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Synchronization problems with message-passing

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Principles of Concurrent Programming

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Today's menu

Barriers

Resource allocator

Producer-consumer

Readers-writers

Dining philosophers

A gallery of synchronization problems

In today's class, we go through several **classical synchronization problems** and solve them using processes and **message passing**.

On the course website you can download fully working implementations of some of the problems.

A gallery of synchronization problems

In today's class, we go through several **classical synchronization problems** and solve them using processes and **message passing**.

On the course website you can download fully working implementations of some of the problems.

Solving these problems with message passing has a **different style** than using semaphores or monitors:

- **mutual exclusion** is not an issue, since there are **no shared variables**
- **coordination** is the main problem, which is achieved by exchanging messages asynchronously

The solutions are in the style of **servers**, which run event-loop functions that handle requests from clients thus **coordinating** them.

Barriers

Reusable barriers – recap

```
-module(barrier).
```

```
% initialize barrier for 'Expected' processes
```

```
init(Expected) -> todo.
```

```
% block at 'Barrier' until all processes have reached it
```

```
wait(Barrier) -> todo.
```

Reusable barrier: implement module barrier such that:

- a process blocks on wait until all processes have reached the Barrier
- after Expected threads have executed wait, the barrier is closed again

Processes at a reusable barrier

Processes **continuously approach** the barrier, which must guarantee that they synchronize each access.

```
                                processk
process(Barrier) ->
    % code before barrier
    barrier:wait(Barrier) % synchronize at barrier
    % code after barrier
    process(Barrier).
```

Barrier process

The **barrier** process keeps track of the processes that have arrived at the barrier:

- when a new process **arrives**, it sends an arrived message to the barrier; the barrier updates its list of arrived processes
- when the list of arrived processes is **complete**, the barrier sends a continue message to all processes
- after notifying all processes, the barrier goes back to the **initial state**, ready for a new iteration

We implement the barrier's event loop as a server function:

```
barrier(Arrived, Expected, PidRefs)
```

where `Arrived` processes have arrived so far, out of a total of `Expected`; `PidRefs` is a list of the pids and unique references of arrived messages sent to the barrier (thus it has `Arrived` elements).

The server function barrier

```
% event loop of barrier for 'Expected' processes
% Arrived: number of processes arrived so far
% PidRefs: list of {Pid, Ref} of processes arrived so far
barrier(Arrived, Expected, PidRefs)
  when Arrived == Expected ->    % all processes arrived
    % notify all waiting processes
    [To ! {continue, Ref} || {To, Ref} <- PidRefs],
    % reset barrier
    barrier(0, Expected, []);
barrier(Arrived, Expected, PidRefs) ->
  receive % still waiting for some processes
    {arrived, From, Ref} ->
      % one more arrived: add {From, Ref} to PidRefs list
      barrier(Arrived+1, Expected, [{From, Ref}|PidRefs])
  end.
```

`Arrived` is redundant because it is equal to `length(PidRefs)`, but we keep it for clarity.

The function `wait`

The function `wait` exchanges messages with the `Barrier` process running `barrier`; it is used so that synchronizing processes do not need to know about the format of exchanged messages.

% block at 'Barrier' until all processes have reached it

```
wait(Barrier) ->
```

```
    Ref = make_ref(),
```

```
        % notify barrier of arrival
```

```
    Barrier ! {arrived, self(), Ref},
```

```
        % wait for signal to continue
```

```
    receive {continue, Ref} -> through end.
```

The function `wait`

The function `wait` exchanges messages with the `Barrier` process running `barrier`; it is used so that synchronizing processes do not need to know about the format of exchanged messages.

% block at 'Barrier' until all processes have reached it

```
wait(Barrier) ->
  Ref = make_ref(),
  % notify barrier of arrival
  Barrier ! {arrived, self(←), Ref},
  % wait for signal to continue
  receive {continue, Ref} -> through end.
```

pid of process executing `wait`

↑
dummy value

Barrier initialization

Initializing a barrier consists of spawning a process running barrier.

```
% initialize barrier for 'Expected' processes  
init(Expected) ->  
    spawn(fun () -> barrier(0, Expected, []) end).
```

↑
initially, no processes have arrived yet



The caller gets the barrier's pid, which should be distributed to all processes that want to use the barrier.

Resource allocator

Resource allocator: the problem – recap

An **allocator** grants **users** exclusive access to a number of resources:

- **users** asynchronously request resources and release them back
- the **allocator** ensures resources are given exclusively to one user at a time, and keeps tracks of how many resources are available

```
-module(allocator).
```

```
% register 'allocator' with list of Resources
```

```
init(Resources) -> todo.
```

```
% get 'N' resources from 'allocator'
```

```
request(N) -> todo.
```

```
% release 'Resources' to 'allocator'
```

```
release(Resources) -> todo.
```

Resource allocator problem: implement `allocator` such that:

- an arbitrary number of users can access the allocator
- users are granted exclusive access to resources

Users continuously and asynchronously access the allocator, which must guarantee proper synchronization.

$user_k$

```
user() ->  
  % how many resources are needed?  
  N = howMany(),  
  % get resources from allocator  
  Resources = allocator:request(N),  
  % do something with resources  
  use(Resources),  
  % release resources  
  allocator:release(Resources),  
  user().
```

Allocator process

The **allocator** process keeps track of the list of available resources:

- when a process **requests** some resources that are available, the allocator sends a granted message to the process, and removes those just granted from the list of available resources
- when a process **releases** some resources, the allocator sends a released message to the process, and adds those just released to the list of available resources
- requests that **exceed** the availability implicitly queue in the allocator's mailbox; they will be served as soon as enough resources are available

We implement the allocator's event loop as a server function:

```
allocator(Resources)
```

where **Resources** is the list of available resources.

The server function allocator: handling requests

```
allocator(Resources) ->  
  % count how many resources are available  
  Available = length(Resources),  
  receive          does not match if N > Available  
  % serve requests if enough resources are available  
  {request, From, Ref, N} when N =< Available ->  
    % Granted ++ Remaining := Resources  
    % length(Granted) := N  
    {Granted, Remaining} = lists:split(N, Resources),  
    % send resources to requesting process  
    From ! {granted, Ref, Granted},  
    % continue with Remaining resources  
    allocator(Remaining);
```

The server function allocator: handling releases

```
allocator(Resources) ->  
  % count how many resources are available  
  Available = length(Resources),  
receive  
  % serve requests: previous slide...  
  
  % serve releases  
  {release, From, Ref, Released} ->  
    % notify releasing process  
    From ! {released, Ref},  
    % continue with previous and released resources  
    allocator(Resources ++ Released)  
end.
```

The functions request and release

The functions request and release **exchange messages** with the process registered as allocator; they are used so that synchronizing processes do not need to know about the format of exchanged messages.

```
% get 'N' resources from 'allocator'; block if not available
```

```
request(N) ->
```

```
    Ref = make_ref(),
```

```
    allocator ! {request, self(), Ref, N},
```

```
    receive {granted, Ref, Granted} -> Granted end.
```

```
% release 'Resources' to 'allocator'
```

```
release(Resources) ->
```

```
    Ref = make_ref(),
```

```
    allocator ! {release, self(), Ref, Resources},
```

```
    receive {released, Ref} -> released end.
```

Producer-consumer

Producer-consumer: the problem – recap

```
-module(buffer).  
  
% initialize buffer with size 'Bound'  
init_buffer(Bound) -> todo.  
  
% put 'Item' in 'Buffer'; block if full  
put(Buffer, Item) -> todo.  
  
% get item from 'Buffer'; block if empty  
get(Buffer) -> todo.
```

Producer-consumer problem: implement buffer such that:

- producers and consumer access the buffer atomically
- consumers block when the buffer is empty
- producers block when the buffer is full (bounded buffer variant)

Producers and consumers

Producers and consumers continuously and asynchronously access the buffer, which must guarantee proper synchronization.

producer_n

```
producer(Buffer) ->  
  % create a new item  
  Item = produce(),  
  buffer:put(Buffer, Item),  
  producer(Buffer).
```

consumer_m

```
consumer(Buffer) ->  
  Item = buffer:get(Buffer),  
  % do something with 'item'  
  consume(Item),  
  consumer(Buffer).
```

Note that **atomic access** is not an issue with processes: a single sequential process will actively modify the content of the buffer in response to messages sent by other processes.

Buffer process: bounded buffer

The **buffer** process keeps track of the items stored in the buffer:

- when a process asks to **get** one item and the buffer is not empty, the buffer sends an item message to the process, and removes the item just taken from the buffer list
- when a process asks to **put** one item and the buffer is not full, the buffer sends a done message to the process, and adds the item just sent to the buffer list
- as in the allocator example, requests that cannot be satisfied (get with empty buffer, and put with full buffer) implicitly queue in the allocator's mailbox; they will be served as soon as it is possible

We implement the buffer's event loop as a server function:

```
buffer(Content, Count, Bound)
```

where **Content** is the list of **Count** available resources, and **Bound** is the buffer's size.

The server function buffer: handling requests

```
buffer(Content, Count, Bound) ->
```

```
  receive
```

```
    % serve gets when buffer not empty
```

```
    {get, From, Ref} when Count > 0 ->
```

```
      [First|Rest] = Content,           % match first item
```

```
      From ! {item, Ref, First},       % send it out
```

```
      buffer(Rest, Count-1, Bound); % remove it from buffer
```

```
    % serve puts when buffer not full
```

```
    {put, From, Ref, Item} when Count < Bound ->
```

```
      From ! {done, Ref},               % send ack
```

```
      buffer(Content ++ [Item], Count+1, Bound) % add item to end
```

```
  end.
```


The server function buffer: handling requests

```
buffer(Content, Count, Bound) ->
  receive
    % serve gets when buffer not empty
    {get, From, Ref} when Count > 0 ->
      [First|Rest] = Content,           % match first item
      From ! {item, Ref, First},       % send it out
      buffer(Rest, Count-1, Bound);    % remove it from buffer
    % serve puts when buffer not full
    {put, From, Ref, Item} when Count < Bound ->
      From ! {done, Ref},              % send ack
      buffer(Content ++ [Item], Count+1, Bound) % add item to end
  end.
```

Content managed as FIFO queue

Starvation is not possible: when the buffer is neither full nor empty, requests are served in the order they arrive in the mailbox. If the buffer fills up, `put` is disabled; after finitely many `gets` are served the buffer is no longer full, which disables `get`, thus allowing `put` to be served. Similarly, `put` activates `get` when the buffer is empty.

Buffer process: unbounded buffer

In an **unbounded buffer**, the condition `Count < Bound` always holds:

```
% serve puts
{put, From, Ref, Item} when Count < Bound ->
  % ...
```

Instead of removing the condition (as well as all the occurrences of `Bound`), we can take advantage of Erlang's order between numbers and atoms (every number is less than any atom): setting `Bound` to infinity ensures that `Count < Bound` will always evaluate to `true`. This way, we can use the very same implementation both in the bounded and in the unbounded case.

The functions `get` and `put`

The functions `get` and `put` exchange messages with the process with pid `Buffer`; they are used so that synchronizing processes do not need to know about the format of exchanged messages.

```
% get item from 'Buffer'; block if empty  
get(Buffer) ->  
    Ref = make_ref(),  
    Buffer ! {get, self(), Ref},  
    receive {item, Ref, Item} -> Item end.
```

```
% put 'Item' in 'Buffer'; block if full  
put(Buffer, Item) ->  
    Ref = make_ref(),  
    Buffer ! {put, self(), Ref, Item},  
    receive {done, Ref} -> done end.
```

Readers-writers

Readers-writers: the problem – recap

```
-module(board).  
init(Name) -> todo.           % register board with 'Name'  
begin_read(Board) -> todo.    % get read access to 'Board'  
end_read(Board) -> todo.      % release read access to 'Board'  
begin_write(Board) -> todo.   % get write access to 'Board'  
end_write(Board) -> todo.     % release write access to 'Board'
```

Readers-writers problem: implement board such that:

- multiple reader can operate concurrently
- each writer has exclusive access

Invariant: $\#WRITERS = 0 \vee (\#WRITERS = 1 \wedge \#READERS = 0)$

Other properties that a good solution should have:

- support an arbitrary number of readers and writers
- no starvation of readers or writers

Readers and writers

Readers and writers continuously and asynchronously try to access the board, which must guarantee proper synchronization.

reader_n

```
reader(Board) ->  
  board:begin_read(Board),  
  % read messages  
  board:end_read(Board),  
  reader(Board).
```

writer_m

```
writer(Board) ->  
  board:begin_write(Board),  
  % write messages  
  board:end_write(Board),  
  writer(Board).
```

Board process – first version

A first solution to the readers-writers problem can **extend the idea behind the allocator**: serve requests when possible, and let other requests queue in the mailbox. The **board** process keeps track of the number of readers and writers that are active on the board:

- when a new request to **begin reading** arrives and no writer is active, the board sends an OK to read message to the requester, and increases the count of readers;
- when a new request to **begin writing** arrives and no readers or writers are active, the board sends an OK to write message to the requester, and increases the count of writers;
- conversely, when notifications to **end read** or **end write** arrive, the board decreases the count of readers or writers;
- requests that **cannot be served** implicitly queue in the board's mailbox; they will be served as soon as the board is freed

The server function board_RoW – first version

```
% 'Readers' active readers and 'Writers' active writers
board_RoW(Readers, Writers) ->
receive
  {begin_read, From, Ref} when Writers == 0 ->
    From ! {ok_to_read, Ref},
    board_RoW(Readers+1, Writers);
  {begin_write, From, Ref} when (Writers == 0) and (Readers == 0) ->
    From ! {ok_to_write, Ref},
    board_RoW(Readers, Writers+1);
  {end_read, From, Ref} ->
    From ! {ok, Ref},
    board_RoW(Readers-1, Writers);
  {end_write, From, Ref} ->
    From ! {ok, Ref},
    board_RoW(Readers, Writers-1)
end.
```


Readers-writers: the first version prioritizes readers

In `board_RoW`, the “waiting conditions” follow directly from the invariant; thus, the resulting solution is **correct** in that it ensures **mutual exclusion** according to the readers-writers invariant.

However, it gives **priority** to readers over writers:

- new reading requests get served without waiting as long as a reader is active
- writing requests waiting in the mailbox have to wait until the last reader sends an `end_read` message
- as long as reading requests keep arriving and queuing in the mailbox, the waiting writing requests will never execute

Exchanging the order of clauses in the **receive** does not solve the problem (nor does it give priority to writers over readers): the scenario where readers starve writers can still happen because the condition for writing is **stronger** than the condition for reading, and writers cannot maintain their condition without the cooperation of readers.

Readers-writers: towards a fair solution

We could achieve **fairness** by replicating the pattern behind the solution with monitors:

- the board keeps track of the lists of **pending read and write requests**
- **read requests** are served as long as there are no active writers and no pending write requests
- notifications to **end write** let in one pending read request, or one waiting write request if there are no reading requests

This approach **works**, but it is quite **cumbersome** to implement with message passing. The main issue is that it requires a duplication of the information that is already implicit in the mailbox queue, which complicates ensuring that messages are processed exactly once.

Readers-writers: fair solution

We implement a fair solution where the board can be in one of two macro states:

- empty**: there are neither active readers nor active writers
- readers**: there are some active readers and no active writers

When the board is in macro state **empty**:

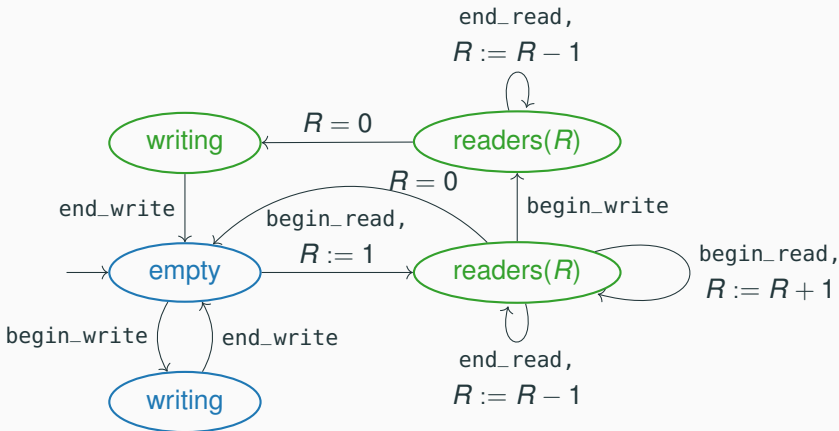
- read requests** are served immediately, then the board switches to macro state **readers**
- write requests** are served immediately and synchronously: the board waits until writing ends, then the board is **empty** again

When the board is in macro state **readers**:

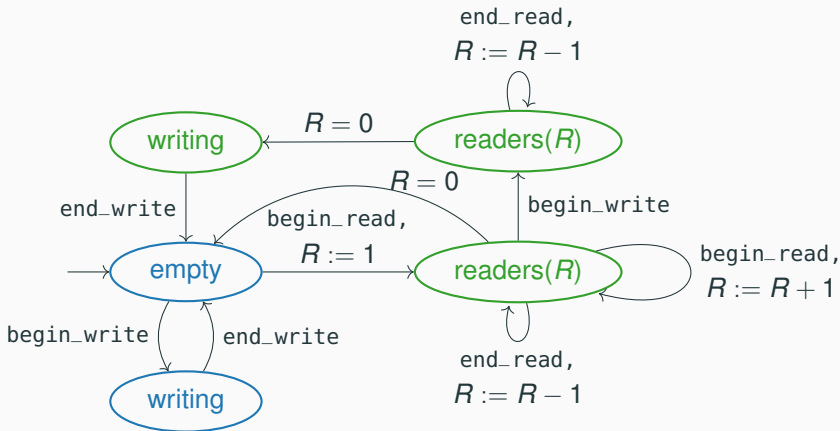
- read requests** are served immediately, and the macro state remains **readers**
- write requests** are served as soon as possible: the board waits until all reading ends, then the writing request is served synchronously, and then the board is **empty** again

Readers-writers: fair solution (cont'd)

This **state/transition diagram** formalizes the solution illustrated informally above. The partitioning of states in the diagram according to their color corresponds to the macro states **empty** and **readers**.



Readers-writers: fair solution (cont'd)



By inspecting the diagram we can understand that it guarantees fairness **provided** outgoing transitions from the same state have the same priority (they are served in arrival order). The solution in Erlang implements the behavior of this diagram, using **two** server functions `empty_board` and `readers_board` which call each other.

The server function `empty_board`

```
% board with no readers and no writers
```

```
empty_board() ->
```

```
receive
```

```
% serve read request
```

```
{begin_read, From, Ref} ->
```

```
    From ! {ok_to_read, Ref}, % notify reader
```

```
    readers_board(1);           % board has one reader
```

```
% serve write request synchronously
```

```
{begin_write, From, Ref} ->
```

```
    From ! {ok_to_write, Ref}, % notify writer
```

```
receive                               % wait for writer to finish
```

```
    {end_write, _From, _Ref} ->
```

```
        empty_board()           % board is empty again
```

```
end
```

```
end.
```

The server function `readers_board`: serving write requests

```
% board with no readers (and no writers)
```

```
readers_board(0) -> empty_board();
```

```
% board with 'Readers' active readers (and no writers)
```

```
readers_board(Readers) ->
```

```
receive
```

```
% serve write request
```

```
{begin_write, From, Ref} ->
```

```
% wait until all 'Readers' have finished
```

```
[receive {end_read, _From, _Ref} -> end_read end
```

```
  || _ <- lists:seq(1, Readers)],
```

```
From ! {ok_to_write, Ref}, % notify writer
```

```
receive
```

```
% wait for writer to finish
```

```
{end_write, _From, _Ref} -> empty_board()
```

```
end;
```

```
% board is empty again
```

The server function `readers_board`: serving read requests

Now the order of clauses in the **receive** does not matter: requests are processed in the mailbox order because none of the three clauses (`begin_read`, `end_read`, and `begin_write`) has a condition stronger than the others.

```
readers_board(Readers) ->
```

```
  receive
```

```
    % serve write requests: previous slide...
```

```
    % serve read request
```

```
    {begin_read, From, Ref} ->
```

```
      From ! {ok_to_read, Ref}, % notify reader
```

```
      readers_board(Readers+1); % board has one more reader
```

```
    % serve end read
```

```
    {end_read, _From, _Ref} ->
```

```
      readers_board(Readers-1) % board has one less reader
```

```
  end.
```


The functions `begin_read`, `end_read`, `begin_write`, and `end_write`

As usual, the functions `begin_read`, `end_read`, `begin_write`, and `end_write` **exchange messages** with the board server process with pid `Board`; they are used so that synchronizing processes do not need to know about the format of exchanged messages.

For example:

```
% get read access to 'Board'  
begin_read(Board) ->  
  Ref = make_ref(),  
  Board ! {begin_read, self(), Ref},  
  receive  
    {ok_to_read, Ref} -> ok_to_read  
  end.
```

Note that the behavior of the board process changes over time, but the pid `Board` stays the same.

Board initialization

Initializing a board consists of spawning a process running `empty_board`.

```
% initialize empty board and register with 'Name'  
init(Name) ->  
    register(Name, spawn(fun empty_board/0)).
```

After initialization, `Name` can be used to access the board.

Dining philosophers

Dining philosophers: the problem – recap

```
-module(philosophers).  
% set up table of 'N' philosophers  
init(N) -> todo.  
% philosopher picks up 'Fork'  
get_fork(Fork) -> todo.  
% philosopher releases 'Fork'  
put_fork(Fork) -> todo.
```



Dining philosophers problem: implement philosophers such that:

- forks are held exclusively by one philosopher at a time
- each philosopher only accesses adjacent forks
- no philosopher starves

Philosophers with waiter

We could replicate solutions based on locking; for example, setting up a server for each **pair of forks**, which grants access to both forks atomically to the first philosopher that sends a request.

Instead, let's explore an approach that is more congenial to message passing. A **waiter process** supervises access to the table. Each philosopher asks the waiter for **permission to sit** before picking up both forks, and notifies the waiter after putting down both forks.

As long as the waiter allows **strictly fewer** philosophers than the total number of forks to sit around the table at the same time, **deadlock** and **starvation** are avoided.

The **waiter's interface** consists of two functions:

```
% ask 'Waiter' to be seated; may wait  
sit(Waiter) -> todo.  
% ask 'Waiter' to leave  
leave(Waiter) -> todo.
```

Philosophers

Philosophers **continuously alternate** between thinking and eating, while coordinating with the waiter.

```
philosopherk
% Forks: fork#{left, right} of fork pids
% Waiter: waiter process
philosopher(Forks, Waiter) ->
    think(),
    sit(Waiter),                % ask to be seated
    get_fork(Forks#forks.left), % pick up left fork
    get_fork(Forks#forks.right), % pick up right fork
    eat(),
    put_fork(Forks#forks.left), % put down left fork
    put_fork(Forks#forks.right), % put down right fork
    leave(Waiter),             % notify leaving
    philosopher(Forks, Waiter).
```

Waiter process

The **waiter** process keeps track of how many philosophers are eating at the table:

- when a philosopher asks to be **seated** and the table is not full, the waiter sends an `ok_to_sit` message to the philosopher and increases the count of eating philosophers
- when a philosopher notifies **leaving**, the waiter sends an `ok_to_leave` message to the philosopher and decreases the count of eating philosophers
- requests to sit that arrive when the table is full queue in the waiter's mailbox; they will be served as soon as a seat frees up

We implement the waiter's event loop as a server function:

```
waiter(Eating, Seats)
```

where `Eating` philosophers are sitting and eating, out of a total of `Seats` available seats (`Seats` is the number of seats that can be occupied **at the same time**).

The server function waiter

```
waiter(Eating, Seats) ->  
  receive  
    % serve as long as seats are available  
    {sit, From, Ref} when Eating < Seats ->  
      io:format("~p eating (~p at table)~n", [From, Eating+1]),  
      From ! {ok_to_sit, Ref},  
      waiter(Eating+1, Seats); % one more eating  
    % can leave at any time  
    {leave, From, Ref} ->  
      io:format("~p leaving (~p at table)~n", [From, Eating-1]),  
      From ! {ok_to_leave, Ref},  
      waiter(Eating-1, Seats) % one less eating  
  end.
```

Printing the table's state at every change is for debugging purposes.

The functions `sit` and `leave`

As usual, the functions `sit` and `leave` hide the format of messages exchanged between philosophers and waiter.

```
% ask 'Waiter' to be seated; may wait  
sit(Waiter) ->  
    Ref = make_ref(),  
    Waiter ! {sit, self(), Ref},  
    receive {ok_to_sit, Ref} -> ok end.
```

```
% ask 'Waiter' to leave  
leave(Waiter) ->  
    Ref = make_ref(),  
    Waiter ! {leave, self(), Ref},  
    receive {ok_to_leave, Ref} -> ok end.
```

The fork processes and functions

Each fork has a **fork** process which keeps track of whether the fork is free (on the table) or held by a philosopher.

The server function for a fork can be in two states according to whether the fork is held or not.

```
% a fork not held by anyone  
fork() ->  
  receive  
    {get, From, Ref} ->  
      From ! {ack, Ref},  
      fork(From) % fork held  
end.
```

```
% a fork held by Owner  
fork(Owner) ->  
  receive  
    {put, Owner, _Ref} ->  
      fork() % fork not held  
end.
```

For simplicity, **put** requests do not get an acknowledgment; they just take effect immediately.

The functions `get_fork` and `put_fork`

The structure of `get_fork` and `put_fork` should be obvious by now:

```
% pick up 'Fork'; block until available
```

```
get_fork(Fork) ->
```

```
    Ref = make_ref(),
```

```
    Fork ! {get, self(), Ref},
```

```
    receive {ack, Ref} -> ack end.
```

```
% put down 'Fork'
```

```
put_fork(Fork) ->
```

```
    Ref = make_ref(),
```

```
    Fork ! {put, self(), Ref}.
```

Table initialization

Initializing a table consists of spawning the processes running waiter, fork, and philosopher, as well as connecting each philosopher to their pair of forks.

```
% set up table of 'N' philosophers
```

```
init(N) -> at most N-1 eating philosophers at once
```

```
  % spawn waiter process
```

```
  Waiter = spawn(fun () -> waiter(0, N-1) end),
```

```
  Ids = lists:seq(1,N), % [1, 2, ..., N]
```

```
  % spawn fork processes
```

```
  Forks = [spawn(fun fork/0) || _ <- Ids],
```

```
  % spawn philosopher processes
```

```
  [spawn(fun () ->
```

```
    Left = lists:nth(I, Forks),
```

```
    Right = lists:nth(1+(I rem N), Forks), % 1-based indexes
```

```
    philosopher(#forks{left=Left, right=Right},
```

```
              Waiter) end) || I <- Ids].
```

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