages using checkouts from svn and provide them using the openSUSE BuildService at http://download.opensuse.org/repositories/home:/scalaris/. Packages are available for

- Fedora 12, 13, 14,
- Mandriva 2009.1, 2010, 2010.1,
- openSUSE 11.2, 11.3, 11.4, Factory, Tumbleweed
- SLE 10, 11, 11SP1,
- CentOS 5.5,
- RHEL 5.5, 6,
- Debian 5.0, 6.0 and

- Ubuntu 9.04, 9.10, 10.04, 10.10.

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

Inside those repositories you will also find an Erlang package - you don't need this if you already have a recent enough Erlang version (ref. Section 2.1 on page 8)!

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`:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Settings for distributed Erlang
% (see scalaris.hrl to switch)

% {mgmt_server, {mgmt_server,'mgmt_server@foo.bar.com'}}.
% {known_hosts, [{service_per_vm, 'firstnode@foo.bar.com'}]}.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Settings for TCP mode.
% (see scalaris.hrl to switch)

%% 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 51, 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:

```
% 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}]}.
```

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/scalarisctl -h
```

```
usage: scalarisctl [options] [services] <cmd>
 options:
    -h         - print this help message
    -d         - daemonize
    -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')
    -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
 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. The appropriate JSON calls are shown in Section 4.1.2 on page 17.

Special care needs to be taken when trying to delete keys (no matter which API is used). 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 module	Java class in `de.zib.scalaris`	Python / Ruby class in module `scalaris`
Transaction Layer	`api_tx`	`Transaction`, `TransactionSingleOp`	`Transaction`, `TransactionSingleOp`
	`api_pubsub`	`PubSub`	`PubSub`
Replication Layer	`api_rdht`	`ReplicatedDHT`	`ReplicatedDHT`
P2P Layer	`api_dht` `api_dht_raw`		

Table 4.1.: Layered API structure

	Erlang	Java	JSON	Python	Ruby
boolean	`boolean()`	`bool`, `Boolean`	`true`, `false`	`True`, `False`	`true`, `false`

integer	`integer()`	`int`, `Integer`
		`long`, `Long`
		`BigInteger`
			`int`	`int`	`Fixnum`,
					`Bignum`

float	`float()`	`double`, `Double`	`int frac`
			`int exp`
			`int frac exp`
				`float`	`Float`

string	`string()`	`String`	`string`	`str`	`String`
binary	`binary()`	`byte[]`	`string` (base64-encoded)	`bytearray`	`String`
list(type)	`[type()]`	`List<Object>`	`array`	`list`	`Array`
JSON	`json_obj()`*	`Map<String, Object>`	`object`	`dict`	`Hash`
custom	`any()`	`OtpErlangObject`	/	/	/

*
```
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 Scalaris 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.

[1] see `http://json.org/`

4.1.2. 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 the page `jsonrpc.yaws` (For example at: `http://localhost:8000/jsonrpc.yaws`). 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):

- `nop(Value)` - no operation, result:

```
"ok"
```

single read/write:

- `req_list_commit_each(<req_list_rw>)` - 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"}]}
```

- `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"}
```

- `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:

- `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"}]}
```

- `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"}]}
```

replication layer functions:

- `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:

- `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:

- `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>]
```

Note:

```
<json_value> = {"type": "as_is" or "as_bin", "value": <value>}
<req_list_rw> = [{"read", <key>} | {"write", {<key>: <json_value>}}]
<req_list> = [{"read", <key>} | {"write", {<key>: <json_value>}} | {"commit", _}]
```

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 **Scalaris node**

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 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.

4.1.3. 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 --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]
 -b,--minibench <runs> <benchmarks>   run selected mini benchmark(s)
                                      [1|...|9|all] (default: all
                                      benchmarks, 100 test runs)
 -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.
 -g,--getsubscribers <topic>          get subscribers of a topic
 -h,--help                            print this message
 -lh,--localhost                      gets the local host's name as known
                                      to Java (for debugging purposes)
 -p,--publish <topic> <message>       publish a new message for the given
                                      topic
 -r,--read <key>                      read an item
 -s,--subscribe <topic> <url>         subscribe to a topic
 -u,--unsubscribe <topic> <url>       unsubscribe from a topic
 -v,--verbose                         print verbose information, e.g. the
                                      properties read
 -w,--write <key> <value>             write an item
```

`read`, `write` and `delete` 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
 -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
 -g,--getsubscribers <topic>          get subscribers of a topic
 -u,--unsubscribe <topic> <url>       unsubscribe from a topic
 -h,--help                            print this message
 -b,--minibench <runs> <benchmarks>   run selected mini benchmark(s)
```

```
                                          [1|...|9|all] (default: all
                                          benchmarks, 100 test runs)
```

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
    -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.scalaris.PeerNodeTest
    [junit] Testsuite: de.zib.scalaris.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.scalaris.PubSubTest
    [junit] Testsuite: de.zib.scalaris.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.scalaris.ReplicatedDHTTest
    [junit] Testsuite: de.zib.scalaris.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.scalaris.TransactionSingleOpTest
    [junit] Testsuite: de.zib.scalaris.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.scalaris.TransactionTest
    [junit] Testsuite: de.zib.scalaris.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 r1620.

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 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`:

```
-spec behaviour_info(atom()) -> [{atom(), arity()}] | undefined.
behaviour_info(callbacks) ->
    [
     {init, 1}     % initialize component
     % note: can use arbitrary on-handler, but by default on/2 is used:
%%      {on, 2}        % handle a single message
%%                     % on(Msg, State) -> NewState | unknown_event | kill
    ];
```

This is illustrated by the following example:

File `msg_delay.erl`:

```
%% initialize: return initial state.
-spec init([]) -> state().
init([]) ->
    MyGroup = pid_groups:my_groupname(),
    ?TRACE("msg_delay:init for pid group ~p~n", [MyGroup]),
    TimeTableName = list_to_atom(MyGroup ++ "_msg_delay"),
    %% use random table name provided by ets to *not* generate an atom
    %% TableName = pdb:new(?MODULE, [set, private]),
    TimeTable = pdb:new(TimeTableName, [set, protected, named_table]),
    comm:send_local(self(), {msg_delay_periodic}),
    _State = {TimeTable, _Round = 0}.

-spec on(message(), state()) -> state().
on({msg_delay_req, Seconds, Dest, Msg} = _FullMsg,
   {TimeTable, Counter} = State) ->
    ?TRACE("msg_delay:on(~.0p, ~.0p)~n", [_FullMsg, State]),
    Future = trunc(Counter + Seconds),
    case pdb:get(Future, TimeTable) of
        undefined ->
            pdb:set({Future, [{Dest, Msg}]}, TimeTable);
        {_, MsgQueue} ->
            pdb:set({Future, [{Dest, Msg} | MsgQueue]}, TimeTable)
    end,
    State;

%% periodic trigger
on({msg_delay_periodic} = Trigger, {TimeTable, Counter} = _State) ->
    ?TRACE("msg_delay:on(~.0p, ~.0p)~n", [Trigger, State]),
    case pdb:get(Counter, TimeTable) of
        undefined -> ok;
        {_, MsgQueue} ->
            _ = [ comm:send_local(Dest, Msg) || {Dest, Msg} <- MsgQueue ],
            pdb:delete(Counter, TimeTable)
    end,
    comm:send_local_after(1000, self(), Trigger),
    {TimeTable, Counter + 1};

on({web_debug_info, Requestor}, {TimeTable, Counter} = State) ->
    KeyValueList =
        [{"queued messages (in 0-10s, messages):", ""} |
         [begin
              Future = trunc(Counter + Seconds),
```

```
            Queue = case pdb:get(Future, TimeTable) of
                        undefined -> none;
                        {_, Q}    -> Q
                    end,
            {lists:flatten(io_lib:format("~p", [Seconds])),
             lists:flatten(io_lib:format("~p", [Queue]))}
        end || Seconds <- lists:seq(0, 10)]],
    comm:send_local(Requestor, {web_debug_info_reply, KeyValueList}),
    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 called `your_gen_component:on/2`. This can be changed by calling `gen_component:change_handler/2` (see Section 8.3.6). 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. 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.

8.3.5. 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.

8.3.6. 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.

8.3.7. 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.

8.3.8. Halting and pausing a gen_component

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

8.3.9. 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.

8.3.10. 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.

8.3.11. 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:

```
-spec prop_rnd_interleave(1..4, 4..16, {pos_integer(), pos_integer(), pos_integer()})
        -> true.
prop_rnd_interleave(NumProposers, NumAcceptors, Seed) ->
    ct:pal("Called with: paxos_SUITE:prop_rnd_interleave(~p, ~p, ~p).~n",
           [NumProposers, NumAcceptors, Seed]),
    Majority = NumAcceptors div 2 + 1,
    {Proposers, Acceptors, Learners} =
        make(NumProposers, NumAcceptors, 1, "rnd_interleave"),
    %% set bp on all processes
    _ = [ gen_component:bp_set(comm:make_local(X), proposer_initialize, bp)
            ||  X <- Proposers],
    _ = [ gen_component:bp_set(comm:make_local(X), acceptor_initialize, bp)
            ||  X <- Acceptors ],
    _ = [ gen_component:bp_set(comm:make_local(X), learner_initialize, bp)
            || X <- Learners],
    %% start paxos instances
    _ = [ proposer:start_paxosid(X, paxidrndinterl, Acceptors,
                                 proposal, Majority, NumProposers, Y)
            || {X,Y} <- lists:zip(Proposers, lists:seq(1, NumProposers)) ],
    _ = [ acceptor:start_paxosid(X, paxidrndinterl, Learners)
            || X <- Acceptors ],
    _ = [ learner:start_paxosid(X, paxidrndinterl, Majority,
                                comm:this(), cpaxidrndinterl)
            || X <- Learners],
    %% randomly step through protocol
    OldSeed = random:seed(Seed),
    Steps = step_until_decide(Proposers ++ Acceptors ++ Learners, cpaxidrndinterl, 0),
    ct:pal("Needed ~p steps~n", [Steps]),
    _ = case OldSeed of
            undefined -> ok;
            _ -> random:seed(OldSeed)
        end,
    _ = [ gen_component:kill(comm:make_local(X))
          || X <- lists:flatten([Proposers, Acceptors, Learners])],
    true.

step_until_decide(Processes, PaxId, SumSteps) ->
    %% io:format("Step ~p~n", [SumSteps]),
    Runnable = [ X || X <- Processes, gen_component:runnable(comm:make_local(X)) ],
    case Runnable of
        [] ->
            ct:pal("No runnable processes of ~p~n", [length(Processes)]),
            timer:sleep(5), step_until_decide(Processes, PaxId, SumSteps);
        _ -> ok
    end,
    Num = random:uniform(length(Runnable)),
    _ = gen_component:bp_step(comm:make_local(lists:nth(Num, Runnable))),
    receive
        {learner_decide, cpaxidrndinterl, _, _Res} = _Any ->
            %% io:format("Received ~p~n", [_Any]),
            SumSteps
    after 0 -> step_until_decide(Processes, PaxId, SumSteps + 1)
    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:

```
%-define(TRACE_BP_STEPS(X,Y), io:format(X,Y)). %% output on console
%-define(TRACE_BP_STEPS(X,Y), ct:pal(X,Y)).    %% output even if called by unittest
-define(TRACE_BP_STEPS(X,Y), ok).
```

8.3.12. 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. Writing Unittests

8.6.1. Plain unittests

8.6.2. 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 r1453.

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`:

```
-spec unreliable_lookup(Key::?RT:key(), Msg::comm:message()) -> ok.
unreliable_lookup(Key, Msg) ->
    comm:send_local(pid_groups:find_a(dht_node),
                    {lookup_aux, Key, 0, Msg}).

-spec unreliable_get_key(Key::?RT:key()) -> ok.
unreliable_get_key(Key) ->
    unreliable_lookup(Key, {get_key, comm:this(), Key}).

-spec unreliable_get_key(CollectorPid::comm:mypid(),
                         ReqId::{rdht_req_id, pos_integer()},
                         Key::?RT:key()) -> ok.
unreliable_get_key(CollectorPid, ReqId, Key) ->
    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`:

```
%% @doc Find the node responsible for Key and send him the message Msg.
-spec lookup_aux(State::dht_node_state:state(), Key::intervals:key(),
                 Hops::non_neg_integer(), Msg::comm:message()) -> ok.
lookup_aux(State, Key, Hops, Msg) ->
    Neighbors = dht_node_state:get(State, neighbors),
    case intervals:in(Key, nodelist:succ_range(Neighbors)) of
        true -> % found node -> terminate
            P = node:pidX(nodelist:succ(Neighbors)),
            comm:send(P, {lookup_fin, Key, Hops + 1, Msg});
        _ ->
            P = ?RT:next_hop(State, Key),
            comm:send(P, {lookup_aux, Key, Hops + 1, Msg})
```

```
    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`:

```
%%The RT macro determines which kind of routingtable is used. Uncomment the
%%one that is desired.

%%Standard Chord routingtable
-define(RT, rt_chord).
% first valid key:
-define(MINUS_INFINITY, 0).
% first invalid key:
-define(PLUS_INFINITY, 16#100000000000000000000000000000000).

%%Simple routingtable
%-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`:

```
-spec behaviour_info(atom()) -> [{atom(), arity()}] | undefined.
behaviour_info(callbacks) ->
    [
     % create a default routing table
     {empty, 1}, {empty_ext, 1},
     % mapping: key space -> identifier space
     {hash_key, 1}, {get_random_node_id, 0},
     % routing
     {next_hop, 2},
     % trigger for new stabilization round
     {init_stabilize, 2},
     % adapt RT to changed neighborhood
     {update, 3},
     % dead nodes filtering
     {filter_dead_node, 2},
     % statistics
     {to_pid_list, 1}, {get_size, 1},
     % gets all (replicated) keys for a given (hashed) key
     % (for symmetric replication)
     {get_replica_keys, 1},
     % address space size, range and split key
     % (may all throw 'throw:not_supported' if unsupported by the RT)
     {n, 0}, {get_range, 2}, {get_split_key, 3},
     % for debugging and web interface
     {dump, 1},
     % for bulkowner
     {to_list, 1},
     % convert from internal representation to version for dht_node
     {export_rt_to_dht_node, 2},
     % handle messages specific to a certain routing-table implementation
     {handle_custom_message, 2},
     % common methods
```

```
    {check, 4}, {check, 5},
    {check_config, 0}
   ];
```

`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.

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`:

```
-opaque(state_active() :: {Neighbors    :: nodelist:neighborhood(),
                           RTState      :: ?RT:rt(),
                           TriggerState :: trigger:state()}).
-type(state_inactive() :: {inactive,
                           MessageQueue::msg_queue:msg_queue(),
                           TriggerState::trigger:state()}).
%% -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`:

```
on_active({trigger_rt}, {Neighbors, OldRT, TriggerState}) ->
    % start periodic stabilization
    % log:log(debug, "[ RT ] stabilize"),
    NewRT = ?RT:init_stabilize(Neighbors, OldRT),
    ?RT:check(OldRT, NewRT, Neighbors, true),
    % trigger next stabilization
    NewTriggerState = trigger:next(TriggerState),
    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`:

```
% update routing table with changed ID, pred and/or succ
on_active({update_rt, OldNeighbors, NewNeighbors}, {_Neighbors, OldRT, TriggerState}) ->
    case ?RT:update(OldRT, OldNeighbors, NewNeighbors) of
        {trigger_rebuild, NewRT} ->
            % trigger immediate rebuild
            NewTriggerState = trigger:now(TriggerState),
            ?RT:check(OldRT, NewRT, OldNeighbors, NewNeighbors, true),
            new_state(NewNeighbors, NewRT, NewTriggerState);
        {ok, NewRT} ->
            ?RT:check(OldRT, NewRT, OldNeighbors, NewNeighbors, true),
            new_state(NewNeighbors, NewRT, TriggerState)
    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 rebuild. If so, it will stop any waiting trigger and schedule an immideate (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:

```
-type key_t() :: 0..16#FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF. % 128 bit numbers
-type rt_t() :: Succ::node:node_type().
-type external_rt_t() :: Succ::node:node_type().
-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:

```
%% @doc Creates an "empty" routing table containing the successor.
empty(Neighbors) -> nodelist:succ(Neighbors).
```

File rt_simple.erl:

```
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:

```
%% @doc Generates a random node id, i.e. a random 128-bit number.
get_random_node_id() ->
    case config:read(key_creator) of
        random -> hash_key_(randoms:getRandomId());
        random_with_bit_mask ->
            {Mask1, Mask2} = config:read(key_creator_bitmask),
            (hash_key_(randoms:getRandomId()) band Mask2) bor Mask1
    end.
```

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

File rt_simple.erl:

```
%% @doc Returns the next hop to contact for a lookup.
next_hop(State, _Key) -> node:pidX(dht_node_state:get(State, rt)).
```

Next hop is always the successor.

File rt_simple.erl:

```
%% @doc Triggered by a new stabilization round, renews the routing table.
init_stabilize(Neighbors, _RT) -> empty(Neighbors).
```

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

File rt_simple.erl:

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

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

File `rt_simple.erl`:

```
%% @doc Removes dead nodes from the routing table (rely on periodic
%%      stabilization here).
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`:

```
%% @doc Returns the pids of the routing table entries.
to_pid_list(Succ) -> [node:pidX(Succ)].
```

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

File `rt_simple.erl`:

```
%% @doc Returns the size of the routing table.
get_size(_RT) -> 1.
```

The size of the routing table is always `1`.

File `rt_simple.erl`:

```
%% @doc Returns the replicas of the given key.
get_replica_keys(Key) ->
    [Key,
     Key bxor 16#40000000000000000000000000000000,
     Key bxor 16#80000000000000000000000000000000,
     Key bxor 16#C0000000000000000000000000000000
    ].
```

This `get_replica_keys/1` implements symmetric replication.

File `rt_simple.erl`:

```
%% @doc Returns the size of the address space.
n() -> n_().
%% @doc Helper for n/0 to make dialyzer happy with internal use of n/0.
-spec n_() -> 16#100000000000000000000000000000000.
n_() -> 16#FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF + 1.
```

There are 2^{128} available keys.

File `rt_simple.erl`:

```
%% @doc Dumps the RT state for output in the web interface.
dump(Succ) -> [{"0", lists:flatten(io_lib:format("~p", [Succ]))}].
```

`dump/1` lists the successor.

File `rt_simple.erl`:

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

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

File rt_simple.erl:

```
%% @doc Converts the internal RT to the external RT used by the dht_node. Both
%%      are the same here.
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:

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

```
%% @doc Notifies the dht_node and failure detector if the routing table changed.
%%      Provided for convenience (see check/5).
check(OldRT, NewRT, Neighbors, ReportToFD) ->
    check(OldRT, NewRT, Neighbors, Neighbors, ReportToFD).

%% @doc Notifies the dht_node if the (external) routing table changed.
%%      Also updates the failure detector if ReportToFD is set.
%%      Note: the external routing table only changes the internal RT has
%%      changed.
check(OldRT, NewRT, _OldNeighbors, NewNeighbors, ReportToFD) ->
    case OldRT =:= NewRT of
        true -> ok;
        _ ->
            Pid = pid_groups:get_my(dht_node),
            RT_ext = export_rt_to_dht_node(NewRT, NewNeighbors),
            comm:send_local(Pid, {rt_update, RT_ext}),
            % update failure detector:
            case ReportToFD of
                true ->
                    NewPids = to_pid_list(NewRT),
                    OldPids = to_pid_list(OldRT),
                    fd:update_subscriptions(OldPids, NewPids);
                _ -> ok
            end
    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).

9.3.3. Chord routing table (rt_chord)

The file rt_chord.erl implements Chord's routing.

Data types

File rt_chord.erl:

```
-type key_t() :: 0..16#FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF. % 128 bit numbers
-type rt_t() :: gb_tree().
```

```
-type external_rt_t() :: gb_tree().
-type index() :: {pos_integer(), non_neg_integer()}.
-opaque custom_message() ::
       {rt_get_node, Source_PID::comm:mypid(), Index::index()} |
       {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`:

```
%% @doc Creates an empty routing table.
empty(_Neighbors) -> gb_trees:empty().
```

File `rt_chord.erl`:

```
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`:

```
%% @doc Returns the next hop to contact for a lookup.
%%      If the routing table has less entries than the rt_size_use_neighbors
%%      config parameter, the neighborhood is also searched in order to find a
%%      proper next hop.
%%      Note, that this code will be called from the dht_node process and
%%      it will thus have an external_rt!
next_hop(State, Id) ->
    Neighbors = dht_node_state:get(State, neighbors),
    case intervals:in(Id, nodelist:succ_range(Neighbors)) of
        true -> node:pidX(nodelist:succ(Neighbors));
        _ ->
            % check routing table:
    RT = dht_node_state:get(State, rt),
            RTSize = get_size(RT),
            NodeRT = case util:gb_trees_largest_smaller_than(Id, RT) of
                         {value, _Key, N} ->
                             N;
                         nil when RTSize =:= 0 ->
                             nodelist:succ(Neighbors);
                         nil -> % forward to largest finger
                             {_Key, N} = gb_trees:largest(RT),
                             N
                     end,
            FinalNode =
                case RTSize < config:read(rt_size_use_neighbors) of
                    false -> NodeRT;
                    _     ->
                        % check neighborhood:
                        nodelist:largest_smaller_than(Neighbors, Id, NodeRT)
                end,
            node:pidX(FinalNode)
    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`:

```
%% @doc Starts the stabilization routine.
init_stabilize(Neighbors, RT) ->
    % calculate the longest finger
    Id = nodelist:nodeid(Neighbors),
    Key = calculateKey(Id, first_index()),
    % trigger a lookup for Key
    api_dht_raw:unreliable_lookup(Key, {send_to_group_member, routing_table,
                                        {rt_get_node, comm:this(), first_index()}}),
    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`:

```
%% @doc Chord reacts on 'rt_get_node_response' messages in response to its
%%      'rt_get_node' messages.
-spec handle_custom_message
        (custom_message(), rt_loop:state_active()) -> rt_loop:state_active();
        (any(), rt_loop:state_active()) -> unknown_event.
handle_custom_message({rt_get_node, Source_PID, Index}, State) ->
    MyNode = nodelist:node(rt_loop:get_neighb(State)),
    comm:send(Source_PID, {rt_get_node_response, Index, MyNode}),
    State;
handle_custom_message({rt_get_node_response, Index, Node}, State) ->
    OldRT = rt_loop:get_rt(State),
    Id = rt_loop:get_id(State),
    Succ = rt_loop:get_succ(State),
    NewRT = stabilize(Id, Succ, OldRT, Index, Node),
    check(OldRT, NewRT, rt_loop:get_neighb(State), true),
    rt_loop:set_rt(State, NewRT);
handle_custom_message(_Message, _State) ->
    unknown_event.
```

File `rt_chord.erl`:

```
%% @doc Updates one entry in the routing table and triggers the next update.
-spec stabilize(MyId::key() | key_t(), Succ::node:node_type(), OldRT::rt(),
                Index::index(), Node::node:node_type()) -> NewRT::rt().
stabilize(Id, Succ, RT, Index, Node) ->
    case (node:id(Succ) =/= node:id(Node))    % reached succ?
        andalso (not intervals:in(            % there should be nothing shorter
                     node:id(Node),           %   than succ
                     node:mk_interval_between_ids(Id, node:id(Succ)))) of
        true ->
            NewRT = gb_trees:enter(Index, Node, RT),
            Key = calculateKey(Id, next_index(Index)),
            Msg = {rt_get_node, comm:this(), next_index(Index)},
            api_dht_raw:unreliable_lookup(
              Key, {send_to_group_member, routing_table, Msg}),
            NewRT;
        _ -> RT
```

```
    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`:

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

```
%% @doc Removes dead nodes from the routing table.
filter_dead_node(RT, DeadPid) ->
    DeadIndices = [Index || {Index, Node}  <- gb_trees:to_list(RT),
                            node:same_process(Node, DeadPid)],
    lists:foldl(fun(Index, Tree) -> gb_trees:delete(Index, Tree) end,
                RT, DeadIndices).
```

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

File `rt_chord.erl`:

```
export_rt_to_dht_node(RT, Neighbors) ->
    Id = nodelist:nodeid(Neighbors),
    Pred = nodelist:pred(Neighbors),
    Succ = nodelist:succ(Neighbors),
    Tree = gb_trees:enter(node:id(Succ), Succ,
                          gb_trees:enter(node:id(Pred), Pred, gb_trees:empty())),
    util:gb_trees_foldl(fun (_K, V, Acc) ->
                                 % only store the ring id and the according node structure
                                 case node:id(V) =:= Id of
                                     true  -> Acc;
                                     false -> gb_trees:enter(node:id(V), V, Acc)
                                 end
                        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`:

```
%% @doc Notifies the dht_node and failure detector if the routing table changed.
%%      Provided for convenience (see check/5).
check(OldRT, NewRT, Neighbors, ReportToFD) ->
    check(OldRT, NewRT, Neighbors, Neighbors, ReportToFD).

%% @doc Notifies the dht_node if the (external) routing table changed.
%%      Also updates the failure detector if ReportToFD is set.
%%      Note: the external routing table also changes if the Pred or Succ
%%      change.
check(OldRT, NewRT, OldNeighbors, NewNeighbors, ReportToFD) ->
    case OldRT =:= NewRT andalso
```

```
            nodelist:pred(OldNeighbors) =:= nodelist:pred(NewNeighbors) andalso
            nodelist:succ(OldNeighbors) =:= nodelist:succ(NewNeighbors) of
        true -> ok;
        _ ->
            Pid = pid_groups:get_my(dht_node),
            RT_ext = export_rt_to_dht_node(NewRT, NewNeighbors),
            case Pid of
                failed -> ok;
                _      -> comm:send_local(Pid, {rt_update, RT_ext})
            end,
            % update failure detector:
            case ReportToFD of
                true ->
                    NewPids = to_pid_list(NewRT),
                    OldPids = to_pid_list(OldRT),
                    fd:update_subscriptions(OldPids, NewPids);
                _ -> ok
            end
    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).

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 `admin:add_nodes(10)` in the Erlang-Shell that the management server opened [1].

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

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

File `admin.erl`:

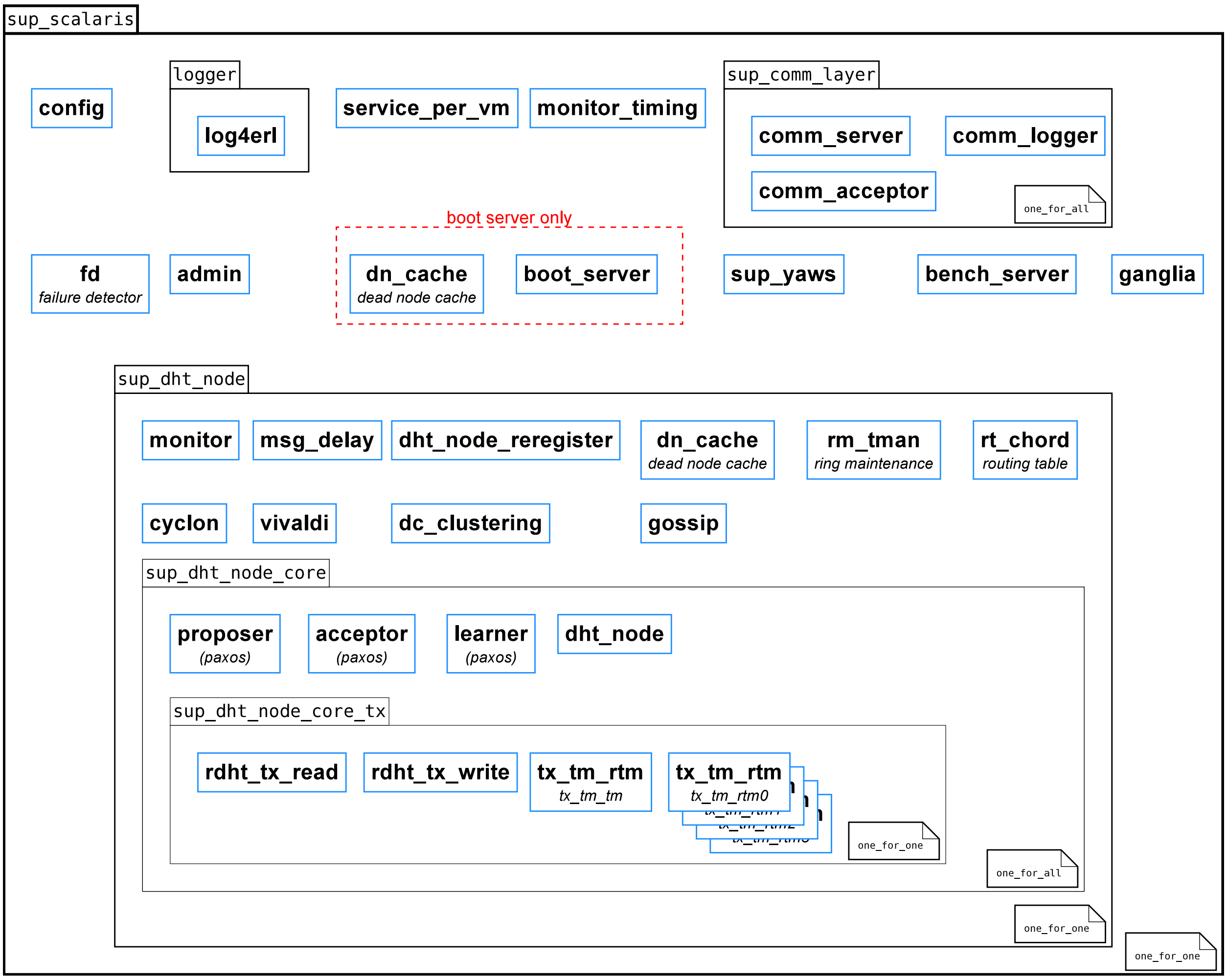
```
% @doc add new Scalaris nodes on the local node
-spec add_node_at_id(?RT:key()) ->
        ok | {error, already_present | {already_started, pid() | undefined} | term()}.
add_node_at_id(Id) ->
    add_node([{{dht_node, id}, Id}, {skip_psv_lb}]).

-spec add_node([tuple()]) ->
        ok | {error, already_present | {already_started, pid() | undefined} | term()}.
add_node(Options) ->
    DhtNodeId = randoms:getRandomId(),
    Desc = util:sup_supervisor_desc(
             DhtNodeId, config:read(dht_node_sup), start_link,
             [[{my_sup_dht_node_id, DhtNodeId} | Options]]),
    case supervisor:start_child(main_sup, Desc) of
        {ok, _Child}         -> ok;
        {ok, _Child, _Info} -> ok;
        {error, _Error} = X -> X
    end.

-spec add_nodes(non_neg_integer()) ->
        nothing_to_do | [ok | {error, already_present |
                                {already_started, pid() | undefined} | term()},...].
add_nodes(0) -> nothing_to_do;
add_nodes(Count) ->
    [add_node([]) || _X <- lists:seq(1, Count)].
```

It calls `admin:add_node([])` Count times. This function starts a new child with the given options for the main supervisor `main_sup`. In particular, it sets a random ID that is passed to the new node as its suggested ID to join at. To actually perform the start, the function `sup_dht_node:start_link/1` is called by the Erlang supervisor mechanism. For more details on the OTP supervisor mechanism see Chapter 18 of the Erlang book [1] or the online documentation at http://www.erlang.org/doc/man/supervisor.html.

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

11.1. Supervisor-tree of a Scalaris node

When a new Erlang VM with a Scalaris node is started, a `sup_scalaris` supervisor is started that creates further workers and supervisors according to the following scheme (processes starting order: left to right, top to bottom):



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:

```
-spec init([tuple()]) -> {ok, {{one_for_one, MaxRetries::pos_integer(),
                                PeriodInSeconds::pos_integer()},
                               [ProcessDescr::any()]}}.
init(Options) ->
    DHTNodeGroup = pid_groups:new("dht_node_"),
    pid_groups:join_as(DHTNodeGroup, ?MODULE),
    mgmt_server:connect(),

    Cyclon = util:sup_worker_desc(cyclon, cyclon, start_link, [DHTNodeGroup]),
    DC_Clustering =
        util:sup_worker_desc(dc_clustering, dc_clustering, start_link,
                             [DHTNodeGroup]),
    DeadNodeCache =
        util:sup_worker_desc(deadnodecache, dn_cache, start_link,
                             [DHTNodeGroup]),
    Delayer =
        util:sup_worker_desc(msg_delay, msg_delay, start_link,
                             [DHTNodeGroup]),
    Gossip =
        util:sup_worker_desc(gossip, gossip, start_link, [DHTNodeGroup]),
    Reregister =
        util:sup_worker_desc(dht_node_reregister, dht_node_reregister,
                             start_link, [DHTNodeGroup]),
    RoutingTable =
        util:sup_worker_desc(routing_table, rt_loop, start_link,
                             [DHTNodeGroup]),
    SupDHTNodeCore_AND =
        util:sup_supervisor_desc(sup_dht_node_core, sup_dht_node_core,
                                 start_link, [DHTNodeGroup, Options]),
    Vivaldi =
        util:sup_worker_desc(vivaldi, vivaldi, start_link, [DHTNodeGroup]),
    Monitor =
        util:sup_worker_desc(monitor, monitor, start_link, [DHTNodeGroup]),
    RepUpdate = case config:read(rep_update_activate) of
                    true -> util:sup_worker_desc(rep_upd, rep_upd,
                                                 start_link, [DHTNodeGroup]);
                    _ -> []
                end,
    %% order in the following list is the start order
    {ok, {{one_for_one, 10, 1},
          lists:flatten([
                Monitor,
                Delayer,
                Reregister,
                DeadNodeCache,
                RoutingTable,
                Cyclon,
                Vivaldi,
                DC_Clustering,
                Gossip,
                SupDHTNodeCore_AND,
                RepUpdate
          ])}}.
```

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:

```
-spec init({pid_groups:groupname(), Options::[tuple()]}) ->
                  {ok, {{one_for_all, MaxRetries::pos_integer(),
                         PeriodInSeconds::pos_integer()},
                        [ProcessDescr::any()]}}.
init({DHTNodeGroup, Options}) ->
    pid_groups:join_as(DHTNodeGroup, ?MODULE),
    PaxosProcesses = util:sup_supervisor_desc(sup_paxos, sup_paxos,
                                              start_link, [DHTNodeGroup, []]),
    DHTNodeModule = config:read(dht_node),
    DHTNode = util:sup_worker_desc(dht_node, DHTNodeModule, start_link,
                                   [DHTNodeGroup, Options]),
    TX =
        util:sup_supervisor_desc(sup_dht_node_core_tx, sup_dht_node_core_tx, start_link,
                                 [DHTNodeGroup]),
    {ok, {{one_for_all, 10, 1},
          [
           PaxosProcesses,
           DHTNode,
           TX
          ]}}.
```

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:

```
%% @doc spawns a scalaris node, called by the scalaris supervisor process
-spec start_link(pid_groups:groupname(), [tuple()]) -> {ok, pid()}.
start_link(DHTNodeGroup, Options) ->
    gen_component:start_link(?MODULE, Options,
                             [{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`:

```
%% @doc joins this node in the ring and calls the main loop
-spec init(Options::[tuple()]) -> dht_node_state:state().
init(Options) ->
    {my_sup_dht_node_id, MySupDhtNode} = lists:keyfind(my_sup_dht_node_id, 1, Options),
    erlang:put(my_sup_dht_node_id, MySupDhtNode),
    % get my ID (if set, otherwise chose a random ID):
    Id = case lists:keyfind({dht_node, id}, 1, Options) of
             {{dht_node, id}, IdX} -> IdX;
             _ -> ?RT:get_random_node_id()
         end,
    case is_first(Options) of
        true -> dht_node_join:join_as_first(Id, 0, Options);
        _    -> dht_node_join:join_as_other(Id, 0, Options)
    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`:

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

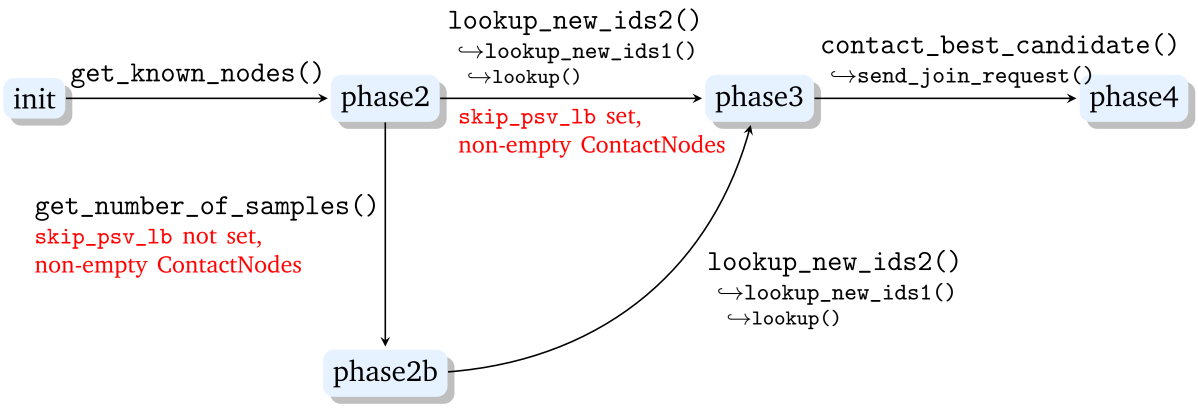
```
-record(state, {rt          = ?required(state, rt)          :: ?RT:external_rt(),
                rm_state    = ?required(state, rm_state)    :: rm_loop:state(),
                join_time   = ?required(state, join_time)   :: util:time(),
                db          = ?required(state, db)          :: ?DB:db(),
                tx_tp_db    = ?required(state, tx_tp_db)    :: any(),
                proposer    = ?required(state, proposer)    :: pid(),
                % slide with pred (must not overlap with 'slide with succ'!):
                slide_pred = null :: slide_op:slide_op() | null,
                % slide with succ (must not overlap with 'slide with pred'!):
                slide_succ = null :: slide_op:slide_op() | null,
                msg_fwd     = []   :: [{intervals:interval(), comm:mypid()}],
                % additional range to respond to during a move:
                db_range    = []   :: [{intervals:interval(), slide_op:id()}]
               }).
-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:

```
-spec join_as_other(Id::?RT:key(), IdVersion::non_neg_integer(), Options::[tuple()])
        -> {'$gen_component', [{on_handler, Handler::on_join}],
            State::{join, phase2(), msg_queue:msg_queue()}}.
join_as_other(Id, IdVersion, Options) ->
    comm:init_and_wait_for_valid_pid(),
    log:log(info,"[ Node ~w ] joining, trying ID: (~.0p, ~.0p)",
            [self(), Id, IdVersion]),
    get_known_nodes(util:get_pids_uid()),
    JoinUUID = util:get_pids_uid(),
```

```
    msg_delay:send_local(get_join_timeout() div 1000, self(),
                         {join, timeout, JoinUUID}),
    gen_component:change_handler(
      {join, {phase2, JoinUUID, Options, IdVersion, [], [Id], []},
       msg_queue:new()},
      on_join).
```

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`:

```
% in phase 2 add the nodes and do lookups with them / get number of samples
process_join_state({get_dht_nodes_response, Nodes} = _Msg,
                   {join, JoinState, QueuedMessages})
  when element(1, JoinState) =:= phase2 ->
    ?TRACE_JOIN1(_Msg, JoinState),
    Connections = [{null, Node} || Node <- Nodes, Node =/= comm:this()],
    JoinState1 = add_connections(Connections, JoinState, back),
    NewJoinState = phase2_next_step(JoinState1, Connections),
    ?TRACE_JOIN_STATE(NewJoinState),
    {join, NewJoinState, QueuedMessages};

% in all other phases, just add the provided nodes:
process_join_state({get_dht_nodes_response, Nodes} = _Msg,
                   {join, JoinState, QueuedMessages})
  when element(1, JoinState) =:= phase2b orelse
         element(1, JoinState) =:= phase3 orelse
         element(1, JoinState) =:= phase4 ->
    ?TRACE_JOIN1(_Msg, JoinState),
    Connections = [{null, Node} || Node <- Nodes, Node =/= comm:this()],
    JoinState1 = add_connections(Connections, JoinState, back),
    ?TRACE_JOIN_STATE(JoinState1),
    {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`:

```
% note: although this message was send in phase2, also accept message in
% phase2, e.g. messages arriving from previous calls
process_join_state({join, get_number_of_samples, Samples, Conn} = _Msg,
                   {join, JoinState, QueuedMessages})
  when element(1, JoinState) =:= phase2 orelse
         element(1, JoinState) =:= phase2b ->
```

```
    ?TRACE_JOIN1(_Msg, JoinState),
    % prefer node that send get_number_of_samples as first contact node
    JoinState1 = reset_connection(Conn, JoinState),
    % (re-)issue lookups for all existing IDs and
    % create additional samples, if required
    NewJoinState = lookup_new_ids2(Samples, JoinState1),
    ?TRACE_JOIN_STATE(NewJoinState),
    {join, NewJoinState, QueuedMessages};

% ignore message arriving in other phases:
process_join_state({join, get_number_of_samples, _Samples, Conn} = _Msg,
                   {join, JoinState, QueuedMessages}) ->
    ?TRACE_JOIN1(_Msg, JoinState),
    NewJoinState = reset_connection(Conn, JoinState),
    ?TRACE_JOIN_STATE(NewJoinState),
    {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`:

```
process_join_msg({join, get_candidate, Source_PID, Key, LbPsv, Conn} = _Msg, State) ->
    ?TRACE1(_Msg, State),
    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`:

```
process_join_state({join, get_candidate_response, OrigJoinId, Candidate, Conn} = _Msg,
                   {join, JoinState, QueuedMessages})
  when element(1, JoinState) =:= phase3 ->
    ?TRACE_JOIN1(_Msg, JoinState),
    JoinState0 = reset_connection(Conn, JoinState),
    JoinState1 = remove_join_id(OrigJoinId, JoinState0),
    JoinState2 = integrate_candidate(Candidate, JoinState1, front),
    NewJoinState =
        case get_join_ids(JoinState2) of
            [] -> % no more join ids to look up -> join with the best:
                contact_best_candidate(JoinState2);
            [_|_] -> % still some unprocessed join ids -> wait
                JoinState2
        end,
    ?TRACE_JOIN_STATE(NewJoinState),
    {join, NewJoinState, QueuedMessages};

% In phase 2 or 2b, also add the candidate but do not continue.
% In phase 4, add the candidate to the end of the candidates as they are sorted
% and the join with the first has already started (use this candidate as backup
% if the join fails). Do not start a new join.
process_join_state({join, get_candidate_response, OrigJoinId, Candidate, Conn} = _Msg,
                   {join, JoinState, QueuedMessages})
  when element(1, JoinState) =:= phase2 orelse
```

```
            element(1, JoinState) =:= phase2b orelse
            element(1, JoinState) =:= phase4 ->
    ?TRACE_JOIN1(_Msg, JoinState),
    JoinState0 = reset_connection(Conn, JoinState),
    JoinState1 = remove_join_id(OrigJoinId, JoinState0),
    JoinState2 = case get_phase(JoinState1) of
                     phase4 -> integrate_candidate(Candidate, JoinState1, back);
                     _      -> integrate_candidate(Candidate, JoinState1, front)
                 end,
    ?TRACE_JOIN_STATE(JoinState2),
    {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`:

```
%% @doc Contacts the best candidate among all stored candidates and sends a
%%      join_request (Timeouts = 0).
-spec contact_best_candidate(JoinState::phase_2_4())
        -> phase2() | phase2b() | phase4().
contact_best_candidate(JoinState) ->
    contact_best_candidate(JoinState, 0).
%% @doc Contacts the best candidate among all stored candidates and sends a
%%      join_request. Timeouts is the number of join_request_timeout messages
%%      previously received.
-spec contact_best_candidate(JoinState::phase_2_4(), Timeouts::non_neg_integer())
        -> phase2() | phase2b() | phase4().
contact_best_candidate(JoinState, Timeouts) ->
    JoinState1 = sort_candidates(JoinState),
    send_join_request(JoinState1, Timeouts).
```

File `dht_node_join.erl`:

```
%% @doc Sends a join request to the first candidate. Timeouts is the number of
%%      join_request_timeout messages previously received.
%%      PreCond: the id has been set to the ID to join at and has been updated
%%               in JoinState.
-spec send_join_request(JoinState::phase_2_4(), Timeouts::non_neg_integer())
        -> phase2() | phase2b() | phase4().
send_join_request(JoinState, Timeouts) ->
    case get_candidates(JoinState) of
        [] -> % no candidates -> start over (should not happen):
            start_over(JoinState);
        [BestCand | _] ->
            Id = node_details:get(lb_op:get(BestCand, n1_new), new_key),
            IdVersion = get_id_version(JoinState),
            NewSucc = node_details:get(lb_op:get(BestCand, n1succ_new), node),
            Me = node:new(comm:this(), Id, IdVersion),
            CandId = lb_op:get(BestCand, id),
            ?TRACE_SEND(node:pidX(NewSucc), {join, join_request, Me, CandId}),
            comm:send(node:pidX(NewSucc), {join, join_request, Me, CandId}),
            msg_delay:send_local(
              get_join_request_timeout() div 1000, self(),
              {join, join_request_timeout, Timeouts, CandId, get_join_uuid(JoinState)}),
            set_phase(phase4, JoinState)
    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.

File `dht_node_join.erl`:

```
process_join_msg({join, join_request, NewPred, CandId} = _Msg, State)
```

```erlang
  when (not is_atom(NewPred)) -> % avoid confusion with not_responsible message
    ?TRACE1(_Msg, State),
    TargetId = node:id(NewPred),
    case dht_node_move:can_slide_pred(State, TargetId, {join, 'rcv'}) of
        true ->
            try
                % TODO: implement step-wise join
                MoveFullId = util:get_global_uid(),
                Neighbors = dht_node_state:get(State, neighbors),
                SlideOp = slide_op:new_sending_slide_join(
                            MoveFullId, NewPred, join, Neighbors),
                SlideOp1 = slide_op:set_phase(SlideOp, wait_for_pred_update_join),
                RMSubscrTag = {move, slide_op:get_id(SlideOp1)},
                rm_loop:subscribe(self(), RMSubscrTag,
                                  fun(_OldNeighbors, NewNeighbors) ->
                                          NewPred =:= nodelist:pred(NewNeighbors)
                                  end,
                                  fun dht_node_move:rm_notify_new_pred/4, 1),
                State1 = dht_node_state:add_db_range(
                           State, slide_op:get_interval(SlideOp1),
                           slide_op:get_id(SlideOp1)),
                send_join_response(State1, SlideOp1, NewPred, CandId)
            catch throw:not_responsible ->
                    ?TRACE_SEND(node:pidX(NewPred),
                                {join, join_response, not_responsible, CandId}),
                    comm:send(node:pidX(NewPred),
                              {join, join_response, not_responsible, CandId}),
                    State
            end;
        _ ->
            ?TRACE("[ ~.0p ]~n  ignoring join_request from ~.0p due to a running slide~n",
                   [self(), NewPred]),
            State
    end;
```

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:

```erlang
-spec send_join_response(State::dht_node_state:state(),
                         NewSlideOp::slide_op:slide_op(),
                         NewPred::node:node_type(), CandId::lb_op:id())
        -> dht_node_state:state().
send_join_response(State, SlideOp, NewPred, CandId) ->
    MoveFullId = slide_op:get_id(SlideOp),
    NewSlideOp =
        slide_op:set_timer(SlideOp, get_join_response_timeout(),
                           {join, join_response_timeout, NewPred, MoveFullId, CandId}),
    MyOldPred = dht_node_state:get(State, pred),
    MyNode = dht_node_state:get(State, node),
    ?TRACE_SEND(node:pidX(NewPred),
                {join, join_response, MyNode, MyOldPred, MoveFullId, CandId}),
    comm:send(node:pidX(NewPred),
              {join, join_response, MyNode, MyOldPred, MoveFullId, CandId}),
    % no need to tell the ring maintenance -> the other node will trigger an update
    % also this is better in case the other node dies during the join
%%     rm_loop:notify_new_pred(comm:this(), NewPred),
    dht_node_state:set_slide(State, pred, NewSlideOp).
```

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`:

```
process_join_state({join, join_response, not_responsible, CandId} = _Msg,
                   {join, JoinState, QueuedMessages} = State)
  when element(1, JoinState) =:= phase4 ->
    ?TRACE_JOIN1(_Msg, JoinState),
    % the node we contacted is not responsible for the selected key anymore
    % -> try the next candidate, if the message is related to the current candidate
    case get_candidates(JoinState) of
        [] -> % no candidates -> should not happen in phase4!
            log:log(error, "[ Node ~w ] empty candidate list in join phase 4, "
                        "starting over", [self()]),
            NewJoinState = start_over(JoinState),
            ?TRACE_JOIN_STATE(NewJoinState),
            {join, NewJoinState, QueuedMessages};
        [Candidate | _Rest] ->
            case lb_op:get(Candidate, id) =:= CandId of
                false -> State; % unrelated/old message
                _ ->
                    log:log(info,
                            "[ Node ~w ] node contacted for join is not responsible "
                            "for the selected ID (anymore), trying next candidate",
                            [self()]),
                    NewJoinState = try_next_candidate(JoinState),
                    ?TRACE_JOIN_STATE(NewJoinState),
                    {join, NewJoinState, QueuedMessages}
            end
    end;

% in other phases remove the candidate from the list (if it still exists):
process_join_state({join, join_response, not_responsible, CandId} = _Msg,
                   {join, JoinState, QueuedMessages}) ->
    ?TRACE_JOIN1(_Msg, JoinState),
    {join, remove_candidate(CandId, JoinState), QueuedMessages};

% note: accept (delayed) join_response messages in any phase
process_join_state({join, join_response, Succ, Pred, MoveId, CandId} = _Msg,
                   {join, JoinState, QueuedMessages} = State) ->
    ?TRACE_JOIN1(_Msg, JoinState),
    % only act on related messages, i.e. messages from the current candidate
    Phase = get_phase(JoinState),
    State1 = case get_candidates(JoinState) of
        [] when Phase =:= phase4 -> % no candidates -> should not happen in phase4!
            log:log(error, "[ Node ~w ] empty candidate list in join phase 4, "
                           "starting over", [self()]),
            NewJoinState = start_over(JoinState),
            ?TRACE_JOIN_STATE(NewJoinState),
            {join, NewJoinState, QueuedMessages};
        [] -> State; % in all other phases, ignore the delayed join_response
                     % if no candidates exist
        [Candidate | _Rest] ->
            CandidateNode = node_details:get(lb_op:get(Candidate, n1succ_new), node),
            CandidateNodeSame = node:same_process(CandidateNode, Succ),
            case lb_op:get(Candidate, id) =:= CandId of
                false ->
                    log:log(warn, "[ Node ~w ] ignoring old or unrelated "
                                  "join_response message", [self()]),
                    State; % ignore old/unrelated message
```

```
                _ when not CandidateNodeSame ->
                    % id is correct but the node is not (should never happen!)
                    log:log(error, "[ Node ~w ] got join_response but the node "
                                  "changed, trying next candidate", [self()]),
                    NewJoinState = try_next_candidate(JoinState),
                    ?TRACE_JOIN_STATE(NewJoinState),
                    {join, NewJoinState, QueuedMessages};
                _ ->
                    MyId = node_details:get(lb_op:get(Candidate, n1_new), new_key),
                    MyIdVersion = get_id_version(JoinState),
                    case MyId =:= node:id(Succ) orelse MyId =:= node:id(Pred) of
                        true ->
                            log:log(warn, "[ Node ~w ] chosen ID already exists, "
                                          "trying next candidate", [self()]),
                            % note: can not keep Id, even if skip_psv_lb is set
                            JoinState1 = remove_candidate_front(JoinState),
                            NewJoinState = contact_best_candidate(JoinState1),
                            ?TRACE_JOIN_STATE(NewJoinState),
                            {join, NewJoinState, QueuedMessages};
                        _ ->
                            ?TRACE("[ ~.0p ]~n  joined MyId:~.0p, MyIdVersion:~.0p~n  "
                                   "Succ: ~.0p~n  Pred: ~.0p~n",
                                   [self(), MyId, MyIdVersion, Succ, Pred]),
                            Me = node:new(comm:this(), MyId, MyIdVersion),
                            log:log(info, "[ Node ~w ] joined between ~w and ~w",
                                    [self(), Pred, Succ]),
                            rm_loop:notify_new_succ(node:pidX(Pred), Me),
                            rm_loop:notify_new_pred(node:pidX(Succ), Me),

                            finish_join_and_slide(Me, Pred, Succ, ?DB:new(),
                                                  QueuedMessages, MoveId)
                    end
            end
    end,
    State1;
```

File dht_node_join.erl:

```
%% @doc Finishes the join and sends all queued messages.
-spec finish_join(Me::node:node_type(), Pred::node:node_type(),
                  Succ::node:node_type(), DB::?DB:db(),
                  QueuedMessages::msg_queue:msg_queue())
        -> dht_node_state:state().
finish_join(Me, Pred, Succ, DB, QueuedMessages) ->
    RMState = rm_loop:init(Me, Pred, Succ),
    Neighbors = rm_loop:get_neighbors(RMState),
    % wait for the ring maintenance to initialize and tell us its table ID
    rt_loop:activate(Neighbors),
    cyclon:activate(),
    vivaldi:activate(),
    dc_clustering:activate(),
    gossip:activate(node:mk_interval_between_nodes(Pred, Me)),
    dht_node_reregister:activate(),
    msg_queue:send(QueuedMessages),
    NewRT_ext = ?RT:empty_ext(Neighbors),
    dht_node_state:new(NewRT_ext, RMState, DB).

%% @doc Finishes the join by setting up a slide operation to get the data from
%%      the other node and sends all queued messages.
-spec finish_join_and_slide(Me::node:node_type(), Pred::node:node_type(),
                  Succ::node:node_type(), DB::?DB:db(),
                  QueuedMessages::msg_queue:msg_queue(), MoveId::slide_op:id())
        -> {'$gen_component', [{on_handler, Handler::on}],
            State::dht_node_state:state()}.
finish_join_and_slide(Me, Pred, Succ, DB, QueuedMessages, MoveId) ->
    State = finish_join(Me, Pred, Succ, DB, QueuedMessages),
    SlideOp = slide_op:new_receiving_slide_join(MoveId, Pred, Succ, node:id(Me), join),
    SlideOp1 = slide_op:set_phase(SlideOp, wait_for_node_update),
    State1 = dht_node_state:set_slide(State, succ, SlideOp1),
    State2 = dht_node_state:add_msg_fwd(
```

```
                State1 , slide_op:get_interval(SlideOp1),
                node:pidX(slide_op:get_node(SlideOp1))),
    RMSubscrTag = {move, slide_op:get_id(SlideOp1)},
    comm:send_local(self(), {move, node_update, RMSubscrTag}),
    gen_component:change_handler(State2, on).
```

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 39.

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	re-start join → phase 2 or 2b
phase3b	ignore	ignore	ignore	ignore	
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.

[2] set by the `join_request_timeouts` config parameter

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.

12. Directory Structure of the Source Code

The directory tree of Scalaris is structured as follows:

`bin`	contains shell scripts needed to work with Scalaris (e.g. start the management server, start a node, ...)
`contrib`	necessary third party packages (yaws and log4erl)
`doc`	generated Erlang documentation
`docroot`	root directory of the node's webserver
`ebin`	the compiled Erlang code (beam files)
`java-api`	a Java API to Scalaris
`log`	log files
`src`	contains the Scalaris source code
`test`	unit tests for Scalaris
`user-dev-guide`	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.scalaris.Transaction` for (multiple) operations inside a transaction
- `de.zib.scalaris.TransactionSingleOp` for single transactional operations
- `de.zib.scalaris.ReplicatedDHT` for non-transactional (inconsistent) access to the replicated DHT items, e.g. deleting items
- `de.zib.scalaris.PubSub` for topic-based publish/subscribe operations

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