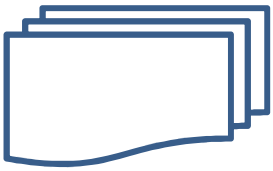
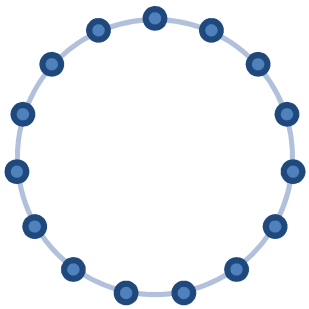
TRANSACTIONS





Scalaris:

Users and Developers Guide

Version 0.2.0 draft December 16, 2010

Contents

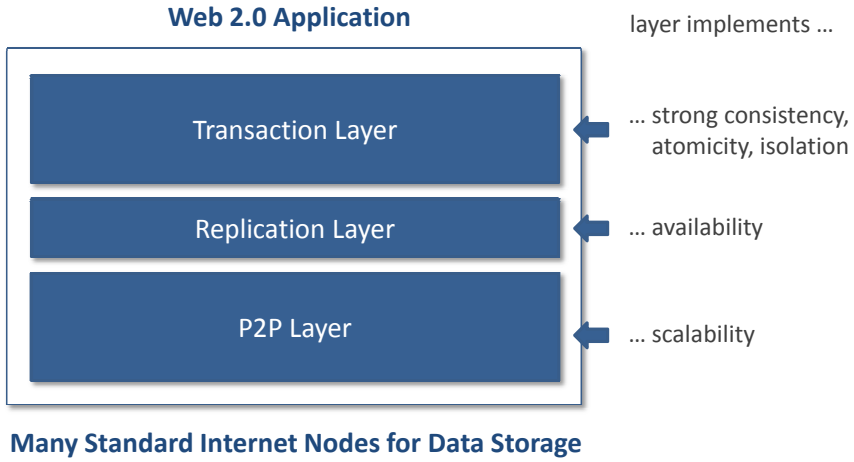
Part I

Users Guide

1 Introduction

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

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



Scalaris takes care of:

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

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

1.1 Brewer's CAP Theorem

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

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

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

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

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

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

1.2 Scientific Background

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

The main routines of our Chord node are in `src/dht_node.erl` and the join protocol is implemented in `src/dht_node_join.erl` (see also Chap. [**?**]). Our implementation of the routing algorithms is described in more detail in Sect. 8.3 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].

We have currently two generations of transaction algorithms. The older one is in `src/transstore`. The newer one is more modular. It provides an implementation of the paxos algorithm in `src/paxos` and the transaction algorithms itself in `src/transactions` (see also Chap. 9).

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`.

2 Download and Installation

2.1 Requirements

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

- Erlang R13B01 or newer
- GNU-like Make

To build the Java API (and the command-line client) the following modules are required additionally:

- 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.

2.2 Download

The sources can be obtained from http://code.google.com/p/scalaris. RPMs and DEBs are available from http://download.opensuse.org/repositories/home:/tschuett/.

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 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)

% {boot_host, {boot,'boot@foo.bar.com'}}.
% {known_hosts, [{service_per_vm, 'boot@foo.bar.com'}]}.

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

% Insert the appropriate IP-addresses for your setup
% as comma separated integers:
% IP Address, Port, and label of the boot server
{boot_host, {{127,0,0,1},14195,boot}}.

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

Scalaris currently distinguishes two different kinds of nodes: (a) the boot-server and (b) regular nodes. For the moment, we limit the number of boot-servers to exactly one. The remaining nodes are regular nodes. The boot-server is contacted to join the system. On all servers, the `boot_host` option defines the server where the boot server is running. In the example, it is an IP address plus a TCP port.

2.4 Build

2.4.1 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.

2.4.2 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 `boot.bat`, `cs_local.bat`, `cs_local2.bat` and `cs_local3.bat`
- run `boot.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.

2.4.3 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
```

2.5 Running Scalaris

As mentioned above, in Scalaris there are two kinds of nodes:

- boot servers
- regular nodes

In every Scalaris, at least one boot server is required. It will maintain a list of nodes taking part in the system and allows other nodes to join the ring. For redundancy, it is also possible to have several boot servers. In the future, we want to eliminate this distinction, so any node is also a boot-server.

2.5.1 Running on a local machine

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

```
%> ./bin/boot.sh
```

This will start the boot server. On success http://localhost:8000 should point to the management interface page of the boot server. The main page will show you the number of nodes currently in

the system. After a couple of seconds a first Scalaris should have started in the boot server and the number should increase to one. 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 Chapter 3 on page 13 for application APIs.

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

```
%> ./bin/cs_local.sh
```

The second node will read the configuration file and use this information to contact the boot server and join the ring. 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/cs_local2.sh
```

In a fourth shell:

```
%> ./bin/cs_local3.sh
```

This will add 3 nodes to the network. The web pages at `http://localhost:8000` should show the additional nodes.

On linux you can also use the `scalarisctl` script to start boot and 'regular' nodes.

2.5.2 Running distributed

Scalaris can be installed on other machines in the same way as described in Section 2.6. In the default configuration, nodes will look for the boot server on `localhost` on port 14195. You should create a `scalaris.local.cfg` pointing to the node running the boot server.

```
% Insert the appropriate IP-addresses for your setup
% as comma separated integers:
% IP Address, Port, and label of the boot server
{boot_host, {{127,0,0,1},14195,boot}}.
```

If you are using the default configuration on the boot server it will listen on port 14195 and you only have to change the IP address in the configuration file. Otherwise the other nodes will not find the boot server. On the remote nodes, you only need to call `./cs_local.sh` and they will automatically contact the configured boot server.

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

- Fedora 9, 10, 11, 12, 13,
- Mandriva 2008, 2009, 2009.1, 2010,
- openSUSE 11.0, 11.1, 11.2, 11.3, Factory,
- SLE 10, 11,
- CentOS 5.4,
- RHEL 5,
- Debian 5.0 and
- Ubuntu 9.04, 9.10, 10.04.

Inside those repositories you will also find an erlang package - you don't need this if you already have a recent enough erlang version!

2.7 Logging

Description is based on SVN revision r1083.

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 10.2 on page 42, 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 Using the system

3.1 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`). The following example illustrates the message flow:

Client → **Scalaris node**

Make a transaction, that sets two keys:

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

← Scalaris sends results back

```
{ "result":
  { "results":
      [
        { "op":"commit",
          "value":"ok",
          "key":"ok" },
        { "op":"write",
          "value":"valueB",
          "key":"keyB" },
        { "op":"write",
          "value":"valueA",
          "key":"keyA" }
      ],
    "translog":
     [...]
  },
  "id" : 0
}
```

In a second transaction: Read the two keys →

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

← Scalaris sends results back

```
{ "result":
  {"results":
    [
      { "op":"read",
        "value":"valueB",
        "key":"keyB" },
      { "op":"read",
        "value":"valueA",
        "key":"keyA" }
    ],
   "translog":
    [...] // this list is the translog
          // for further operations!
          // We name it TLOG here.
  },
  "id" : 0
}
```

Calculate something with the read values and make further requests, here a write and the commit for the whole transaction. Also include the latest translog we got from Scalaris (named `TLOG` here).

→

```
{
  "method":"req_list",
  "version":"1.1",
  "params":
    [
      TLOG, // translog from prev. result
      [
        { "write":{"keyA":"valueA2"} },
        { "commit":"commit" }
      ]
    ],
  "id" : 0
}
```

← Scalaris sends results back

```
{ "result":
  { "results":
    [ { "op":"commit",
        "value":"ok",
        "key":"ok" },
      { "op":"write",
        "value":"valueA2",
        "key":"keyA" }
    ],
    "translog":
    [...]
  },
  "id" : 0
}
```

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

A single request list must not contain a key more than once!

The allowed requests are:

```
{ "read":"any_key" }

{ "write":{"any_key":"any_value"} }

{ "commit":"commit" }
```

The possible results are:

```
{ "op":"read", "key":"any_key", "value":"any_value" }
{ "op":"read", "key":"any_value", "fail":"reason" } // 'not_found' or 'timeout'

{ "op":"write",  "key":"any_key", "value":"any_value" }
{ "op":"read", "key":"any_key", "fail":"reason" }

{ "op":"commit", "value":"ok", "key":"ok" }
{ "op":"commit", "value":"fail", "fail":"reason" }
```

3.1.1 Deleting a key

Outside transactions keys can also be deleted, but it has to be done with care, as explained in the following thread on the mailing list: http://groups.google.com/group/scalaris/browse_thread/thread/ff1d9237e218799.

```
{
  "method":"delete",
  "version":"1.1",
  "params":
    [
      { "key":"any_key" }
    ],
  "id" : 0
}
```

Two sample results

```
{ "result":
  { "ok":2, // how many replicas were deleted successsfully
    "results": [ "ok", "ok", "locks_set", "undef" ]
  }
}
```

```
{ "result":
  { "failure":"reason" }
}
```

3.2 Java command line interface

The 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
Script Options:
  --help, --h             print this message and scalaris help
  --noconfig              suppress sourcing of /etc/scalaris/scalaris-java.conf
                          and $HOME/.scalaris/scalaris-java.conf config files
  --execdebug             print scalaris exec line generated by this
                          launch script

usage: scalaris [Options]
 -b,--minibench                    run mini benchmark
 -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 boot 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`.

3.3 Java API

The `scalaris.jar` provides the 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 we refer the reader to the Javadoc:

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

4 Testing the system

4.1 Running the unit tests

There are some unit tests in the `test` directory. 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 3 minutes, depending on your machine. Only if the complete suite finishes, it will present statistics on failed and successful tests.

5 Troubleshooting

5.1 Network

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

8000	HTTP Server on the boot node
8001	HTTP Server on the other nodes
14195	Port for inter-node communication (boot server)
14196	Port for inter-node communication (other nodes)

Please make sure that at least 14195 and 14196 are not blocked by firewalls.

Part II

Developers Guide

6 General Hints

6.1 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.

6.2 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/boot.sh` and run the tests by `cd java; ant test`)
- Run the Ruby client by starting Scalaris and running `cd contrib; ./jsonrpc.rb`

6.3 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 `boot_server:number_of_nodes(). flush().`
- use `admin_checkring(). flush().`

7 System Infrastructure

7.1 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)

7.2 The Communication Layer `comm`

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

7.3 The `gen_component`

Description is based on SVN revision r993.

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`).

7.3.1 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`:

```
49 -spec behaviour_info(atom()) -> [{atom(), arity()}] | undefined.
50 behaviour_info(callbacks) ->
51     [
52      {init, 1}      % initialize component
53      % note: can use arbitrary on-handler, but by default on/2 is used:
54 %%       {on, 2}         % handle a single message
55 %%                       % on(Msg, State) -> NewState | unknown_event | kill
56     ];
```

This is illustrated by the following example:

File `idholder.erl`:

```
73 %% @doc Initialises the idholder with a random key and a counter of 0.
74 -spec init([{{idholder, id}, Id::?RT:key()} | tuple()]) -> state().
75 init(Options) ->
76     Id = case lists:keyfind({idholder, id}, 1, Options) of
77              {{idholder, id}, IdX} -> IdX;
78              _ -> ?RT:get_random_node_id()
79          end,
80     log:log(info, "[ idholder ~w ] init: ~p", [comm:this(), Id]),
81     {Id, 0}.
82
83 -spec on(message(), state()) -> state().
84 on({reinit}, _State) ->
85     {?RT:get_random_node_id(), 0};
86 on({get_id, PID}, {Id, IdVersion} = State) ->
87     comm:send_local(PID, {idholder_get_id_response, Id, IdVersion}),
88     State;
89 on({set_id, NewId, NewIdVersion}, _State) ->
90     {NewId, NewIdVersion};
91 on({web_debug_info, Requestor}, {Id, IdVersion} = State) ->
92     KeyValueList =
93         [{"id", lists:flatten(io_lib:format("~p", [Id]))},
94          {"id_version", lists:flatten(io_lib:format("~p", [IdVersion]))}],
95     comm:send_local(Requestor, {web_debug_info_reply, KeyValueList}),
96     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 7.3.6). 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`.

7.3.2 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}.

7.3.3 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.

7.3.4 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 7.1) 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.

7.3.5 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.

7.3.6 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.

7.3.7 Halting and pausing a `gen_component`

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

7.3.8 Integration with `pid_groups`: Redirecting events / 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 7.1) 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.

7.3.9 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.

7.3.10 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 7.2 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`:

```
223 -spec(prop_rnd_interleave/3 :: (1..4, 4..16, {pos_integer(), pos_integer(), pos_integer()})
224  -> boolean()).
225 prop_rnd_interleave(NumProposers, NumAcceptors, Seed) ->
226     ct:pal("Called with: paxos_SUITE:prop_rnd_interleave(~p, ~p, ~p).~n",
227            [NumProposers, NumAcceptors, Seed]),
228     Majority = NumAcceptors div 2 + 1,
229     {Proposers, Acceptors, Learners} =
230         make(NumProposers, NumAcceptors, 1, rnd_interleave),
231     %% set bp on all processes
232     [ gen_component:bp_set(element(3, X), proposer_initialize, bp)
233       ||  X <- Proposers],
234     [ gen_component:bp_set(element(3, X), acceptor_initialize, bp)
235       ||  X <- Acceptors ],
236     [ gen_component:bp_set(element(3, X), learner_initialize, bp)
237       || X <- Learners],
238     %% start paxos instances
239     [ proposer:start_paxosid(X, paxidrndinterl, Acceptors,
240                              proposal, Majority, NumProposers, Y)
241       || {X,Y} <- lists:zip(Proposers, lists:seq(1, NumProposers)) ],
242     [ acceptor:start_paxosid(X, paxidrndinterl, Learners)
243       || X <- Acceptors ],
244     [ learner:start_paxosid(X, paxidrndinterl, Majority,
245                             comm:this(), cpaxidrndinterl)
246       || X <- Learners],
247     %% randomly step through protocol
248     OldSeed = random:seed(Seed),
249     Steps = step_until_decide(Proposers ++ Acceptors ++ Learners, cpaxidrndinterl, 0),
250     ct:pal("Needed ~p steps~n", [Steps]),
251     case OldSeed of
252         undefined -> ok;
253         _ -> random:seed(OldSeed)
254     end,
255     true.
256
257 step_until_decide(Processes, PaxId, SumSteps) ->
258     %% io:format("Step ~p~n", [SumSteps]),
259     Runnable = [ X || X <- Processes, gen_component:runnable(element(3,X)) ],
260     case Runnable of
261         [] ->
262             ct:pal("No runnable processes of ~p~n", [length(Processes)]),
263             timer:sleep(5), step_until_decide(Processes, PaxId, SumSteps);
264         _ -> ok
265     end,
266     Num = random:uniform(length(Runnable)),
267     gen_component:bp_step(element(3,lists:nth(Num, Runnable))),
268     receive
269         {learner_decide, cpaxidrndinterl, _, _Res} = _Any ->
270             %% io:format("Received ~p~n", [_Any]),
271             SumSteps
272     after 0 -> step_until_decide(Processes, PaxId, SumSteps + 1)
273     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`:

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

7.3.11 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.

7.4 The Process' Database (`pdb`)

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

7.5 Writing Unittests

7.5.1 Plain unittests

7.5.2 Randomized Testing using `tester.erl`

8 Basic Structured Overlay

8.1 Ring Maintenance

8.2 T-Man

8.3 Routing Tables

Description is based on SVN revision r1236.

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 `lookup.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`:

```
28 %% @doc Find the node responsible for Key and send him the message Msg.
29 -spec lookup_aux(State::dht_node_state:state(), Key::intervals:key(),
30                  Hops::non_neg_integer(), Msg::comm:message()) -> ok.
31 lookup_aux(State, Key, Hops, Msg) ->
32     case intervals:in(Key, dht_node_state:get(State, succ_range)) of
33         true -> % found node -> terminate
34             P = dht_node_state:get(State, succ_pid),
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`:

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

```
33 -spec behaviour_info(atom()) -> [{atom(), arity()}] | undefined.
34 behaviour_info(callbacks) ->
35     [
36      % create a default routing table
37      {empty, 1}, {empty_ext, 1},
38      % mapping: key space -> identifier space
39      {hash_key, 1}, {get_random_node_id, 0},
40      % routing
41      {next_hop, 2},
42      % trigger for new stabilization round
43      {init_stabilize, 2},
44      % adapt RT to changed neighborhood
45      {update, 3},
46      % dead nodes filtering
47      {filter_dead_node, 2},
48      % statistics
49      {to_pid_list, 1}, {get_size, 1},
50      % gets all (replicated) keys for a given (hashed) key
51      % (for symmetric replication)
52      {get_replica_keys, 1},
53      % address space size, range and split key
54      % (may all throw 'throw:not_supported' if unsupported by the RT)
55      {n, 0}, {get_range, 2}, {get_split_key, 2},
56      % for debugging and web interface
57      {dump, 1},
58      % for bulkowner
59      {to_list, 1},
60      % convert from internal representation to version for dht_node
61      {export_rt_to_dht_node, 2},
62      % handle messages specific to a certain routing-table implementation
63      {handle_custom_message, 2},
64      % common methods
65      {check, 4}, {check, 5},
66      {check_config, 0}
67     ];
```

`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/2` 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.

8.3.1 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`:

```
41 -opaque(state_active() :: {NeighbTable  :: tid(),
42                            RTState      :: ?RT:rt(),
43                            TriggerState :: trigger:state()}).
```

```
44 -type(state_inactive() :: {inactive,
45                            MessageQueue::msg_queue:msg_queue(),
46                            TriggerState::trigger:state()}).
47 %% -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`:

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

```
139 % update routing table with changed ID, pred and/or succ
140 on_active({update_rt, OldNeighbors}, {NeighbTable, OldRT, TriggerState}) ->
141     NewNeighbors = rm_loop:get_neighbors(NeighbTable),
142     case ?RT:update(OldRT, OldNeighbors, NewNeighbors) of
143         {trigger_rebuild, NewRT} ->
144             % trigger immediate rebuild
145             NewTriggerState = trigger:now(TriggerState),
146             ?RT:check(OldRT, NewRT, OldNeighbors, NewNeighbors, true),
147             new_state(NeighbTable, NewRT, NewTriggerState);
148         {ok, NewRT} ->
149             ?RT:check(OldRT, NewRT, OldNeighbors, NewNeighbors, true),
150             new_state(NeighbTable, NewRT, TriggerState)
151     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 re-build. If so, it will stop any waiting trigger and schedule an immideate (periodic) stabilization.

8.3.2 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`:

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

```
29 -type external_rt_t() :: Succ::node:node_type().
30 -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`:

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

File `rt_simple.erl`:

```
207 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`:

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

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

File `rt_simple.erl`:

```
211 %% @doc Returns the next hop to contact for a lookup.
212 next_hop(State, _Key) -> node:pidX(dht_node_state:get(State, rt)).
```

Next hop is always the successor.

File `rt_simple.erl`:

```
77 %% @doc Triggered by a new stabilization round, renews the routing table.
78 init_stabilize(Neighbors, _RT) -> empty(Neighbors).
```

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

File `rt_simple.erl`:

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

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

File `rt_simple.erl`:

```
90  %% @doc Removes dead nodes from the routing table (rely on periodic
91  %%      stabilization here).
92  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`:

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

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

File `rt_simple.erl`:

```
101 %% @doc Returns the size of the routing table.
102 get_size(_RT) -> 1.
```

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

File `rt_simple.erl`:

```
139 %% @doc Returns the replicas of the given key.
140 get_replica_keys(Key) ->
141     [Key,
142      Key bxor 16#40000000000000000000000000000000,
143      Key bxor 16#80000000000000000000000000000000,
144      Key bxor 16#C0000000000000000000000000000000
145     ].
```

This `get_replica_keys/1` implements symmetric replication.

File `rt_simple.erl`:

```
106 %% @doc Returns the size of the address space.
107 n() -> n_().
108 %% @doc Helper for n/0 to make dialyzer happy with internal use of n/0.
109 -spec n_() -> key_t().
110 n_() -> 16#100000000000000000000000000000000.
```

There are 2^{128} available keys.

File `rt_simple.erl`:

```
149 %% @doc Dumps the RT state for output in the web interface.
150 dump(Succ) -> [{"0", lists:flatten(io_lib:format("~p", [Succ]))}].
```

`dump/1` lists the successor.

File `rt_simple.erl`:

```
222 %% @doc Converts the (external) representation of the routing table to a list
223 %%      in the order of the fingers, i.e. first=succ, second=shortest finger,
224 %%      third=next longer finger,...
225 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:

```
216 %% @doc Converts the internal RT to the external RT used by the dht_node. Both
217 %%      are the same here.
218 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:

```
168 %% @doc There are no custom messages here.
169 -spec handle_custom_message
170         (custom_message() | any(), rt_loop:state_active()) -> unknown_event.
171 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:

```
175 %% @doc Notifies the dht_node and failure detector if the routing table changed.
176 %%      Provided for convenience (see check/5).
177 check(OldRT, NewRT, Neighbors, ReportToFD) ->
178     check(OldRT, NewRT, Neighbors, Neighbors, ReportToFD).
179
180 %% @doc Notifies the dht_node if the (external) routing table changed.
181 %%      Also updates the failure detector if ReportToFD is set.
182 %%      Note: the external routing table only changes the internal RT has
183 %%      changed.
184 check(OldRT, NewRT, _OldNeighbors, NewNeighbors, ReportToFD) ->
185     case OldRT =:= NewRT of
186         true -> ok;
187         _ ->
188             Pid = pid_groups:get_my(dht_node),
189             RT_ext = export_rt_to_dht_node(NewRT, NewNeighbors),
190             comm:send_local(Pid, {rt_update, RT_ext}),
191             % update failure detector:
192             case ReportToFD of
193                 true ->
194                     NewPids = to_pid_list(NewRT),
195                     OldPids = to_pid_list(OldRT),
196                     fd:update_subscriptions(OldPids, NewPids);
197                 _ -> ok
198             end
199     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).

8.3.3 Chord routing table (rt_chord)

The file rt_chord.erl implements Chord's routing.

Data types

File rt_chord.erl:

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

```
29 -type external_rt_t() :: gb_tree().
30 -type index() :: {pos_integer(), non_neg_integer()}.
31 -opaque custom_message() ::
32         {rt_get_node, Source_PID::comm:mypid(), Index::index()} |
33         {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`:

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

File `rt_chord.erl`:

```
274 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`:

```
278 %% @doc Returns the next hop to contact for a lookup.
279 %%      If the routing table has less entries than the rt_size_use_neighbors
280 %%      config parameter, the neighborhood is also searched in order to find a
281 %%      proper next hop.
282 %%      Note, that this code will be called from the dht_node process and
283 %%      it will thus have an external_rt!
284 next_hop(State, Id) ->
285     case intervals:in(Id, dht_node_state:get(State, succ_range)) of
286         true -> dht_node_state:get(State, succ_pid);
287         _ ->
288             % check routing table:
289     RT = dht_node_state:get(State, rt),
290             RTSize = get_size(RT),
291             NodeRT = case util:gb_trees_largest_smaller_than(Id, RT) of
292                          {value, _Key, N} ->
293                              N;
294                          nil when RTSize =:= 0 ->
295                              dht_node_state:get(State, succ);
296                          nil -> % forward to largest finger
297                              {_Key, N} = gb_trees:largest(RT),
298                              N
299                      end,
300             FinalNode =
301                 case RTSize < config:read(rt_size_use_neighbors) of
302                     false -> NodeRT;
303                     _     ->
304                         % check neighborhood:
305                         nodelist:largest_smaller_than(
306                           dht_node_state:get(State, neighbors), Id, NodeRT)
307                 end,
308             node:pidX(FinalNode)
309     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`:

```
78  %% @doc Starts the stabilization routine.
79  init_stabilize(Neighbors, RT) ->
80      % calculate the longest finger
81      Id = nodelist:nodeid(Neighbors),
82      Key = calculateKey(Id, first_index()),
83      % trigger a lookup for Key
84      lookup:unreliable_lookup(Key, {send_to_group_member, routing_table,
85                                     {rt_get_node, comm:this(), first_index()}}),
86      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`:

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

File `rt_chord.erl`:

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

```
167     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`:

```
171 %% @doc Updates the routing table due to a changed node ID, pred and/or succ.
172 -spec update(OldRT::rt(), OldNeighbors::nodelist:neighborhood(),
173               NewNeighbors::nodelist:neighborhood()) -> {trigger_rebuild, rt()}.
174 update(_OldRT, _OldNeighbors, NewNeighbors) ->
175     % to be on the safe side ...
176     {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`:

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

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

File `rt_chord.erl`:

```
313 export_rt_to_dht_node(RT, Neighbors) ->
314     Id = nodelist:nodeid(Neighbors),
315     Pred = nodelist:pred(Neighbors),
316     Succ = nodelist:succ(Neighbors),
317     Tree = gb_trees:enter(node:id(Succ), Succ,
318                           gb_trees:enter(node:id(Pred), Pred, gb_trees:empty())),
319     util:gb_trees_foldl(fun (_K, V, Acc) ->
320                                 % only store the ring id and the according node structure
321                                 case node:id(V) =:= Id of
322                                     true  -> Acc;
323                                     false -> gb_trees:enter(node:id(V), V, Acc)
324                                 end
325                         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`:

```
240 %% @doc Notifies the dht_node and failure detector if the routing table changed.
241 %%      Provided for convenience (see check/5).
242 check(OldRT, NewRT, Neighbors, ReportToFD) ->
243     check(OldRT, NewRT, Neighbors, Neighbors, ReportToFD).
244
245 %% @doc Notifies the dht_node if the (external) routing table changed.
246 %%      Also updates the failure detector if ReportToFD is set.
247 %%      Note: the external routing table also changes if the Pred or Succ
248 %%      change.
249 check(OldRT, NewRT, OldNeighbors, NewNeighbors, ReportToFD) ->
250     case OldRT =:= NewRT andalso
```

```
251                 nodelist:pred(OldNeighbors) =:= nodelist:pred(NewNeighbors) andalso
252                 nodelist:succ(OldNeighbors) =:= nodelist:succ(NewNeighbors) of
253             true -> ok;
254             _ ->
255                 Pid = pid_groups:get_my(dht_node),
256                 RT_ext = export_rt_to_dht_node(NewRT, NewNeighbors),
257                 comm:send_local(Pid, {rt_update, RT_ext}),
258                 % update failure detector:
259                 case ReportToFD of
260                     true ->
261                         NewPids = to_pid_list(NewRT),
262                         OldPids = to_pid_list(OldRT),
263                         fd:update_subscriptions(OldPids, NewPids);
264                     _ -> ok
265                 end
266     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).

8.4 Local Datastore

8.5 Cyclon

8.6 Vivaldi Coordinates

8.7 Estimated Global Information (Gossiping)

8.8 Load Balancing

8.9 Broadcast Trees

9 Transactions in Scalaris

9.1 The Paxos Module

9.2 Transactions using Paxos Commit

9.3 Applying the Tx-Modules to replicated DHTs

Introduces transaction processing on top of a Overlay

10 How a node joins the system

10.1 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.

10.2 Starting additional local nodes after boot

Description is based on SVN revision r1267.

After booting a new Scalaris-System as described in Section 2.5.1 on page 10, ten additional local nodes can be started by typing `admin:add_nodes(10)` in the Erlang-Shell that the boot process opened [1].

```
scalaris> ./bin/boot.sh
[...]
(boot@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(int)` is defined as follows.

File `admin.erl`:

```
38 % @doc add new Scalaris nodes on the local node
39 -spec add_node_at_id(?RT:key()) -> ok.
40 add_node_at_id(Id) ->
41     add_node([{{idholder, id}, Id}]).
42
43 -spec add_node([tuple()]) -> ok.
44 add_node(Options) ->
45     DhtNodeId = randoms:getRandomId(),
46     Desc = util:sup_supervisor_desc(
47               DhtNodeId, config:read(dht_node_sup), start_link,
48               [[{my_sup_dht_node_id, DhtNodeId} | Options]]),
49     supervisor:start_child(main_sup, Desc),
50     ok.
51
```

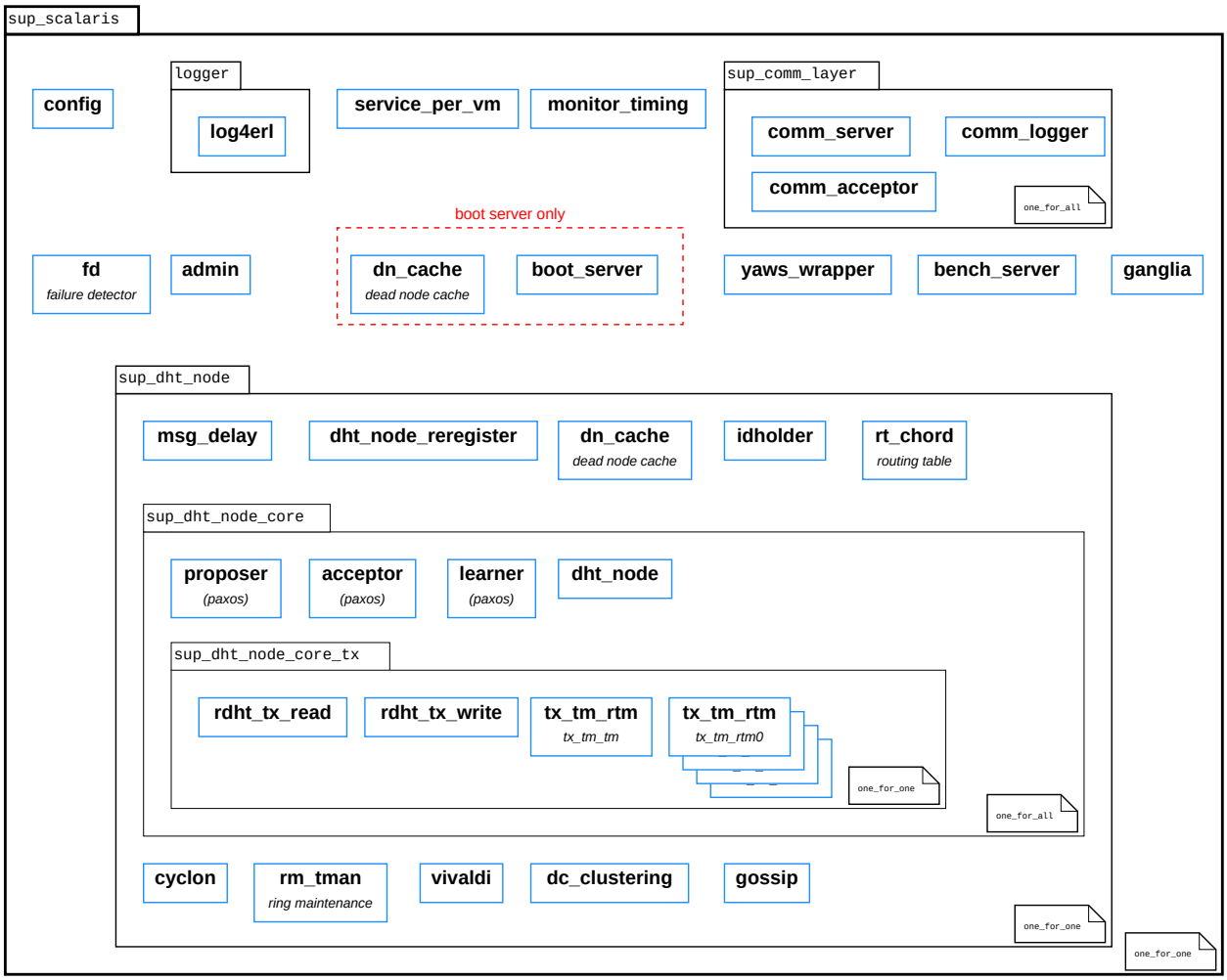
[1] Increase the log level to `info` to get more detailed startup logs. See Section 2.7 on page 12

```
52 -spec add_nodes(non_neg_integer()) -> ok.
53 add_nodes(0) -> ok;
54 add_nodes(Count) ->
55     add_node([]),
56     add_nodes(Count - 1).
```

It calls `admin:add_node([])` Count times. This function starts a new child with the given options for the main supervisor `main_sup`. As defined by the parameters, 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`.

10.2.1 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.

10.2.2 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 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`:

```
45 -spec init([tuple()]) -> {ok, {{one_for_one, MaxRetries::pos_integer(),
46                                  PeriodInSeconds::pos_integer()},
47                                 [ProcessDescr::any()]}}.
48 init(Options) ->
49     DHTNodeGroup = pid_groups:new("dht_node_"),
50     pid_groups:join_as(DHTNodeGroup, ?MODULE),
51     boot_server:connect(),
52
53     Cyclon = util:sup_worker_desc(cyclon, cyclon, start_link, [DHTNodeGroup]),
54     DC_Clustering =
55         util:sup_worker_desc(dc_clustering, dc_clustering, start_link,
56                              [DHTNodeGroup]),
57     DeadNodeCache =
58         util:sup_worker_desc(deadnodecache, dn_cache, start_link,
59                              [DHTNodeGroup]),
60     Delayer =
61         util:sup_worker_desc(msg_delay, msg_delay, start_link,
62                              [DHTNodeGroup]),
63     Gossip =
64         util:sup_worker_desc(gossip, gossip, start_link, [DHTNodeGroup]),
65     IdHolder =
66         util:sup_worker_desc(idholder, idholder, start_link,
67                              [DHTNodeGroup, Options]),
68     Reregister =
69         util:sup_worker_desc(dht_node_reregister, dht_node_reregister,
70                              start_link, [DHTNodeGroup]),
71     RingMaintenance =
72         util:sup_worker_desc(ring_maintenance, rm_loop, start_link, [DHTNodeGroup]),
73     RoutingTable =
74         util:sup_worker_desc(routing_table, rt_loop, start_link,
75                              [DHTNodeGroup]),
76     SupDHTNodeCore_AND =
77         util:sup_supervisor_desc(sup_dht_node_core, sup_dht_node_core,
78                                  start_link, [DHTNodeGroup, Options]),
79     Vivaldi =
80         util:sup_worker_desc(vivaldi, vivaldi, start_link, [DHTNodeGroup]),
81
82     %% order in the following list is the start order
83     {ok, {{one_for_one, 10, 1},
84           [
85            Delayer,
86            Reregister,
87            DeadNodeCache,
88            IdHolder,
89            RingMaintenance,
90            RoutingTable,
91            Cyclon,
92            Vivaldi,
93            DC_Clustering,
94            Gossip,
95            SupDHTNodeCore_AND
96           ]}}.
```

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: `Delayer`, `Reregister`, `DeadNodeCache`, `IdHolder`, `RoutingTable`, `SupDHTNodeCore_AND`, `Cyclon`, `RingMaintenance`, `Vivaldi`, `DC_Clustering` and a `Gossip` 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.

The `sup_dht_node:init/1` is finished and 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.

10.2.3 Starting the sup_dht_node_core supervisor with a peer and some paxos processes

Similarly, the supervisor will call the `sup_dht_node_core:init/1` function:

File `sup_dht_node_core.erl`:

```
41 -spec init({pid_groups:groupname(), Options::[tuple()]}) ->
42                   {ok, {{one_for_all, MaxRetries::pos_integer(),
43                          PeriodInSeconds::pos_integer()},
44                         [ProcessDescr::any()]}}.
45 init({DHTNodeGroup, Options}) ->
46     pid_groups:join_as(DHTNodeGroup, ?MODULE),
47     Proposer =
48         util:sup_worker_desc(proposer, proposer, start_link, [DHTNodeGroup]),
49     Acceptor =
50         util:sup_worker_desc(acceptor, acceptor, start_link, [DHTNodeGroup]),
51     Learner =
52         util:sup_worker_desc(learner, learner, start_link, [DHTNodeGroup]),
53     DHTNode =
54         util:sup_worker_desc(dht_node, dht_node, start_link,
55                              [DHTNodeGroup, Options]),
56     TX =
57         util:sup_supervisor_desc(sup_dht_node_core_tx, sup_dht_node_core_tx, start_link,
58                                  [DHTNodeGroup]),
59     {ok, {{one_for_all, 10, 1},
60           [
61            Proposer, Acceptor, Learner,
62            DHTNode,
63            TX
64           ]}}.
```

It defines five processes, that have to be observed using an `one_for_all`-supervisor, which means, that if one fails, all have to be restarted. Passed to the `init` function is the processes' group that is used with the `pid_groups` module and 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]).
```

`dht_node` implements the `gen_component` behaviour. This component 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, the component 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`).

10.2.4 Initializing a `dht_node`-process

File `dht_node.erl`:

```
372 %% @doc joins this node in the ring and calls the main loop
373 -spec init(Options::[tuple()]) -> {join, {as_first | phase1}, msg_queue:msg_queue()}.
374 init(Options) ->
375     {my_sup_dht_node_id, MySupDhtNode} = lists:keyfind(my_sup_dht_node_id, 1, Options),
376     erlang:put(my_sup_dht_node_id, MySupDhtNode),
377     % first node in this vm and also vm is marked as first
378     % or unit-test
379     case is_first(Options) of
380         true ->
381             trigger_known_nodes(),
382             idholder:get_id(),
383             {join, {as_first}, msg_queue:new()};
384         _ ->
385             idholder:get_id(),
386             {join, {phase1}, msg_queue:new()}
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 the `dht_node` is the first node, it will start immediately by triggering all known nodes (to initialize the comm layer) and entering the join process accordingly. The node also retrieves its `Id` from the idholder: `idholder:get_id()`. In the first call, a random identifier is returned, otherwise the latest set value. If the `dht_node`-process failed and is restarted by its supervisor, this call to the idholder ensures, that the node still keeps its `Id`, assuming that the idholder process is not failing. This is important for the load-balancing and for consistent responsibility of nodes to ensure consistent lookup in the structured overlay.

If a node changes its position in the ring for load-balancing, the idholder will be informed and the `dht_node` finishes itself. This triggers a restart of the corresponding database process via the and-supervisor. When the supervisor restarts both processes, they will retrieve the new position in the ring from the idholder and join the ring there.

10.2.5 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_msg(Message, State)`.

File `dht_node_join.erl`:

```
56 process_join_state({idholder_get_id_response, Id, IdVersion},
57                    {join, {as_first}, QueuedMessages}) ->
58     log:log(info, "[ Node ~w ] joining as first: ~p",[self(), Id]),
59     Me = node:new(comm:this(), Id, IdVersion),
60     % join complete, State is the first "State"
61     finish_join(Me, Me, Me, ?DB:new(), QueuedMessages);
```

If the ring is empty, the joining node is the only node in the ring and will be responsible for the whole key space. `join_first` just creates a new state for a Scalaris node consisting of an empty routing table, a successorlist containing itself, itself as its predecessor, a reference to itself, its responsibility area from `Id` to `Id` (the full ring), and a load balancing schema.

The state is defined in

File dht_node_state.erl:

```
66 -spec new(?RT:external_rt(), Neighbors::tid(), ?DB:db()) -> state().
67 new(RT, NeighbTable, DB) ->
68     #state{rt = RT,
69            neighbors = NeighbTable,
70            join_time = now(),
71            trans_log = #translog{tid_tm_mapping = dict:new(),
72                                  decided        = gb_trees:empty(),
73                                  undecided      = gb_trees:empty()
74                                 },
75            db = DB,
76            tx_tp_db = tx_tp:init(),
77            proposer = pid_groups:get_my(paxos_proposer)
78           }.
```

If a node joins an existing ring, it will at first try to contact all dht_node processes in any VM configured in known_hosts.

File dht_node_join.erl:

```
68 % 1. get my key
69 process_join_state({idholder_get_id_response, Id, IdVersion},
70                    {join, {phase1}, QueuedMessages}) ->
71     %io:format("p1: got key~n"),
72     log:log(info,"[ Node ~w ] joining",[self()]),
73     get_known_nodes(),
74     msg_delay:send_local(get_join_timeout() div 1000, self(), {join, timeout}),
75     {join, {phase2, Id, IdVersion}, QueuedMessages};
76
77 % 2. Find known hosts
78 process_join_state({join, known_hosts_timeout},
79                    {join, {phase2, _Id, _IdVersion}, _QueuedMessages} = State) ->
80     %io:format("p2: known hosts timeout~n"),
81     get_known_nodes(),
82     State;
83
84 process_join_state({get_dht_nodes_response, []},
85                    {join, {phase2, _Id, _IdVersion}, _QueuedMessages} = State) ->
86     %io:format("p2: got empty dht_nodes_response~n"),
87     % there is a VM with no nodes
88     State;
89
90 process_join_state({get_dht_nodes_response, Nodes = [_|_]},
91                    {join, {phase2, Id, IdVersion}, QueuedMessages} = State) ->
92     %io:format("p2: got dht_nodes_response ~p~n", [lists:delete(comm:this(), Nodes)]),
93     ContactNodes = [Node || Node <- Nodes, Node =/= comm:this()],
94     % note: lookup will start in phase 2 when it gets an empty ContactNodes list
95     case ContactNodes of
96         [] -> State;
97         _  -> lookup(Id, IdVersion, QueuedMessages, ContactNodes)
98     end;
```

These nodes will be send a lookup request for the node currently responsible for the new node's id – the successor for the joining node. If this lookup fails for some reason, it is tried again.

File dht_node_join.erl:

```
102 % 3. lookup my position
103 process_join_state({get_dht_nodes_response, Nodes = [_|_]},
104                    {join, {phase3, Id, IdVersion, ContactNodes}, QueuedMessages}) ->
105     % although in phase3, collect further nodes to contact
106     % (messages have been send anyway):
107     FurtherNodes = [Node || Node <- Nodes, Node =/= comm:this()],
108     {join, {phase3, Id, IdVersion, lists:append(ContactNodes, FurtherNodes)},
109      QueuedMessages};
110
111 process_join_state({join, lookup_timeout, Node},
```

```
112                     {join, {phase3, Id, IdVersion, ContactNodes}, QueuedMessages}) ->
113     %io:format("p3: lookup_timeout~n"),
114     lookup(Id, IdVersion, QueuedMessages,
115            [N || N <- ContactNodes, not node:same_process(N, Node)]);
116
117 process_join_state({join, get_node_response, Id, Succ},
118                     {join, {phase3, Id, IdVersion, ContactNodes}, QueuedMessages}) ->
119     %io:format("p3: lookup success~n"),
120     % got my successor
121     case Id =:= node:id(Succ) of
122         true ->
123             log:log(warn, "[ Node ~w ] chosen ID already exists, trying a "
124                     "new ID (~w retries)", [self(), IdVersion]),
125             try_new_id(IdVersion, QueuedMessages, ContactNodes);
126         _ ->
127             Me = node:new(comm:this(), Id, IdVersion),
128             send_join_request(Me, Succ, 0),
129             {join, {phase4, ContactNodes, Succ, Me}, QueuedMessages}
130     end;
```

If its (future) successor is found and the `Id` is not the same, this new node will send a `join_request` message including a reference to itself and the chosen `Id`. If the chosen `Id` already exists, i.e. it is the successor's `Id`, the node will try a new (randomly chosen) `Id`. Assuming the `join_request` message was send, it will be received by the existing node in `dht_node.erl`

File `dht_node.erl`:

```
73 on(Msg, State) when element(1, State) =:= join ->
74     dht_node_join:process_join_state(Msg, State);
75 on(Msg, State) when element(1, Msg) =:= join ->
76     dht_node_join:process_join_msg(Msg, State);
```

and trigger a call to `dht_node_join:process_join_msg/2` which will set up a slide operation with the new node or deny the request if it is not responsible for the key (anymore) any reply with a :

File `dht_node_join.erl`:

```
226 process_join_msg({join, join_request, NewPred}, State) when (not is_atom(NewPred)) ->
227     TargetId = node:id(NewPred),
228     % only reply to join request with keys in our range:
229     KeyInRange = dht_node_state:is_responsible(node:id(NewPred), State),
230     case KeyInRange andalso
231              dht_node_move:can_slide_pred(State, TargetId, {join, 'rcv'}) of
232         true ->
233             % TODO: implement step-wise join
234             MoveFullId = util:get_global_uid(),
235             SlideOp = slide_op:new_sending_slide_join(
236                         MoveFullId, NewPred, join, State),
237             SlideOp1 = slide_op:set_phase(SlideOp, wait_for_pred_update_join),
238             RMSubscrTag = {move, slide_op:get_id(SlideOp1)},
239             rm_loop:subscribe(self(), RMSubscrTag,
240                               fun(_OldNeighbors, NewNeighbors) ->
241                                       NewPred =:= nodelist:pred(NewNeighbors)
242                               end,
243                               fun dht_node_move:rm_notify_new_pred/4),
244             State1 = dht_node_state:add_db_range(
245                        State, slide_op:get_interval(SlideOp1)),
246             send_join_response(State1, SlideOp1, NewPred);
247         _ when not KeyInRange ->
248             comm:send(node:pidX(NewPred), {join, join_response, not_responsible,
249                                            dht_node_state:get(State, node)}),
250             State;
251         _ -> State
252     end;
253 process_join_msg({join, join_response_timeout, NewPred, MoveFullId}, State) ->
254     % almost the same as dht_node_move:safe_operation/5 but we tolerate wrong pred:
255     case dht_node_state:get_slide_op(State, MoveFullId) of
```

```
256         {pred, SlideOp} ->
257             ResponseReceived =
258                 lists:member(slide_op:get_phase(SlideOp),
259                              [wait_for_req_data, wait_for_pred_update_join]),
260             case (slide_op:get_timeouts(SlideOp) < 3) of
261                 _ when ResponseReceived -> State;
262                 true ->
263                     NewSlideOp = slide_op:inc_timeouts(SlideOp),
264                     send_join_response(State, NewSlideOp, NewPred);
265                 _ ->
266                     % abort the slide operation set up for the join:
267                     % (similar to dht_node_move:abort_slide/*)
268                     log:log(warn, "abort_join(op: ~p, reason: timeout)~n",
269                             [SlideOp]),
270                     slide_op:reset_timer(SlideOp), % reset previous timeouts
271                     RMSubscrTag = {move, slide_op:get_id(SlideOp)},
272                     rm_loop:unsubscribe(self(), RMSubscrTag),
273                     State1 = dht_node_state:rm_db_range(
274                                State, slide_op:get_interval(SlideOp)),
275                     dht_node_state:set_slide(State1, pred, null)
276             end;
277         not_found -> State
278     end;
```

File dht_node_join.erl:

```
341 -spec send_join_response(State::dht_node_state:state(),
342                          NewSlideOp::slide_op:slide_op(),
343                          NewPred::node:node_type())
344         -> dht_node_state:state().
345 send_join_response(State, SlideOp, NewPred) ->
346     MoveFullId = slide_op:get_id(SlideOp),
347     NewSlideOp = slide_op:set_timer(SlideOp, get_join_response_timeout(),
348                                     {join, join_response_timeout, NewPred, MoveFullId}),
349     MyOldPred = dht_node_state:get(State, pred),
350     comm:send(node:pidX(NewPred), {join, join_response, MyOldPred, MoveFullId}),
351     % no need to tell the ring maintenance -> the other node will trigger an update
352     % also this is better in case the other node dies during the join
353 %%      rm_loop:notify_new_pred(comm:this(), NewPred),
354     dht_node_state:set_slide(State, pred, NewSlideOp).
```

The joining node will receive the `join_response` message in phase 4 of the join protocol. If everything is ok, i.e. `MyKey` is unique, it will notify its ring maintenance process that it enters the ring, start all required processes and join the slide operation in order to receive data from the existing node. The macro `?RT` maps to the configured routing algorithm and `?RM` to the configured ring maintenance algorithm. It is defined in `include/scalaris.hrl`. For further details on the routing see Chapter 8.3 on page 30.

File dht_node_join.erl:

```
134 % 4. joining my neighbor
135 process_join_state({get_dht_nodes_response, Nodes = [_|_]},
136                    {join, {phase4, ContactNodes, Succ, Me}, QueuedMessages}) ->
137     % although in phase4, collect further nodes to contact
138     % (messages have been send anyway):
139     FurtherNodes = [Node || Node <- Nodes, Node =/= comm:this()],
140     {join, {phase4, lists:append(ContactNodes, FurtherNodes), Succ, Me}, QueuedMessages};
141
142 process_join_state({join, join_request_timeout, Timeouts},
143                    {join, {phase4, ContactNodes, Succ, Me}, QueuedMessages} = State) ->
144     case Timeouts < 3 of
145         true ->
146             send_join_request(Me, Succ, Timeouts + 1),
147             State;
148         _ ->
149             % no response from responsible node -> select new Id and try again
150             log:log(warn, "[ Node ~w ] no response on join request for the "
```

```
                    "chosen ID ~w, trying a new ID (~w retries)",
                     [self(), node:id(Me), node:id_version(Me)]),
            try_new_id(node:id_version(Me), QueuedMessages, ContactNodes)
    end;

process_join_state({join, join_response, not_responsible, Node},
                   {join, {phase4, ContactNodes, _Succ, Me}, QueuedMessages}) ->
    % the node we contacted is not responsible for our key (anymore)
    % -> start a new lookup (back to phase 3)
    lookup(node:id(Me), node:id_version(Me), QueuedMessages,
           [N || N <- ContactNodes, not node:same_process(N, Node)]);

process_join_state({join, join_response, Pred, MoveId},
                   {join, {phase4, ContactNodes, Succ, Me}, QueuedMessages}) ->
    %io:format("p4: join_response~n"),
    MyKey = node:id(Me),
    case MyKey =:= node:id(Succ) orelse MyKey =:= node:id(Pred) of
        true ->
            log:log(warn, "[ Node ~w ] chosen ID already exists, trying a "
                    "new ID (~w retries)", [self(), node:id_version(Me)]),
            try_new_id(node:id_version(Me), QueuedMessages, ContactNodes);
        _ ->
            log:log(info, "[ Node ~w ] joined between ~w and ~w", [self(), Pred, Succ]),
            rm_loop:notify_new_succ(node:pidX(Pred), Me),
            rm_loop:notify_new_pred(node:pidX(Succ), Me),

            State = finish_join(Me, Pred, Succ, ?DB:new(), QueuedMessages),
            SlideOp = slide_op:new_receiving_slide_join(MoveId, Pred, Succ, MyKey, join),
            SlideOp1 = slide_op:set_phase(SlideOp, wait_for_node_update),
            State1 = dht_node_state:set_slide(State, succ, SlideOp1),
            State2 = dht_node_state:add_msg_fwd(
                       State1, slide_op:get_interval(SlideOp1),
                       node:pidX(slide_op:get_node(SlideOp1))),
            RMSubscrTag = {move, slide_op:get_id(SlideOp1)},
            NewMsgQueue = msg_queue:add(QueuedMessages,
                                        {move, node_update, RMSubscrTag}),
            msg_queue:send(NewMsgQueue),
            State2
    end;
```

File `dht_node_join.erl`:

```
-spec finish_join(Me::node:node_type(), Pred::node:node_type(),
                  Succ::node:node_type(), DB::?DB:db(),
                  QueuedMessages::msg_queue:msg_queue())
        -> dht_node_state:state().
finish_join(Me, Pred, Succ, DB, QueuedMessages) ->
    rm_loop:activate(Me, Pred, Succ),
    % wait for the ring maintenance to initialize and tell us its table ID
    NeighbTable = rm_loop:get_neighbors_table(),
    rt_loop:activate(NeighbTable),
    cyclon:activate(),
    vivaldi:activate(),
    dc_clustering:activate(),
    gossip:activate(),
    dht_node_reregister:activate(),
    msg_queue:send(QueuedMessages),
    dht_node_state:new(?RT:empty_ext(rm_loop:get_neighbors(NeighbTable)), NeighbTable, DB).
```

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.

The `join_timeout` parameter in the config files defines an overall timeout for the whole join operation. If it takes longer than `join_timeout` ms, the join will be re-started using `dht_node_join:restart_join/2`

File `dht_node_join.erl`:

```
-spec restart_join(OldIdVersion::non_neg_integer(), QueuedMessages::msg_queue:msg_queue())
        -> {join, {phase1}, QueuedMessages::msg_queue:msg_queue()}.
restart_join(OldIdVersion, QueuedMessages) ->
    log:log(warn, "[ Node ~w ] join procedure taking longer than ~Bs, re-starting...",
            [self(), get_join_timeout()]),
    NewId = ?RT:get_random_node_id(),
    NewIdVersion = OldIdVersion + 1,
    idholder:set_id(NewId, NewIdVersion),
    idholder:get_id(),
    {join, {phase1}, QueuedMessages}.
```

11 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 boot services, 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

12 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).

We provide two kinds of APIs:

- high-level access with `de.zib.scalaris.Scalaris`
- low-level access with `de.zib.scalaris.Transaction`

The former provides general functions for reading, writing and deleting single key-value pairs and an API for the built-in PubSub-service. The latter allows the user to write custom transactions which can modify an arbitrary number of key-value pairs within one transaction.

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