

Synchronization problems with message-passing

Lecture 8 of TDA384/DIT391

Principles of Concurrent Programming

Nir Piterman and Gerardo Schneider

Chalmers University of Technology | University of Gothenburg



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Today's menu

- Barriers
- Resource allocator
- Producer-consumer
- Readers-writers
- Dining philosophers

Barriers



Resource allocator



Dining philosophers



Readers-writers

TIME	DEPARTURE	FLIGHT
19:02	SEYCHELLES	...
05:02	TAHITI	...
11:02	BAHAMAS	...
03:02	FIJI	...
18:02	JCR&EV	...

Producer-consumer



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.

Process_k

```
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) ->` pid of process executing `wait`

`Ref = make-ref(),`

% notify barrier of arrival

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

% wait for signal to continue

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

↑
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

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  $N > \text{Available}$ 
```

```
  % serve requests if enough resources are available
```

```
  {request, From, Ref, N} when  $N \leq \text{Available}$  ->
```

```
    % 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

Content managed as FIFO queue

```
% 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.

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

 Office Holiday Departures		17:02:53	
TIME	DEPARTURE	FLIGHT 	
19:02	SEYCHELLES		
05:02	TAHITI		
11:02	BAHAMAS		
03:02	FIJI		
18:02	ICRANEM	Office Holiday	

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**:

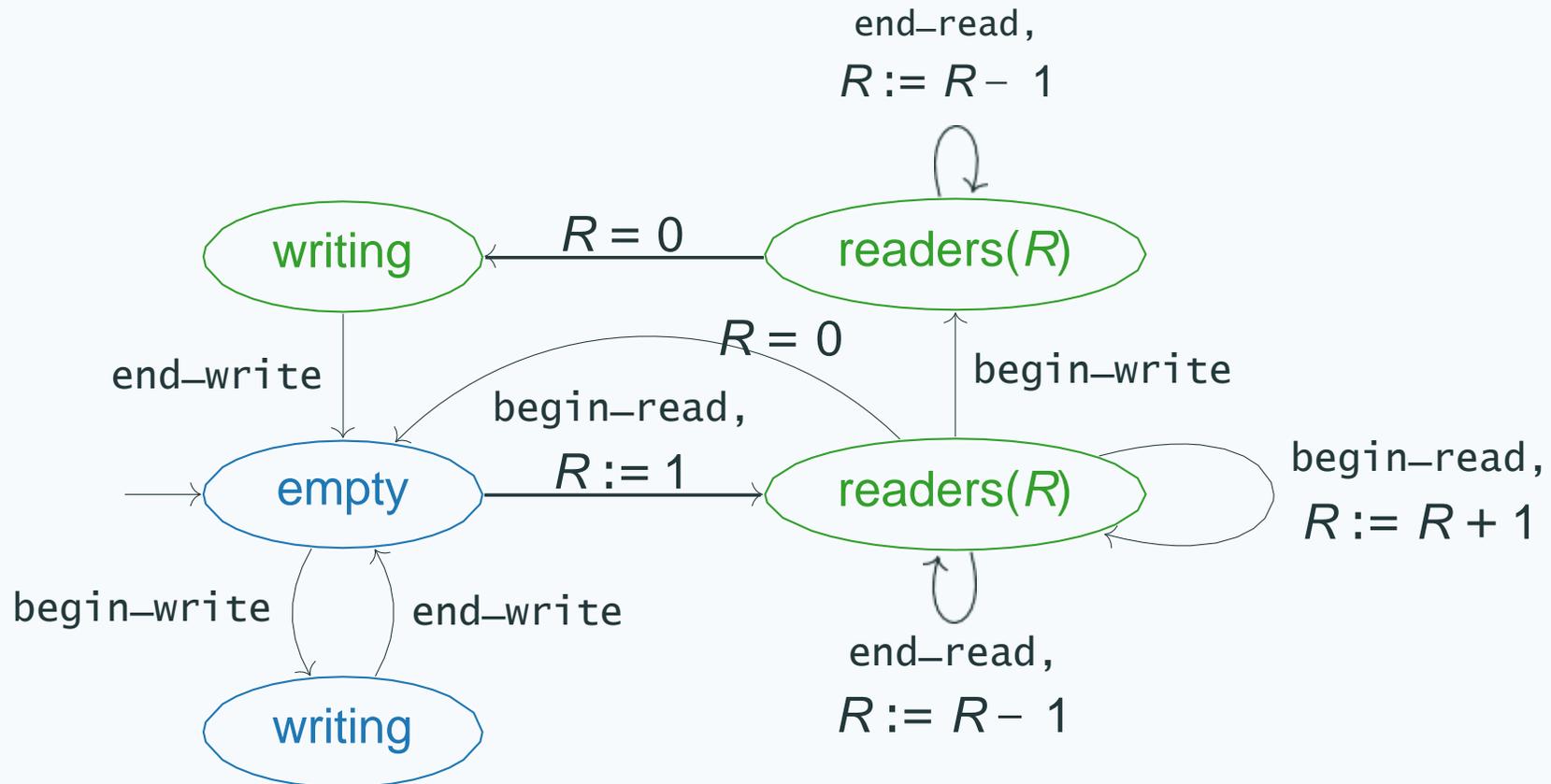
- **read requests** are served immediately, then the board switches to macro state **readers**
- **write requests** are served immediately and synchronously: the board waits until writing ends, then the board is **empty** again

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

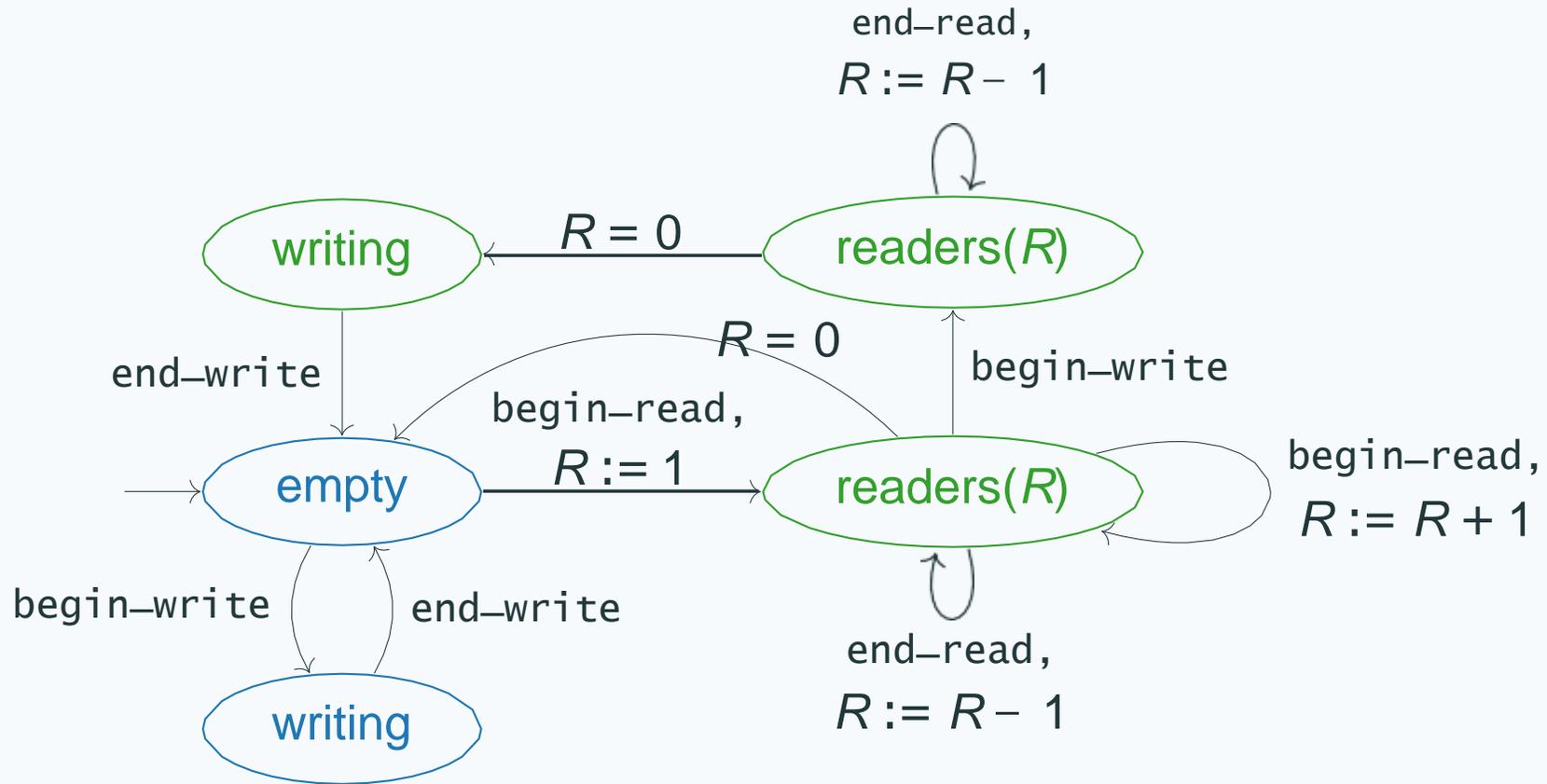
- **read requests** are served immediately, and the macro state remains **readers**
- **write requests** are served as soon as possible: the board waits until all reading ends, then the writing request is served synchronously, and then the board is **empty** again

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.
```

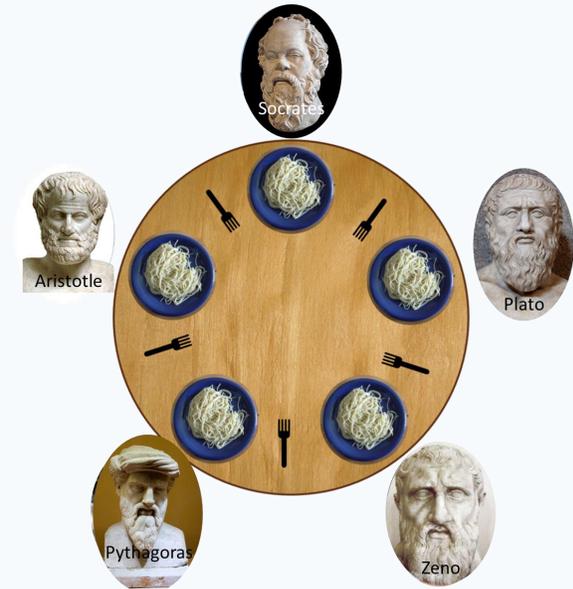
Note that the behavior of the board process changes over time, but the pid `Board` stays the same.

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.

philosopher_k

```
% 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` are similar to things we've seen:

```
% 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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