TRANSACTIONS

Scalaris:

Users and Developers Guide

Version 0.3.0 draft   April 27, 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.

Web 2.0 Application

layer implements ...

Transaction Layer ← ... strong consistency, atomicity, isolation

Replication Layer ← ... availability

P2P Layer ← ... scalability

Many Standard Internet Nodes for Data Storage

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 50). Our implementation of the routing algorithms is described in more detail in Sect. 9.3 on page 38 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 49).

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

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

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

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

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

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

2. Download and Installation

2.1. Requirements

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

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

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

- Java Development Kit 6
- Apache Ant

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

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

- Python >= 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:/tschuett/` 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

Python will compile required modules on demand when executing the scripts for the first time.

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:/tschuett/. 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 r1618.

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 50, 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 14 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`:

```
12  % Insert the appropriate IP-addresses for your setup
13  % as comma separated integers:
14  % IP Address, Port, and label of the boot server
15  {mgmt_server, {{127,0,0,1}, 14194, mgmt_server}}.
16
17  % IP Address, Port, and label of a node which is already in the system
18  {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. See

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

for a list of options accepted by `scalarisctl`.

4. Using the system

Description is based on SVN revision r1618.

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* 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 and Python and their mapping to these layers. The appropriate JSON calls are shown in Section 4.1.2 on page 16.

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 class in module `Scalaris`
Transaction Layer	`api_tx.erl`	Transaction, TransactionSingleOp	Transaction, TransactionSingleOp
	`api_pubsub.erl`	PubSub	PubSub
Replication Layer	`api_rdht.erl`	ReplicatedDHT	ReplicatedDHT
P2P Layer	`api_dht.erl` `api_dht_raw.erl`		

Table 4.1.: Layered API structure

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

[a]
```
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 is an opaque TransLog and a list containing the results of the requests. 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.

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

```
{
  "version": "1.1",
  "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:

- read(Key) - read the value at Key, result:

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

- write(Key, Value) - write 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), 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(ReqList) - 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, ReqList)` - 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`, result:

```
{"status": "ok"}
```

- `subscribe(Topic, URL)` - subscribe `URL` to `Topic`, result:

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

- `unsubscribe(Topic, URL)` - unsubscribe `URL` from `Topic`, result:

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

- `get_subscribers(Topic)` - get subscribers of `Topic`, result:

```
[<urls>]
```

Note:

```
<json_value> = {"type": "as_is" or "as_bin", "value": <value>}
```

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

JSON-Example

The following example illustrates the message flow:

Client   **Scalaris node**

Make a transaction, that sets two keys $\rightarrow$

```json
{"version": "1.1",
 "params": [
   [
     { "write": { "keyA": {"type": "as_is", "value": "valueA"} } },
     { "write": { "keyB": {"type": "as_is", "value": "valueB"} } },
     { "commit": "commit" }
   ]
 ],
 "method": "req_list",
 "id": 0
}
```

$\leftarrow$ Scalaris sends results back

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

In a second transaction: Read the two keys $\rightarrow$

```json
{"version": "1.1",
 "params": [
   [
     { "read": "keyA" },
     { "read": "keyB" }
   ]
 ],
 "method": "req_list",
 "id": 0
}
```

$\leftarrow$ Scalaris sends results back

```json
{"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 $\rightarrow$
and make further requests, here a write
and the commit for the whole transac-
tion. Also include the latest translog we
got from Scalaris (named <TLOG> here).

```
{"version": "1.1",
 "params": [
  <TLOG>,
  [
   { "write": { "keyA": {"type": "as_is", "value": "valueA2"} } },
   { "commit": "commit" }
  ]
 ],
 "method": "req_list",
 "id": 0
}
```

$\leftarrow$ Scalaris sends results back

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

A sample usage of the JSON API using Ruby can be found in `contrib/jsonrpc.rb`.

Another example of how to use the JSON API is the Python API which uses 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 two classes:

- `Scalaris` provides a high-level API similar to the command line client.

- `Transaction` provides a low-level API to the transaction mechanism.

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.py --help
usage: Scalaris.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
 -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
                                       topic
```

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 14 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().`

7.4. General Erlang server loop

Servers in Erlang often use the following structure to maintain a state while processing received messages:

```
loop(State) ->
  receive
    Message ->
      State1 = f(State),
      loop(State1)
  end.
```

The server runs an endless loop, that waits for a message, processes it and calls itself using tail-recursion in each branch. The loop works on a `State`, which can be modified when a message is handled.

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`:

```
58   -spec behaviour_info(atom()) -> [{atom(), arity()}] | undefined.
59   behaviour_info(callbacks) ->
60       [
61        {init, 1}      % initialize component
62        % note: can use arbitrary on-handler, but by default on/2 is used:
63   %%      {on, 2}         % handle a single message
64   %%                      % on(Msg, State) -> NewState | unknown_event | kill
65       ];
```

This is illustrated by the following example:

File `msg_delay.erl`:

```
70   %% initialize: return initial state.
71   -spec init([]) -> state().
72   init([]) ->
73       MyGroup = pid_groups:my_groupname(),
74       ?TRACE("msg_delay:init for pid group ~p~n", [MyGroup]),
75       TimeTableName = list_to_atom(MyGroup ++ "_msg_delay"),
76       %% use random table name provided by ets to *not* generate an atom
77       %% TableName = pdb:new(?MODULE, [set, private]),
78       TimeTable = pdb:new(TimeTableName, [set, protected, named_table]),
79       comm:send_local(self(), {msg_delay_periodic}),
80       _State = {TimeTable, _Round = 0}.
81
82   -spec on(message(), state()) -> state().
83   on({msg_delay_req, Seconds, Dest, Msg} = _FullMsg,
84      {TimeTable, Counter} = State) ->
85       ?TRACE("msg_delay:on(~.0p, ~.0p)~n", [_FullMsg, State]),
86       Future = trunc(Counter + Seconds),
87       case pdb:get(Future, TimeTable) of
88           undefined ->
89               pdb:set({Future, [{Dest, Msg}]}, TimeTable);
90           {_, MsgQueue} ->
91               pdb:set({Future, [{Dest, Msg} | MsgQueue]}, TimeTable)
92       end,
93       State;
94
95   %% periodic trigger
96   on({msg_delay_periodic} = Trigger, {TimeTable, Counter} = _State) ->
97       ?TRACE("msg_delay:on(~.0p, ~.0p)~n", [Trigger, State]),
98       case pdb:get(Counter, TimeTable) of
99           undefined -> ok;
100          {_, MsgQueue} ->
101              _ = [ comm:send_local(Dest, Msg) || {Dest, Msg} <- MsgQueue ],
102              pdb:delete(Counter, TimeTable)
103      end,
104      comm:send_local_after(1000, self(), Trigger),
105      {TimeTable, Counter + 1};
106
107  on({web_debug_info, Requestor}, {TimeTable, Counter} = State) ->
108      KeyValueList =
109          [{"queued messages (in 0-10s, messages):", ""} |
110           [begin
111               Future = trunc(Counter + Seconds),
```

```
112                    Queue = case pdb:get(Future, TimeTable) of
113                              undefined -> none;
114                              {_, Q}      -> Q
115                          end,
116                    {lists:flatten(io_lib:format("~p", [Seconds])),
117                     lists:flatten(io_lib:format("~p", [Queue]))}
118              end || Seconds <- lists:seq(0, 10)]],
119        comm:send_local(Requestor, {web_debug_info_reply, KeyValueList}),
120        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`:

```erlang
228  -spec prop_rnd_interleave(1..4, 4..16, {pos_integer(), pos_integer(), pos_integer()})
229          -> true.
230  prop_rnd_interleave(NumProposers, NumAcceptors, Seed) ->
231      ct:pal("Called with: paxos_SUITE:prop_rnd_interleave(~p, ~p, ~p).~n",
232          [NumProposers, NumAcceptors, Seed]),
233      Majority = NumAcceptors div 2 + 1,
234      {Proposers, Acceptors, Learners} =
235          make(NumProposers, NumAcceptors, 1, "rnd_interleave"),
236      %% set bp on all processes
237      _ = [ gen_component:bp_set(comm:make_local(X), proposer_initialize, bp)
238              || X <- Proposers],
239      _ = [ gen_component:bp_set(comm:make_local(X), acceptor_initialize, bp)
240              || X <- Acceptors ],
241      _ = [ gen_component:bp_set(comm:make_local(X), learner_initialize, bp)
242              || X <- Learners],
243      %% start paxos instances
244      _ = [ proposer:start_paxosid(X, paxidrndinterl, Acceptors,
245                              proposal, Majority, NumProposers, Y)
246              || {X,Y} <- lists:zip(Proposers, lists:seq(1, NumProposers)) ],
247      _ = [ acceptor:start_paxosid(X, paxidrndinterl, Learners)
248              || X <- Acceptors ],
249      _ = [ learner:start_paxosid(X, paxidrndinterl, Majority,
250                              comm:this(), cpaxidrndinterl)
251              || X <- Learners],
252      %% randomly step through protocol
253      OldSeed = random:seed(Seed),
254      Steps = step_until_decide(Proposers ++ Acceptors ++ Learners, cpaxidrndinterl, 0),
255      ct:pal("Needed ~p steps~n", [Steps]),
256      _ = case OldSeed of
257              undefined -> ok;
258              _ -> random:seed(OldSeed)
259          end,
260      true.
261
262  step_until_decide(Processes, PaxId, SumSteps) ->
263      %% io:format("Step ~p~n", [SumSteps]),
264      Runnable = [ X || X <- Processes, gen_component:runnable(comm:make_local(X)) ],
265      case Runnable of
266          [] ->
267              ct:pal("No runnable processes of ~p~n", [length(Processes)]),
268              timer:sleep(5), step_until_decide(Processes, PaxId, SumSteps);
269          _ -> ok
270      end,
271      Num = random:uniform(length(Runnable)),
272      _ = gen_component:bp_step(comm:make_local(lists:nth(Num, Runnable))),
273      receive
274          {learner_decide, cpaxidrndinterl, _, _Res} = _Any ->
275              %% io:format("Received ~p~n", [_Any]),
276              SumSteps
277      after 0 -> step_until_decide(Processes, PaxId, SumSteps + 1)
278      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`:

```erlang
31  %-define(TRACE_BP_STEPS(X,Y), io:format(X,Y)). %% output on console
32  %-define(TRACE_BP_STEPS(X,Y), ct:pal(X,Y)).    %% output even if called by unittest
33  -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`:

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

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

```
39        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`:

```
25    %%The RT macro determines which kind of routingtable is used. Uncomment the
26    %%one that is desired.
27
28    %%Standard Chord routingtable
29    -define(RT, rt_chord).
30    % first valid key:
31    -define(MINUS_INFINITY, 0).
32    % first invalid key:
33    -define(PLUS_INFINITY, 16#100000000000000000000000000000000).
34
35    %%Simple routingtable
36    %-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`:

```
32    -spec behaviour_info(atom()) -> [{atom(), arity()}] | undefined.
33    behaviour_info(callbacks) ->
34        [
35        % create a default routing table
36        {empty, 1}, {empty_ext, 1},
37        % mapping: key space -> identifier space
38        {hash_key, 1}, {get_random_node_id, 0},
39        % routing
40        {next_hop, 2},
41        % trigger for new stabilization round
42        {init_stabilize, 2},
43        % adapt RT to changed neighborhood
44        {update, 3},
45        % dead nodes filtering
46        {filter_dead_node, 2},
47        % statistics
48        {to_pid_list, 1}, {get_size, 1},
49        % gets all (replicated) keys for a given (hashed) key
50        % (for symmetric replication)
51        {get_replica_keys, 1},
52        % address space size, range and split key
53        % (may all throw 'throw:not_supported' if unsupported by the RT)
54        {n, 0}, {get_range, 2}, {get_split_key, 3},
55        % for debugging and web interface
56        {dump, 1},
57        % for bulkowner
58        {to_list, 1},
59        % convert from internal representation to version for dht_node
60        {export_rt_to_dht_node, 2},
61        % handle messages specific to a certain routing-table implementation
62        {handle_custom_message, 2},
63        % common methods
```

```
64        {check, 4}, {check, 5},
65        {check_config, 0}
66      ];
```

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`:

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

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

File `rt_loop.erl`:

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

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

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

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

A simple `rm_beh` behaviour

File `rt_simple.erl`:

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


File `rt_simple.erl`:

```
204  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`:

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

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

File `rt_simple.erl`:

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

Next hop is always the successor.

File `rt_simple.erl`:

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

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

File `rt_simple.erl`:

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

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

File `rt_simple.erl`:

```
86  %% @doc Removes dead nodes from the routing table (rely on periodic
87  %%      stabilization here).
88  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`:

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

to_pid_list/1 returns the pid of the successor.

File `rt_simple.erl`:

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

The size of the routing table is always 1.

File `rt_simple.erl`:

```
136  %% @doc Returns the replicas of the given key.
137  get_replica_keys(Key) ->
138      [Key,
139       Key bxor 16#40000000000000000000000000000000,
140       Key bxor 16#80000000000000000000000000000000,
141       Key bxor 16#C0000000000000000000000000000000
142      ].
```

This get_replica_keys/1 implements symmetric replication.

File `rt_simple.erl`:

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

There are 2^{128} available keys.

File `rt_simple.erl`:

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

dump/1 lists the successor.

File `rt_simple.erl`:

```
219  %% @doc Converts the (external) representation of the routing table to a list
220  %%      in the order of the fingers, i.e. first=succ, second=shortest finger,
221  %%      third=next longer finger,...
222  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`:

```
213  %% @doc Converts the internal RT to the external RT used by the dht_node. Both
214  %%      are the same here.
215  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`:

```
165  %% @doc There are no custom messages here.
166  -spec handle_custom_message
167          (custom_message() | any(), rt_loop:state_active()) -> unknown_event.
168  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`:

```
172  %% @doc Notifies the dht_node and failure detector if the routing table changed.
173  %%      Provided for convenience (see check/5).
174  check(OldRT, NewRT, Neighbors, ReportToFD) ->
175      check(OldRT, NewRT, Neighbors, Neighbors, ReportToFD).
176
177  %% @doc Notifies the dht_node if the (external) routing table changed.
178  %%      Also updates the failure detector if ReportToFD is set.
179  %%      Note: the external routing table only changes the internal RT has
180  %%      changed.
181  check(OldRT, NewRT, _OldNeighbors, NewNeighbors, ReportToFD) ->
182      case OldRT =:= NewRT of
183          true -> ok;
184          _ ->
185              Pid = pid_groups:get_my(dht_node),
186              RT_ext = export_rt_to_dht_node(NewRT, NewNeighbors),
187              comm:send_local(Pid, {rt_update, RT_ext}),
188              % update failure detector:
189              case ReportToFD of
190                  true ->
191                      NewPids = to_pid_list(NewRT),
192                      OldPids = to_pid_list(OldRT),
193                      fd:update_subscriptions(OldPids, NewPids);
194                  _ -> ok
195              end
196      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`:

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

```
28  -type external_rt_t() :: gb_tree().
29  -type index() :: {pos_integer(), non_neg_integer()}.
30  -opaque custom_message() ::
31         {rt_get_node, Source_PID::comm:mypid(), Index::index()} |
32         {rt_get_node_response, Index::index(), Node::node:node_type()}.
```

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

The `rm_beh` behaviour for Chord (excerpt)

File `rt_chord.erl`:

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

File `rt_chord.erl`:

```
271  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`:

```
275  %% @doc Returns the next hop to contact for a lookup.
276  %%      If the routing table has less entries than the rt_size_use_neighbors
277  %%      config parameter, the neighborhood is also searched in order to find a
278  %%      proper next hop.
279  %%      Note, that this code will be called from the dht_node process and
280  %%      it will thus have an external_rt!
281  next_hop(State, Id) ->
282      Neighbors = dht_node_state:get(State, neighbors),
283      case intervals:in(Id, nodelist:succ_range(Neighbors)) of
284          true -> node:pidX(nodelist:succ(Neighbors));
285          _ ->
286              % check routing table:
287      RT = dht_node_state:get(State, rt),
288              RTSize = get_size(RT),
289              NodeRT = case util:gb_trees_largest_smaller_than(Id, RT) of
290                          {value, _Key, N} ->
291                              N;
292                          nil when RTSize =:= 0 ->
293                              nodelist:succ(Neighbors);
294                          nil -> % forward to largest finger
295                              {_Key, N} = gb_trees:largest(RT),
296                              N
297                      end,
298              FinalNode =
299                  case RTSize < config:read(rt_size_use_neighbors) of
300                      false -> NodeRT;
301                      _     ->
302                          % check neighborhood:
303                          nodelist:largest_smaller_than(Neighbors, Id, NodeRT)
304                  end,
305              node:pidX(FinalNode)
306      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`:

```erlang
74  %% @doc Starts the stabilization routine.
75  init_stabilize(Neighbors, RT) ->
76      % calculate the longest finger
77      Id = nodelist:nodeid(Neighbors),
78      Key = calculateKey(Id, first_index()),
79      % trigger a lookup for Key
80      api_dht_raw:unreliable_lookup(Key, {send_to_group_member, routing_table,
81                                          {rt_get_node, comm:this(), first_index()}}),
82      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`:

```erlang
216  %% @doc Chord reacts on 'rt_get_node_response' messages in response to its
217  %%      'rt_get_node' messages.
218  -spec handle_custom_message
219          (custom_message(), rt_loop:state_active()) -> rt_loop:state_active();
220          (any(), rt_loop:state_active()) -> unknown_event.
221  handle_custom_message({rt_get_node, Source_PID, Index}, State) ->
222      MyNode = nodelist:node(rt_loop:get_neighb(State)),
223      comm:send(Source_PID, {rt_get_node_response, Index, MyNode}),
224      State;
225  handle_custom_message({rt_get_node_response, Index, Node}, State) ->
226      OldRT = rt_loop:get_rt(State),
227      Id = rt_loop:get_id(State),
228      Succ = rt_loop:get_succ(State),
229      NewRT = stabilize(Id, Succ, OldRT, Index, Node),
230      check(OldRT, NewRT, rt_loop:get_neighb(State), true),
231      rt_loop:set_rt(State, NewRT);
232  handle_custom_message(_Message, _State) ->
233      unknown_event.
```

File `rt_chord.erl`:

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

```
164        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`:

```
168   %% @doc Updates the routing table due to a changed node ID, pred and/or succ.
169   -spec update(OldRT::rt(), OldNeighbors::nodelist:neighborhood(),
170               NewNeighbors::nodelist:neighborhood()) -> {trigger_rebuild, rt()}.
171   update(_OldRT, _OldNeighbors, NewNeighbors) ->
172       % to be on the safe side ...
173       {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`:

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

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

File `rt_chord.erl`:

```
310   export_rt_to_dht_node(RT, Neighbors) ->
311       Id = nodelist:nodeid(Neighbors),
312       Pred = nodelist:pred(Neighbors),
313       Succ = nodelist:succ(Neighbors),
314       Tree = gb_trees:enter(node:id(Succ), Succ,
315                             gb_trees:enter(node:id(Pred), Pred, gb_trees:empty())),
316       util:gb_trees_foldl(fun (_K, V, Acc) ->
317                                   % only store the ring id and the according node structure
318                                   case node:id(V) =:= Id of
319                                       true  -> Acc;
320                                       false -> gb_trees:enter(node:id(V), V, Acc)
321                                   end
322                           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`:

```
237   %% @doc Notifies the dht_node and failure detector if the routing table changed.
238   %%      Provided for convenience (see check/5).
239   check(OldRT, NewRT, Neighbors, ReportToFD) ->
240       check(OldRT, NewRT, Neighbors, Neighbors, ReportToFD).
241
242   %% @doc Notifies the dht_node if the (external) routing table changed.
243   %%      Also updates the failure detector if ReportToFD is set.
244   %%      Note: the external routing table also changes if the Pred or Succ
245   %%      change.
246   check(OldRT, NewRT, OldNeighbors, NewNeighbors, ReportToFD) ->
247       case OldRT =:= NewRT andalso
```

```
248            nodelist:pred(OldNeighbors) =:= nodelist:pred(NewNeighbors) andalso
249            nodelist:succ(OldNeighbors) =:= nodelist:succ(NewNeighbors) of
250        true -> ok;
251        _ ->
252            Pid = pid_groups:get_my(dht_node),
253            RT_ext = export_rt_to_dht_node(NewRT, NewNeighbors),
254            comm:send_local(Pid, {rt_update, RT_ext}),
255            % update failure detector:
256            case ReportToFD of
257                true ->
258                    NewPids = to_pid_list(NewRT),
259                    OldPids = to_pid_list(OldRT),
260                    fd:update_subscriptions(OldPids, NewPids);
261                _ -> ok
262            end
263    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 12, 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`:

```
37  % @doc add new Scalaris nodes on the local node
38  -spec add_node_at_id(?RT:key()) ->
39           ok | {error, already_present | {already_started, pid() | undefined} | term()}.
40  add_node_at_id(Id) ->
41      add_node([{{dht_node, id}, Id}, {skip_psv_lb}]).
42
43  -spec add_node([tuple()]) ->
44           ok | {error, already_present | {already_started, pid() | undefined} | term()}.
45  add_node(Options) ->
46      DhtNodeId = randoms:getRandomId(),
47      Desc = util:sup_supervisor_desc(
48              DhtNodeId, config:read(dht_node_sup), start_link,
49              [[{my_sup_dht_node_id, DhtNodeId} | Options]]),
50      case supervisor:start_child(main_sup, Desc) of
51          {ok, _Child}        -> ok;
52          {ok, _Child, _Info} -> ok;
53          {error, _Error} = X -> X
54      end.
55
56  -spec add_nodes(non_neg_integer()) ->
57           nothing_to_do | [ok | {error, already_present |
58                           {already_started, pid() | undefined} | term()},...].
59  add_nodes(0) -> nothing_to_do;
60  add_nodes(Count) ->
61      [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 11

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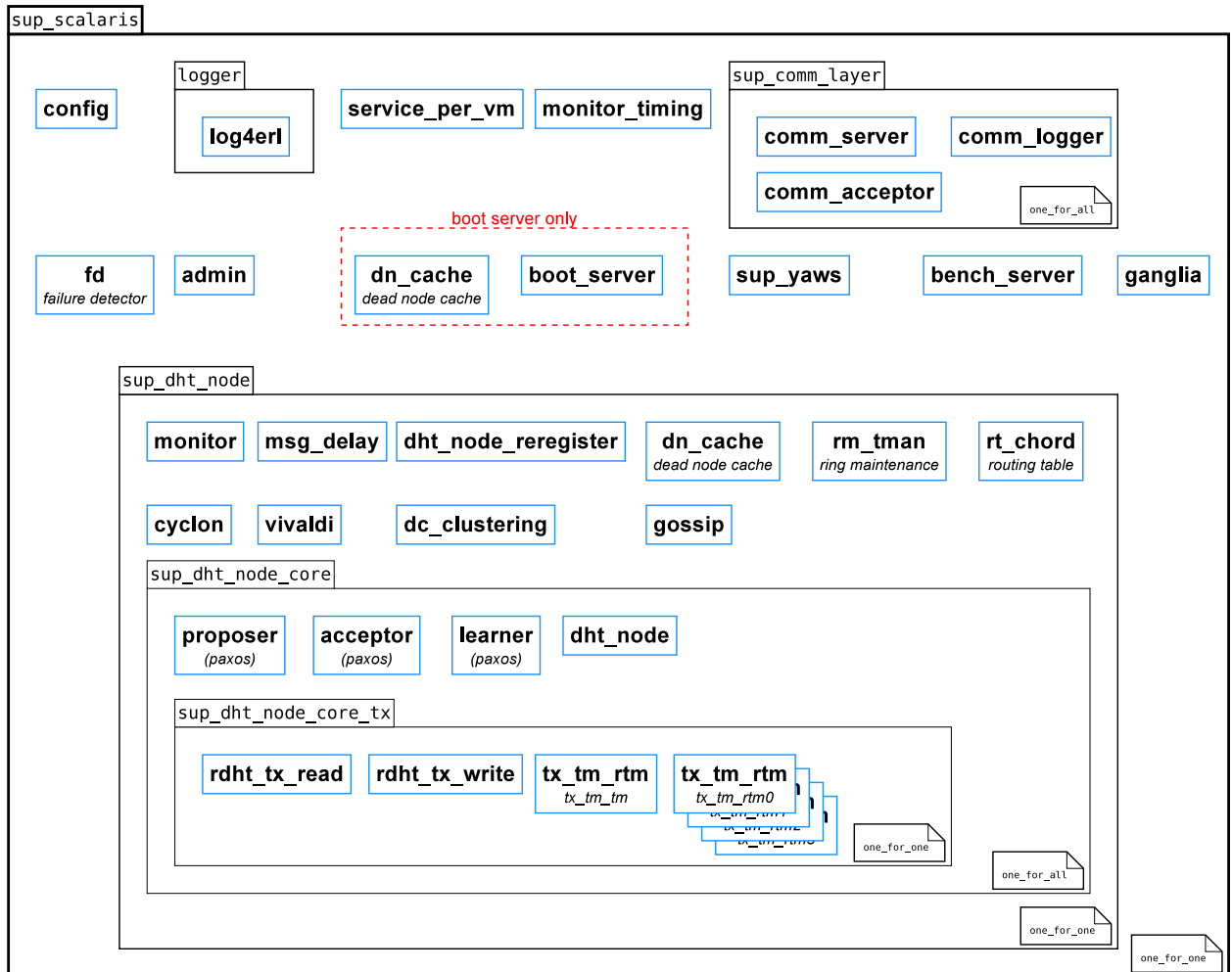
When new nodes are started using `admin:add_node/1`, only new `sup_dht_node` supervisors are started.

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:

```erlang
44  -spec init([tuple()]) -> {ok, {{one_for_one, MaxRetries::pos_integer(),
45                                   PeriodInSeconds::pos_integer()},
46                                  [ProcessDescr::any()]}}.
47  init(Options) ->
48      DHTNodeGroup = pid_groups:new("dht_node_"),
49      pid_groups:join_as(DHTNodeGroup, ?MODULE),
50      mgmt_server:connect(),
51
52      Cyclon = util:sup_worker_desc(cyclon, cyclon, start_link, [DHTNodeGroup]),
53      DC_Clustering =
54          util:sup_worker_desc(dc_clustering, dc_clustering, start_link,
55                               [DHTNodeGroup]),
56      DeadNodeCache =
57          util:sup_worker_desc(deadnodecache, dn_cache, start_link,
58                               [DHTNodeGroup]),
59      Delayer =
60          util:sup_worker_desc(msg_delay, msg_delay, start_link,
61                               [DHTNodeGroup]),
62      Gossip =
63          util:sup_worker_desc(gossip, gossip, start_link, [DHTNodeGroup]),
64      Reregister =
65          util:sup_worker_desc(dht_node_reregister, dht_node_reregister,
66                               start_link, [DHTNodeGroup]),
67      RoutingTable =
68          util:sup_worker_desc(routing_table, rt_loop, start_link,
69                               [DHTNodeGroup]),
70      SupDHTNodeCore_AND =
71          util:sup_supervisor_desc(sup_dht_node_core, sup_dht_node_core,
72                                   start_link, [DHTNodeGroup, Options]),
73      Vivaldi =
74          util:sup_worker_desc(vivaldi, vivaldi, start_link, [DHTNodeGroup]),
75      Monitor =
76          util:sup_worker_desc(monitor, monitor, start_link, [DHTNodeGroup]),
77      %% order in the following list is the start order
78      {ok, {{one_for_one, 10, 1},
79            [
80              Monitor,
81              Delayer,
82              Reregister,
83              DeadNodeCache,
84              RoutingTable,
85              Cyclon,
86              Vivaldi,
87              DC_Clustering,
88              Gossip,
89              SupDHTNodeCore_AND
90            ]}}.
```

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`:

```
40  -spec init({pid_groups:groupname(), Options::[tuple()]}) ->
41                  {ok, {{one_for_all, MaxRetries::pos_integer(),
42                         PeriodInSeconds::pos_integer()},
43                        [ProcessDescr::any()]}}.
44  init({DHTNodeGroup, Options}) ->
45      pid_groups:join_as(DHTNodeGroup, ?MODULE),
46      PaxosProcesses = util:sup_supervisor_desc(sup_paxos, sup_paxos,
47                                                start_link, [DHTNodeGroup, []]),
48      DHTNodeModule = config:read(dht_node),
49      DHTNode = util:sup_worker_desc(dht_node, DHTNodeModule, start_link,
50                                     [DHTNodeGroup, Options]),
51      TX =
52          util:sup_supervisor_desc(sup_dht_node_core_tx, sup_dht_node_core_tx, start_link,
53                                   [DHTNodeGroup]),
54      {ok, {{one_for_all, 10, 1},
55            [
56             PaxosProcesses,
57             DHTNode,
58             TX
59            ]}}.
```

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`:

```
391  %% @doc spawns a scalaris node, called by the scalaris supervisor process
392  -spec start_link(pid_groups:groupname(), [tuple()]) -> {ok, pid()}.
393  start_link(DHTNodeGroup, Options) ->
394      gen_component:start_link(?MODULE, Options,
395                               [{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`:

```
374  %% @doc joins this node in the ring and calls the main loop
```

```
375  -spec init(Options::[tuple()]) -> dht_node_state:state().
376  init(Options) ->
377      {my_sup_dht_node_id, MySupDhtNode} = lists:keyfind(my_sup_dht_node_id, 1, Options),
378      erlang:put(my_sup_dht_node_id, MySupDhtNode),
379      % get my ID (if set, otherwise chose a random ID):
380      Id = case lists:keyfind({dht_node, id}, 1, Options) of
381              {{dht_node, id}, IdX} -> IdX;
382              _ -> ?RT:get_random_node_id()
383          end,
384      case is_first(Options) of
385          true -> dht_node_join:join_as_first(Id, 0, Options);
386          _    -> dht_node_join:join_as_other(Id, 0, Options)
387      end.
```

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

11.5. Actually joining the ring

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

11.5.1. A single node joining an empty ring

File `dht_node_join.erl`:

```
100  -spec join_as_first(Id::?RT:key(), IdVersion::non_neg_integer(), Options::[tuple()])
101          -> dht_node_state:state().
102  join_as_first(Id, IdVersion, _Options) ->
103      % ugly hack to get a valid ip-address into the comm-layer
104      dht_node:trigger_known_nodes(),
105      log:log(info, "[ Node ~w ] joining as first: (~.0p, ~.0p)",
106              [self(), Id, IdVersion]),
107      Me = node:new(comm:this(), Id, IdVersion),
108      % join complete, State is the first "State"
109      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`:

```
50  -record(state, {rt          = ?required(state, rt)        :: ?RT:external_rt(),
51                  rm_state    = ?required(state, rm_state)  :: rm_loop:state(),
52                  join_time   = ?required(state, join_time) :: util:time(),
53                  db          = ?required(state, db)        :: ?DB:db(),
```

```
54                     tx_tp_db   = ?required(state, tx_tp_db)   :: any(),
55                     proposer   = ?required(state, proposer)   :: pid(),
56                     % slide with pred (must not overlap with 'slide with succ'!):
57                     slide_pred = null :: slide_op:slide_op() | null,
58                     % slide with succ (must not overlap with 'slide with pred'!):
59                     slide_succ = null :: slide_op:slide_op() | null,
60                     msg_fwd    = []    :: [{intervals:interval(), comm:mypid()}],
61                     % additional range to respond to during a move:
62                     db_range   = []    :: [{intervals:interval(), slide_op:id()}]
63                   }).
64   -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.
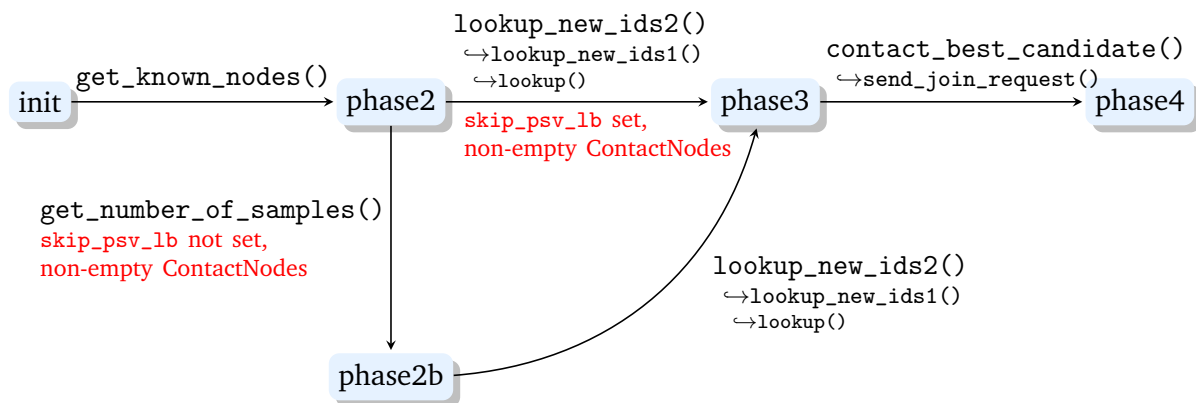
At first all nodes set in the known_hosts configuration parameter are contacted. Their responses are then handled in phase 2. In order to separate the join state from the ordinary dht_node state, the gen_component is instructed to use the dht_node:on_join/2 message handler which delegates every message to dht_node_join:process_join_state/2.

File dht_node_join.erl:

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

```
154  % in phase 2 add the nodes and do lookups with them / get number of samples
155  process_join_state({get_dht_nodes_response, Nodes} = _Msg,
156                     {join, JoinState, QueuedMessages})
157    when element(1, JoinState) =:= phase2 ->
158      ?TRACE_JOIN1(_Msg, JoinState),
159      Connections = [{null, Node} || Node <- Nodes, Node =/= comm:this()],
160      JoinState1 = add_connections(Connections, JoinState, back),
161      NewJoinState = phase2_next_step(JoinState1, Connections),
162      ?TRACE_JOIN_STATE(NewJoinState),
163      {join, NewJoinState, QueuedMessages};
164
165  % in all other phases, just add the provided nodes:
166  process_join_state({get_dht_nodes_response, Nodes} = _Msg,
167                     {join, JoinState, QueuedMessages})
168    when element(1, JoinState) =:= phase2b orelse
169           element(1, JoinState) =:= phase3 orelse
170           element(1, JoinState) =:= phase4 ->
171      ?TRACE_JOIN1(_Msg, JoinState),
172      Connections = [{null, Node} || Node <- Nodes, Node =/= comm:this()],
173      JoinState1 = add_connections(Connections, JoinState, back),
174      ?TRACE_JOIN_STATE(JoinState1),
175      {join, JoinState1, QueuedMessages};
```

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

File `dht_node_join.erl`:

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

```
217   process_join_state({join, get_number_of_samples, _Samples, Conn} = _Msg,
218                       {join, JoinState, QueuedMessages}) ->
219       ?TRACE_JOIN1(_Msg, JoinState),
220       NewJoinState = reset_connection(Conn, JoinState),
221       ?TRACE_JOIN_STATE(NewJoinState),
222       {join, NewJoinState, QueuedMessages};
```

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

File `dht_node_join.erl`:

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

Phase 3

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

File `dht_node_join.erl`:

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

```
288        {join, JoinState2, QueuedMessages};
```

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

File `dht_node_join.erl`:

```
793    %% @doc Contacts the best candidate among all stored candidates and sends a
794    %%      join_request (Timeouts = 0).
795    -spec contact_best_candidate(JoinState::phase_2_4())
796            -> phase2() | phase2b() | phase4().
797    contact_best_candidate(JoinState) ->
798        contact_best_candidate(JoinState, 0).
799    %% @doc Contacts the best candidate among all stored candidates and sends a
800    %%      join_request. Timeouts is the number of join_request_timeout messages
801    %%      previously received.
802    -spec contact_best_candidate(JoinState::phase_2_4(), Timeouts::non_neg_integer())
803            -> phase2() | phase2b() | phase4().
804    contact_best_candidate(JoinState, Timeouts) ->
805        JoinState1 = sort_candidates(JoinState),
806        send_join_request(JoinState1, Timeouts).
```

File `dht_node_join.erl`:

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

```
502    process_join_msg({join, join_request, NewPred, CandId} = _Msg, State)
503      when (not is_atom(NewPred)) -> % avoid confusion with not_responsible message
504        ?TRACE1(_Msg, State),
505        TargetId = node:id(NewPred),
506        case dht_node_move:can_slide_pred(State, TargetId, {join, 'rcv'}) of
507            true ->
508                try
509                    % TODO: implement step-wise join
510                    MoveFullId = util:get_global_uid(),
511                    Neighbors = dht_node_state:get(State, neighbors),
512                    SlideOp = slide_op:new_sending_slide_join(
```

```
513                          MoveFullId, NewPred, join, Neighbors),
514              SlideOp1 = slide_op:set_phase(SlideOp, wait_for_pred_update_join),
515              RMSubscrTag = {move, slide_op:get_id(SlideOp1)},
516              rm_loop:subscribe(self(), RMSubscrTag,
517                                fun(_OldNeighbors, NewNeighbors) ->
518                                        NewPred =:= nodelist:pred(NewNeighbors)
519                                end,
520                                fun dht_node_move:rm_notify_new_pred/4, 1),
521              State1 = dht_node_state:add_db_range(
522                        State, slide_op:get_interval(SlideOp1),
523                        slide_op:get_id(SlideOp1)),
524              send_join_response(State1, SlideOp1, NewPred, CandId)
525          catch throw:not_responsible ->
526                  ?TRACE_SEND(node:pidX(NewPred),
527                              {join, join_response, not_responsible, CandId}),
528                  comm:send(node:pidX(NewPred),
529                            {join, join_response, not_responsible, CandId}),
530                  State
531          end;
532      _ ->
533          ?TRACE("[ ~.0p ]~n  ignoring join_request from ~.0p due to a running slide~n",
534                 [self(), NewPred]),
535          State
536   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:

```
869  -spec send_join_response(State::dht_node_state:state(),
870                           NewSlideOp::slide_op:slide_op(),
871                           NewPred::node:node_type(), CandId::lb_op:id())
872         -> dht_node_state:state().
873  send_join_response(State, SlideOp, NewPred, CandId) ->
874      MoveFullId = slide_op:get_id(SlideOp),
875      NewSlideOp =
876          slide_op:set_timer(SlideOp, get_join_response_timeout(),
877                             {join, join_response_timeout, NewPred, MoveFullId, CandId}),
878      MyOldPred = dht_node_state:get(State, pred),
879      MyNode = dht_node_state:get(State, node),
880      ?TRACE_SEND(node:pidX(NewPred),
881                  {join, join_response, MyNode, MyOldPred, MoveFullId, CandId}),
882      comm:send(node:pidX(NewPred),
883                {join, join_response, MyNode, MyOldPred, MoveFullId, CandId}),
884      % no need to tell the ring maintenance -> the other node will trigger an update
885      % also this is better in case the other node dies during the join
886  %%      rm_loop:notify_new_pred(comm:this(), NewPred),
887      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:

```erlang
327  process_join_state({join, join_response, not_responsible, CandId} = _Msg,
328                     {join, JoinState, QueuedMessages} = State)
329    when element(1, JoinState) =:= phase4 ->
330      ?TRACE_JOIN1(_Msg, JoinState),
331      % the node we contacted is not responsible for the selected key anymore
332      % -> try the next candidate, if the message is related to the current candidate
333      case get_candidates(JoinState) of
334          [] -> % no candidates -> should not happen in phase4!
335              log:log(error, "[ Node ~w ] empty candidate list in join phase 4, "
336                          "starting over", [self()]),
337              NewJoinState = start_over(JoinState),
338              ?TRACE_JOIN_STATE(NewJoinState),
339              {join, NewJoinState, QueuedMessages};
340          [Candidate | _Rest] ->
341              case lb_op:get(Candidate, id) =:= CandId of
342                  false -> State; % unrelated/old message
343                  _ ->
344                      log:log(info,
345                              "[ Node ~w ] node contacted for join is not responsible "
346                              "for the selected ID (anymore), trying next candidate",
347                              [self()]),
348                      NewJoinState = try_next_candidate(JoinState),
349                      ?TRACE_JOIN_STATE(NewJoinState),
350                      {join, NewJoinState, QueuedMessages}
351              end
352      end;
353
354  % in other phases remove the candidate from the list (if it still exists):
355  process_join_state({join, join_response, not_responsible, CandId} = _Msg,
356                     {join, JoinState, QueuedMessages}) ->
357      ?TRACE_JOIN1(_Msg, JoinState),
358      {join, remove_candidate(CandId, JoinState), QueuedMessages};
359
360  % note: accept (delayed) join_response messages in any phase
361  process_join_state({join, join_response, Succ, Pred, MoveId, CandId} = _Msg,
362                     {join, JoinState, QueuedMessages} = State) ->
363      ?TRACE_JOIN1(_Msg, JoinState),
364      % only act on related messages, i.e. messages from the current candidate
365      Phase = get_phase(JoinState),
366      State1 = case get_candidates(JoinState) of
367          [] when Phase =:= phase4 -> % no candidates -> should not happen in phase4!
368              log:log(error, "[ Node ~w ] empty candidate list in join phase 4, "
369                          "starting over", [self()]),
370              NewJoinState = start_over(JoinState),
371              ?TRACE_JOIN_STATE(NewJoinState),
372              {join, NewJoinState, QueuedMessages};
373          [] -> State; % in all other phases, ignore the delayed join_response
374                       % if no candidates exist
375          [Candidate | _Rest] ->
376              CandidateNode = node_details:get(lb_op:get(Candidate, n1succ_new), node),
377              CandidateNodeSame = node:same_process(CandidateNode, Succ),
378              case lb_op:get(Candidate, id) =:= CandId of
379                  false ->
380                      log:log(warn, "[ Node ~w ] ignoring old or unrelated "
381                                  "join_response message", [self()]),
382                      State; % ignore old/unrelated message
383                  _ when not CandidateNodeSame ->
384                      % id is correct but the node is not (should never happen!)
385                      log:log(error, "[ Node ~w ] got join_response but the node "
386                                  "changed, trying next candidate", [self()]),
387                      NewJoinState = try_next_candidate(JoinState),
388                      ?TRACE_JOIN_STATE(NewJoinState),
389                      {join, NewJoinState, QueuedMessages};
390                  _ ->
391                      MyId = node_details:get(lb_op:get(Candidate, n1_new), new_key),
392                      MyIdVersion = get_id_version(JoinState),
393                      case MyId =:= node:id(Succ) orelse MyId =:= node:id(Pred) of
```

```
394                         true ->
395                             log:log(warn, "[ Node ~w ] chosen ID already exists , "
396                                             "trying next candidate", [self()]),
397                             % note: can not keep Id, even if skip_psv_lb is set
398                             JoinState1 = remove_candidate_front(JoinState),
399                             NewJoinState = contact_best_candidate(JoinState1),
400                             ?TRACE_JOIN_STATE(NewJoinState),
401                             {join, NewJoinState, QueuedMessages};
402                         _ ->
403                             ?TRACE("[ ~.0p ]~n  joined MyId:~.0p, MyIdVersion:~.0p~n  "
404                                             "Succ: ~.0p~n  Pred: ~.0p~n",
405                                             [self(), MyId, MyIdVersion, Succ, Pred]),
406                             Me = node:new(comm:this(), MyId, MyIdVersion),
407                             log:log(info, "[ Node ~w ] joined between ~w and ~w",
408                                     [self(), Pred, Succ]),
409                             rm_loop:notify_new_succ(node:pidX(Pred), Me),
410                             rm_loop:notify_new_pred(node:pidX(Succ), Me),
411
412                             finish_join_and_slide(Me, Pred, Succ, ?DB:new(),
413                                                     QueuedMessages, MoveId)
414                     end
415             end
416     end,
417     State1;
```

File `dht_node_join.erl`:

```
891 %% @doc Finishes the join and sends all queued messages.
892 -spec finish_join(Me::node:node_type(), Pred::node:node_type(),
893                   Succ::node:node_type(), DB::?DB:db(),
894                   QueuedMessages::msg_queue:msg_queue())
895        -> dht_node_state:state().
896 finish_join(Me, Pred, Succ, DB, QueuedMessages) ->
897     RMState = rm_loop:init(Me, Pred, Succ),
898     Neighbors = rm_loop:get_neighbors(RMState),
899     % wait for the ring maintenance to initialize and tell us its table ID
900     rt_loop:activate(Neighbors),
901     cyclon:activate(),
902     vivaldi:activate(),
903     dc_clustering:activate(),
904     gossip:activate(node:mk_interval_between_nodes(Pred, Me)),
905     dht_node_reregister:activate(),
906     msg_queue:send(QueuedMessages),
907     NewRT_ext = ?RT:empty_ext(Neighbors),
908     dht_node_state:new(NewRT_ext, RMState, DB).
909
910 %% @doc Finishes the join by setting up a slide operation to get the data from
911 %%      the other node and sends all queued messages.
912 -spec finish_join_and_slide(Me::node:node_type(), Pred::node:node_type(),
913                   Succ::node:node_type(), DB::?DB:db(),
914                   QueuedMessages::msg_queue:msg_queue(), MoveId::slide_op:id())
915        -> {'$gen_component', [{on_handler, Handler::on}],
916            State::dht_node_state:state()}.
917 finish_join_and_slide(Me, Pred, Succ, DB, QueuedMessages, MoveId) ->
918     State = finish_join(Me, Pred, Succ, DB, QueuedMessages),
919     SlideOp = slide_op:new_receiving_slide_join(MoveId, Pred, Succ, node:id(Me), join),
920     SlideOp1 = slide_op:set_phase(SlideOp, wait_for_node_update),
921     State1 = dht_node_state:set_slide(State, succ, SlideOp1),
922     State2 = dht_node_state:add_msg_fwd(
923                 State1, slide_op:get_interval(SlideOp1),
924                 node:pidX(slide_op:get_node(SlideOp1))),
925     RMSubscrTag = {move, slide_op:get_id(SlideOp1)},
926     comm:send_local(self(), {move, node_update, RMSubscrTag}),
927     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 38.

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.

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.

---

[2]set by the `join_request_timeouts` config parameter

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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