Erlang – a platform for developing distributed software systems

Lars-Åke Fredlund

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- Distributed programming is **hard**
- Challenges for concurrency:
  - process coordination and communication
- And challenges for distributed software:
  - heterogeneous systems
  - security, reliability (lack of control)
  - performance

Distributed Programming Today

Todays contrasts:

- Vision – easy programming of distributed systems
- The nightmare/reality – Web services, XML, Apache, SOAP, WSDL, . . .
- Why are Web services a nightmare?
  Too many standards, too many tools, too many layers, too complex!
- Erlang is an Industrially proven solution for developing and maintaining demanding distributed applications
- Good qualities of Erlang as a distributed systems platform:
  Complexity encapsulated in a programming language, good performance, efficient data formats, debuggable, not complex

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- Component programming is facilitated by using **design patterns** (client/server patterns, patterns for fault tolerant systems, etc) and **larger components** (web server, database)
- Component **maintenance**, and **fault tolerance** is facilitated by language features and design patterns
- But the devil is in the details: let’s see them!

Erlang/OTP

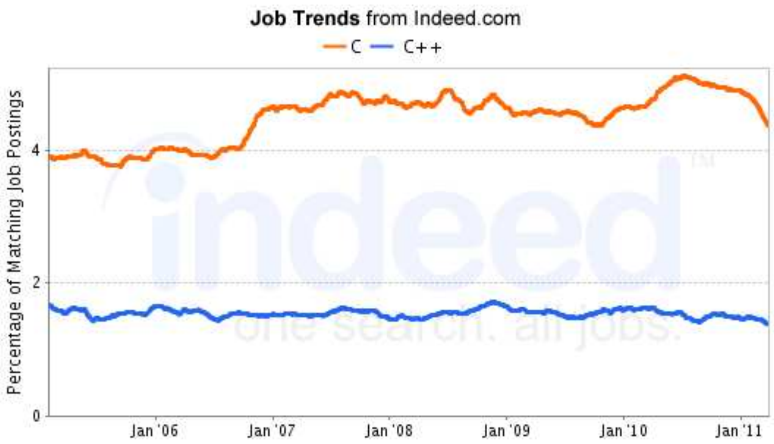
- Basis: a general purpose functional programming language
- Automatic Garbage Collection
- With lightweight processes
  (in terms of speed and memory requirements)
- Typical software can make use of many thousands of processes; **smp** supported on standard platforms
- Implemented using virtual machine technology and compilation to native code (Intel x86, Sparc, Power PC)
  Available on many OS:es (Windows, Linux, Solaris, . . .)
- Supported by extensive libraries:
  OTP – open telecom platform – provides tools such as components, distributed database, web server, etc

Erlang/OTP History

- Erlang language born in 1983
- Used inside and outside Ericsson for telecommunication applications, for soft real-time systems, ...
- Industrial users: Ericsson, Swedish Telecom, T-Mobile (UK), and many smaller start-up companies (LambdaStream in A Coruña)
- Application example: High-speed ATM switch developed in Erlang (2 million lines of Erlang code), C code (350 000 lines of code), and 5 000 lines of Java code
- Other examples: parts of Facebook chat written in Erlang (70 million users), CouchDB (integrated in Ubuntu 9.10), users at Amazon, Yahoo, ...
- Open-source; install from `http://www.erlang.org/`

Erlang is becoming popular

C and C++ job offers over the last 5 years:



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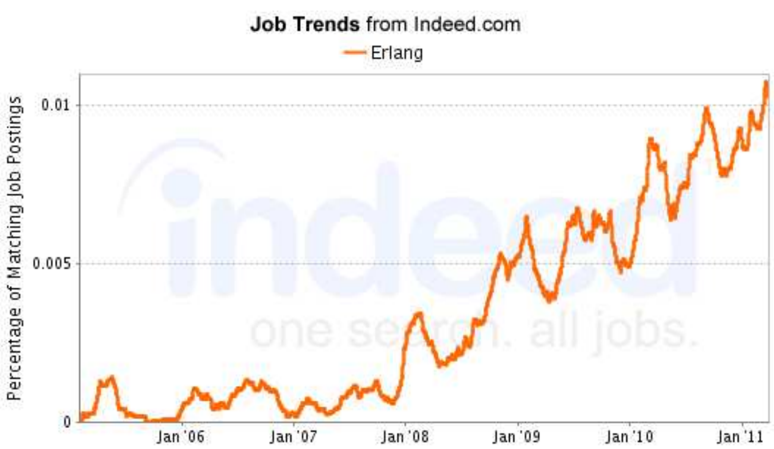

Erlang as a source of inspiration

- Concurrency and communication model from Erlang are also influencing other programming languages and libraries like Scala, Node.js, Clojure, …
- So lets see the main features…

Erlang basis

A simple functional programming language:

- Simple data constructors:
  integers (`2`), floats (`2.3`), atoms (`hola`), tuples (`{2,hola}`) and lists (`[2,hola]`,`[2|X]`), records (`#process{label=hola}`), bit strings (`<<1:1,0:1>>`)
- Call-by-value
- Variables can be assigned once only (Prolog heritage)
- *No static type system!*
  That is, expect runtime errors and exceptions
- Similar to a scripting language (python, perl) – why popular?

Erlang basis, II

- Example:

```
fac(N) ->
  if
      N == 0 -> 1;
      true -> N*fac(N-1)
  end.
```

Variables begin with a capital (`N`)
Atoms (symbols) begin with a lowercase letter (`fac`,`true`)

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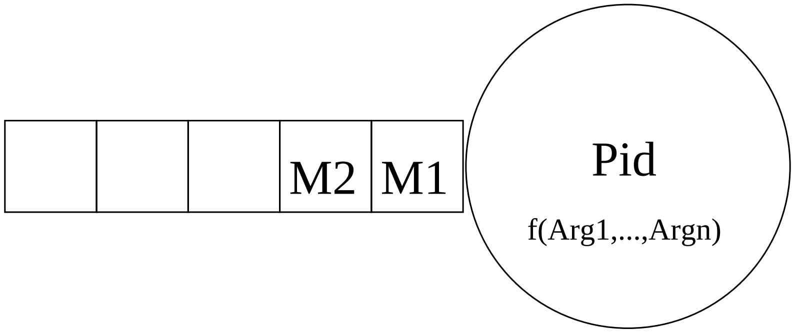
- And this call is permitted (what happens?): `fac(0.5)`

Concurrency and Communication

- Concurrency and Communication model inspired by the *Actor model* (and earlier Ericsson software/hardware products)
- Processes execute Erlang functions
- No implicit sharing of data (shared variables) between proceses
- Two interprocess communication mechanisms exists:
  - processes can send asynchronous messages to each other (**message passing**)
  - processes get notified when a related process dies (**failure detectors**)

Erlang Processes



- Processes execute Erlang functions ($f(Arg1, \ldots, Argn)$)
- A process has a unique name, a **process identifier** (Pid)
- Messages sent to a process is stored in a **mailbox** ($M2$, $M1$)

Erlang Communication and Concurrency Primitives

- Sending a message to a process:

```
Pid!{request, self(), a}
```

- Retrieving messages from the process mailbox (queue):

```
receive
  {request, RequestPid, Resource} ->
      lock(Resource), RequestPid!ok
end
```

- Creating a new process:

```
spawn(fun () -> locker!{request,B} end)
```

- A name server assigns symbolic names to processes:

```
locker!{request,a}
```

Communication Primitives, receiving

Retrieving a message from the process mailbox:

```
receive
  pat1 when g1 -> expr1 ;
  ...;
  patn when gn -> exprn
  after time -> expr'
end
```

- pat_1 is matched against the oldest message, and checked against the guard g_1. If a match, it is removed from the mailbox and $expr_1$ is executed
- If there is no match, pattern pat_2 is tried, and so on...
- If no pattern matches the first message, it is kept in the mailbox and the second oldest message is checked, etc
- `after` provides a timeout if no message matches any pattern

Receive Examples

- Given a receive statement:

```
receive
    {inc,X} -> X+1;
    Other -> error
end
```

and the queue is $a \cdot \{inc, 5\}$ what happens?

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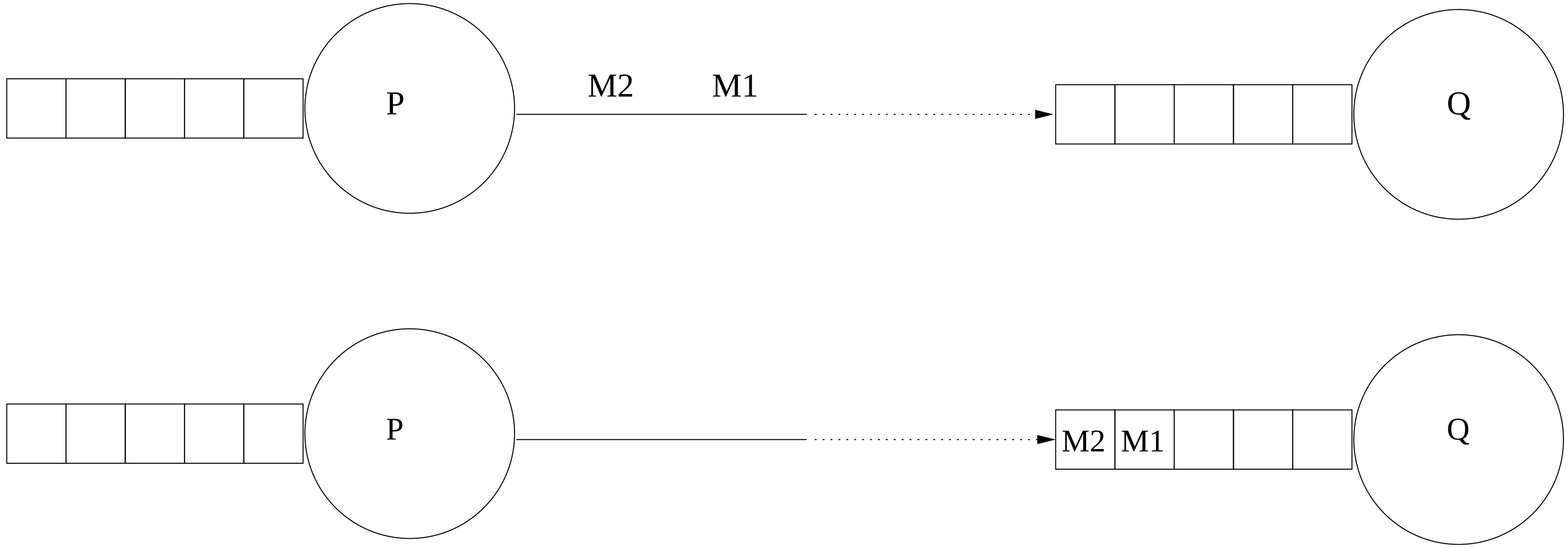
- And if the queue is $a \cdot b$?

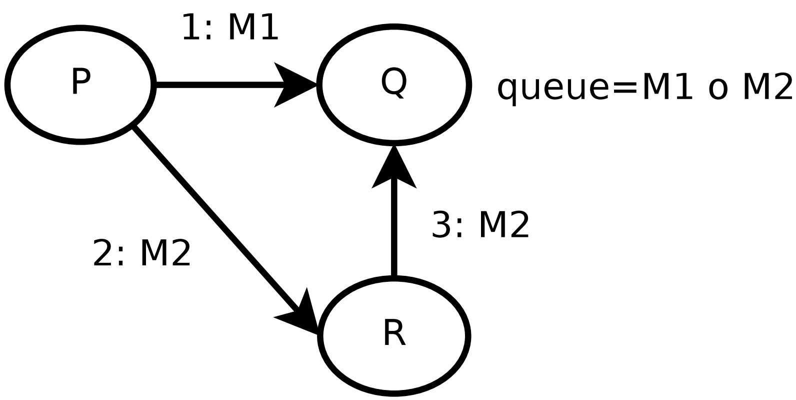
Communication Guarantees

Messages sent from any process P to any process Q is delivered in order (or P or Q crashes)



Communication Guarantees Part II

- But the following situation is possible:
  - Process P sends a message M1 to process Q
  - and P then a message M2 to process R
  - R forwards the message M2 to Q
  - **Process Q may receive M2 from R before M1 from Q**



- Mimics TCP/IP communication guarantees

A Simple Concurrent Program

```
facserver() ->
  receive
    {request, N, Pid}
    when is_integer(N), N>0, pid(Pid) ->
        spawn(fun () -> Pid!(fac:fac(N)) end),
        facserver()
  end.
```

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3>  X!{request,2,self()}.
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2>  X = spawn(server,facserver,[]).
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3>  X!{request,2,self()}.
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4>  X!{request,4,self()}, receive Y -> Y end.
2
```

Erlang and Errors

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- Higher-level Erlang components offer convenient handling of errors

Erlang and Errors, part II

- Error handling example:

```
g(Y) ->
  X = f(Y),
  case X of
    {ok, Result} -> Result;
    reallyBadError -> 0 % May crash because of ...
  end.
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- The local process will crash; another process is responsible from recovering (restaring the crashed process)
- Error detection and recovery is localised to special processes, to special parts of the code (*aspect oriented programming*)

Error Detection and Recovery: local level

- Exceptions are generated at runtime due to:
  - type mismatches ($10 * $ `"upm"`)
  - failed pattern matches, processes crashing, . . .
- Exceptions caused by an expression e may be recovered inside a process using the construct **`try`** e **`catch`** m **`end`**
- Example:

```
try
  g(Y)
catch
  Error -> 0
end
```

Error Detection and Recovery: process level

- Within a set of processes, via bidirectional process links set up using the **`link`**`(pid)` function call
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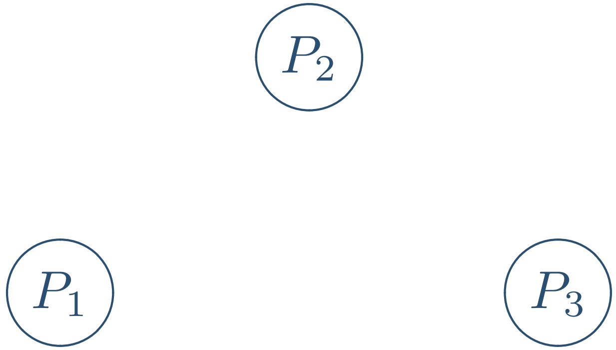
  Initially we have a system of 3 independent processes:



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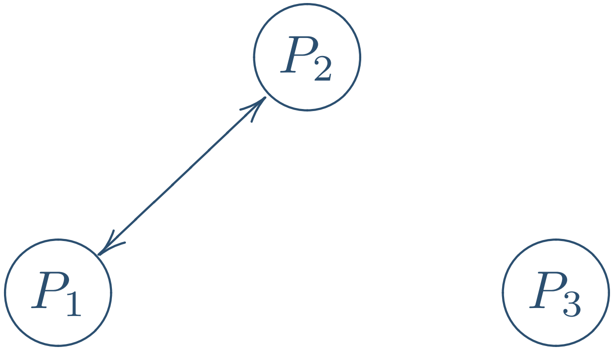

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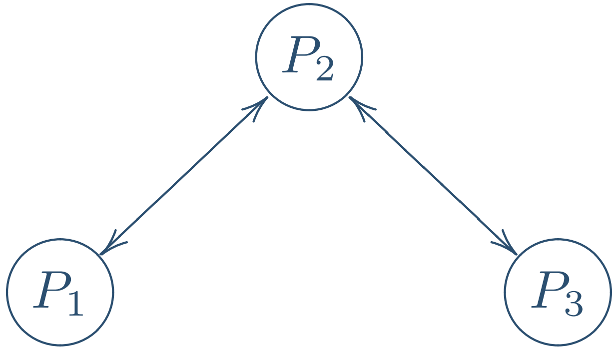

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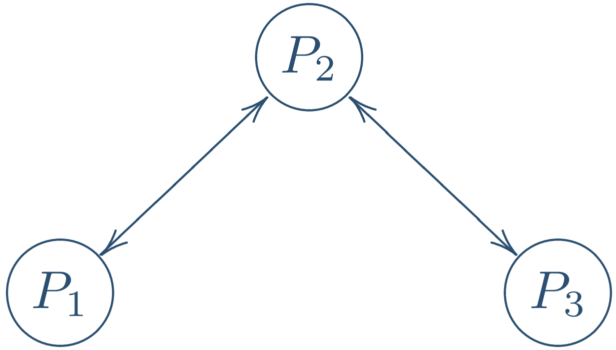

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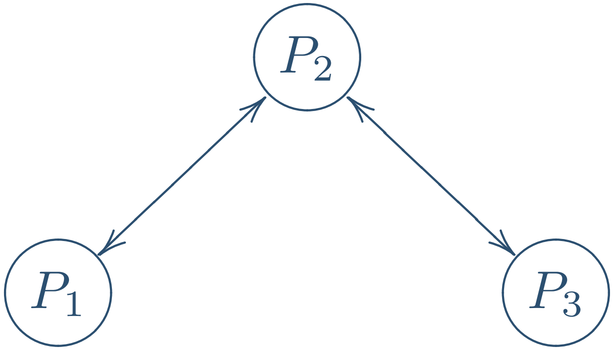


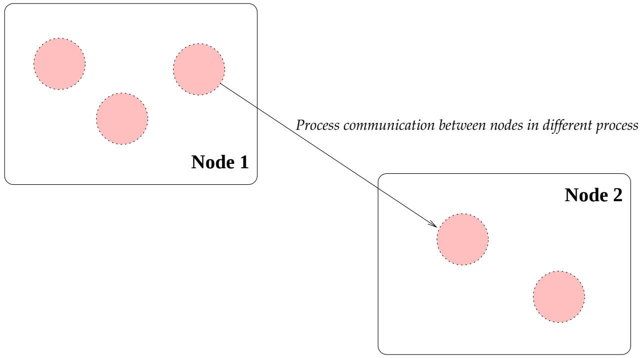
- If P_2 dies abnormally then P_1 and P_3 can *choose* to die
  If P_1 dies abnormally then P_2 can *choose* to die as well
- Alternatively when P_2 dies both P_1 and P_3 receives a message concerning the termination

What is Erlang suitable for?

- Generally intended for long-running programs
- Processes with state, that perform concurrent (and maybe distributed) activities
- Typical is to have a continously running system (24/7)
- Programs need to be fault-tolerant (because hardware and software invariably fail)
- So hardware is typically replicated as well – and thus we have a need for distributed programming (addressing physically isolated processors)

Distributed Erlang

- Processes run on nodes (computers) in a network



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  - No syntactic difference between inter-node or intra-node process communication
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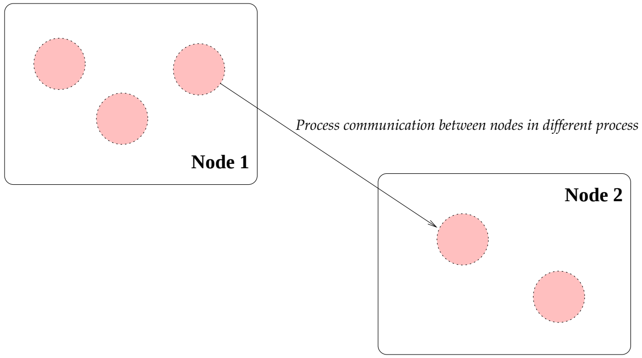

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  - No syntactic difference between inter-node or intra-node process communication
  - Communication link failure or node failures are interpreted as process failures (detected using linking)
  - Compare with Java: no references to objects which are difficult to communicate in messages (copy?)
  - The only references are process identifiers which have the same meaning at both sending and receiving process

Erlang Programming Styles

- Using only the basic communication primitives (send/receive) makes for messy code – everybody invents their own style and repeats lots of code for every program
- We need at least a standard way to:
  - **ask** processes about their status
  - a standard way to handle process **start, termination and restarts**
  - to handle **code upgrading**
  - and maybe more structured communication patterns: *who* communicates with *whom*, in *what role*?...

Erlang Software Architecture

- We need to structure the code according to some more design principles, to obtain more ”regular” code
- For Erlang one generally uses the components and the framework of the **OTP library – Open Telecom Platform** – as an infrastructure
- Today we are going to illustrate a number of these design principles, and how they are used in practise

OTP – an Erlang library of components

- A library of components for typical programming patterns (e.g., client–server, managing processes, . . .)
- In contrast to many component frameworks OTP is not concerned with how to *link components together* but with:
  - operation and management of components
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- In contrast to many component frameworks OTP is not concerned with how to *link components together* but with:
  - operation and management of components
  - fault-handling for components
- OTP components uses similar behaviour wrt management concerns such as
  - Starting a component
  - Terminating a component
  - Dynamic code update (change code at runtime)
  - Inspecting components
  - Handling errors

Component/Behaviour Style

- Declarative specifications are preferred
- **Callback style** – Component descriptions are composed of two parts:
  - A generic part containg the generic component code
  - A concrete one where the default behaviour is specialised to the concrete application by supplying **function definitions**
- As a result: a weak object-orientation style (very weak type checking of component specialisation)
- Except it is based on processes, a pretty powerful concept

OTP components

Example OTP components:

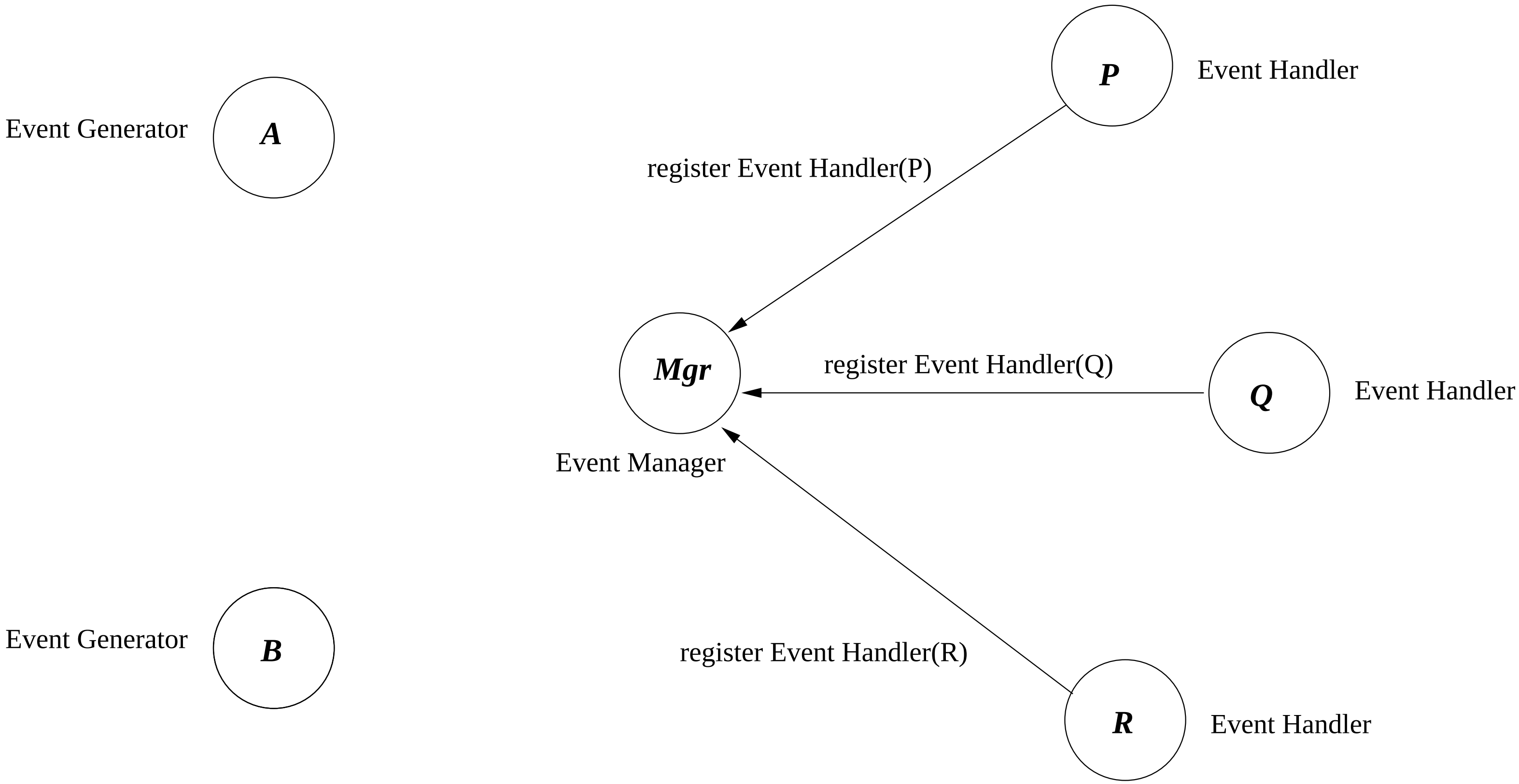
- Application
  – provides bigger building blocks like a database (Mnesia)
- Supervisor
  – used to start and bring down a set of processes, and to manage processes when errors occur
- Generic Server
  – provides a client–server communication facility
- Event Handling
  – for reporting system events to interested processes
- Finite State Machine
  – provides a component facilitating the programming of finite state machines in Erlang

Event Handling: Processes

- An implementation of a publish-and-subscribe behaviour
- An *Event manager* controls the publishing of events
- *Event handlers* register interest to receive events from a particular event manager by sending a message to the event manager
- Some process generates an event, which is sent to all the interested event handlers (*Event generator*)

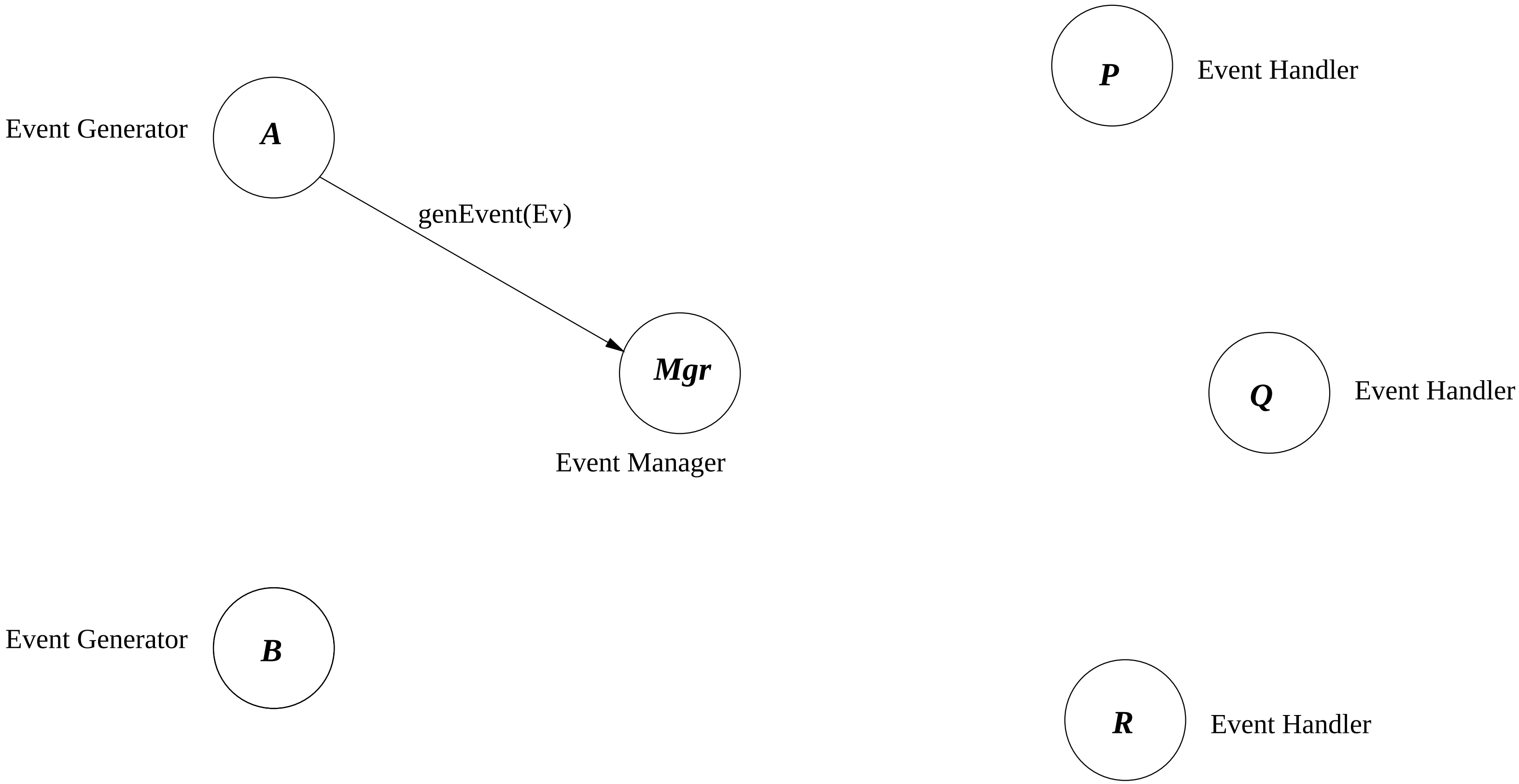
Event Handling: Behaviour

(1): The event handlers registers themselves:



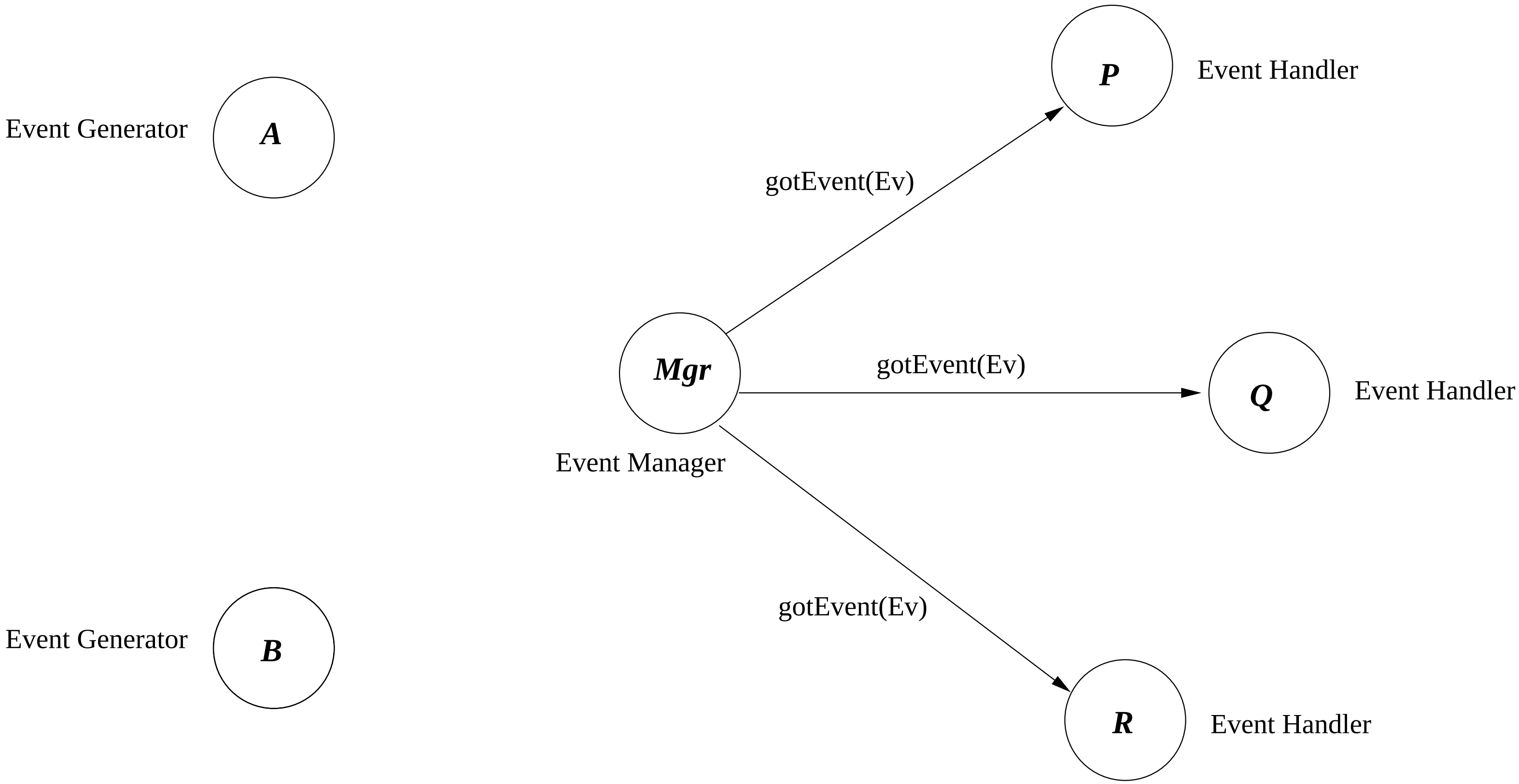
Event Handling: Behaviour

(2): Some process generates an event:



Event Handling: Behaviour

(3): The event is handled by the event handlers:



Event Handling: Behaviour part II

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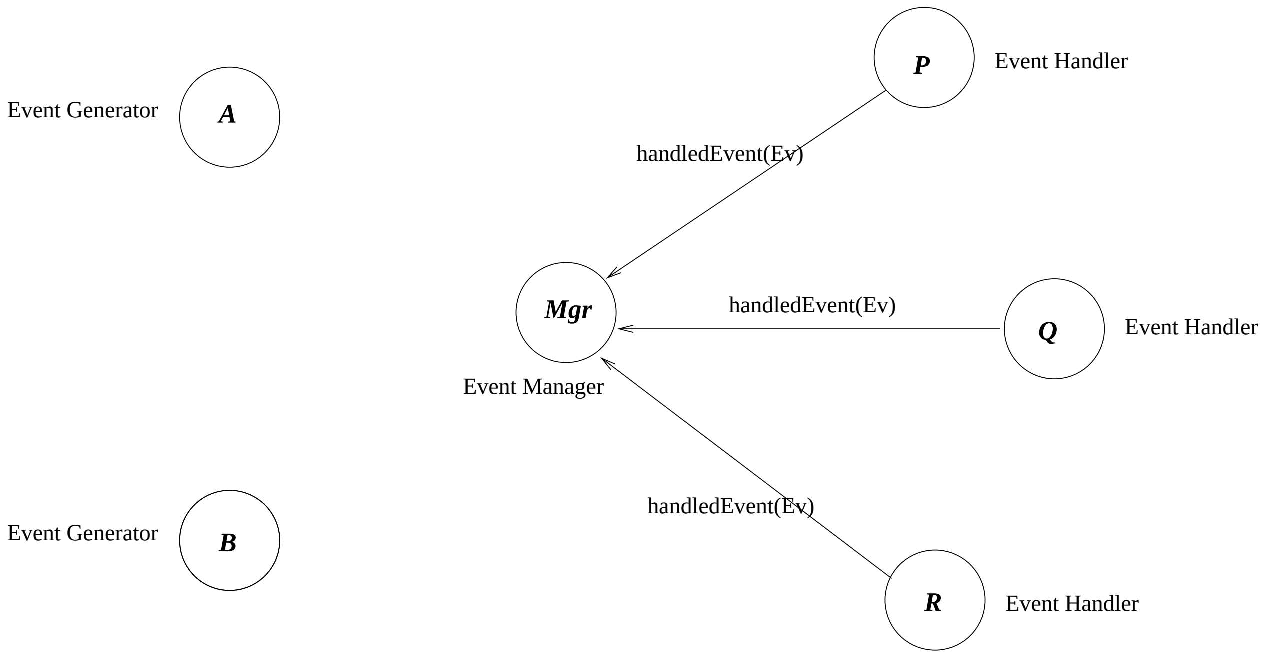
(4): All event handlers return their status to the event handler when they have finished:



Event Handling: Behaviour part II

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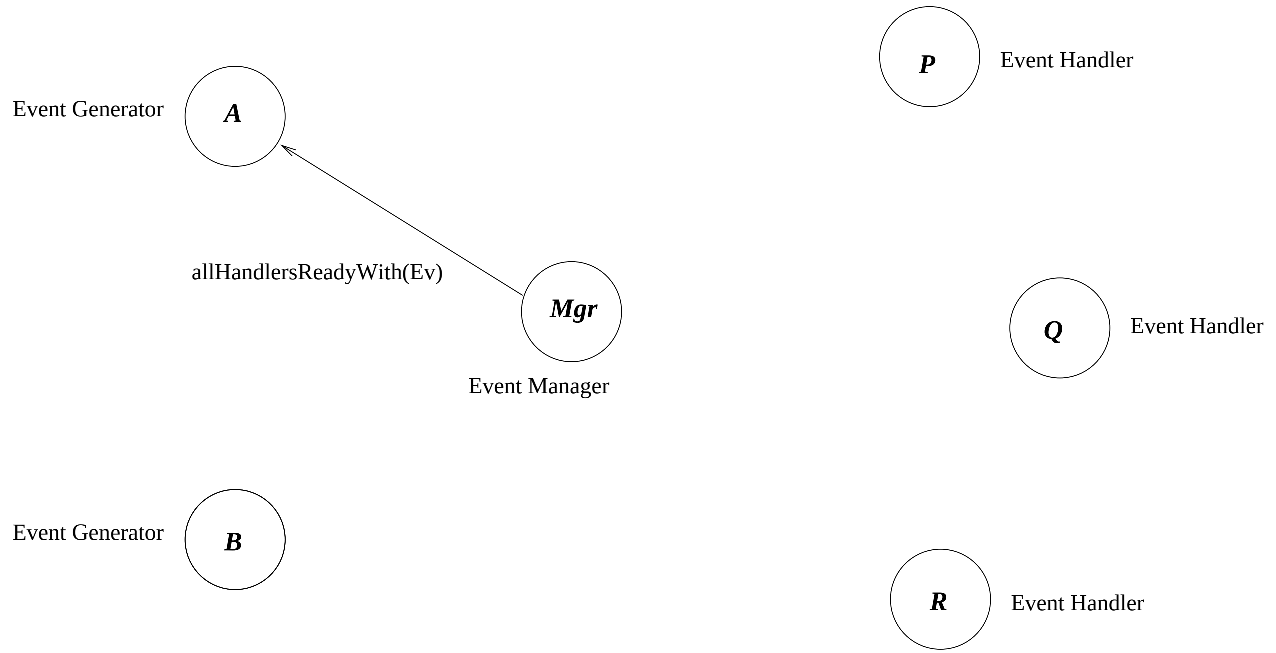
(5): And the event handler tells the event generator when it has finished its execution

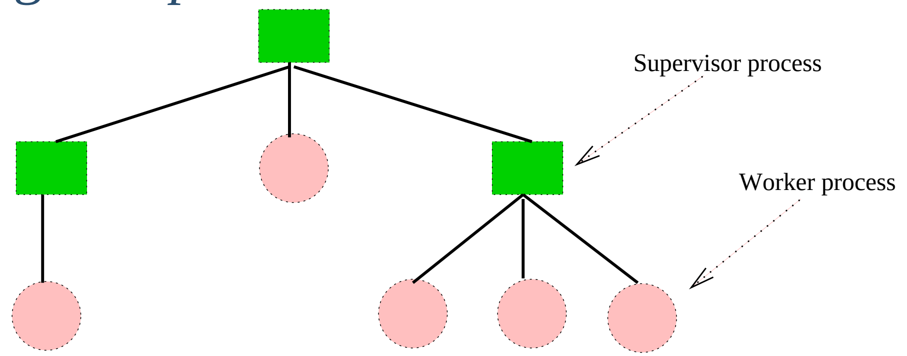


Event Handling, behaviour overview

- Works distributedly, like all other components (behaviours)
- Includes managerial aspects:
    - Error handling: what happens if an event handler crashes?
    - Permits changing event handlers
    - Permits shutting down event handlers
    - Includes code upgrade facility

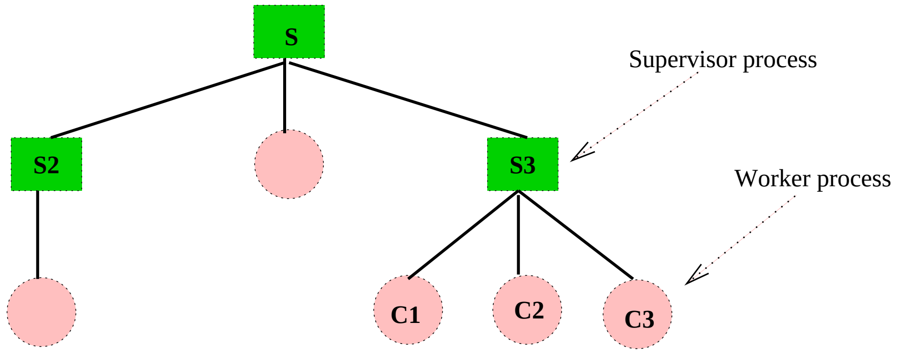
The Supervisor Component

- Applications are often structured as *supervision trees*, consisting of *supervisors* and *workers*



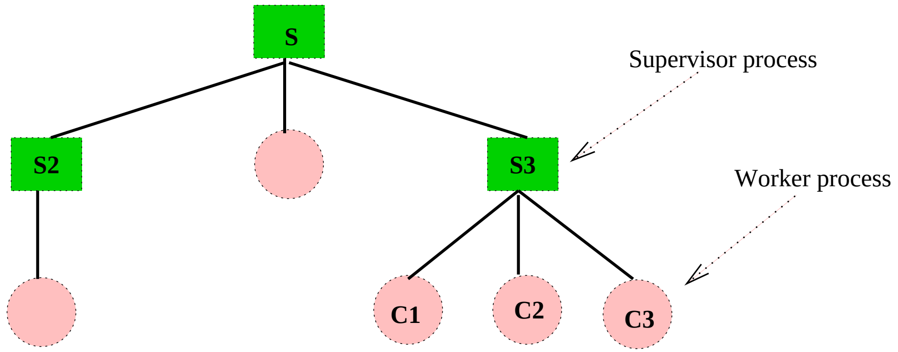
- A supervisor starts child processes, monitors them, handles termination and stops them on request
- The actions of the supervisor are described in a declarative fashion (as a text description)
- A child process may itself be a supervisor

Supervision Dynamics



- When a child process C1 dies (due to an error condition), its supervisor S3 is notified and can elect to:
  - do nothing
  - itself die (in turn notifying its supervisor S)
  - restart the child process (and maybe its siblings)
  - kill all the sibling processes (C2,C3) of the dead process

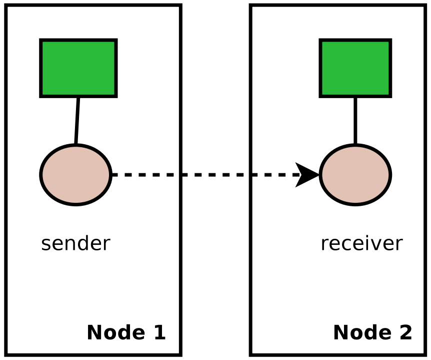
Supervision Dynamics



- When a child process C1 dies (due to an error condition), its supervisor S3 is notified and can elect to:
  - do nothing
  - itself die (in turn notifying its supervisor S)
  - restart the child process (and maybe its siblings)
  - kill all the sibling processes (C2,C3) of the dead process
- One can control the frequency of restarts, and the maximum number of restarts to attempt – it is no good having a process continuing to restart and crash

Supervision Examples

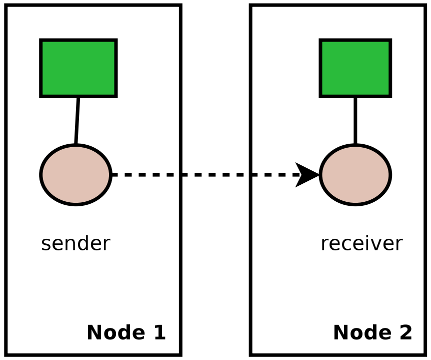
- A file streaming application:



If the sender crashes, its supervisor restarts it
(and vice versa for the receiver)

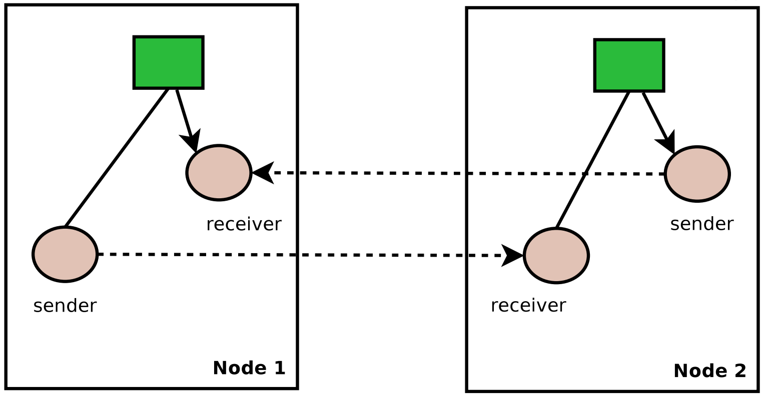
Supervision Examples

- A file streaming application:



If the sender crashes, its supervisor restarts it (and vice versa for the receiver)

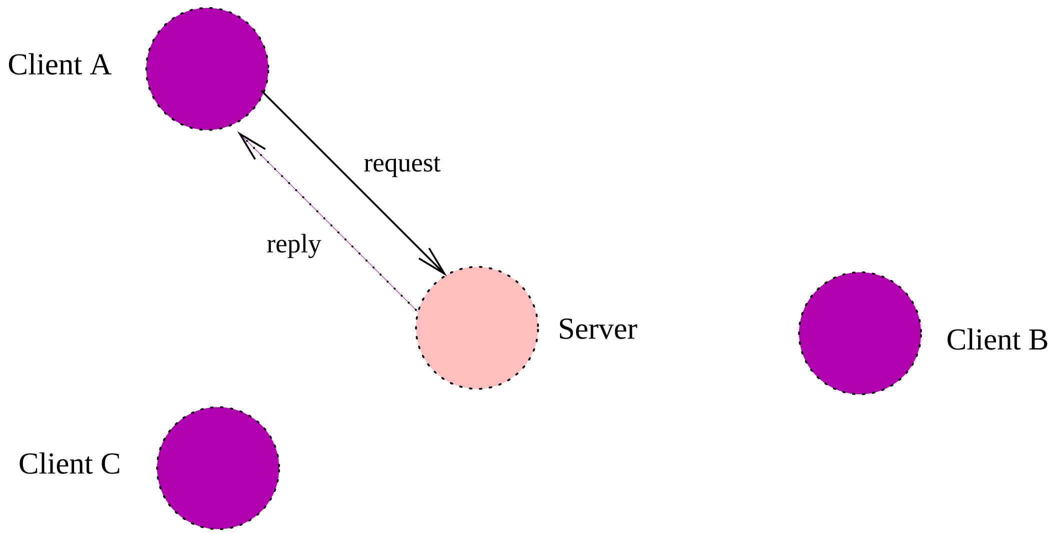
- A file transfer application (with acknowledgment handling):



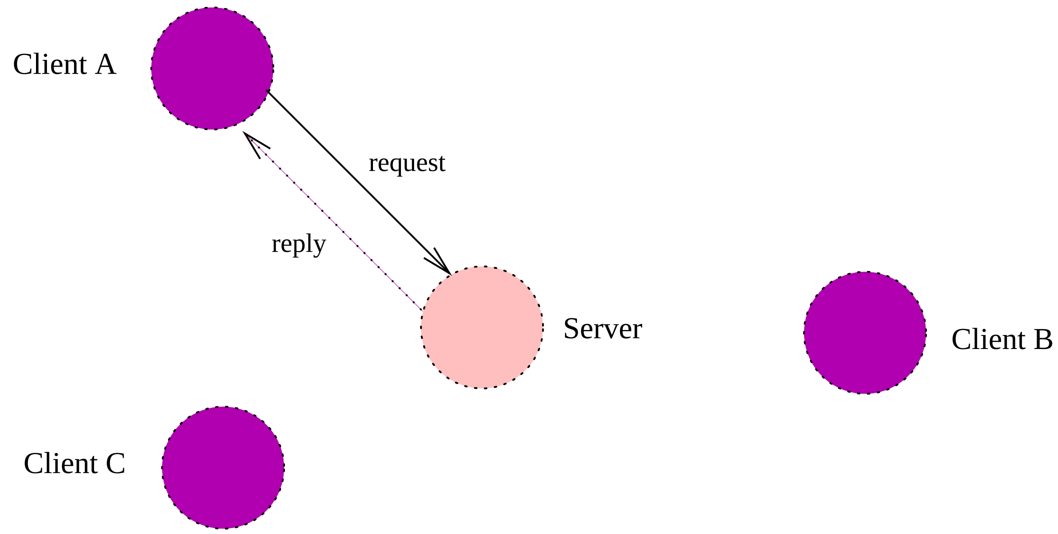
If the sender crashes, both it and the receiver is restarted

The Generic Server Component

- `gen_server` is *the* most used component in Erlang systems
- Provides a standard way to implement a server process, and interface code for clients to access the server
- The client–server model has a central server, and an arbitrary number of clients:



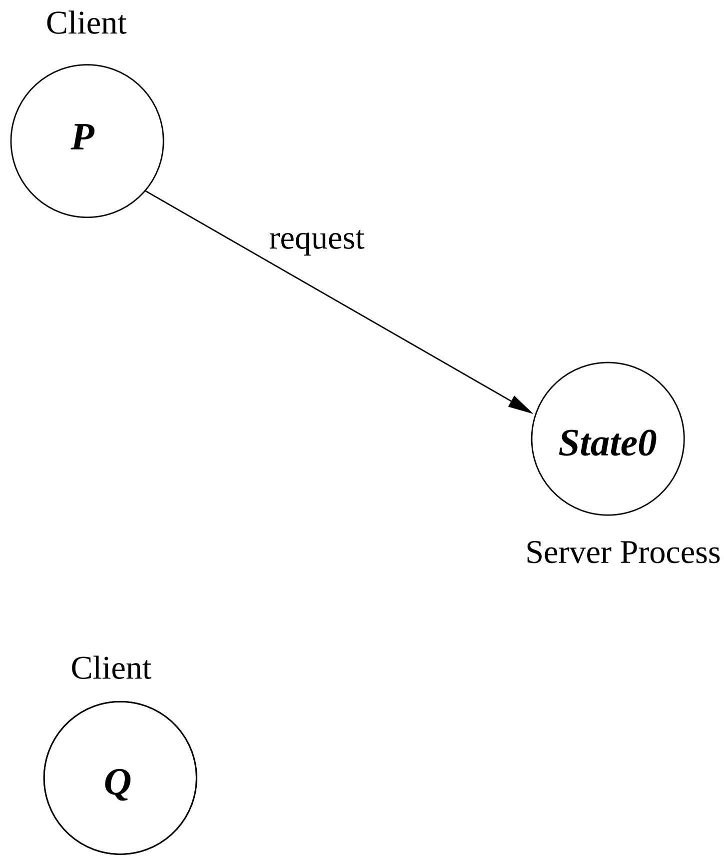
The Generic Server Component



- Clients makes *requests* to the server, who optionally *replies*
- A server has a state, which is preserved between requests
- A generic server is implemented by providing a callback module specifying the concrete actions of the server (server state handling, and response to messages)

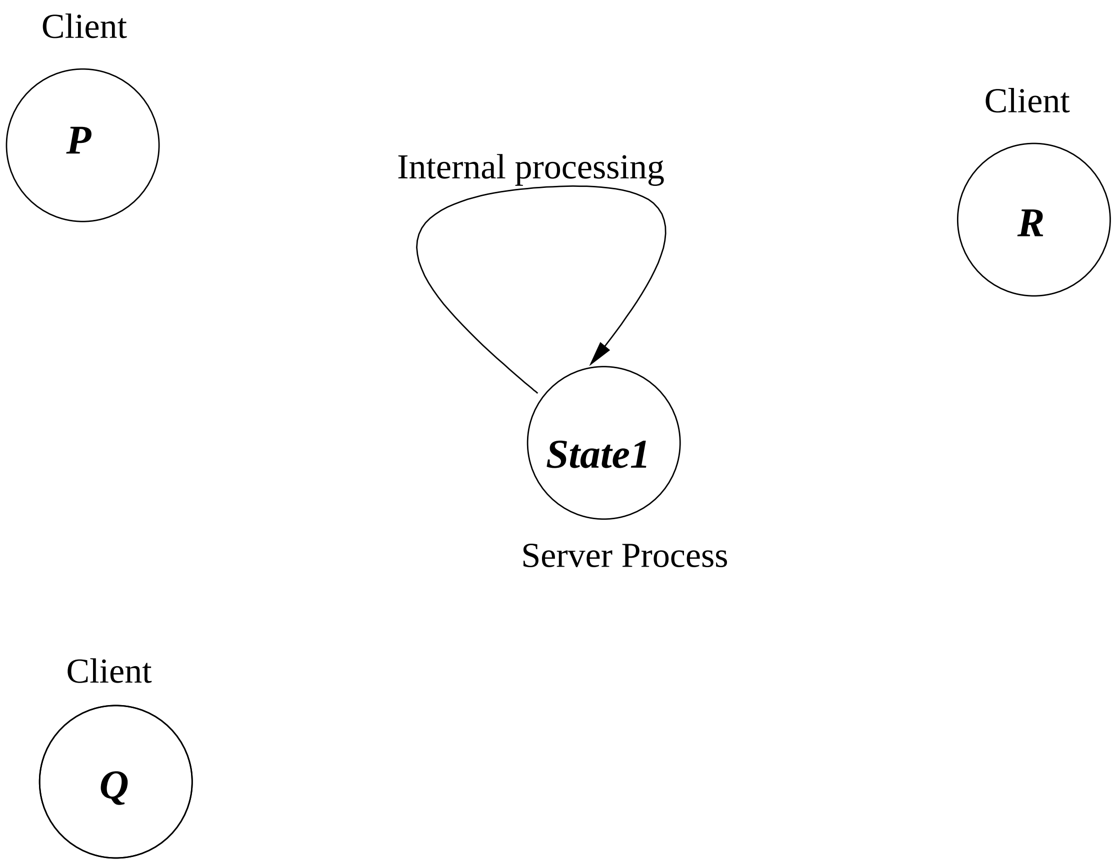
Generic Server Interaction

(1): A client sends a request:

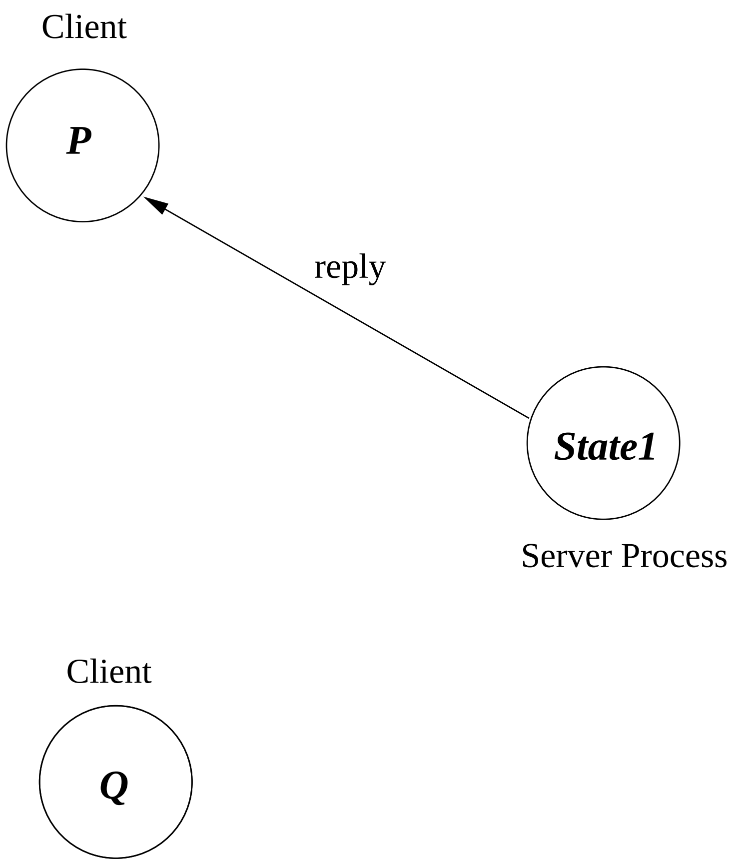


Generic Server Interaction

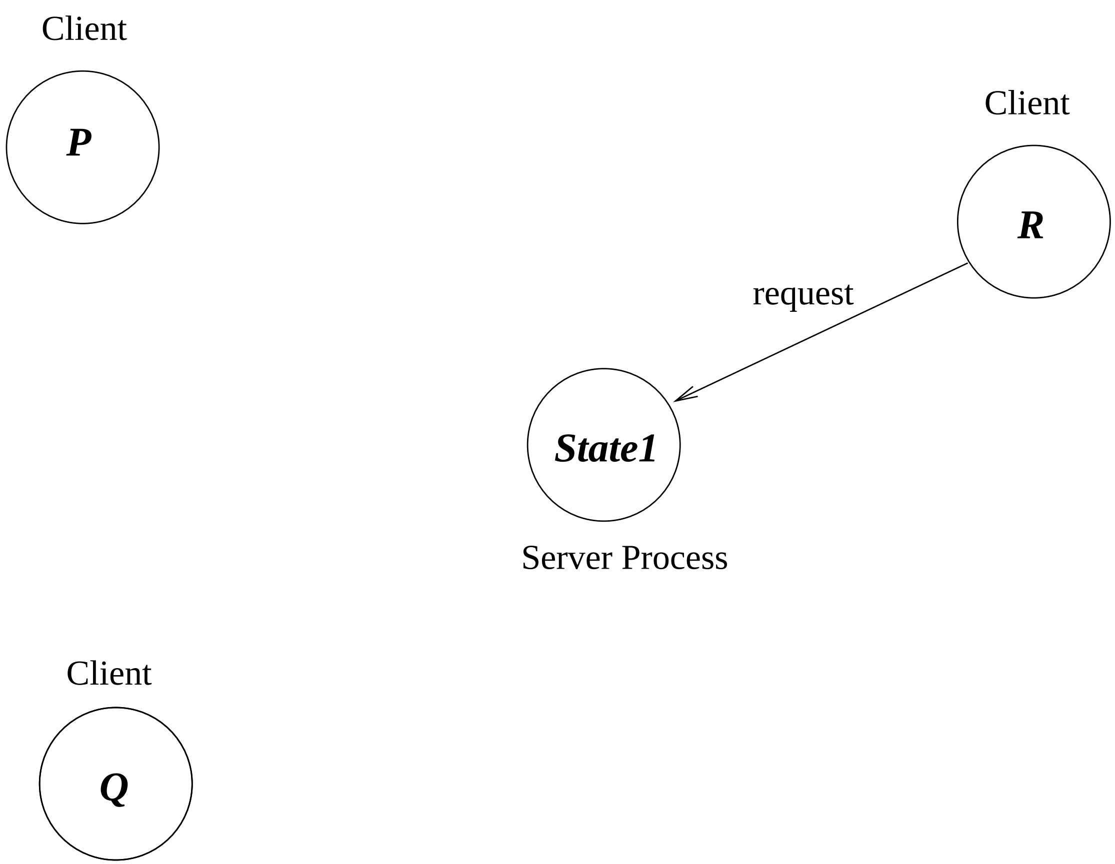
(2): The server does some internal processing to answer, resulting in a new server state **State1**:



(3a): And eventually sends the reply to the client:



(3b): Or it doesn't send a reply, but may do so in the future, and in the meanwhile accepts a new request:



Generic Server: client interface

Client interface:

- `Res = gen_server:call(ServerName, Message)`
  A call to `ServerName` (a pid) with a return value
- `gen_server:cast(ServerName, Message)`
  When no return value is expected

Generic Server: server interface

Server interface:

- `init(Args)` – at startup, returns the initial state of the server
- `handle_call(Message, ClientId, ServerState)`
  called when a `gen_server:call` is made, `ServerState` is the current state of the server.
  Should return a new server state
- `handle_cast(Message, ServerState)`
  called when a `gen_server:cast` is made.
  Should return a new server state

Generic Server: server returns

Server return values:

- **{**`reply, Value, NewState`**}**
  server replies with `Value`, and new server state is `NewState`
- **{**`noreply, NewState`**}**
  server send no reply (yet), but may do so in the future, the new server state is `NewState`
- **{**`stop, Value`**}**
  server stops but first returns `Value` to the current request

A simple generic server example

- We want to implement a simple server `locker` that grants access to a resource for only a single client at a time
- Clients request access to the server using a message `request`
- Once a client has finished with the resource it is released by sending the message `release`
- A client function that requests the resource, applies a function F on the resource, and then releases:

```
client(F) ->
  {ok, Resource} = gen_server:call(locker, request),
  %% We have resource, call F
  NewResource = apply(F,[Resource]),
  gen_server:call(locker, {release, NewResource}).
```

Server side: server state example

- The state of the server is a tuple of two components:
  - the current value of the resource, and
  - a list where the first element is the client currently accessing the resource, and the rest of the list is the queue of clients wanting to access it
- The initial state is `{Res, []}` – no clients accessing
- An example state: `{Res, [Pid1,Pid2,Pid3]}` – `Pid1` is accessing the resource, `Pid2,Pid3` are awaiting their turn

Server side: callback module example

```
init(Res) -> {ok, {Res, []}}.
%% No clients queued

handle_call(request, Client, {Res,Queue}) ->
  if
    Queue==[] -> {reply, {ok,Res}, {Res, [Client]}};
    Queue=/=[] -> {noreply, {Res, Queue++[Client]}}
  end;

handle_call({release,Res}, Client, {_, Queue}) ->
  case Queue of
    [Client] ->
      {reply, done, {Res,[]}};
    [Client,FirstWaiter|RestQueue] ->
      gen_server:reply(FirstWaiter, {ok,Res}),
      {reply, done, {Res, [FirstWaiter|RestQueue]}}
  end.
```

example: handling errors

- But what happens if the client crashes while it has access to the resource

example: handling errors

- But what happens if the client crashes while it has access to the resource
- . . . – well the server will stay locked for ever

example: handling errors

- But what happens if the client crashes while it has access to the resource
- ...– well the server will stay locked for ever
- We had better handle this case; the callback function `handle_info` will be called whenever a linked process terminates

Handling Errors in the example

Modifying `handle_call` to link to the client requesting access:

```
handle_call(request, Client, {Res,Queue}) ->
  link(Client),
  if
    Queue==[] -> {reply, {ok,Res}, {Res, [Client]}};
    Queue=/=[] -> {noreply, {Res, Queue++[Client]}}
  end;
```

Handling Errors in the example

Adding the function which handles errors:

```
handle_info({'EXIT',Client,_},{Res,Queue}) ->
  case Queue of
    [Client,FirstWaiter|RestQueue] ->
      gen_server:reply(FirstWaiter, {ok, Res}),
      {noreply, {Res,[FirstWaiter|RestQueue]}};
    _ ->
      {noreply, {Res,remove(Client,Queue)}}
  end.
```

Error Handling in the Generic Server component

Note some nice properties of error handling in generic servers:

- only handling errors in one (1) place in the code
- only handling errors at very controlled points in time (when not processing a request)
- We control error handling –
  we do not letting error handling control us!
- Such separation of concerns (between error handling and normal processing) is the real key to the power of the OTP components!

Generic Server Actions

- Not shown:
  - handling timeouts
- Generic behaviours handled mostly automatically by the component:
  - How to trace and log the actions of the server
  - How to terminate and restart a server

Generic Server Code Upgrades

- Since components are alive for a long time, it may be necessary to update the code of a component (its implementation) during its lifetime
- The generic server behaviour, like other Erlang behaviours, offers a standard method to do this
  - Upgrades are handled through the `code_change(Info1,OldState,Info2)` callback function which is called when a code change has taken place
  - `OldState` is the state of the server running the old version of the code
  - The callback should return a tuple `{ok,NewState}`

Code Update in the example server

- Suppose that we want to add a field `NumOfRequest` to the server state for counting the number of a requests made to the resource
- Recall that the state is `{Res, WaitingClients}`
- To do a code upgrade we provide in the new server implementation the function:

```
code_change(_, {Res,WaitingClients}, _) ->
  {ok,
      {Res,
       WaitingClients,
       length(WaitingClients)}}.
```

Server Component – messages handling philosophy

- The generic server component processes messages in strict sequential (oldest first) order
- Good: makes for good performance (no searching of mailbox), bounded queues (no messages left in queue)
- Bad: can make for complex processing logic (e.g., how to cleanly implement a one-bit buffer with two messages: `push` and `pop`)
- Normally leads to a more complex server state (having queues inside the server state)
- Other more stateful components are possible, accepting different messages at different times

  But how is low-level performance impacted, and how are unexpected messages handled (growing queues)?
- A central problem in the design of Erlang processes!

Erlang/OTP Tools

- Mnesia database – relational/object data model, soft-real time properties, transactions, language integration, persistence, monitoring …
- Yaws web server – for serving dynamic content produced by Erlang code (good performance, elegant – everything written in Erlang; no need for Perl)
- Interfaces to other applications and systems: SQL databases, libraries for communicating with Java, XML parsers…
  - languages: port concept
  - databases
- And SASL (release upgrade, alarm handling), SNMP, …

Validating Erlang Programs

- Dialyzer – type checking by static analysis (necessary because of dynamic run-time typing)
- As usual, testing: QuickCheck (`http://www.quiviq.com`) - a testing tool both for the sequential and the concurrent part of Erlang
- Trace log inspection (ad-hoc)
- Model checking – my tool McErlang (`http://babel.ls.fi.upm.es/~fred/McErlang`)