Implementation and Verification of a Consensus Protocol in Erlang

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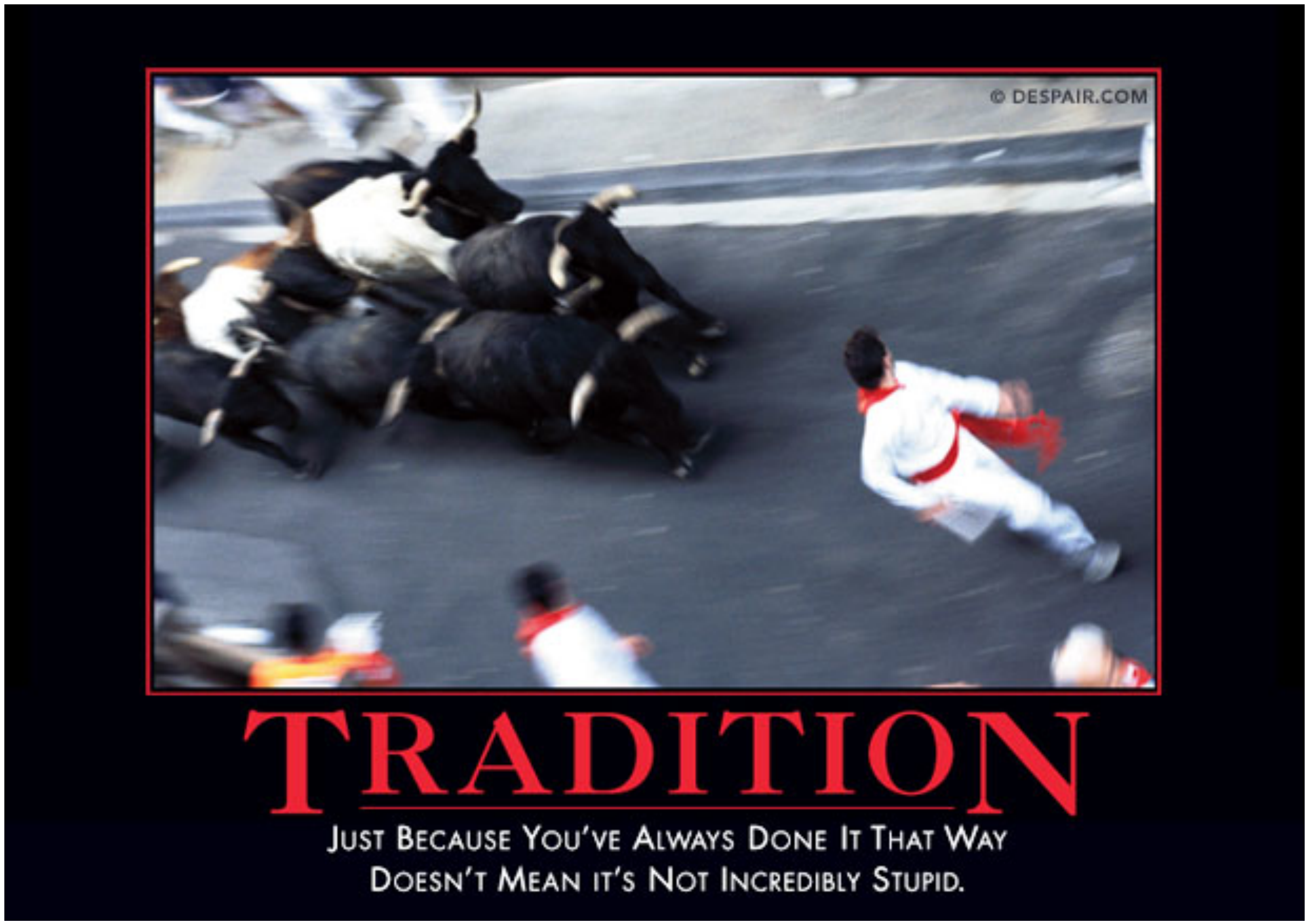
I

about your

Distributed Systems are
HARD

Many ways to skin a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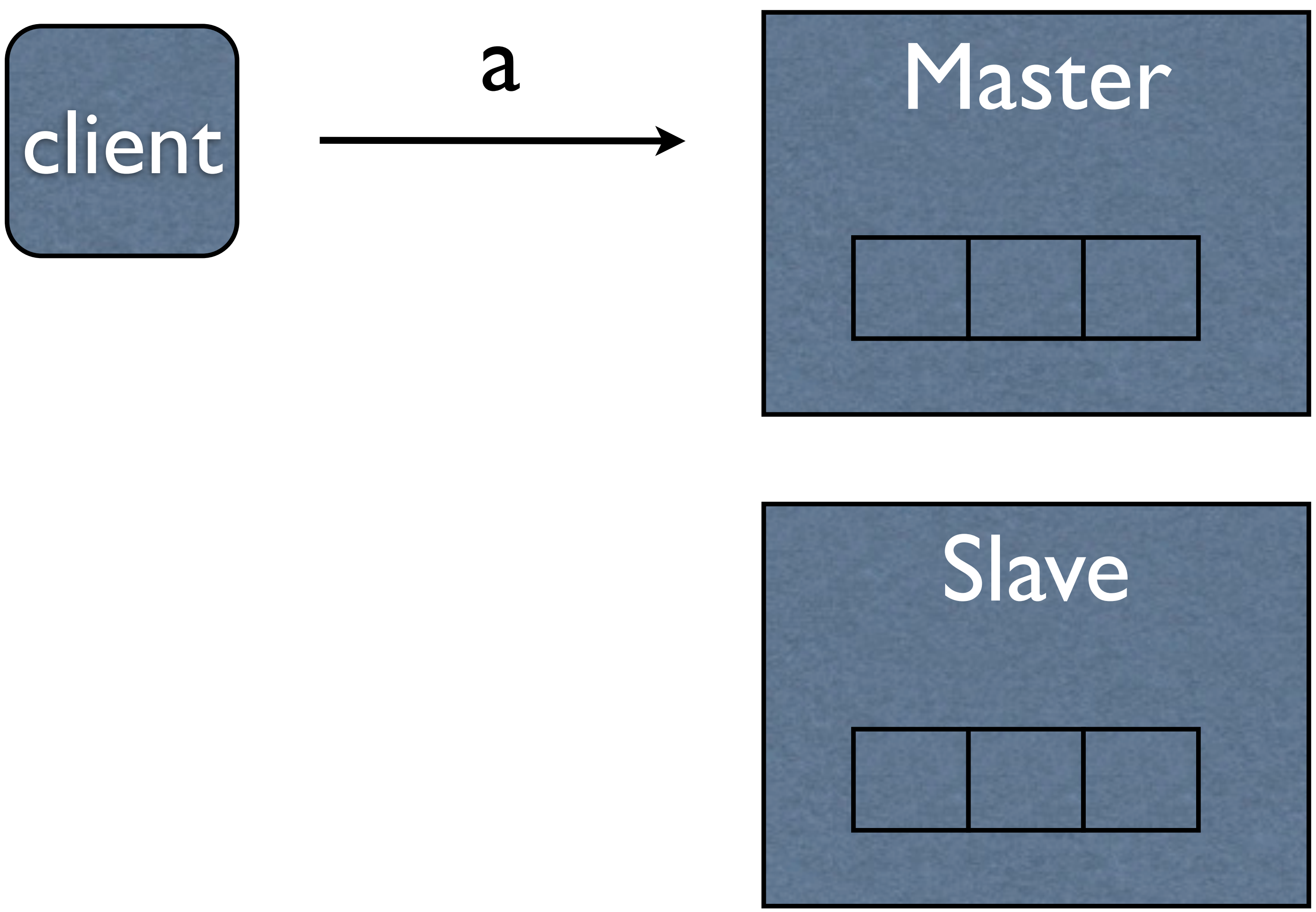
TRADITION
JUST BECAUSE YOU'VE ALWAYS DONE IT THAT WAY
DOESN'T MEAN IT'S NOT INCREDIBLY STUPID.

Asynchronous Replication



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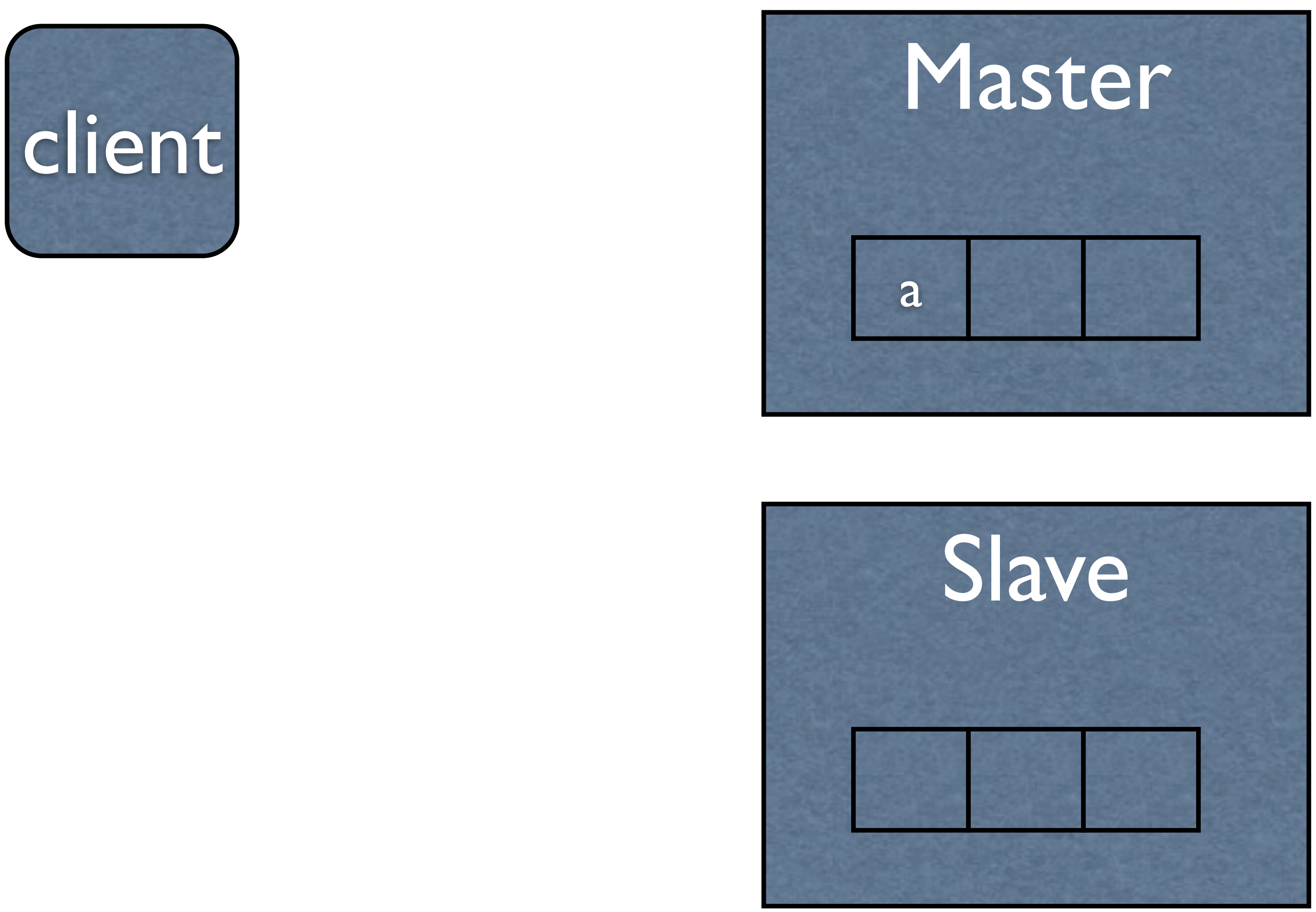

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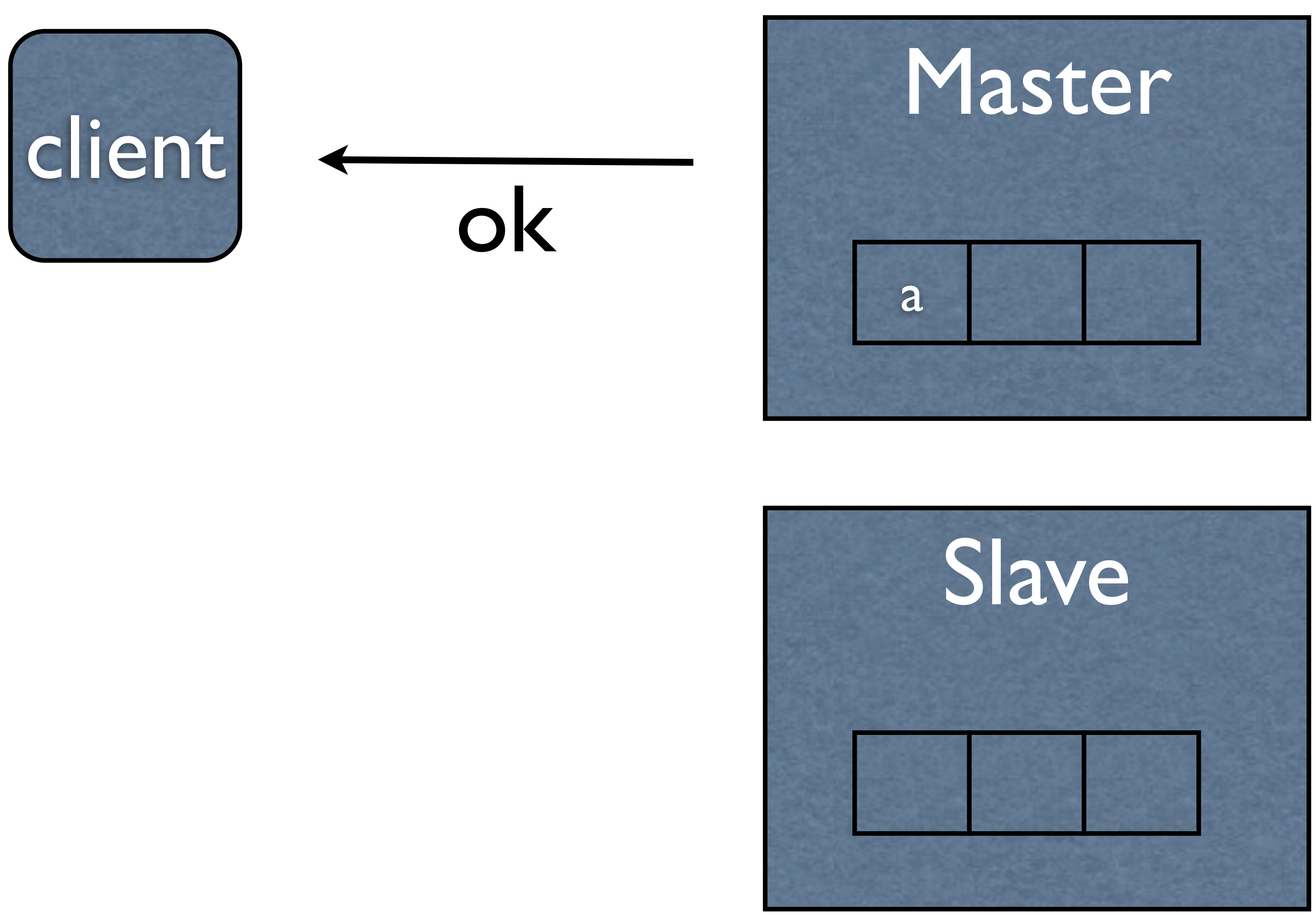

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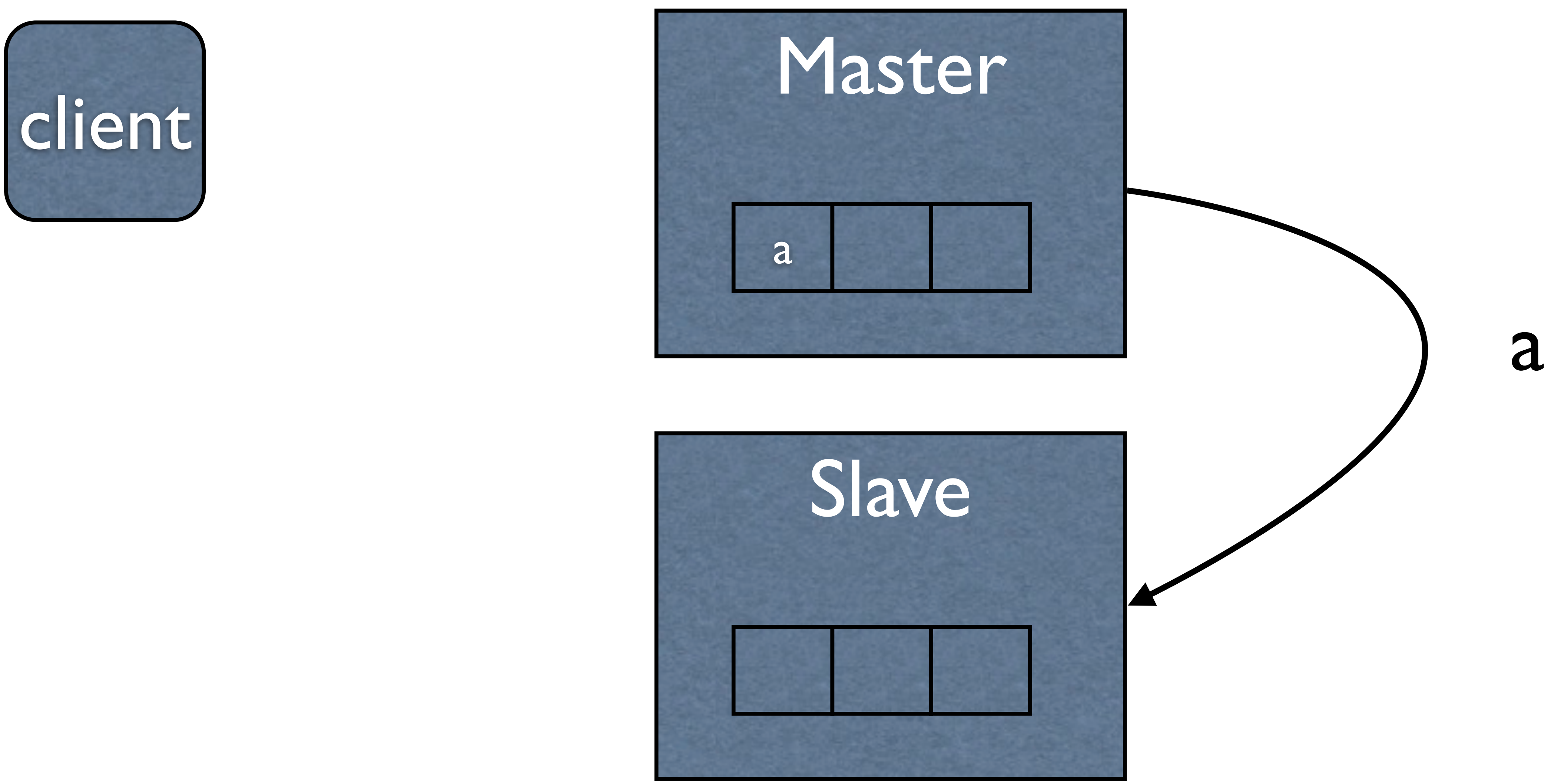

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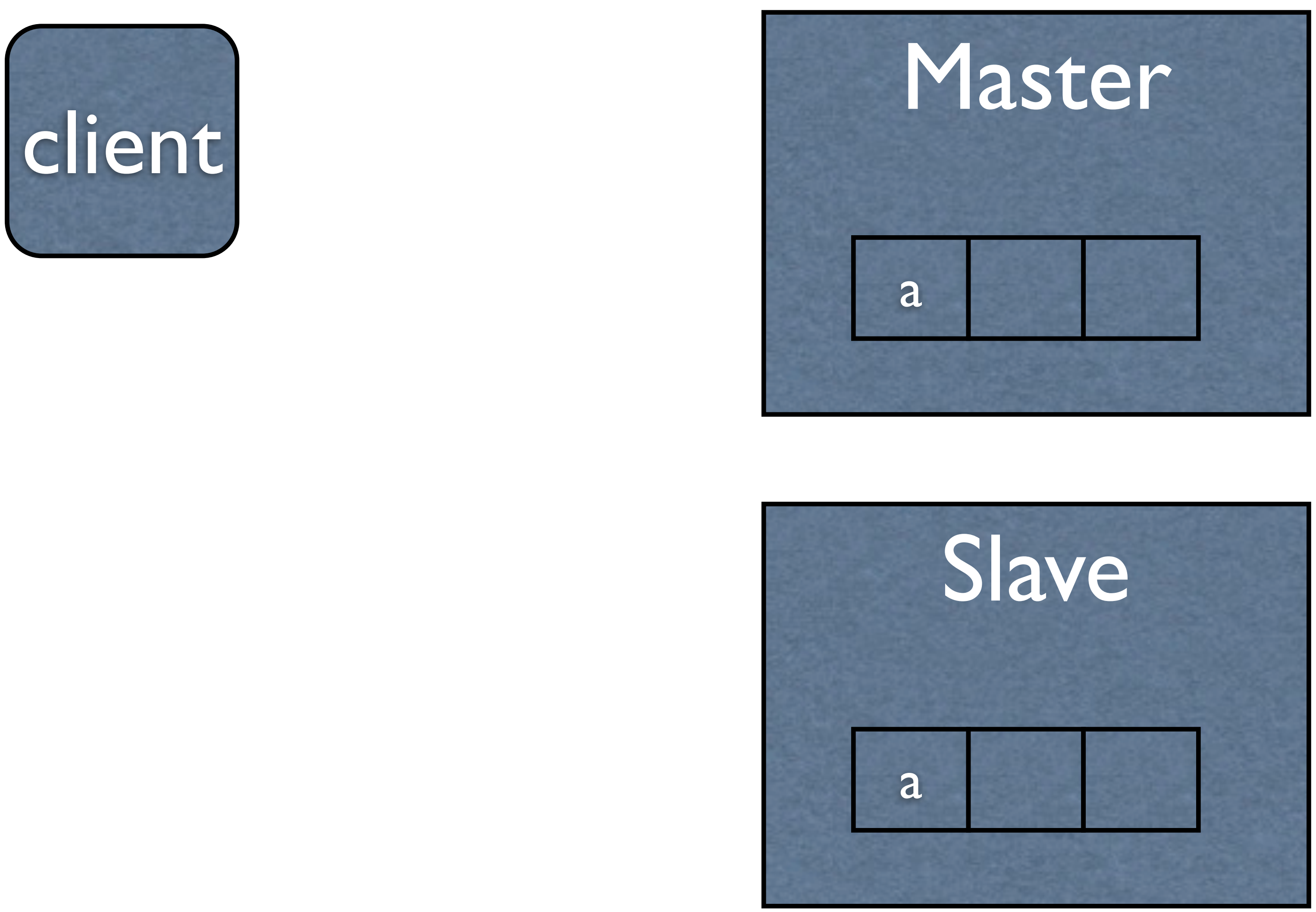

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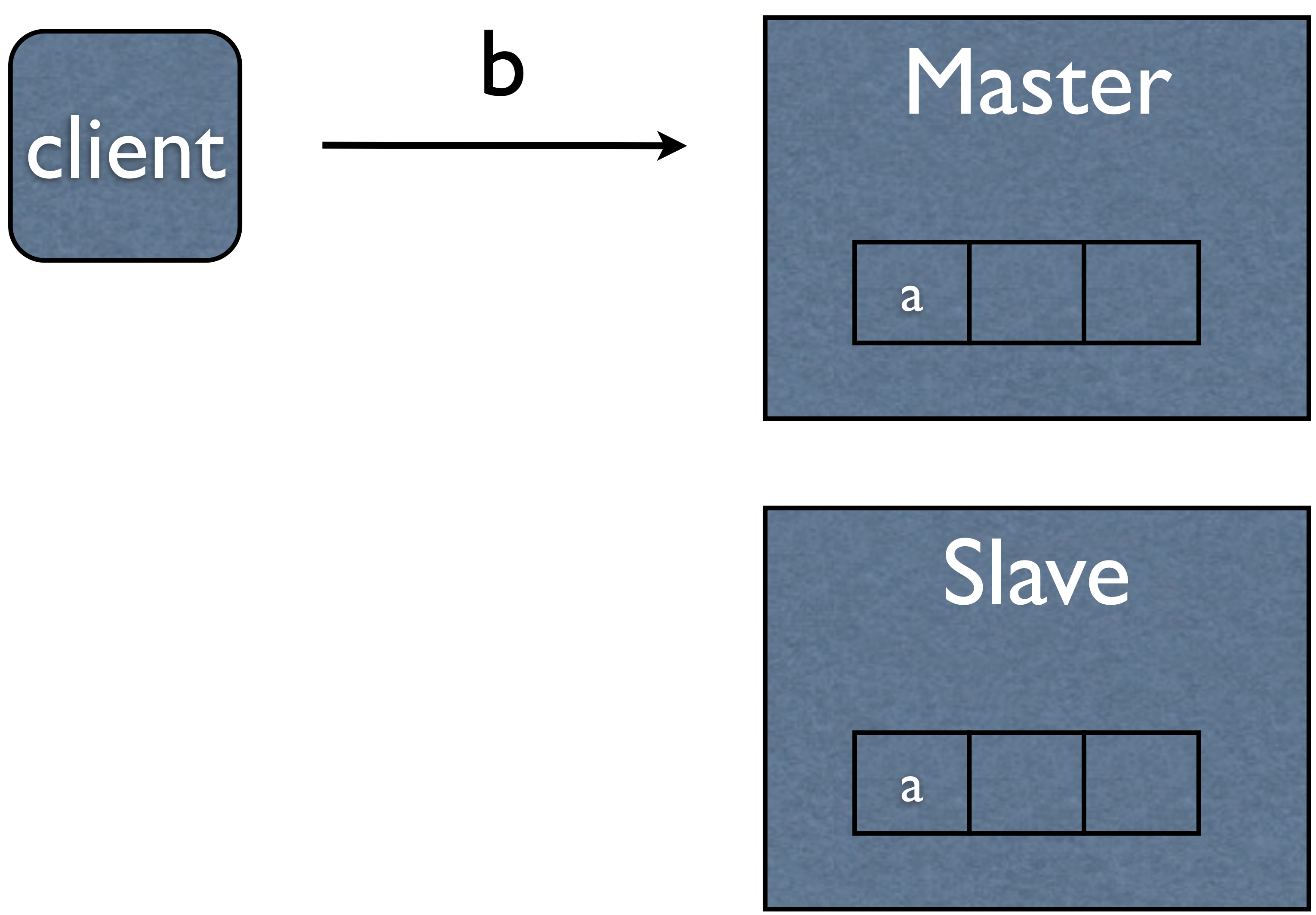

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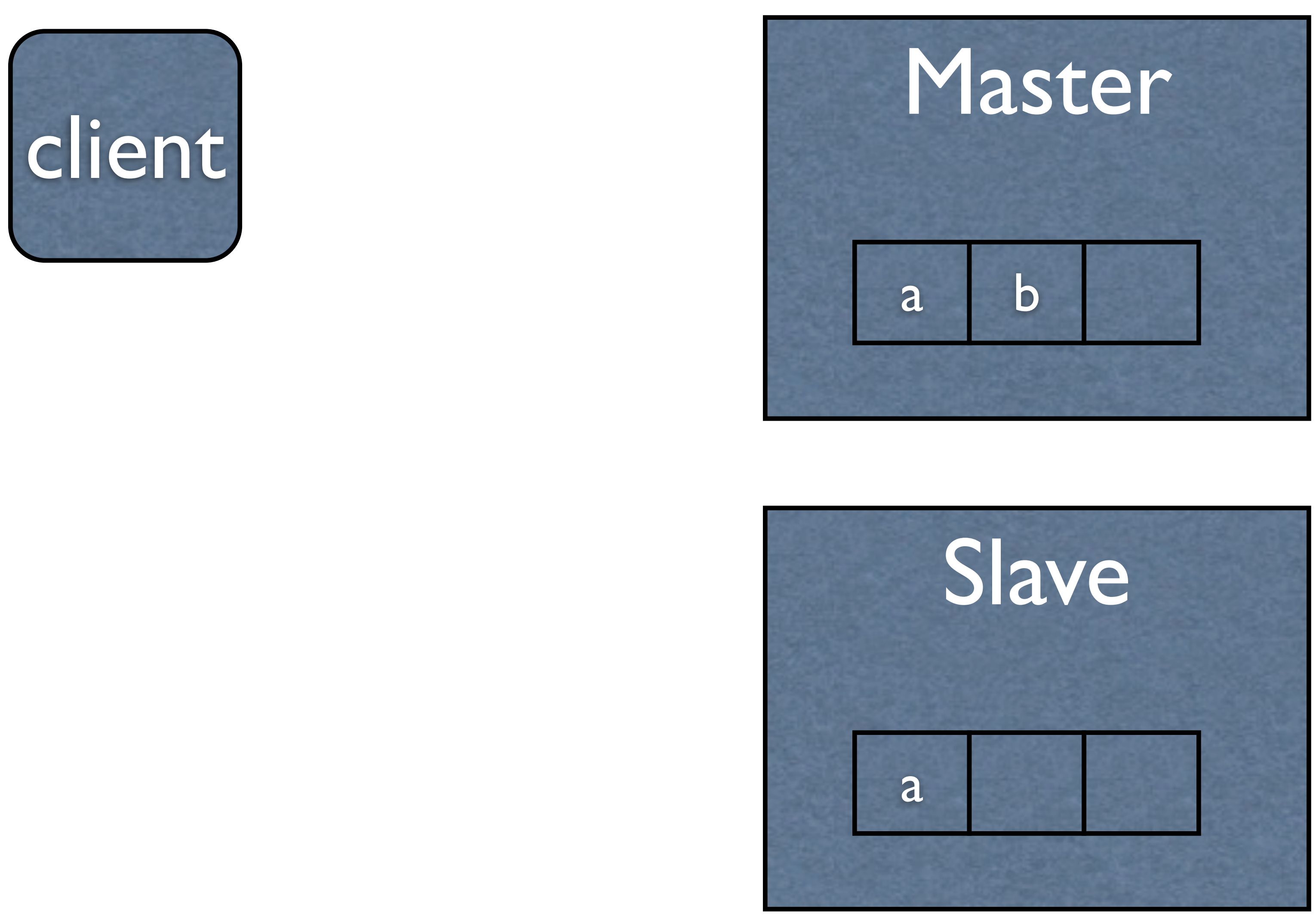

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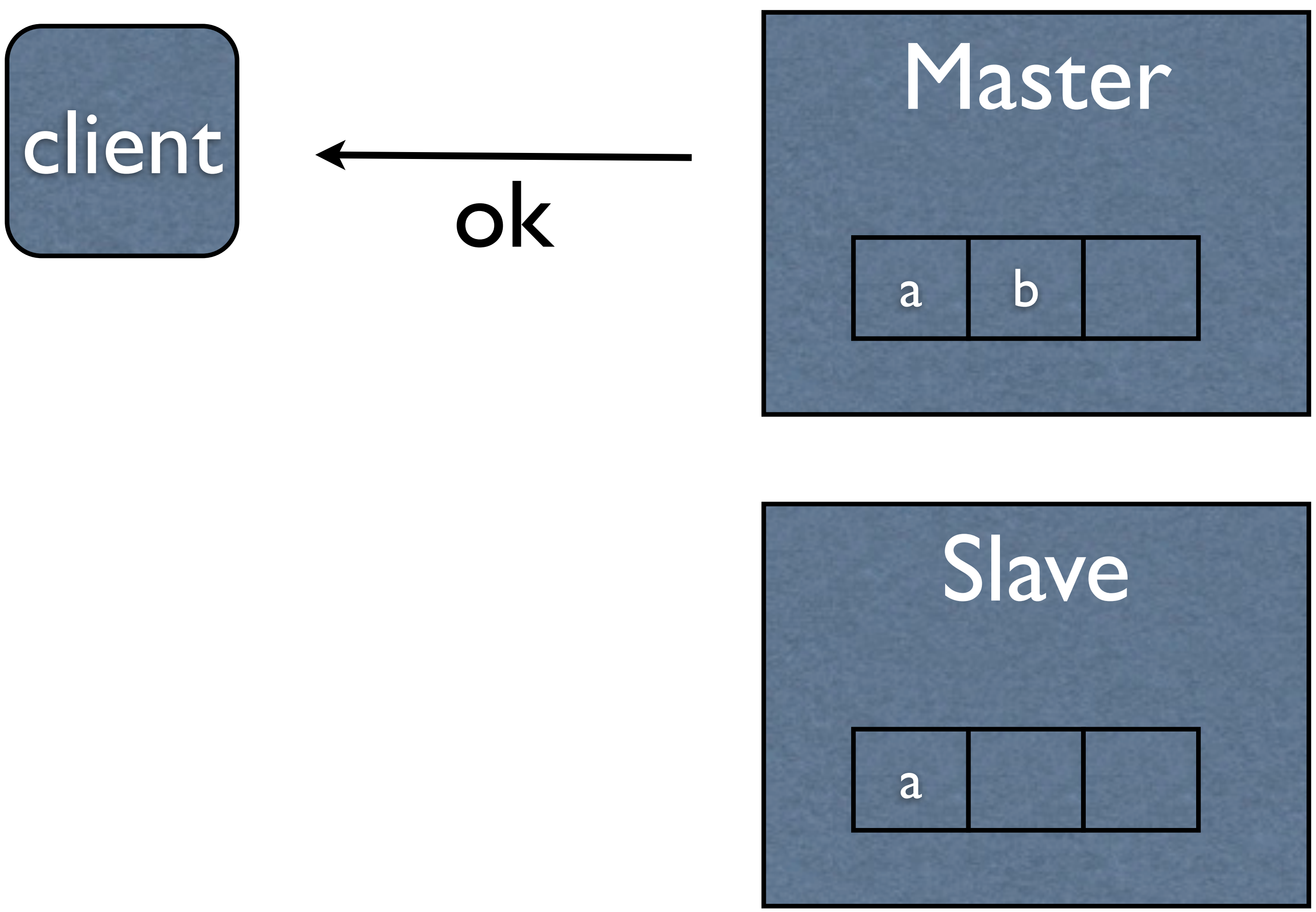

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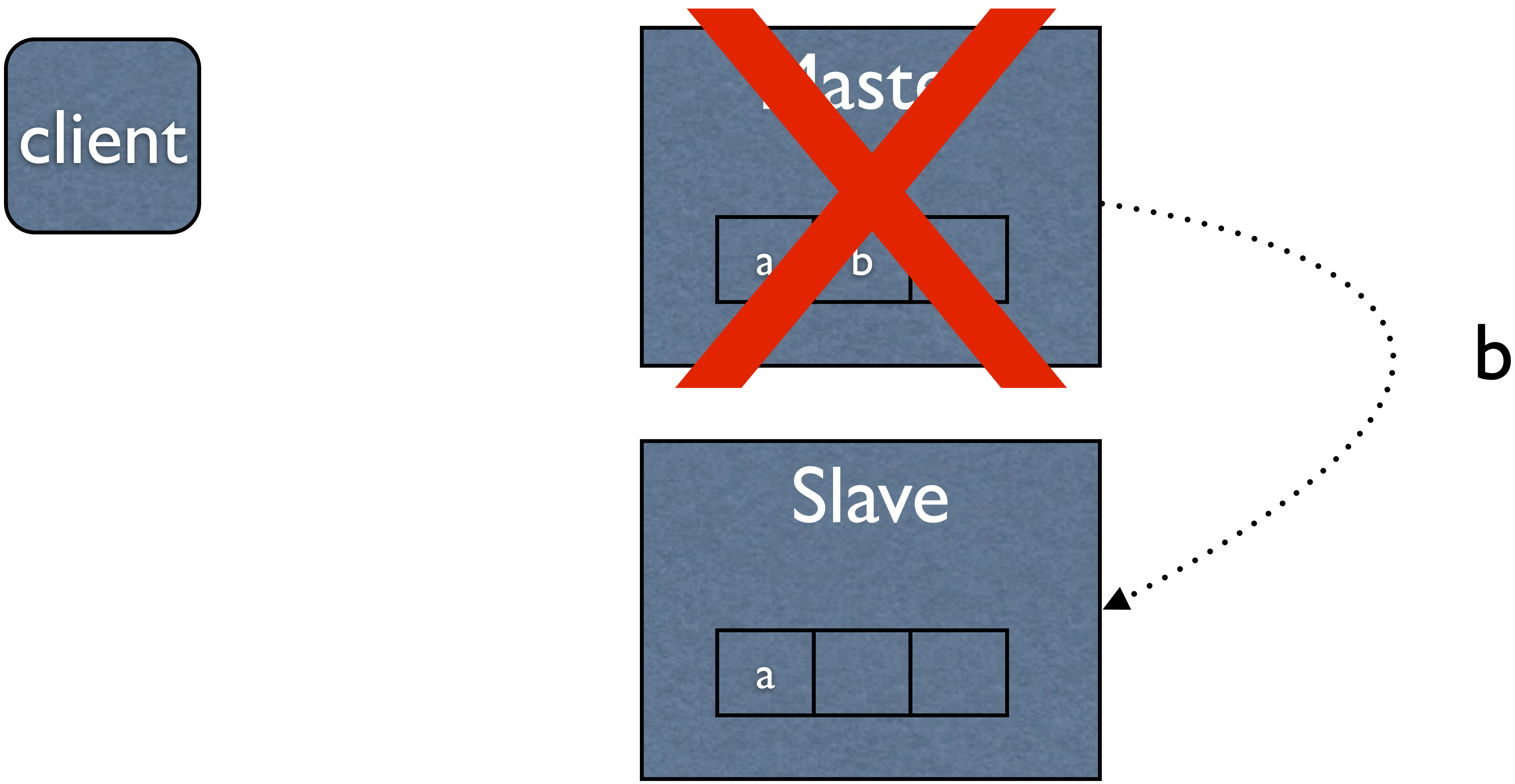

Consistent

or

Available

```
if (promote_secondary){
    stderr(“possible data loss”);
}else{
    stderr(“system unavailable”);
}
```

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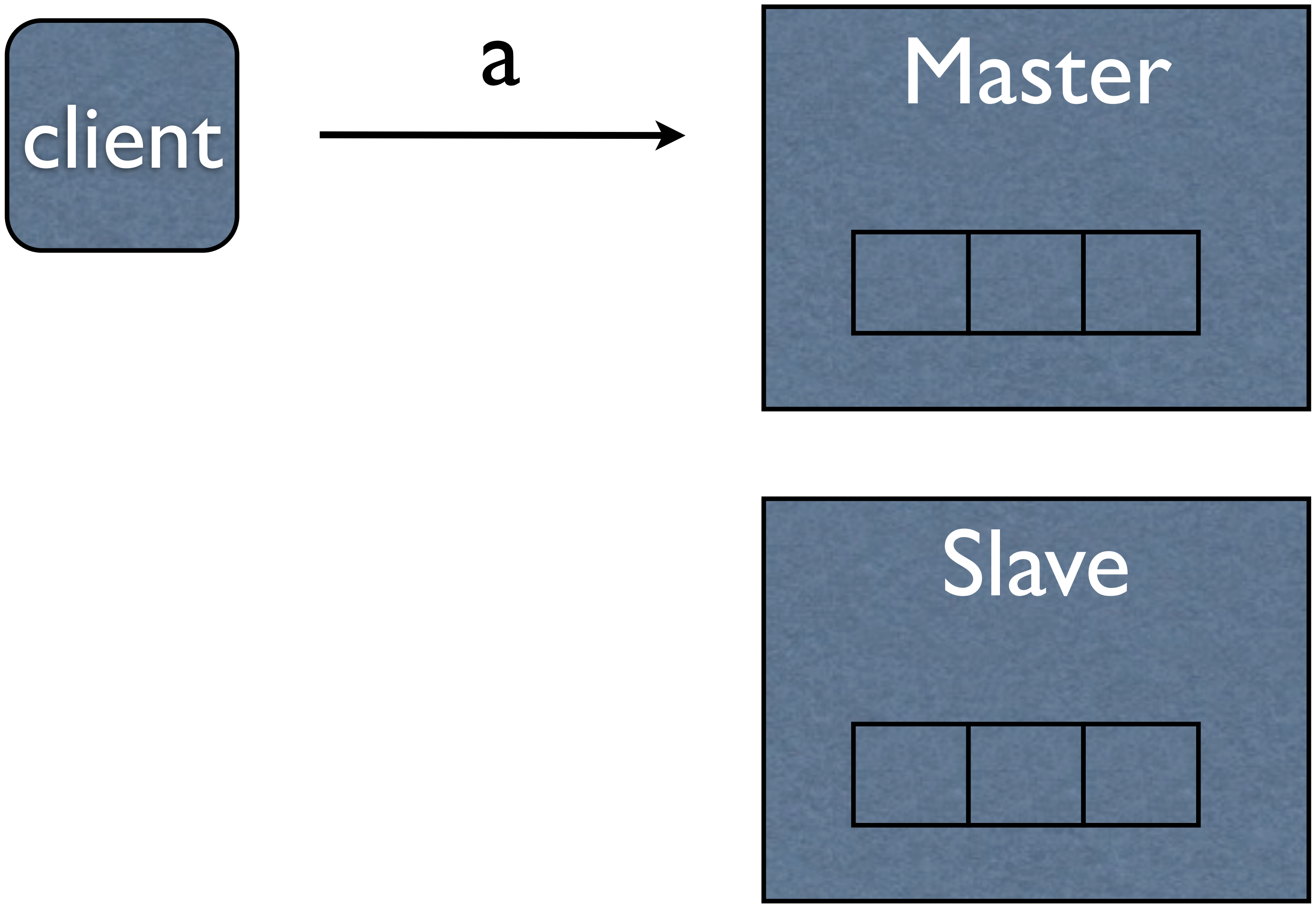
Yep, you just traded safety for latency

Synchronous Replication



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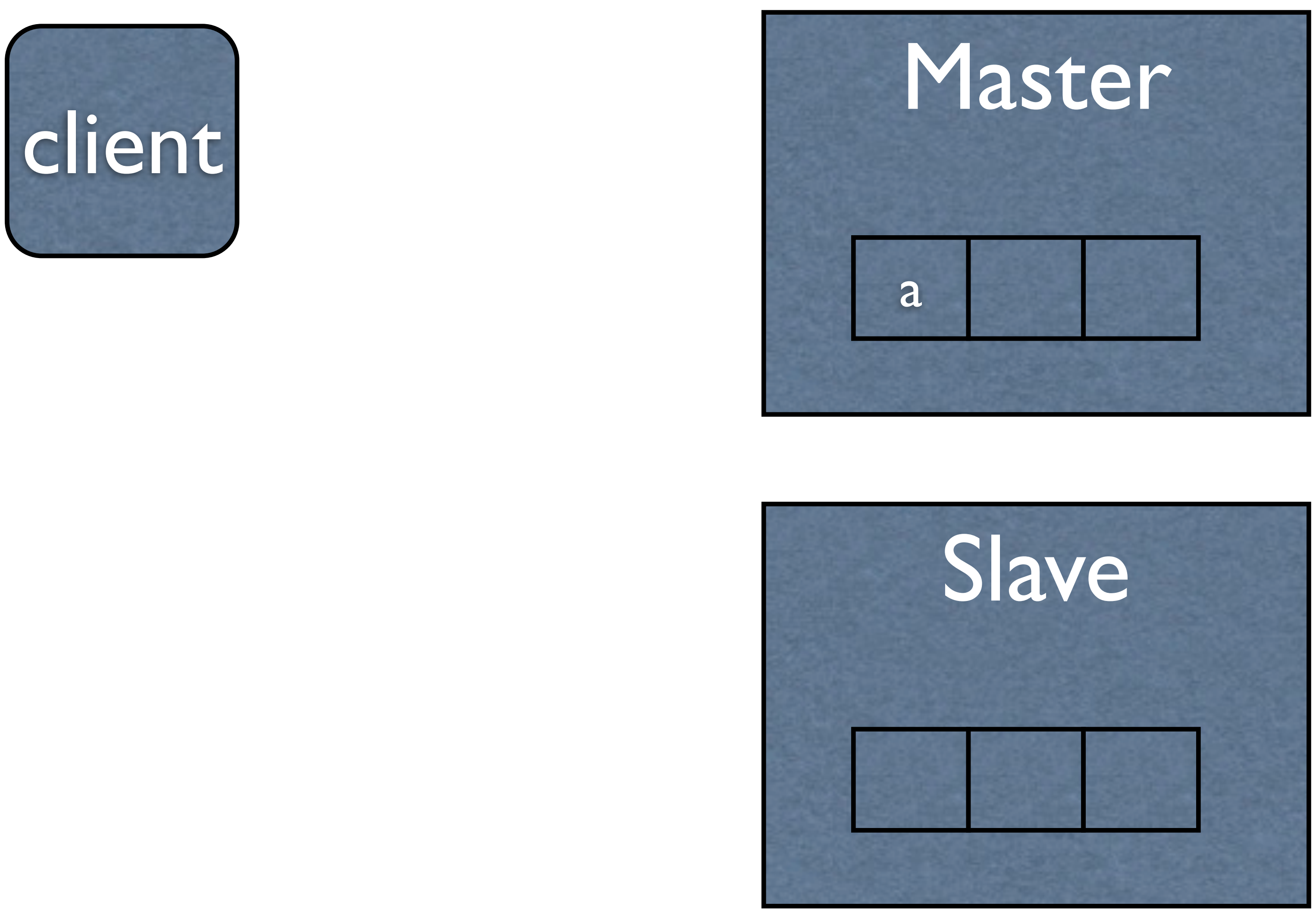

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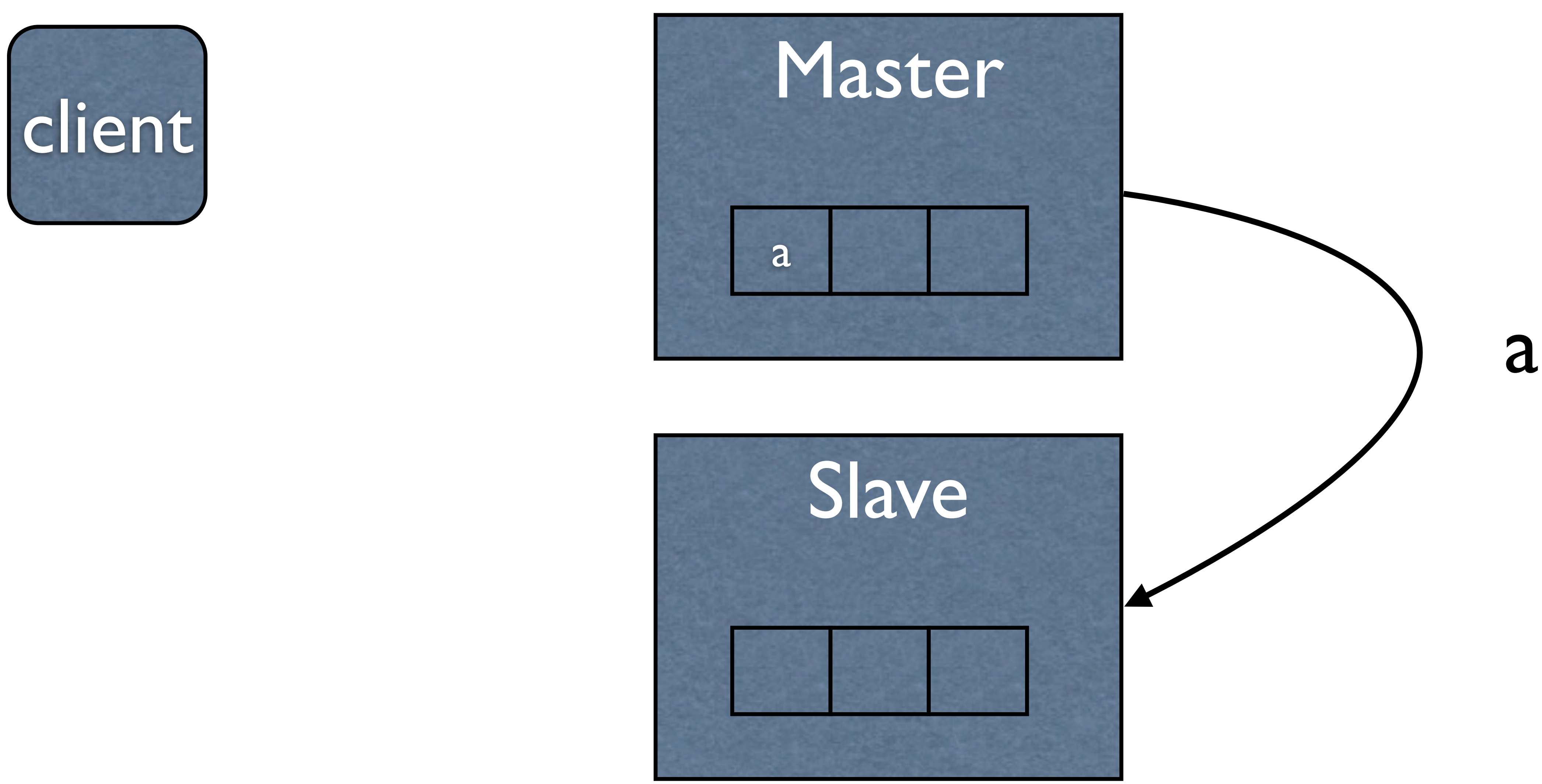

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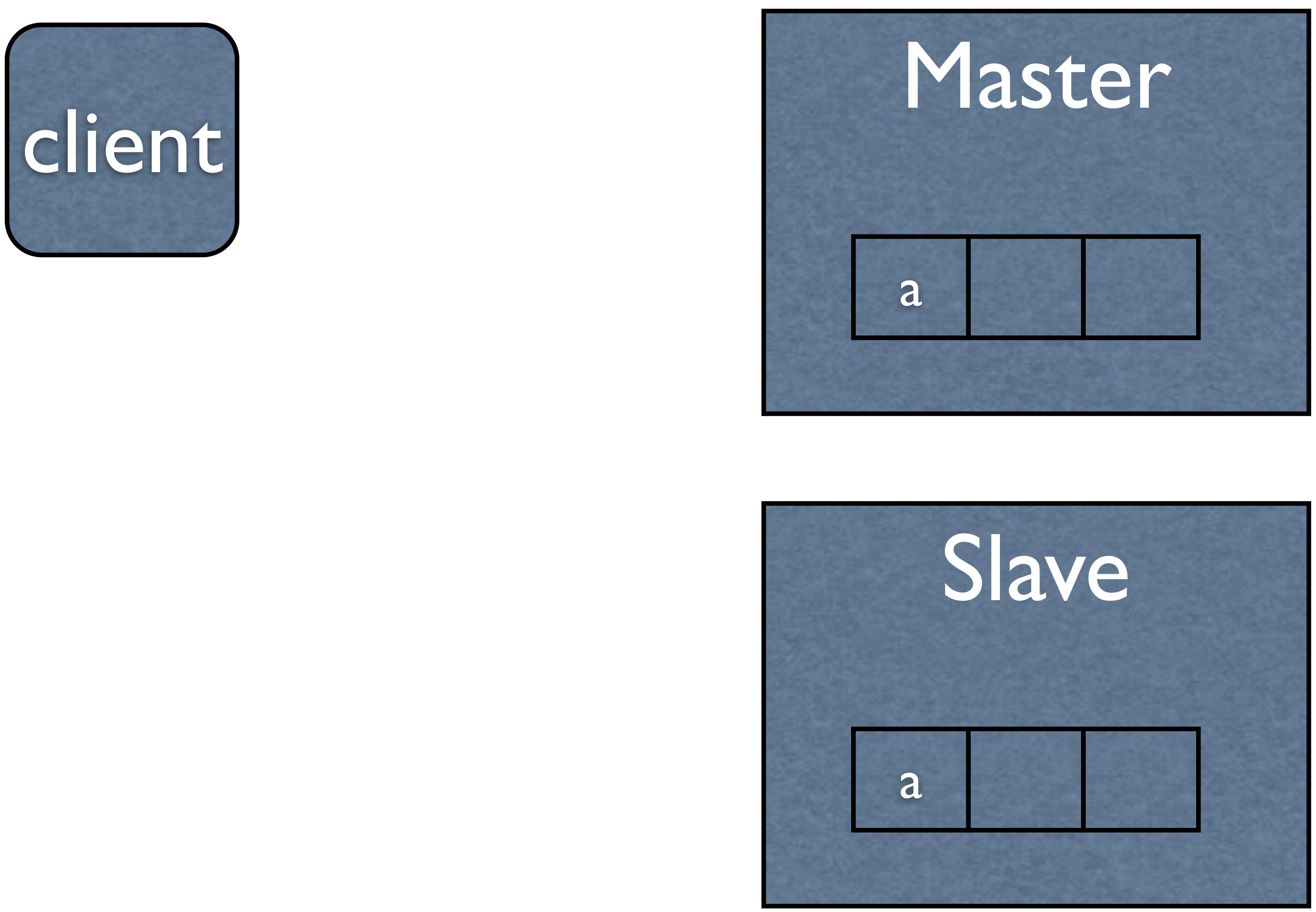

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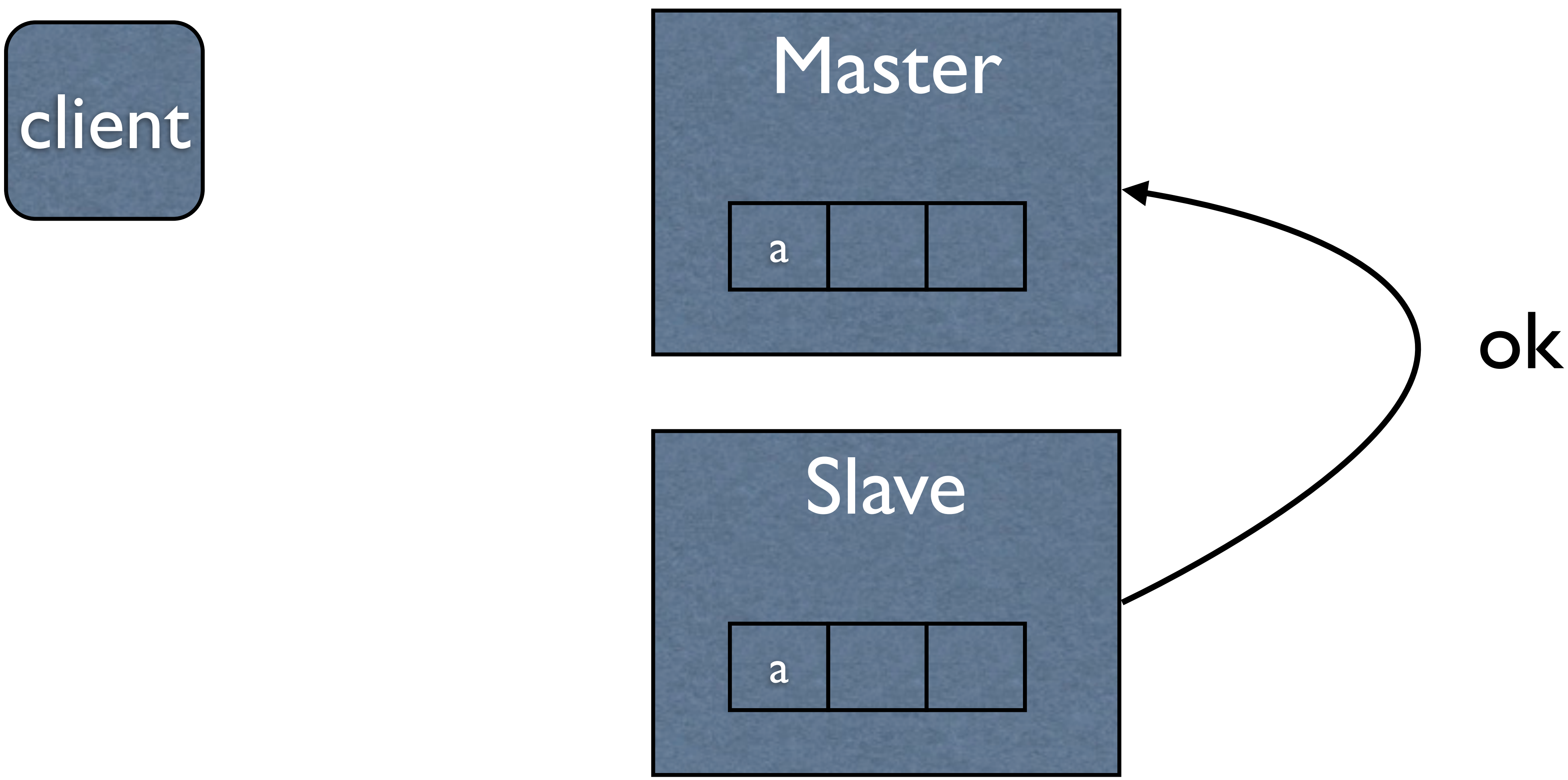

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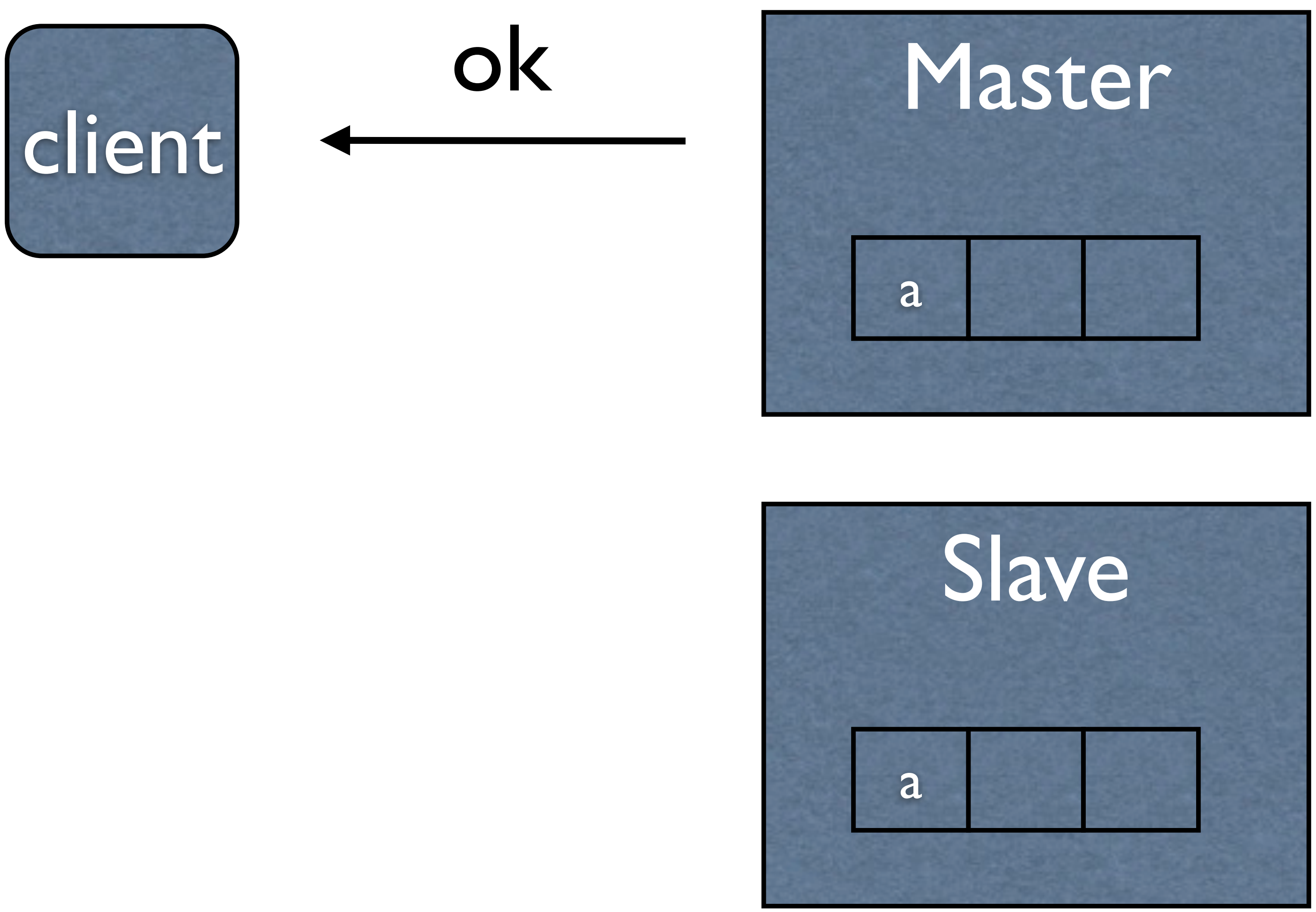

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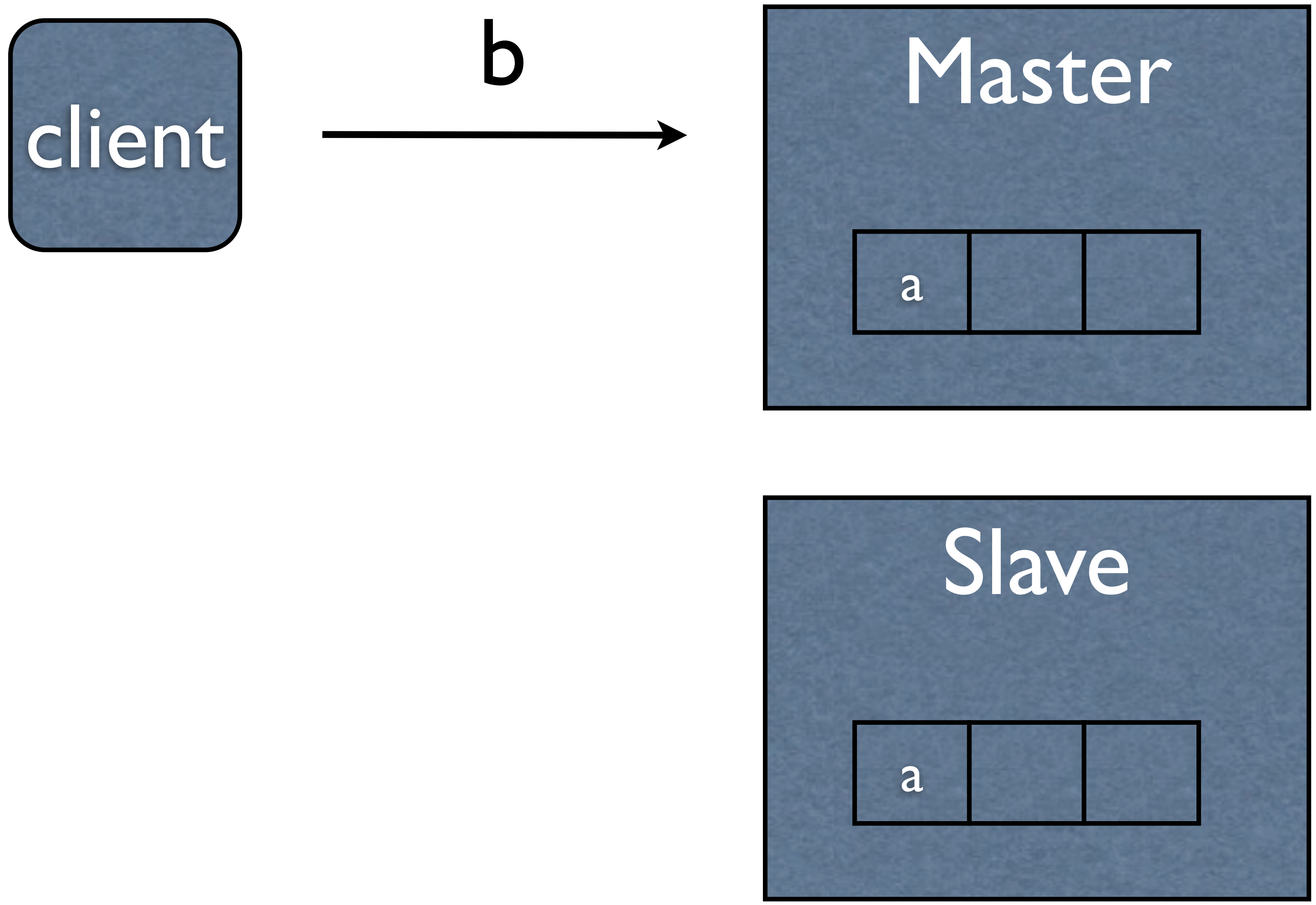

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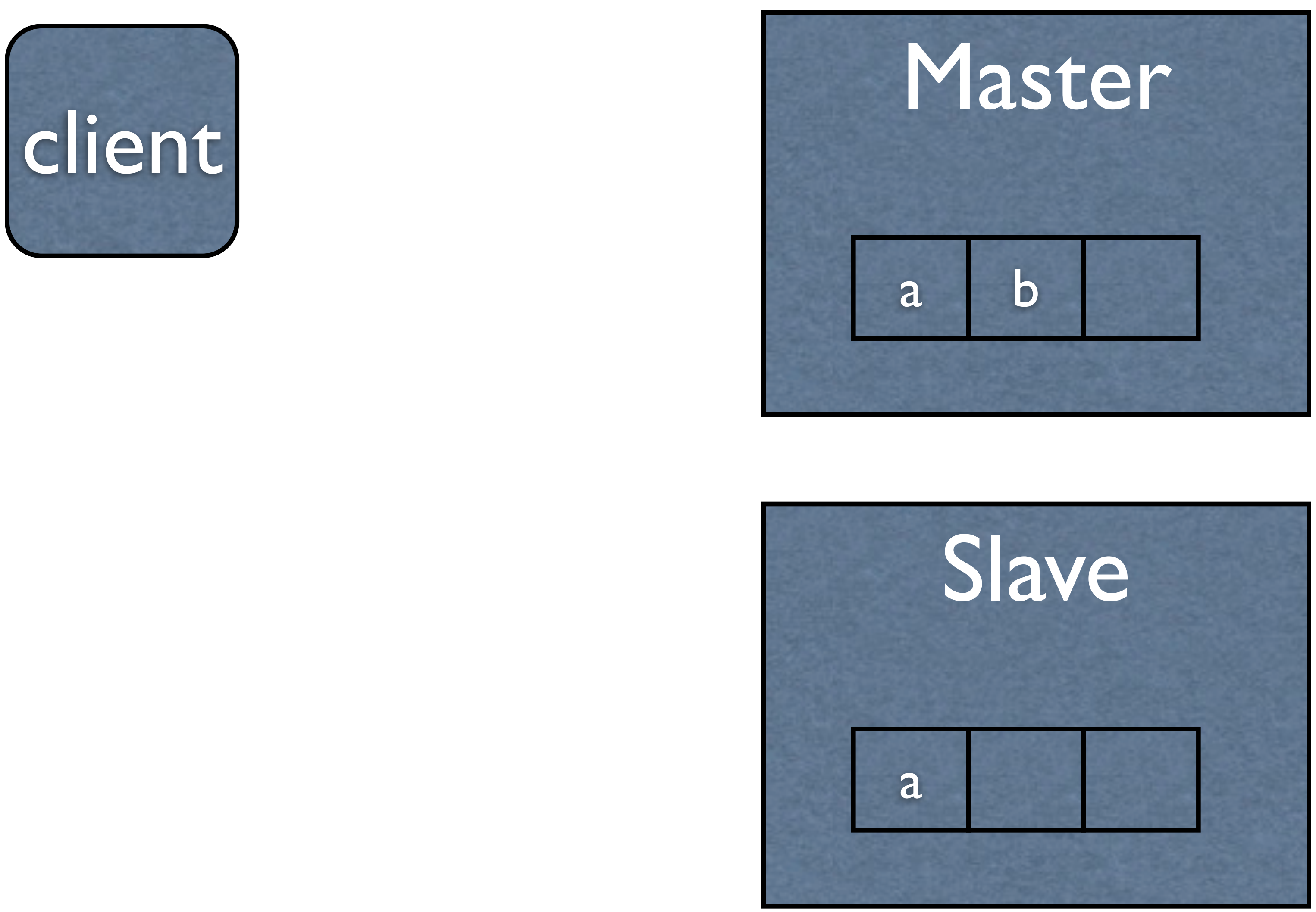

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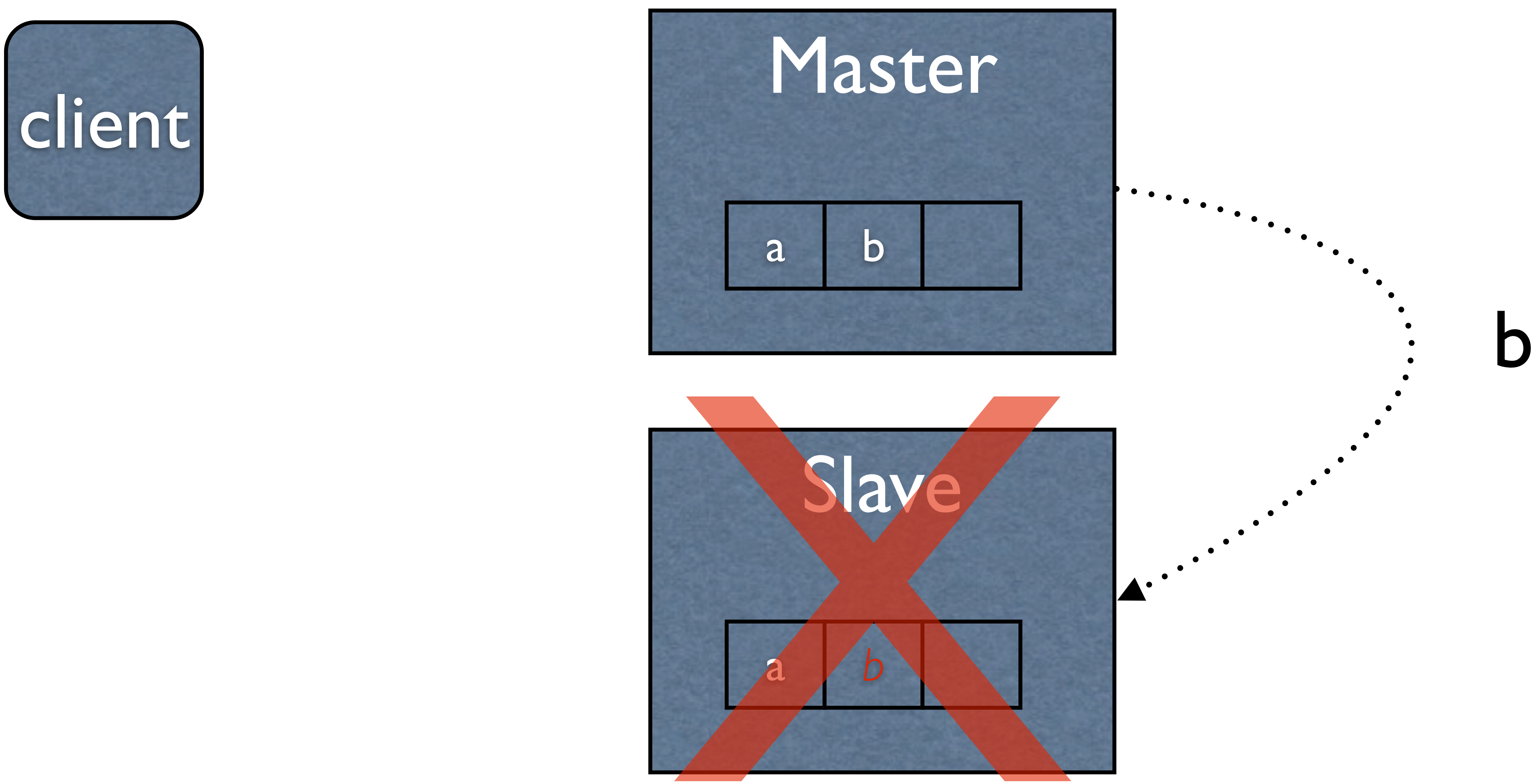

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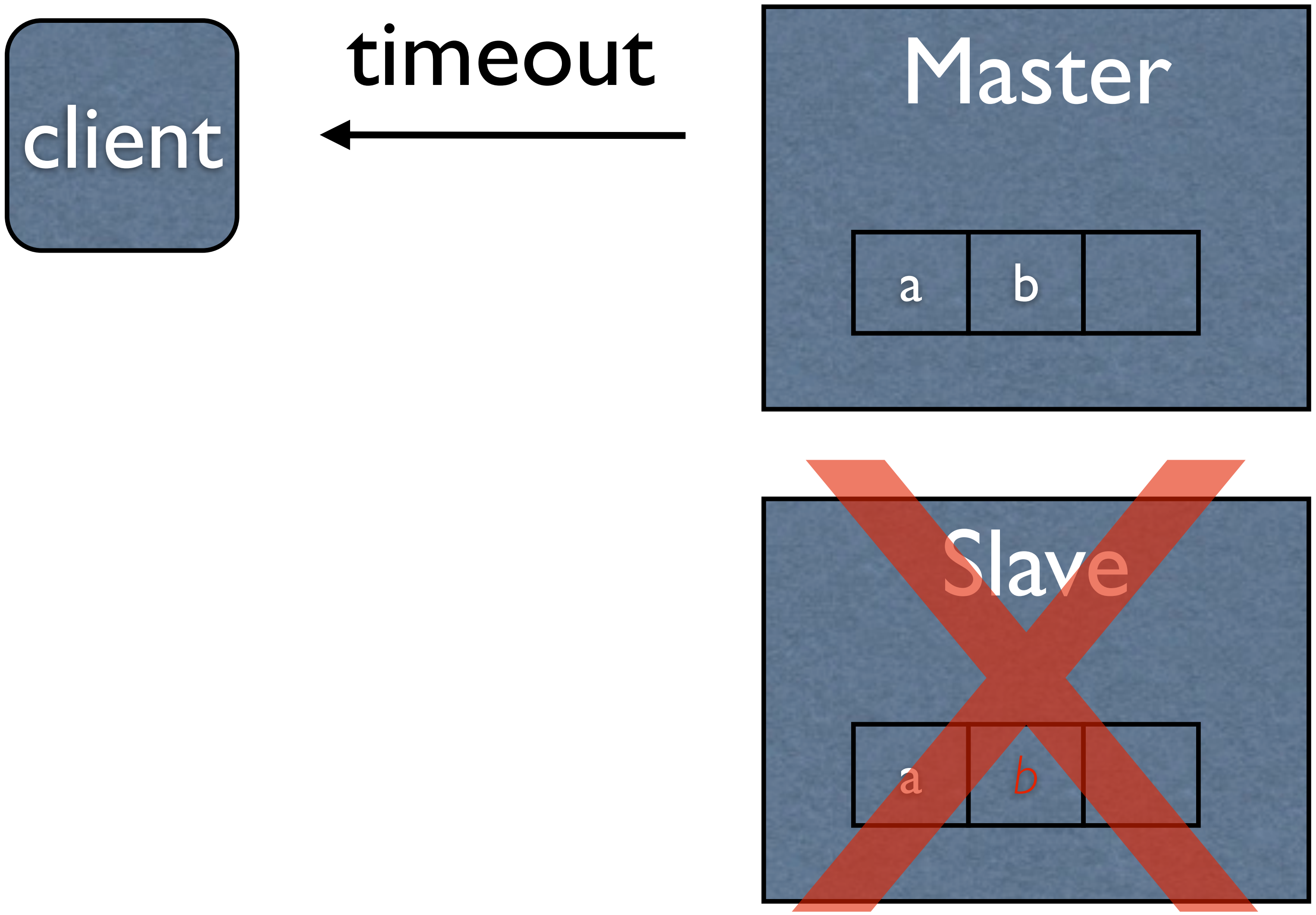
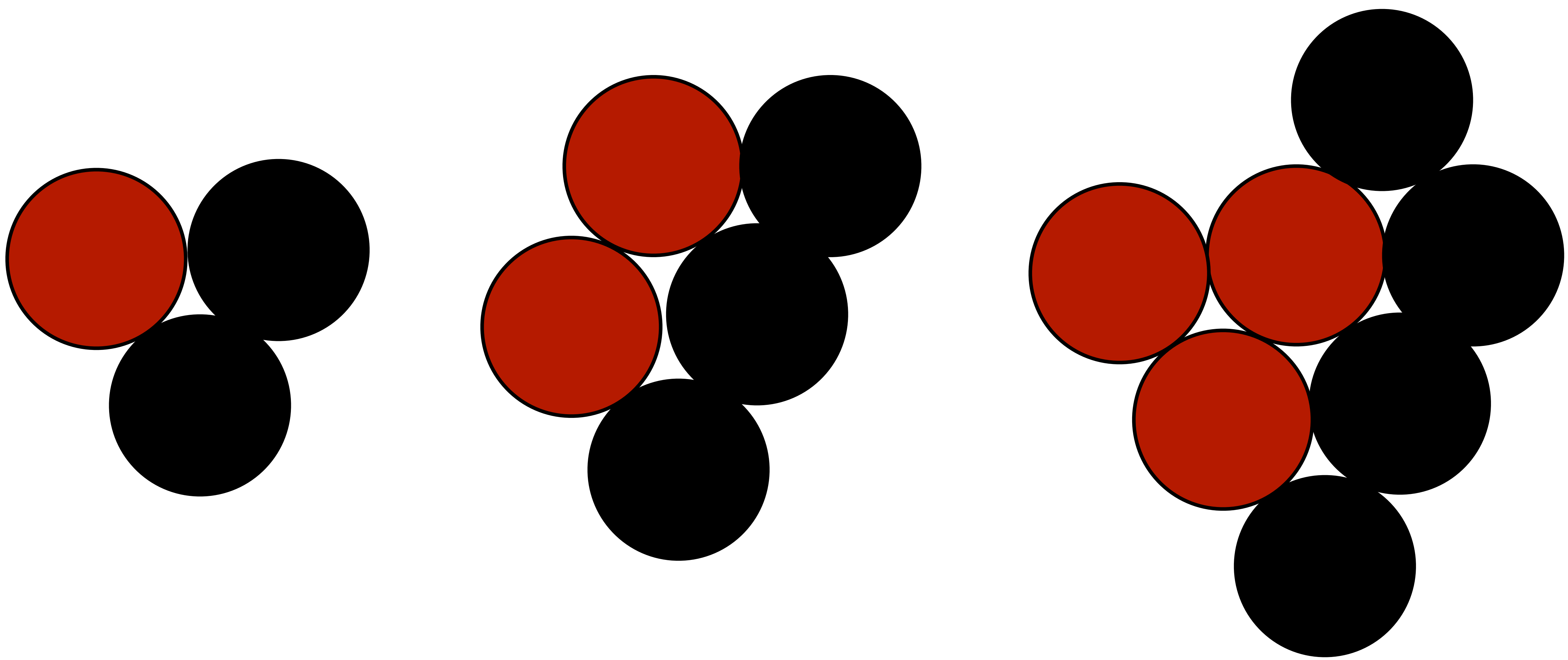
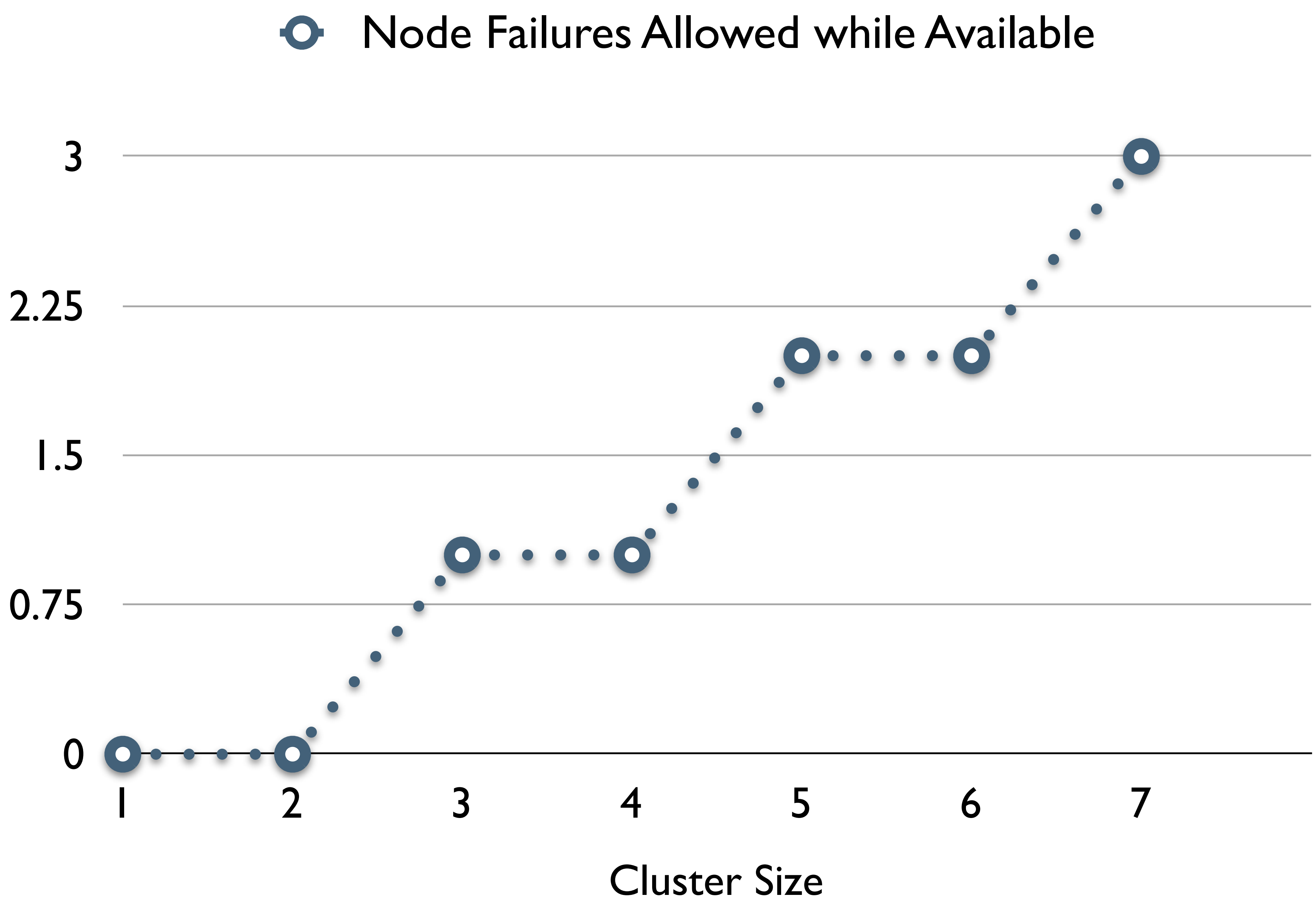


Safety vs. Liveness

Goal: Maintain Safety while tolerating failure



Quorums



Node Failures Allowed while Available
3
2.25
1.5
0.75
0
1
2
3
4
5
6
7
Cluster Size

Problems

- Who coordinates writes and reads?
- What interleavings are ‘safe’?

Consensus

RAFT

- Distributed State Machine Replication
- Designed to facilitate understanding
- John Ousterhout and Diego Ongaro

izability

- All nodes agree on an identical sequence of operations
- Monotonic ‘Term’ acts as a logical clock to prevent time from going backwards
- Operations are committed when written to a log on majority of nodes AND the term of the entry is the current term
- Once committed an operation cannot be removed from the log

Replicated Log

Committed

Uncommitted

NEW Leadership™

Index	1	2	3	4	5
	v1	v2	v3	v4	v5
Term	1	1	1	3	4

Replicated Log

Leader Election

- All nodes start in follower state
- After a random timeout, one becomes candidate
- Candidate increments term, requests a vote
- Followers vote for the candidate if the candidate log and term are up to date

MAJORITY Rules

Log Replication

- Leader sends Append Entries calls to each follower
- If previous log entry and term agree with the follower log contents, follower replies with success
- Leader keeps track of follower log indexes, decrements index on failure and sends older data
- If Majority replies with success, leader commits entry, responds to client and tells followers the latest commit index on next heartbeat

Heartbeats

=:=

Append Entries

- Prevent followers from becoming candidates unnecessarily
- Allow followers to detect failed leader or network partition and start a new election
- Leader replays log to followers who are behind due to either prior failure or netsplit

Rafter

- A Library for building strongly consistent distributed systems in Erlang
- Implements Raft in Erlang
- Isolates the application developer from the intricacies of consensus

Why Raft?

- I wanted to fully grok consensus
- Easier to understand than Paxos
- Every day someone tries to implement consensus in an ad-hoc manner

Why Erlang?

- Erlang is terrific for building reliable distributed systems
- I currently spend > 90% of my coding time in Erlang
- Consensus is NOT solved in Erlang
- mnesia, gen_leader, gproc don't tolerate netsplits

Core Abstractions

Peers

- Each peer is made up of 2 supervised processes
  - A gen_fsm implements the raft protocol
  - A gen_server wraps the persistent log
- An API module hides the implementation

```erlang
-include_lib("rafter/lib/rafter_opts.hrl").

start_node() ->
  Name = peer1,
  Me = {Name, node()},
  Opts = #rafter_opts{state_machine=rafter_backend_ets,
                      logdir="./data"},
  rafter:start_node(Me, Opts).

set_config(Peer, NewServers) ->
  rafter:set_config(Peer, NewServers).

put(Peer, Table, Key, Value) ->
  rafter:op(Peer, {put, Table, Key, Value}).

get(Peer, Table, Key) ->
  rafter:read_op(Peer, {get, Table, Key}).
```

Replicated Log

- API operates on Log Entries
- Log Entries contain commands
- Commands transparent to rafter
- Cmds encoded with term_to_binary/1

```
File Header Format
------------------------
<<Version:8>>
```

```
Entry Format
-----------------
<<Sha1:20/binary, Type:8, Term:64, Index:64, Size:32, Cmd/binary>>
```

```
Entry Trailer Format
-----------------
<<Crc:32, ConfigStart:64, EntryStart:64, ?MAGIC/64>>
```

Backend State Machine

- OTP behaviour
- Operates on commands via callbacks from consensus fsm
- Callbacks run on each node when commands are committed or read quorum achieved

```erlang
-module(rafter_backend).

-export([behaviour_info/1]).

behaviour_info(callbacks) ->
    [{init, 0}, {read, 1}, {write, 1}];
behaviour_info(_) ->
    undefined.
```

```erlang
read({get, Table, Key}) ->
    try
        case ets:lookup(Table, Key) of
            [{Key, Value}] -> {ok, Value};
            [] -> {ok, not_found}
        end
    catch _:E ->
        {error, E}
    end;


write({put, Table, Key, Value}) ->
    try
        ets:insert(Table, {Key, Value}),
        {ok, Value}
    catch _:E ->
        {error, E}
    end;
```

Consensus Module

- Implements Raft protocol in gen_fsm
- 3 states - follower, candidate, leader
- Logs persistent data via rafter_log gen_server
- Pure functions handling dynamic reconfiguration and quorums abstracted out to rafter_config

```erlang
%% API
-export([start/0, stop/1, start/1, start_link/3,
         leader/1, op/2, set_config/2,
         send/2, send_sync/2, get_state/1]).


%% States
-export([follower/2, follower/3,
         candidate/2, candidate/3,
         leader/2, leader/3]).
```

```
%% Election timeout has expired. Go to candidate state iff
we are a voter.
follower(timeout, #state{config=Config, me=Me}=State) ->
    case rafter_config:has_vote(Me, Config) of
        false ->
            Duration = election_timeout(),
            {next_state, follower, State, Duration};
        true ->
            {next_state, candidate, State, 0}
    end;


follower({read_op, _}, _From, #state{leader=Leader}=State) ->
    Reply = {error, {redirect, Leader}},
    {reply, Reply, follower, State, ?timeout()};
```

```erlang
%% We are out of date. Go back to follower state.
candidate(#vote{term=VoteTerm, success=false}, #state{term=Term}=State)
         when VoteTerm > Term ->
    NewState = step_down(VoteTerm, State),
    {next_state, follower, NewState, NewState#state.timer_duration};
```

```erlang
%% Sweet, someone likes us! Do we have enough votes to get elected?
candidate(#vote{success=true, from=From}, #state{responses=Responses, me=Me,
                                                 config=Config}=State) ->
    NewResponses = dict:store(From, true, Responses),
    case rafter_config:quorum(Me, Config, NewResponses) of
        true ->
            NewState = become_leader(State),
            {next_state, leader, NewState, 0};
        false ->
            NewState = State#state{responses=NewResponses},
            {next_state, candidate, NewState, ?timeout()}
    end.
```

```erlang
leader(timeout, State) ->
    Duration = heartbeat_timeout(),
    NewState = State#state{timer_start=os:timestamp(),
                           timer_duration=Duration},
    send_append_entries(State),
    {next_state, leader, NewState, Duration};
```

```erlang
leader({op, {Id, Command }}, From, #state{term=Term}=State) ->
    Entry = #rafter_entry{type=op, term=Term, cmd=Command},
    NewState = append(Id, From, Entry, State, leader),
    {next_state, leader, NewState, ?timeout()}.
```

Implementation Tradeoffs

- Distributed Erlang
- Single FSM for the consensus algorithm
- Separating read path from write path
- Rolling my own log file format

What isn’t done?

- Handling of exactly-once semantics for non-idempotent commands
- Log compaction
- A nice DB built on top of rafter
- More tests, More documentation
- Performance

Testing

Property Based Testing

```
-include_lib("eqc/include/eqc.hrl").

prop_reverse() ->
    ?FORALL(L, list(int()),
            L == lists:reverse(lists:reverse(L))).

 eqc:quickcheck(eqc:numtests(1000, prop_reverse())).
```

Stateful Property Tests

- eqc_statem behaviour
- Create a model of what your testing
- Verify that model

eqc_statem callbacks

- initial_state/0
- precondition/2
- command/1
- postcondition/3
- next_state/3
- invariant/1 (optional)

```erlang
command(_State) ->
    frequency([
        {10, {call, rafter_backend_ets, write, [{new, table_gen()}]}},
        {3, {call, rafter_backend_ets, write, [{delete, table_gen()}]}},
        {100, {call, rafter_backend_ets, write, [{delete, table_gen(), key_gen()}]}},
        {200, {call, rafter_backend_ets, read, [{get, table_gen(), key_gen()}]}},
        {200, {call, rafter_backend_ets, write,
                [{put, table_gen(), key_gen(), value_gen()}]}},
        {20, {call, rafter_backend_ets, read, [list_tables]}},
        {20, {call, rafter_backend_ets, read, [{list_keys, table_gen()}]}}]).
```

```
next_state(#state{tables=Tables}=S, _Result,
    {call, rafter_backend_ets, write, [{new, Table}]}) ->
        S#state{tables={call, sets, add_element, [Table, Tables]}};



postcondition(#state{},
    {call, rafter_backend_ets, write, [{new, Table}]},
    {ok, Table}) ->
        true;
postcondition(#state{tables=Tables},
    {call, rafter_backend_ets, write, [{new, Table}]},
    {error, badarg}) ->
        sets:is_element(Table, Tables);
```

```erlang
invariant(State) ->
    tables_are_listed_in_ets_tables_table(State) andalso
    tables_exist(State) andalso
    data_is_correct(State).



tables_exist(#state{tables=Tables}) ->
    EtsTables = sets:from_list(ets:all()),
    sets:is_subset(Tables, EtsTables).

data_is_correct(#state{data=Data}) ->
    lists:all(fun({{Table, Key}, Value}) ->
                  [{Key, Value}] =:= ets:lookup(Table, Key)
              end, Data).
```

An Actual Bug

```
%% This should only happen if two machines are configured differently during
%% initial configuration such that one configuration includes both proposed leaders
%% and the other only itself. Additionally, there is not a quorum of either
%% configuration's servers running.
%%
%% (i.e. rafter:set_config(b, [k, b, j]), rafter:set_config(d, [i,k,b,d,o]).
%%       when only b and d are running.)
%%
candidate(#vote{term=VoteTerm, success=false},
          #state{term=Term, init_config=[_Id, From]}=State) when VoteTerm > Term ->
    gen_fsm:reply(From, {error, invalid_initial_config}),
    State2 = State#state{init_config=undefined, config=#config{state=blank}},
    NewState = step_down(VoteTerm, State2),
    {next_state, follower, NewState, NewState#state.timer_duration};
```

Model Checking

=/=

Proof of correctness

Other Test Tools

- Pulse - http://quviq.com
- Concuerror - http://concuerror.com/
- PropEr - http://proper.softlab.ntua.gr/


That's all Folks!