

Chordy: a distributed hash table

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February 10, 2025

Introduction

In this assignment you will implement a distributed hash table following the Chord scheme. In order to understand what you're about to do you should have a basic understanding of Chord and preferably read the article "Chord: A Scalable Peer-to-peer Lookup Protocol for Internet Applications".

The first implementation will only maintain a ring structure; we will be able to add nodes in the ring but we will not add any elements to the store yet. Once we have a growing ring we will introduce a store where key-value pairs can be added. Adding and searching for values will only introduce a few new messages and one parameter to represent the store.

Moving forward we will add failure detection to the system. Each node will keep track of the liveness of its successor and predecessor, if they fail the ring must be repaired. If a predecessor dies we don't do very much but if our successor dies we have to contact the next in line. In Chord one will keep a list of potential successors but to keep things simple we will only keep track of one more successor.

Maintaining the ring in the face of failures is of course all well but if a node dies we will lose information. To solve this problem we will have to replicate the values in the store. We will introduce a simple replication scheme.

This assignment includes a number of coding and experimental milestones. On accomplishing each of them, the team must show their outcome to the professor during the practical sessions, so that he can track the progress and evaluate the team accordingly. The team can validate their coding milestones beforehand through the review questionnaires at ATENEA. This assignment also includes a number of open questions. The team must answer each of them through the questionnaire at ATENEA before the deadline (one week after the last session of the seminar).

1 Building a ring

Start this project implementing a module `node1`. It will be our first implementation that only handles a growing ring. It could be good to keep this very simple, to see what functionality introduces new messages.

1.1 Keys

Chord uses hashing of names to create unique keys for elements. We will not use a hash function, instead a random number generated is used when a new key is generated. We will thus not have any “names” only keys. A node that wants to join the network will generate a random number and we will hope that this is unique. This is ok for all of our purposes.

Module `key` implements two functions: `generate()` and `between(Key, From, To)`. The function `generate/0` will simply return a random number between 0 and $2^{30} - 1$ (we use 30-bit identifiers), that will be large enough for our test. Using a hash function such as SHA-1 would give us 160 bits but let's keep things simple. We use the Erlang module `rand` to generate random numbers.

```
-module(key).  
-export([generate/0, between/3]).  
  
-define(m, 30). % 30-bit identifiers  
  
generate() ->  
    rand:uniform(1 bsl ?m) - 1.
```

The `between/3` function will check if a `Key` is between `From` and `To` or equal to `To`, this is called a *partly closed interval* and is denoted $(From, To]$.

Remember that we're dealing with a ring so it could be that `From` is larger than `To`. Also, `From` could be equal to `To` and we will interpret this as the full circle, i.e., anything is in between.

```
between(Key, From, To) ->  
    if  
        From == To ->  
            true;  
        From < To ->  
            (From < Key) and (Key <= To);  
        From > To ->  
            (From < Key) or (Key <= To)  
    end.
```

1.2 Nodes

A node will have the following properties: a key, a predecessor, and a successor (remember that we will add the store later). We need to know the key values of both the predecessor and the successor so these will be represented by tuples `{Key, Pid}`. The messages we need to maintain the ring are:

- `{key, Qref, Peer}`: a peer node wants to know our key
- `{notify, NewPeer}`: a new peer node informs us of its existence
- `{request, Peer}`: a potential predecessor needs to know our current predecessor
- `{status, Pred}`: our successor informs us about its current predecessor

If we delay all the tricky decision to subroutines the implementation of the node process could look like this (insert this code in the module `node1`):

```
node(MyKey, Predecessor, Successor) ->
  receive
    {key, Qref, Peer} ->
      Peer ! {Qref, MyKey},
      node(MyKey, Predecessor, Successor);
    {notify, NewPeer} ->
      NewPredecessor = notify(NewPeer, MyKey, Predecessor),
      node(MyKey, NewPredecessor, Successor);
    {request, Peer} ->
      request(Peer, Predecessor),
      node(MyKey, Predecessor, Successor);
    {status, Pred} ->
      NewSuccessor = stabilize(Pred, MyKey, Successor),
      node(MyKey, Predecessor, NewSuccessor);
  stop ->
    ok;
  Error ->
    io:format("Reception of strange message ~w~n", [Error]),
    node(MyKey, Predecessor, Successor)
end.
```

Note that we included clauses to terminate and a catch-all clause in case some strange messages are received. You could also include clauses to print out some state information for debugging purposes.

1.3 stabilize

The periodic stabilization procedure will consist of a node sending a `{request, self()}` message to its successor and then expecting a `{status, Pred}` in return. When it knows the predecessor of its successor it can check (by means of the `stabilize/3` function) if the ring is stable or if the successor needs to be notified about the node existence through a `{notify, {Key, self()}}` message.

Below is a skeleton for the `stabilize/3` procedure. The `Pred` argument is the current predecessor of our successor. If this is `nil` we should of course notify our successor about our existence. If it is pointing back to us we don't have to do anything. If it is pointing to itself we should of course send a notification to our successor.

If it's pointing to another node we need to be careful. The question is whether we are to slide in between the two nodes or we should place ourselves behind the predecessor. If the key of the predecessor of our successor (`Xkey`) is between us and our successor we should of course adopt this node as our successor and run stabilization again (by sending ourselves a `stabilize` message). If we should be in between the nodes we notify our successor of our existence. At the end, this function must return our updated successor.

```
stabilize(Pred, MyKey, Successor) ->
  {Skey, Spid} = Successor,
  case Pred of
```

```

nil ->
    %% TODO: ADD SOME CODE
    Successor;
{MyKey, _} ->
    Successor;
{Skey, _} ->
    %% TODO: ADD SOME CODE
    Successor;
{Xkey, Xpid} ->
    case key:between(Xkey, MyKey, Skey) of
        true ->
            %% TODO: ADD SOME CODE
            %% TODO: ADD SOME CODE
        false ->
            %% TODO: ADD SOME CODE
            %% TODO: ADD SOME CODE
    end
end.

```

1.4 request

The stabilization procedure must be done with regular intervals so that new nodes are quickly linked into the ring. This can be arranged by starting a timer that sends a **stabilize** message after a predefined interval. In our scenario we might set the interval to be 1000 ms in order to slowly trace what messages are sent. When the **stabilize** message is received, the process will send a **request** message to the successor.

```
-define(Stabilize, 1000).
```

```

schedule_stabilize() ->
    timer:send_interval(?Stabilize, self(), stabilize).

```

The procedure `schedule_stabilize/0` is called when a node is created. When the node receives a **stabilize** message it will call `stabilize/1` procedure.

```

%% TO BE ADDED TO FUNCTION node/3
stabilize ->
    stabilize(Successor),
    node(MyKey, Predecessor, Successor)

```

The `stabilize/1` procedure will then simply send a **request** message to its successor. We could have set up the timer so that it was responsible for sending the **request** message but then the timer would have to keep track of which node was the current successor.

```

stabilize({_, Spid}) ->
    Spid ! {request, self()}.

```

When the **request** message is picked up by a process, it calls the `request/2` procedure. We should of course only inform the peer that sent the request about our predecessor as in the code below.

```

request(Peer, Predecessor) ->
  case Predecessor of
    nil ->
      Peer ! {status, nil};
      {Pkey, Ppid} ->
        Peer ! {status, {Pkey, Ppid}}
  end.

```

OPEN QUESTIONS (0.25 points)

a) What are the pros and cons of a more frequent stabilization procedure?

1.5 notify

Sending a notification is a way for a node to make a friendly proposal that it might be our proper predecessor. We cannot take their word for it, so we have to do our own investigation.

```

notify({Nkey, Npid}, MyKey, Predecessor) ->
  case Predecessor of
    nil ->
      %% TODO: ADD SOME CODE
    {Pkey, _} ->
      case key:between(Nkey, Pkey, MyKey) of
        true ->
          %% TODO: ADD SOME CODE
        false ->
          %% TODO: ADD SOME CODE
      end
  end
end.

```

If our own predecessor is set to `nil` the case is closed, but if we already have a predecessor we of course have to check if the new node actually should be our predecessor or not.

OPEN QUESTIONS (0.25 points)

b) Do we have to inform the new node about our decision? How will it know if we have discarded its friendly proposal?

1.6 Starting a node

The only thing left is how to start a node. There are two possibilities: either we are the first node in the ring or we're connecting to an existing ring. We'll export two procedures, `start/1` and `start/2`, the former will simply call the later with the second argument set to `nil`.

```

start(MyKey) ->
  start(MyKey, nil).

```

```

start(MyKey, PeerPid) ->
    timer:start(),
    spawn(fun() -> init(MyKey, PeerPid) end).

```

In the `init/2` procedure we set our predecessor to `nil`, connect to our successor and schedule the stabilization procedure. This also has to be done even if we are the only node in the system. We then call the `node/3` procedure that implements the message handling.

```

init(MyKey, PeerPid) ->
    Predecessor = nil,
    {ok, Successor} = connect(MyKey, PeerPid),
    schedule_stabilize(),
    node(MyKey, Predecessor, Successor).

```

The `connect/2` procedure is divided into two cases, depending on whether we are the first node or trying to connect to an existing ring. In either case we need to set our successor pointer. If we're all alone we are of course our own successor. If we're connecting to an existing ring we send a `key` message to the peer node that we have been given (we start with this node as our successor) and wait for a reply. Below is the skeleton code for the `connect/2` procedure.

```

-define(Timeout, 5000).

connect(MyKey, nil) ->
    {ok, {... , ...}};    %% TODO: ADD SOME CODE
connect(_, PeerPid) ->
    Qref = make_ref(),
    PeerPid ! {key, Qref, self()},
    receive
        {Qref, Skey} ->
            {ok, {... , ...}}    %% TODO: ADD SOME CODE
    after ?Timeout ->
        io:format("Timeout: no response from ~w~n", [PeerPid])
    end.

```

Notice how the unique reference `Qref` is used to trap exactly the message we're looking for. It might be over-kill in this implementation but it can be quite useful in other situations. Also note that if we for some reason do not receive a reply within some time limit (for example 5 s) we return an error.

OPEN QUESTIONS (0.25 points)

c) What would happen if we did not schedule the stabilization procedure?
--

1.7 Testing

Let's do some experiments to test the ring integrity. To check if the ring is actually connected we can introduce a `{probe, ProbeKey, Nodes, Time}` message.

If the `ProbeKey` is equal to the `MyKey` of the node we know that we sent it and can report the time it took to pass it around the ring. If it is not our probe we simply forward it to our successor but add our own process key to the list of nodes. The timestamp is set when creating the probe, using `erlang:monotonic_time()` (this is local time so the timestamp does not mean anything on other nodes).

```
%% TO BE ADDED TO FUNCTION node/3
probe ->
    create_probe(MyKey, Successor),
    node(MyKey, Predecessor, Successor);
{probe, MyKey, Nodes, T} ->
    remove_probe(MyKey, Nodes, T),
    node(MyKey, Predecessor, Successor);
{probe, RefKey, Nodes, T} ->
    forward_probe(MyKey, RefKey, [MyKey|Nodes], T, Successor),
    node(MyKey, Predecessor, Successor);

create_probe(MyKey, {_, Spid}) ->
    Spid ! {probe, MyKey, [MyKey], erlang:monotonic_time()},
    io:format("Node ~w created probe~n", [MyKey]).

remove_probe(MyKey, Nodes, T) ->
    T2 = erlang:monotonic_time(),
    Time = erlang:convert_time_unit(T2-T, native, microsecond),
    io:format("Node ~w received probe after ~w us -> Ring: ~w~n", [MyKey, Time, Nodes]).

forward_probe(MyKey, RefKey, Nodes, T, {_, Spid}) ->
    Spid ! {probe, RefKey, Nodes, T},
    io:format("Node ~w forwarded probe started by node ~w~n", [MyKey, RefKey]).
```

You can execute the following commands in a single Erlang instance to create a ring and send some probes to verify that the ring is stabilizing correctly.

```
> N2 = node1:start(2).
> N4 = node1:start(4,N2).
> N0 = node1:start(0,N2).
> N3 = node1:start(3,N2).
> N1 = node1:start(1,N2).
> N0 ! probe.
```

You can also create a ring with nodes that execute in different Erlang instances. In that case, remember to start Erlang in distributed mode (giving a `-name` argument). If you run things distributed you must of course register the first node under a name, for example `node`. The remaining nodes will then connect to this node by giving `{node, 'chordy@127.0.0.1'}` (or something similar).

CODE REVIEW (1.5 points)

Stabilization of a growing ring: Erlang file <code>node1.erl</code> .

EXPERIMENTAL MILESTONES (0.75 points)	
MS1 (0.25 points)	Create a ring comprising several nodes and verify the ring integrity.
MS2 (0.5 points)	Create a ring comprising several nodes running in different Erlang instances and verify the ring integrity.

2 Adding a store

We will now add a local store to each node and the possibility to add and search for key-value pairs. Create a new module, `node2`, from a copy of `node1`. Extend the `node/3` procedure to a `node/4` procedure, including a parameter for the `Store`.

2.1 Local storage

The first thing we need to implement is a local storage. This can easily be implemented as a list of tuples `{Key, Value}`, we can then use the key functions in the `lists` module to search for entries. Having a list is of course not optimal but will do for our experiments.

We need a module `storage` that implements functions to: `create/0` a new store, `add/3` a key-value pair, do a `lookup/2` on a key, `split/3` the storage in two parts given a key, and `merge/2` two stores. The split and merge functions will be used when a new node joins the ring and should take over part of the store.

```
-module(storage).
-export([create/0, add/3, lookup/2, merge/2, split/3]).

create() ->
    [].

add(Key, Value, Store) ->
    Present = lists:keymember(Key, 1, Store),
    if Present ->
        io:format("[Store:Add] Key ~w already exists. Replacing ...~n", [Key]),
        lists:keystore(Key, 1, Store, {Key, Value});
    true ->
        lists:keystore(Key, 1, Store, {Key, Value})
    end.

lookup(Key, Store) ->
    case lists:keyfind(Key, 1, Store) of
        {Key, Value} ->
            Value;
        false ->
            io:format("[Store:Lookup] Key ~w does not exist~n", [Key]),
            false
    end.
```



```

merge(Store1, Store2) ->
  lists:keymerge(1, lists:keysort(1, Store1), lists:keysort(1, Store2)).

split(MyKey, NewKey, Store) ->
  lists:partition(fun({K, _}) ->
    key:between(K, NewKey, MyKey)
  end, Store).

```

2.2 New messages

If the ring was not growing we would only have to add two new messages: {add, Key, Value, Qref, Client} and {lookup, Key, Qref, Client}. As before we implement the handlers in separate procedures. The procedures will need information about the predecessor and successor in order to determine if the message is actually for us or if it should be forwarded.

```

%% TO BE ADDED TO FUNCTION node/4
{add, Key, Value, Qref, Client} ->
  Added = add(Key, Value, Qref, Client,
    MyKey, Predecessor, Successor, Store),
  node(MyKey, Predecessor, Successor, Added);
{lookup, Key, Qref, Client} ->
  lookup(Key, Qref, Client, MyKey, Predecessor, Successor, Store),
  node(MyKey, Predecessor, Successor, Store);

```

The Qref parameters will be used to tag the return message to the Client. This allows the client to identify the reply message and makes it easier to implement the client.

2.3 Adding an element

To add a new key-value pair we must first determine if our node is the node that should take care of the key. A node will take care of all keys from (but not including) the identifier of its predecessor to (and including) the identifier of itself. If so we add the key-value pair in the local store (using the function add from the storage module). If we are not responsible (or we are not yet completely stabilized) we simply send an add message to our successor.

```

add(Key, Value, Qref, Client, _, nil, {_, Spid}, Store) ->
  %% TODO: ADD SOME CODE
  Store;
add(Key, Value, Qref, Client, MyKey, {Pkey, _}, {_, Spid}, Store) ->
  case key:between(... , ... , ...) of    %% TODO: ADD SOME CODE
    true ->
      Added = ... ,    %% TODO: ADD SOME CODE
      Client ! {Qref, ok},
      Added;
    false ->
      %% TODO: ADD SOME CODE
      Store
  end.

```

2.4 Looking up an element

The lookup procedure is very similar, we need to do the same test to determine if we are responsible for the key. If so we do a simple lookup in the local store (using the function `lookup` from the `storage` module) and then send the reply to the requester. If it is not our responsibility (or we are not stabilized) we simply forward the request.

```
lookup(Key, Qref, Client, _, nil, {_, Spid}, _) ->
    %% TODO: ADD SOME CODE
lookup(Key, Qref, Client, MyKey, {Pkey, _}, {_, Spid}, Store) ->
    case key:between(... , ... , ...) of      %% TODO: ADD SOME CODE
    true ->
        Result = ... ,      %% TODO: ADD SOME CODE
        Client ! {Qref, Result};
    false ->
        %% TODO: ADD SOME CODE
end.
```

2.5 Elements responsibility

Things are slightly more complicate by the fact that new nodes might join the ring. A new node should take over part of the responsibility by merging some already added elements into its store. We introduce one more message to the node, `{handover, Elements}`, that will be used to delegate the responsibility on some elements.

```
%% TO BE ADDED TO FUNCTION node/4
{handover, Elements} ->
    NewStore = ... ,      %% TODO: ADD SOME CODE
    node(MyKey, Predecessor, Successor, NewStore);
```

When should this message be sent? It's a message from a node that has accepted us as their predecessor. This is only done when a node receives and handles a `notify` message. Go back to the implementation of the `notify/3` procedure. Handling of a `notify` message could mean that we have to give part of a store away; we need to pass the `Store` as an argument and also return a tuple `{Predecessor, Store}` (remember to update the invocation at `node/4` procedure accordingly). The procedure `notify/4` could look like follows:

```
notify({Nkey, Npid}, MyKey, Predecessor, Store) ->
    case Predecessor of
    nil ->
        Keep = handover(Store, MyKey, Nkey, Npid),
        %% TODO: ADD SOME CODE
    {Pkey, _} ->
        case key:between(Nkey, Pkey, MyKey) of
        true ->
            Keep = ... ,      %% TODO: ADD SOME CODE
            %% TODO: ADD SOME CODE
        false ->
```

```

                                %% TODO: ADD SOME CODE
                                end
                                end.

```

So, what's left is simply to implement the `handover/4` procedure. What should be done? Split our `Store` based on `NKey`. Which part should be kept and which part should be handed over to the new predecessor? You have to check how the `storage:split` procedure works, remember that a store contains the range $(Pkey, MyKey]$, that is from (not including) $Pkey$ to (including) $MyKey$.

```

handover(Store, MyKey, Nkey, Npid) ->
    {Keep, Leave} = ... ,      %% TODO: ADD SOME CODE
    Npid ! {handover, Leave},
    Keep.

```

Update also the probe functions to show the `Store` of each node in the ring.

2.6 Testing

We can test now the distributed store. Create a ring comprising several nodes, add some key-value pairs, and send probes to show the local store of each node in the ring. You can for instance execute the following commands.

```

> N2 = node2:start(2).
> P = chordy:connect(N2).
> P ! {add,0,0}.
> P ! {add,1,1}.
> P ! {add,2,2}.
> N2 ! probe.
> N4 = node2:start(4,N2).
> N2 ! probe.
> N0 = node2:start(0,N2).
> N2 ! probe.
> N3 = node2:start(3,N2).
> N2 ! probe.
> N1 = node2:start(1,N2).
> N2 ! probe.
> P ! {add,3,3}.
> P ! {lookup,3}.
> N2 ! probe.

```

You might also try some performance testing. You can build a ring with some nodes and let several test machines add a number (e.g., 10000) of random elements (key-value pairs) to the ring and then do a lookup of the elements, measuring the time it takes. You can use the `test` procedure given in 'Appendix A', which should be given with the ID of the node to contact. You should use the function `key:generate()` to assign the keys of the nodes in the ring, so that elements will get uniformly distributed among them.

CODE REVIEW (1.5 points)

Operation of a local storage on each node: Erlang file `node2.erl`.

EXPERIMENTAL MILESTONES (0.5 points)	
MS3 (0.5 points)	Create a ring comprising several nodes and add/lookup some key-value pairs.

3 Handling failures

To handle failures we need to detect if a node has failed. Both the successor and the predecessor need to detect this and we will use the Erlang built-in procedures to monitor the health of a node. Start a new module `node3` and copy what we have from `node2`.

3.1 Successor of our successor

If our successor dies we need a way to repair the ring. A simple strategy is to keep track of our successor's successor; we will call this the `Next` node. We will be able to survive from one node crashing at a time but if two nodes in a row crash we're doomed. That's ok for now, it makes life a bit simpler. A more general scheme would be to keep track of a list of successors.

Extend the `node/4` procedure to a `node/5` procedure, including a parameter for the `Next` node. The `Next` node will not change unless our successor informs us about a change. Our successor should do so in the `status` message so we extend this to `{status, Pred, Nx}`. This is sent by the `request/2` procedure. This procedure, which is now `request/3`, must be adapted in order to send the correct message.

```
%% TO BE UPDATED IN FUNCTION node/5
{request, Peer} ->
    request(Peer, Predecessor, Successor),
    node(MyKey, Predecessor, Successor, Next, Store);

request(Peer, Predecessor, {Skey, Spid}) ->
    case Predecessor of
        nil ->
            Peer ! {status, nil, {Skey, Spid}};
        {Pkey, Ppid} ->
            Peer ! {status, {Pkey, Ppid}, {Skey, Spid}}
    end.
```

The procedure `stabilize/3` must now be replaced by a `stabilize/4` procedure that also takes the new `Nx` node and returns not only the new successor but also the new `Next` node.

```
%% TO BE UPDATED IN FUNCTION node/5
{status, Pred, Nx} ->
    {NewSuccessor, NewNext} = stabilize(Pred, Nx, MyKey, Successor),
    node(MyKey, Predecessor, NewSuccessor, NewNext, Store);
```

Now `stabilize/4` need to do some more thinking. If our successor does not change we should of course adopt the successor of our successor as our `Next`

node. However, if we detect that a new node has sneaked in between us and our former successor you must do the necessary changes to `stabilize/4` so that it returns the correct successor and Next node.

3.2 Failure detection

We will use the `erlang:monitor/2` procedure to detect failures. The procedure returns a unique reference that can be used to determine which 'DOWN' message belong to which process. Since we need to keep track of both our successor and our predecessor **we will extend the representation of these nodes to a tuple {Key, Ref, Pid}** where the `Ref` is a reference produced by the monitor procedure. To make the code more readable we add wrapper functions for the built-in monitor procedures.

```
monit(Pid) ->
    erlang:monitor(process, Pid).

demonit(nil) ->
    ok;
demonit(MonitorRef) ->
    erlang:demonitor(MonitorRef, [flush]).
```

Now go through the code and change the representation of the predecessor and successor to include also the monitor reference. Note that **the Next node does not need a monitoring reference**. Similarly, **in the messages between nodes we still send only the two element tuple {Key, Pid}** since the receiving node has no use of the reference element of the sending node. When a new node is adopted **as successor or predecessor** we need to demonitor the old node and monitor the new.

You must modify the `connect`, `stabilize`, and `notify` procedures to create a new monitor reference and the `stabilize` and `notify` procedures to demonitor a node.

3.3 Failure handling

Now let's go to the actual handling of failures. When a process is detected as having crashed (the process terminated, the Erlang machine died or the computer stopped replying on heart beats) a message will be sent to a monitoring process. Since we now monitor both our predecessor and successor we should be open to handle both messages. Let's follow our principle of keeping the main loop free of gory details and handle all decisions in a procedure. The extra message handler could then look like follows:

```
%% TO BE ADDED TO FUNCTION node/5
{'DOWN', Ref, process, _, _} ->
    {NewPred, NewSucc, NewNext} = down(Ref, Predecessor, Successor, Next),
    node(MyKey, NewPred, NewSucc, NewNext, Store);
```

The `Ref` obtained in the 'DOWN' message must now be compared to the saved references of our successor and predecessor. For clarity we break this up into two clauses.

```

down(Ref, {_, Ref, _}, Successor, Next) ->
    {nil, Successor, Next};
down(Ref, Predecessor, {_, Ref, _}, {Nkey, Npid}) ->
    %% TODO: ADD SOME CODE
    {Predecessor, ... , nil}.    %% TODO: ADD SOME CODE

```

If our predecessor died things are quite simple. There is no way for us to find the predecessor of our predecessor but if we set our predecessor to `nil` someone will sooner or later knock on our door and present them self as a possible predecessor.

If our successor dies, things are almost as simple. We will of course adopt our Next node as our successor and then only have to remember two things: monitor the node and make sure that we run the stabilizing procedure (by sending ourselves a `stabilize` message).

We can evaluate now the behavior of our implementation when nodes can fail by executing the following commands:

```

> N2 = node3:start(2).
> N4 = node3:start(4,N2).
> N0 = node3:start(0,N2).
> N3 = node3:start(3,N2).
> N1 = node3:start(1,N2).
> N2 ! probe.
> N1 ! stop.
> N2 ! probe.
> N3 ! stop.
> N2 ! probe.
> N0 ! stop.
> N2 ! probe.
> N4 ! stop.
> N2 ! probe.

```

You're done! You have a fault-tolerant distributed storage ... well almost, if a node dies it will bring with it a part of the storage. If this is ok we could stop here, if not we have to do some more work.

CODE REVIEW (1.5 points)	
Stabilization on node failures/departures: Erlang file <code>node3.erl</code> .	

EXPERIMENTAL MILESTONES (0.5 points)	
MS4 (0.5 points)	Create a ring comprising several nodes and verify the ring integrity when nodes leave.

OPEN QUESTIONS (0.25 points)	
d) What will happen if a node is falsely detected of being dead (e.g., it has only been temporally unavailable)?	

4 Replication

The way to maintain the store in face of dying nodes is of course to replicate information. How to replicate is a research area of its own so we will only do something simple that (almost) works.

Take a copy of `node3`, call it `node4` and try to add a replication strategy.

We can handle failures of one node at a time in our ring so let's limit the replication scheme to be on the same level. If a node dies its local store should be replicated so its successor can take over the responsibility. Therefore, the best place to replicate our store is at our successor.

Each node will thus have a second store called the `Replica` where it can keep a duplicate of its predecessor's store. **When we add a key-value element to our own store** we also forward it to our successor as a `{replicate, Key, Value}` message. In addition, **when a node replaces its store, either after making or receiving a handover**, the updated store must be replicated in the successor of this node by sending a `{pushreplica, NewReplica}` message (modify the `node` procedure accordingly).

If a node dies its successor is of course responsible for the store held by the node. This means that **the replica should be merged with its own store**. This merged store should be also replicated in the successor of this node.

Sounds simple but there are however some small details that make our solution not perfect.

If we want to handle failures while adding key-value elements, we should make sure that a confirmation to the client is only sent when an element has been properly added and replicated. Modify your code to ensure this.

A client that does not receive a confirmation could of course choose to re-send the message. Check how our implementation deals with duplicated requests by the same client, in particular when the element was added the first time but the confirmation message was lost.

Update also the probe functions to show the `Replica` of each node in the ring and try the following commands while checking the contents of the store and the replica on each node to check if the replication strategy works.

```
> N2 = node4:start(2).
> P = chordy:connect(N2).
> P ! {add,0,0}.
> P ! {add,1,1}.
> P ! {add,2,2}.
> N2 ! probe.
> N0 = node4:start(0,N2).
> N2 ! probe.
> N1 = node4:start(1,N2).
> N2 ! probe.
> N1 ! stop.
> N2 ! probe.
> N0 ! stop.
> N2 ! probe.
```

CODE REVIEW (1.5 points)	
Storage replication: Erlang file <code>node4.erl</code> .	

EXPERIMENTAL MILESTONES (0.5 points)	
MS5 (0.5 points)	Show that the store and the replica are correct at every node and no key-value pairs are lost even when nodes leave.

OPEN QUESTIONS (0.5 points)	
e)	What node must send the confirmation message to the client when adding a key-value element to the store?
f)	How does the code deal with duplicated requests by the same client to add elements to the store?

5 Carrying on

If you are willing to enhance your Chord implementation, you can try to add a finger table for each node, which will allow us to find any given key in $\log(n)$ hops. This is of course important if we have a large ring.

OPEN QUESTIONS (0.25 points)	
g)	Outline the necessary changes in the code to implement finger tables.

Appendix A: test program

```
-module(chordy).
% use connect/1 for manual 'add' and 'lookup' requests
% use test/2 for automated 'add' and 'lookup' requests
-export([connect/1, test/2]).

% 'Peer' stands for the node used to query the system
connect(Peer) ->
    spawn(fun() -> wait(Peer) end).

wait(Peer) ->
    receive
        {add, Key, Value} ->
            Ref = make_ref(),
            Peer ! {add, Key, Value, Ref, self()},
            receive
                {Ref, ok} -> io:format("[Add] Key added correctly~n")
            end,
            wait(Peer);
        {lookup, Key} ->
            Ref = make_ref(),
            Peer ! {lookup, Key, Ref, self()},
            receive
                {Ref, Value} ->
                    io:format("[Lookup] Key: ~w Value: ~w~n", [Key, Value])
            end,
            wait(Peer)
    end.

test(Peer, NumRequests) ->
    Begin = erlang:monotonic_time(),
    {KeysAdd, RefsAdd} = add(Peer, NumRequests, [], []),
    io:format("Add requests done. Waiting for answers...~n"),
    waitAdds(RefsAdd),
    io:format("Answers received. Making lookups...~n"),
    RefsLook = lookup(Peer, KeysAdd, []),
    io:format("Lookup requests done. Waiting for values...~n"),
    Values = waitLookups(RefsLook, []),
    End = erlang:monotonic_time(),
    Elapsed = erlang:convert_time_unit(End-Begin, native, millisecond),
    io:format("Values received. Checking correctness...~n"),
    checkLookups(Values, KeysAdd),
    io:format("Elapsed Time: ~w ms~n", [Elapsed]).

add(_, 0, KeysDone, RefsDone) ->
    {KeysDone, RefsDone};
add(Peer, NumRequests, KeysDone, RefsDone) ->
    Key = key:generate(),
    Qref = make_ref(),
```

```

    Peer ! {add, Key, Key, Qref, self()},
    add(Peer, NumRequests-1, [Key|KeysDone], [Qref|RefsDone]).

waitAdds([]) ->
    ok;
waitAdds(Refs) ->
    receive
        {Qref, ok} ->
            NewRefs = lists:delete(Qref, Refs),
            waitAdds(NewRefs)
    end.

lookup(_, [], RefsLook) ->
    RefsLook;
lookup(Peer, [Key|KeysAdd], RefsLook) ->
    Qref = make_ref(),
    Peer ! {lookup, Key, Qref, self()},
    lookup(Peer, KeysAdd, [Qref|RefsLook]).

waitLookups([], Values) ->
    Values;
waitLookups(Refs, Values) ->
    receive
        {Qref, Value} ->
            NewRefs = lists:delete(Qref, Refs),
            waitLookups(NewRefs, [Value|Values])
    end.

checkLookups([], _) ->
    io:format("Everything correct!~n"),
    ok;
checkLookups([Value|Values], KeysAdd) ->
    case lists:member(Value, KeysAdd) of
        true ->
            NewKeysAdd = lists:delete(Value, KeysAdd),
            checkLookups(Values, NewKeysAdd);
        false ->
            io:format("Something's wrong!~nValues: ~w~nKeys: ~w~n",
                [[Value|Values], KeysAdd]),
            false
    end.
end.

```