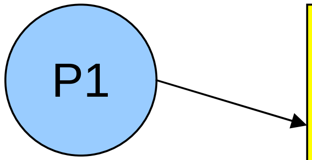
Erlang: An Overview

Part 2 – Concurrency and Distribution

Thanks to Richard Carlsson for most of the slides in this part

Processes



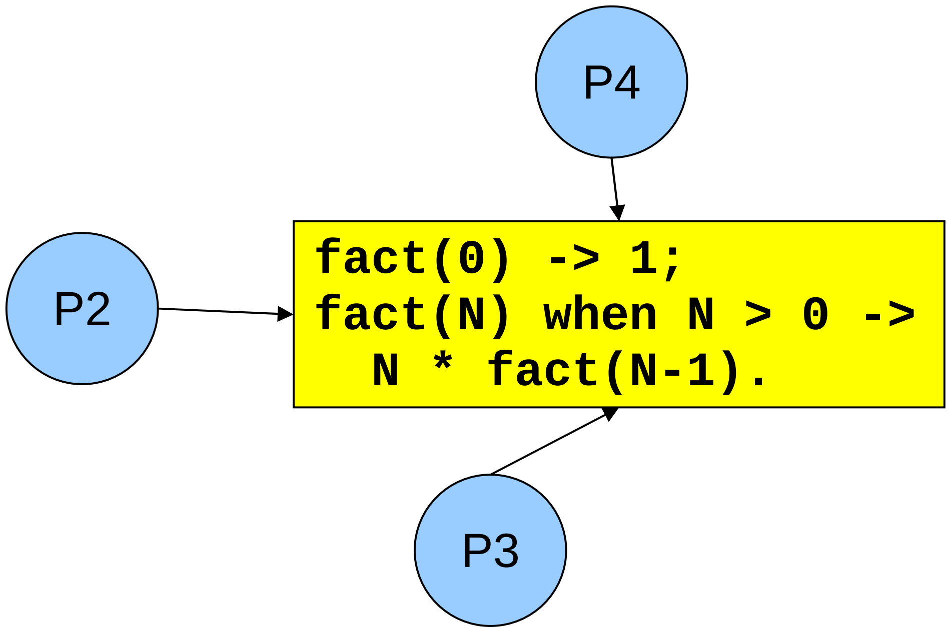

```
fib(0) -> 1;
fib(1) -> 1;
fib(N) when N > 0 ->
  fib(N-1) + fib(N-2).
```

- Whenever an Erlang program is running, the code is executed by a *process*
- The process keeps track of the current program point, the values of variables, the call stack, etc.
- Each process has a unique *Process Identifier ("Pid"),* that can be used to identify the process
- *Processes are concurrent* (they can run in parallel)

Implementation

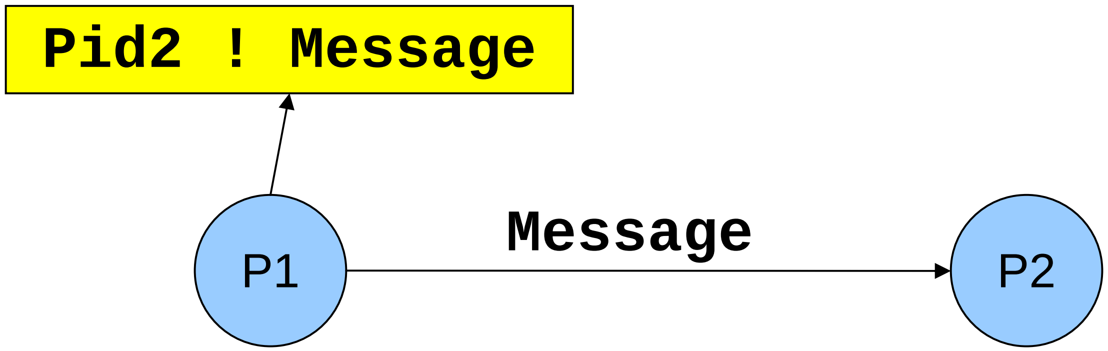
- Erlang processes are implemented by the VM’s runtime system, not by operating system threads
- Multitasking is *preemptive* (the virtual machine does its own process switching and scheduling)
- Processes use very little memory, and switching between processes is very fast
- Erlang VM can handle large numbers of processes
  - Some applications use more than 100.000 processes
- On a multiprocessor/multicore machine, Erlang processes can be scheduled to run in parallel on separate CPUs/cores using multiple schedulers

Concurrent process execution



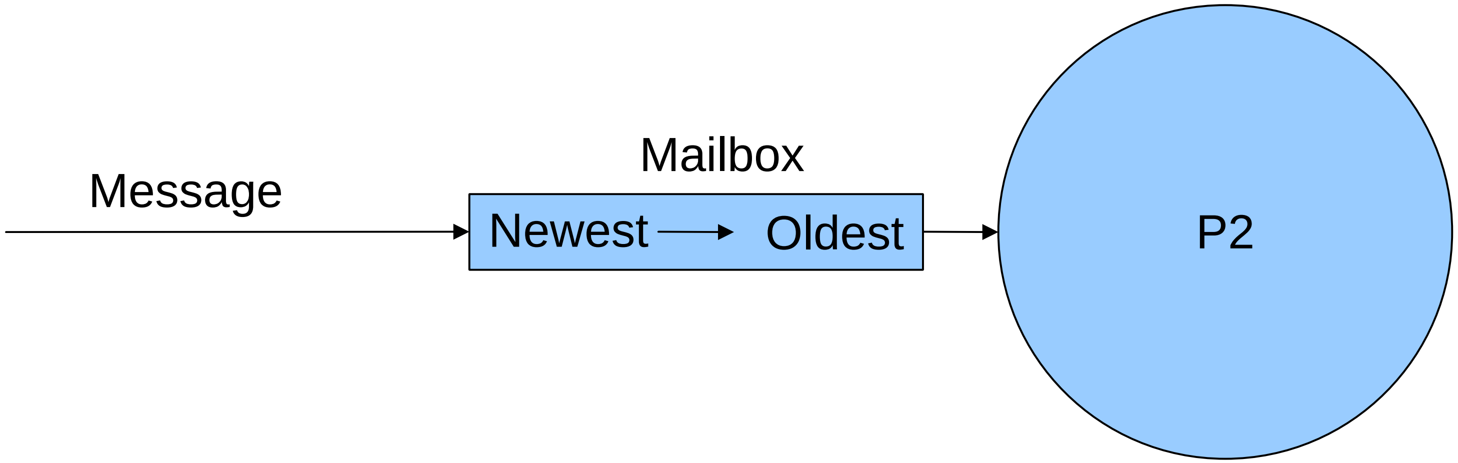
- Different processes may be reading the same program code at the same time
  - They have their own data, program point, and stack – only the text of the program is being shared (well, almost)
  - *The programmer does not have to think about other processes updating the variables*

Message passing



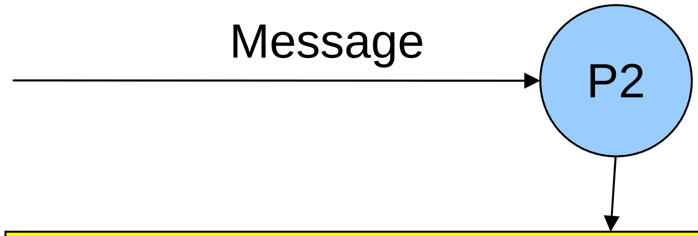
- "`!`" is the *send operator* (often called "bang!")
  - The Pid of the receiver is used as the address
- Messages are sent *asynchronously*
  - The sender continues immediately
- Any value can be sent as a message

Message queues



- Each process has a *message queue* (mailbox)
  - Arriving messages are placed in the queue
  - *No size limit* – messages are kept until extracted
- A process *receives* a message when it extracts it from the mailbox
  - Does not have to take the first message in the queue

Receiving a message




```
receive
  Msg -> io:format("~w\n", [Msg])
end
```

`receive` expressions are similar to **`case`** switches

- Patterns are used to match messages in the mailbox
- Messages in the queue are tested in order
  - The first message that matches will be extracted
  - A variable-pattern will match the first message in the queue
- Only one message can be extracted each time

Selective receive

```
receive
  {foo, X, Y} -> ...;
  {bar, X} when ... -> ...;
  ...
end
```

- Patterns and guards let a programmer control the priority with which messages will be handled
  - Any other messages will remain in the mailbox
- The **`receive`** clauses are tried in order
  - If no clause matches, the next message is tried
- If *no* message in the mailbox matches, the process *suspends*, waiting for a new message

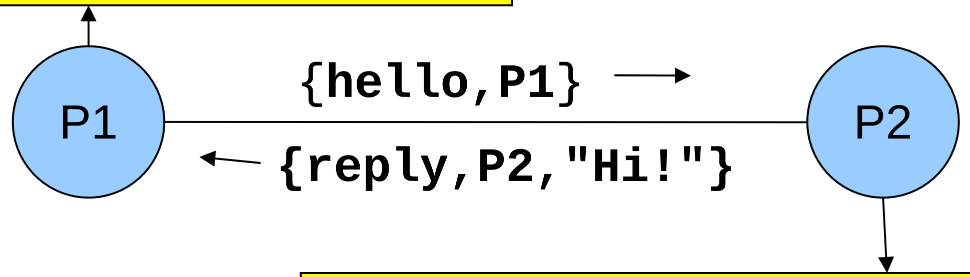
Receive with timeout

```
receive
  {foo, X, Y} -> ...;
  {bar, X} when ... -> ...
after 1000 ->
  ...          % handle timeout
end
```

- A **`receive`** expression can have an **`after`** part
  - The timeout value is either an integer (milliseconds), or the atom **`'infinity'`** (wait forever)
  - 0 (zero) means “just check the mailbox, then continue”
- The process will wait until a matching message arrives, or the timeout limit is exceeded
- **Soft real-time**: approximate, no strict timing guarantees

Send and reply

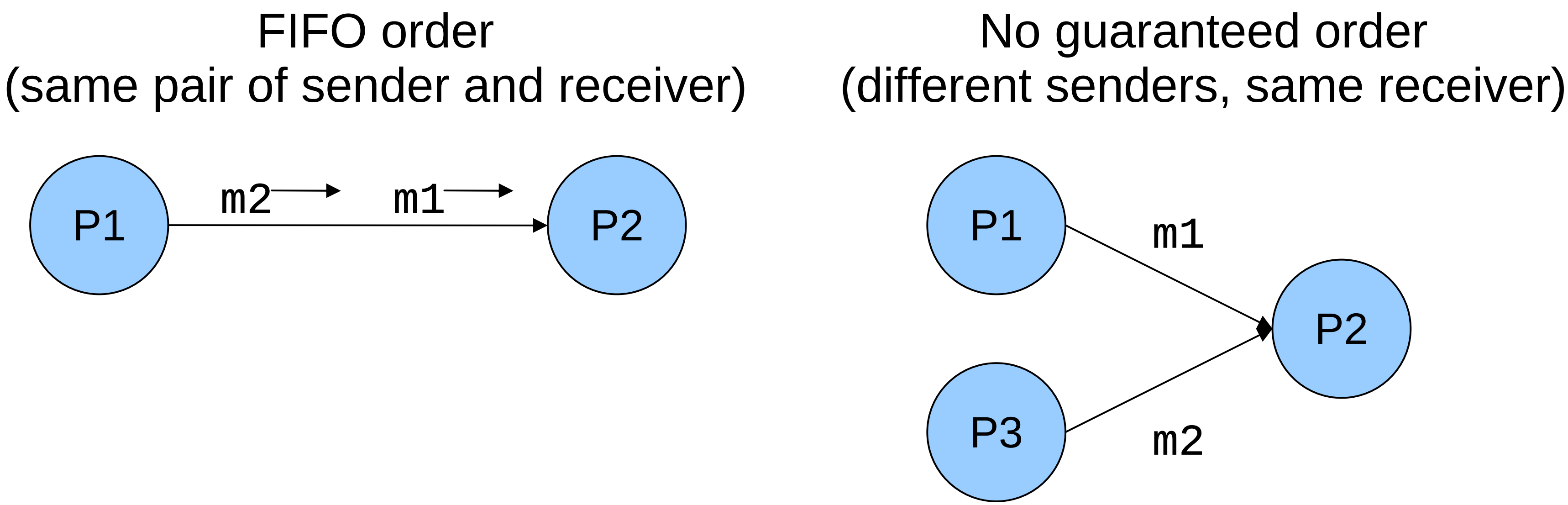
```
Pid ! {hello, self()},
receive
  {reply, Pid, String} ->
    io:put_chars(String)
end
```




```
receive
  {hello, Sender} ->
    Sender ! {reply, self(), "Hi!"}
end
```

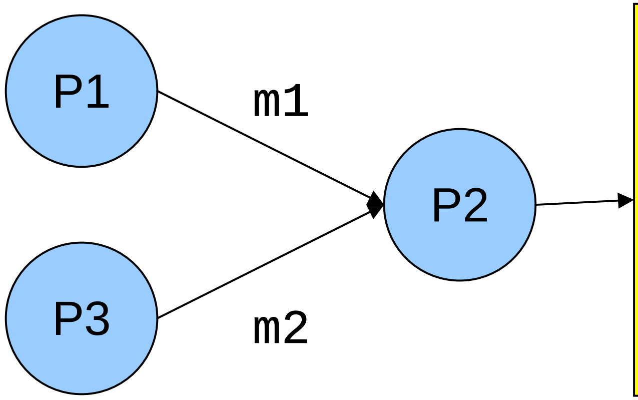
- Pids are often included in messages (**`self()`**), so the receiver can reply to the sender
  - If the reply includes the **`Pid`** of the second process, it is easier for the first process to recognize the reply

Message order



- Within a node, the only guaranteed message order is when both the sender and receiver are the same for both messages (First-In, First-Out)
  - In the left figure, m1 will always arrive before m2 in the message queue of P2 (if m1 is sent before m2)
  - In the right figure, the arrival order can vary

Selecting unordered messages




```
receive
  m1 -> io:format("Got m1!")
end,
receive
  m2 -> io:format("Got m2!")
end
```

- Using selective receive, we can choose which messages to accept, even if they arrive in a different order
- In this example, P2 will always print “Got m1!” before “Got m2!”, even if m2 arrives before m1
  - m2 will be ignored until m1 has been received

Starting processes

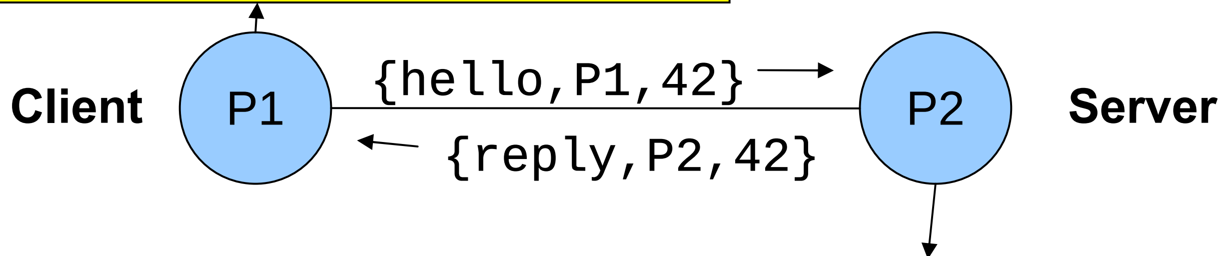
- The **'spawn'** function creates a new process
- There are several versions of '**spawn**':
  - **`spawn(fun() -> ... end)`**
    - can also do **`spawn(fun f/0)`** or **`spawn(fun m:f/0)`**
  - **`spawn(Module, Function, [Arg1, ..., ArgN])`**
    - **`Module:Function/N`** must be an exported function
- The new process will run the specified function
- The spawn operation always returns immediately
  - The return value is the Pid of the new process
  - The "parent" always knows the Pid of the "child"
  - The child will not know its parent unless you tell it

Process termination

- A process *terminates* when:
  - It finishes the function call that it started with
  - There is an exception that is not caught
    - The purpose of '**`exit`**' exceptions is to terminate a process
    - "**`exit(normal)`**" is equivalent to finishing the initial call
- All messages sent to a terminated process will be thrown away, without any warning
  - No difference between throwing away and putting in mailbox just before process terminates
- The same process identifier will not be used again for a long time

A stateless server process

```
run() ->
  Pid = spawn(fun echo/0),

  Pid ! {hello, self(), 42},
  receive
    {reply, Pid, 42} ->
      Pid ! stop
  end.
```




```
echo() ->
  receive
    {hello, Sender, Value} ->
      Sender ! {reply, self(), Value},
      echo();  % loop!
    stop ->
      ok
  end.
```

A server process with state

```
server(State) ->
  receive
    {get, Sender} ->
      Sender ! {reply, self(), State},
      server(State);
    {set, Sender, Value} ->
      Sender ! {reply, self(), ok},
      server(Value);    % loop with new state!
    stop ->
      ok
  end.
```

- The parameter variables of a server loop can be used to remember the current state
- Note: the recursive calls to **`server()`** are *tail calls (last calls) – the loop does not use stack space*
- *A server like this can run forever*

A simple server example

```
-module(simple_server).
-export([start/0]).

-spec start() -> pid().
start() ->
  spawn(fun() -> loop(0) end).

-spec loop(integer()) -> no_return().
loop(Count) ->
  NC = receive
         {report, Pid} -> Pid ! Count;
         _AnyOtherMsg  -> Count + 1
       end,
  loop(NC).
```

```
Eshell V5.10.3 (abort ...^G)
1> P = simple_server:start().
<0.42.0>
2> P ! foo.
foo
3> [P ! X || lists:seq(1,9)].
[1,2,3,4,5,6,7,8,9]
4> P ! {report, self()},
   receive M -> M end.
10
```

Hot code swapping

```
-module(server).
-export([start/0, loop/1]).

start() -> spawn(fun() -> loop(0) end).

loop(State) ->
  receive
    {get, Sender} ->
      ...,
      server:loop(State);
    {set, Sender, Value} ->
      ...,
      server:loop(Value);
  ...
```

- When we use "**`module:function(...)`**", Erlang will always call the latest version of the module
  - If we recompile and reload the **`server`** module, the process will jump to the new code after handling the next message – we can fix bugs without restarting!

Hiding message details

```
get_request(ServerPid) ->
  ServerPid ! {get, self()}.

set_request(Value, ServerPid) ->
  ServerPid ! {set, self(), Value}.

wait_for_reply(ServerPid) ->
  receive
    {reply, ServerPid, Value} -> Value
  end.

stop_server(ServerPid) ->
  ServerPid ! stop.
```

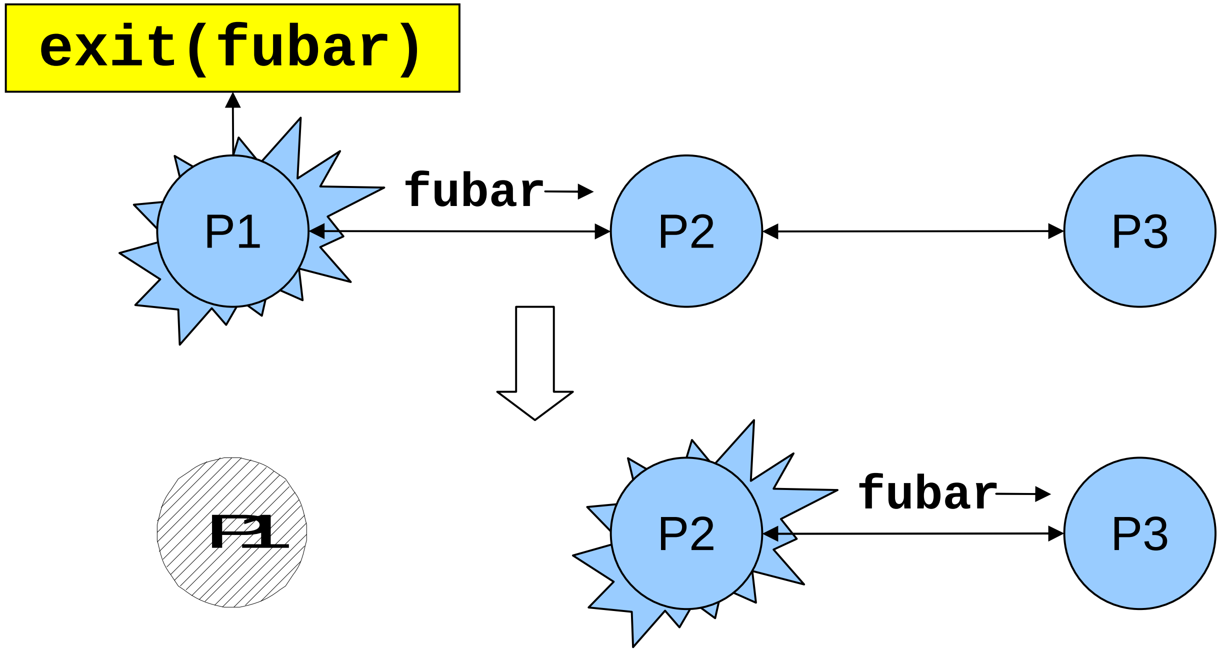
- Using interface functions keeps the clients from knowing about the format of the messages
  - You may need to change the message format later
- It is the client who calls the **`self()`** function here

Registered processes

```
Pid = spawn(...),

register(my_server, Pid),

my_server ! {set, self(), 42},

42 = get_request(my_server),

Pid = whereis(my_server)
```

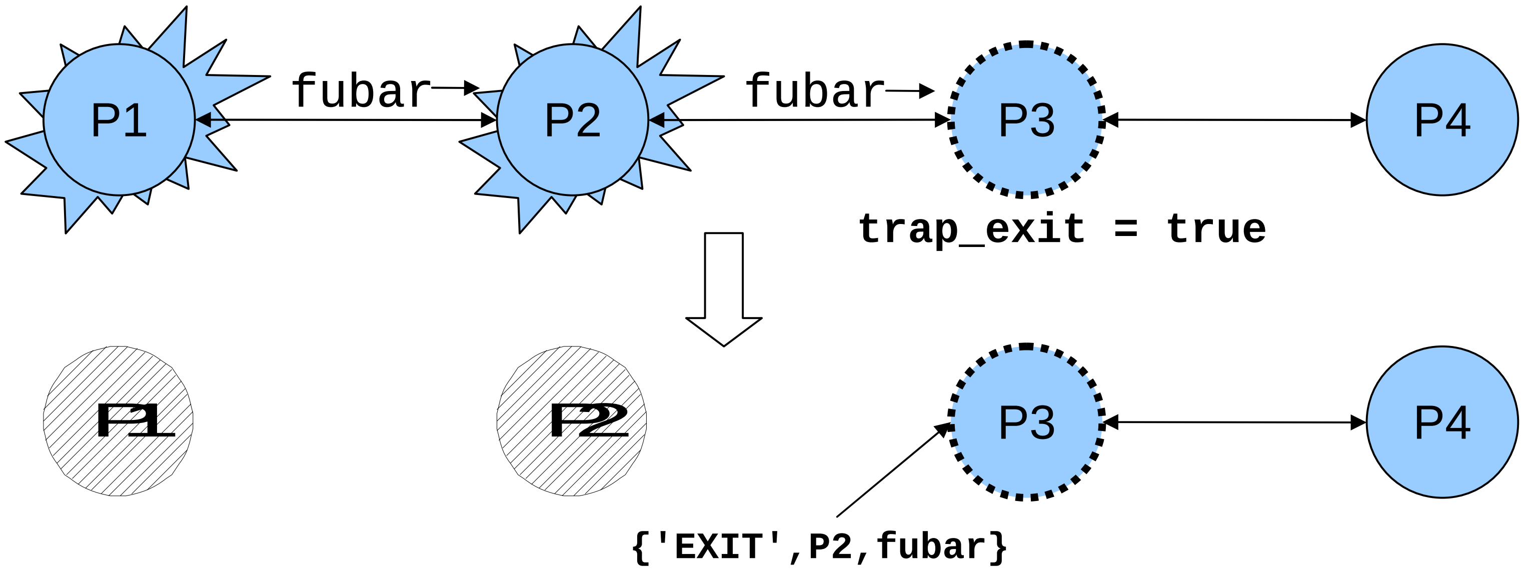
- A process can be registered under a name
  - the name can be any atom
- Any process can send a message to a registered process, or look up the Pid
- The Pid might change (if the process is restarted and re-registered), but the name stays the same

Links and exit signals



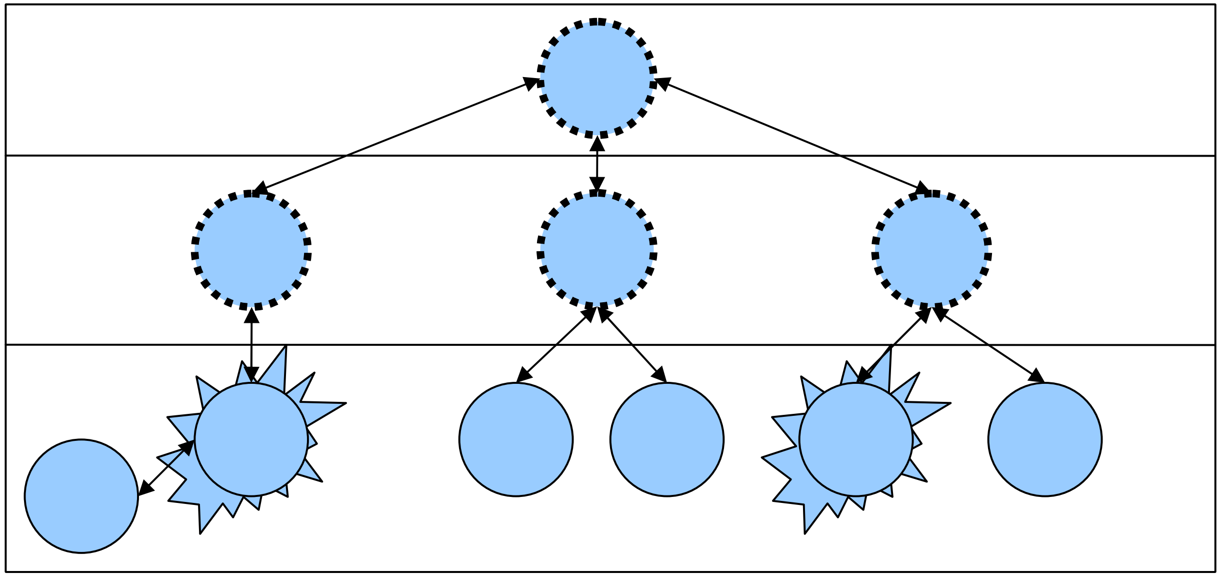
- Any two processes can be *linked*
  - Links are always bidirectional (two-way)
- When a process dies, an *exit signal* is sent to all linked processes, which are also killed
  - Normal exit does not kill other processes

Trapping exit signals



- If a process sets its **`trap_exit`** flag, all signals will be caught and turned into normal messages
  - **`process_flag(trap_exit, true)`**
  - **`{'EXIT', Pid, ErrorTerm}`**
- This way, a process can watch other processes
  - 2-way links guarantee that sub-processes are dead

Robust systems through layers



- Each layer supervises the next layer and restarts the processes if they crash
- The top layers use well-tested, very reliable libraries (OTP) that practically never crash
- The bottom layers may be complicated and less reliable programs that can crash or hang

Distribution

```
[foo.bar.se] $ erl -name fred
Erlang (BEAM) emulator version 5.10.3

Eshell V5.10.3 (abort with ^G)
(fred@foo.bar.se)1> node().
'fred@foo.bar.se'
(fred@foo.bar.se)2>
```

- Running “**`erl`**” with the flag “**`-name xxx`**”
  - starts the Erlang network distribution system
  - makes the virtual machine emulator a “*node*”
    - the node name is the atom '**`xxx@host.domain`**'
- Erlang nodes can communicate over the network
  - but first they must find each other
  - simple security based on secret cookies

Connecting nodes

```
(fred@foo.bar.se)2> net_adm:ping('barney@foo.bar.se').
pong
(fred@foo.bar.se)3> net_adm:ping('wilma@foo.bar.se').
pang
(fred@foo.bar.se)4>
```

- Nodes are connected the first time they try to communicate – after that, they stay in touch
  - A node can also supervise another node
- The function "**`net_adm:ping(Node)`**" is the easiest way to set up a connection between nodes
  - returns either "**`pong`**" or "**`pang`**" ☺
- We can also send a message to a registered process using "**`{Name,Node} ! Message`**"

Distribution is transparent

- One can send a Pid from one node to another
  - Pids are unique, even over different nodes
- We can send a message to *any* process through its Pid – even if the process is on another node
  - There is no difference (except that it takes more time to send messages over networks)
  - We don't have to know where processes are
  - We can make programs work on multiple computers with no changes at all in the code (no shared data)
- We can run several Erlang nodes (with different names) on the same computer – good for testing

Running remote processes

```
P = spawn('barney@foo.bar.se', Module, Function, ArgList),

global:register_name(my_global_server, P),

global:send(my_global_server, Message)
```

- We can use variants of the **`spawn`** function to start new processes directly on another node
- The module **`'global'`** contains functions for
  - registering and using named processes over the whole network of connected nodes
    - not same namespace as the local "**`register(...)`**"
    - must use "**`global:send(...)`**", not "`!`"
  - setting global locks

Ports – talking to the outside

```
PortId = open_port({spawn, "command"}, [binary]),

PortId ! {self(), {command, Data}}

PortId ! {self(), close}
```

- Talks to an external (or linked-in) C program
- A port is connected to the process that opened it
- The port sends data to the process in messages
  - binary object
  - packet (list of bytes)
  - one line at a time (list of bytes/characters)
- A process can send data to the port

Part 5 – Parallel Programming in Erlang

Benchmarking programs

- Recall the Quick Sort function

```
qsort([]) -> [];
qsort([P|Xs]) ->
  qsort([X || X <- Xs, X =< P])
  ++ [P]  % pivot element
  ++ qsort([X || X <- Xs, P < X]).
```

- Let’s create some test data for it

```
random_list(N) ->
  [random:uniform(12345678) || _ <- lists:seq(1,N)].
```

```
4> L = qsort:random_list(200000).
... A random list with 200000 elements ...
5> timer:tc(qsort, qsort, [L]).
{427404,
 [42,237,342,401,593,623,858,911,959,1111,1144,1267,
  1402,1405,1529,1563,1638,1643,1729,1755,1864,1899,
  1926,1968,2014|...]}
```

microseconds

result

Benchmarking programs

- Let's define a benchmarking function

```
benchmark(Fun, L) ->
  Rs = [timer:tc(?MODULE, Fun, [L])
        || _ <- lists:seq(1, 100)],
  lists:sum([T || {T,_} <- Rs]) / (1000*length(Rs)).
```

- I.e. run 100 times, average and convert to msecs

```
10> qsort:benchmark(qsort, L).
427.64902
11> erlang:system_info(schedulers).
8
```

milliseconds

number of OS threads that the runtime system of the VM uses for running Erlang processes

Parallel sorting (naive)

- Let's parallelize the function (start of attempt)

sort elements greater than pivot in another process

```
pqsort([]) -> [];
pqsort([P|Xs]) ->
  spawn_link(fun () ->
                   pqsort([X || X <- Xs, P < X])
                 end),
  pqsort([X || X <- Xs, X =< P])
  ++ [P]
  ++ ???.
```

how do we get the result here?

Parallel sorting (naive)

- Let’s parallelize the function (complete attempt)

```
pqsort([]) -> [];
pqsort([P|Xs]) ->
  Parent = self(),
  spawn_link(fun () ->
                Parent ! pqsort([X || X <- Xs, P < X])
             end),
  pqsort([X || X <- Xs, X =< P])
  ++ [P]
  ++ receive Ys -> Ys end.
```

get the Pid of the executing process

send the result back to the parent

wait to get the result of sorting the elements greater than pivot

```
14> qsort:benchmark(qsort, L).
427.64902
15> qsort:benchmark(pqsort, L).
826.27111
```

☹

Controlling granularity

```
pqsort2(L) -> pqsort2(5, L).

pqsort2(0, L) -> qsort(L);
pqsort2(_, []) -> [];
pqsort2(D, [P|Xs]) ->
  Par = self(),
  spawn_link(fun () ->
                 Par ! pqsort2(D-1,[X || X <- Xs, P < X])
               end),
  pqsort2(D-1, [X || X <- Xs, X =< P])
  ++ [P]
  ++ receive Ys -> Ys end.
```

```
17> qsort:benchmark(qsort, L).
427.64902
18> qsort:benchmark(pqsort, L).
826.27111
19> qsort:benchmark(pqsort2,L).
236.19359
```

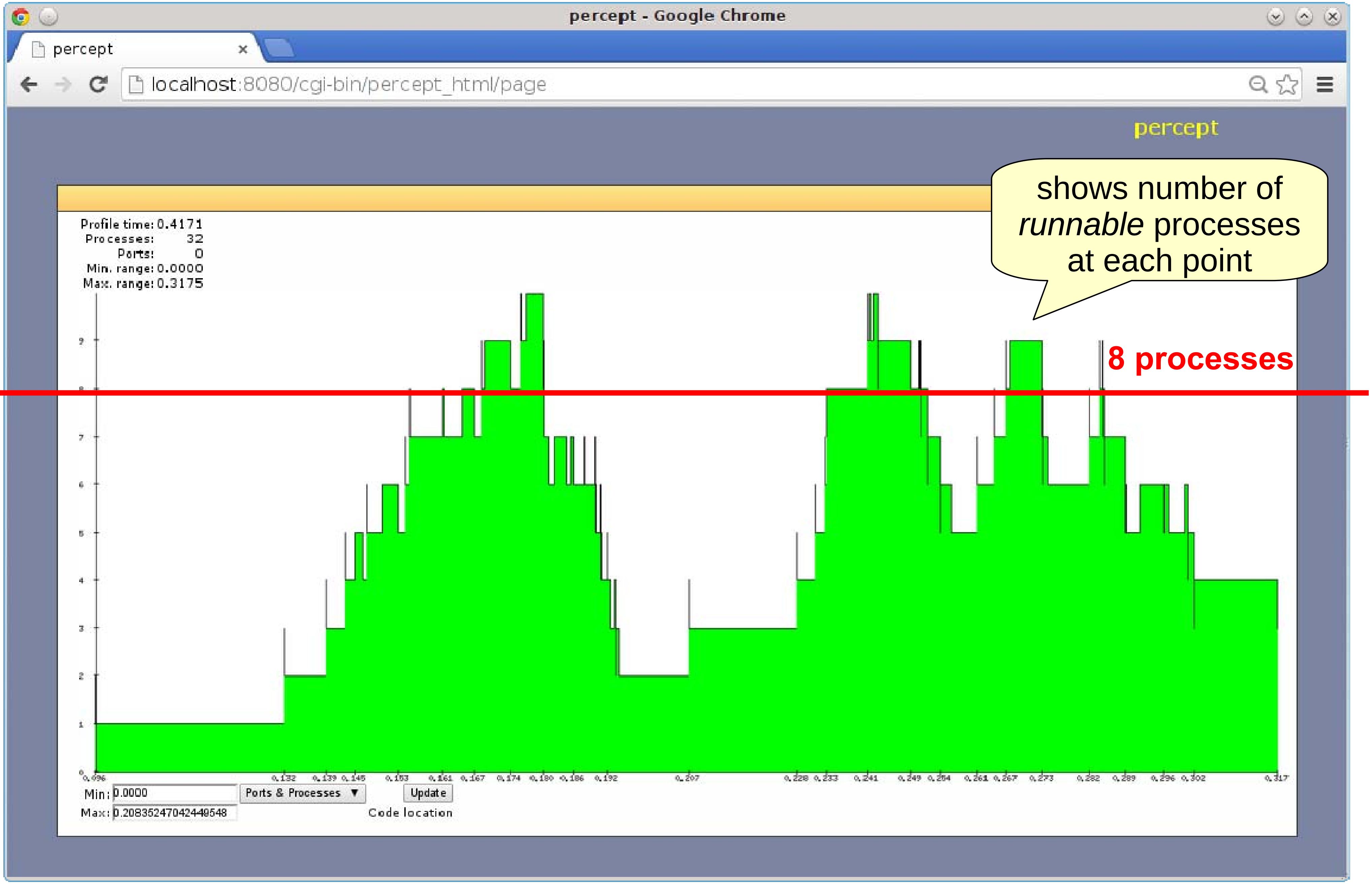
Profiling parallelism

file to store profiling information in

function to profile

```
21> percept:profile("prof.data",
                    {qsort,pqsort2,[L]}, [procs]).
Starting profiling.
ok
22> percept:analyze("prof.data").
Parsing: "prof.data"
Consolidating...
Parsed 255 entries in 0.116107 s.
Consolidating...
    32 created processes.
     0 opened ports.
ok
23> percept:start_webserver(8080).
{started,"laptop",8080}
```

Profiling with percept



Correctness?

```
31> qsort:pqsort2(L) == qsort:qsort(L).
false
32> qsort:pqsort2("hello world").
" edhllloorw"
```

Oops!

What's going on?

```
pqsort2(D, [P|Xs]) ->
  Par = self(),
  spawn_link(fun () ->
                 Par ! ...
               end),
  pqsort2(D-1, [X || X <- Xs, X =< P])
  ++ [P]
  ++ receive Ys -> Ys end.
```

What's going on?

```
pqsort2(D, [P|Xs]) ->
  Par1 = self(),
  spawn_link(fun () ->
                 Par1 ! ...
             end),
  Par = self(),
  spawn_link(fun () ->
                 Par ! ...
             end),
  pqsort2(D-2, [X || X <- Xs, X =< P])
  ++ [P]
  ++ receive Ys -> Ys end
  ++ [P1]
  ++ receive Ys1 -> Ys1 end.
```

Tagging messages

- Create a globally unique reference

```
Ref = make_ref()
```

- Send the message tagged with the reference

```
Par ! {Ref, Msg}
```

- Match the reference on receipt

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

- Picks the right message from the mailbox

A correct parallel sort

```
pqsort3(L) -> pqsort3(5, L).

pqsort3(0, L) -> qsort(L);
pqsort3(_, []) -> [];
pqsort3(D, [P|Xs]) ->
  Par = self(),
  Ref = make_ref(),
  spawn_link(fun () ->
                 Gs = [X || X <- Xs, P < X],
                 Par ! {Ref, pqsort3(D-1, Gs)}
               end),
  pqsort3(D-1, [X || X <- Xs, X =< P])
  ++ [P]
  ++ receive {Ref, Ys} -> Ys end.
```

Performance?

```
36> qsort:benchmark(qsort, L).
427.64902
37> qsort:benchmark(pqsort, L).
826.27111
38> qsort:benchmark(pqsort2, L).
236.19359
39> qsort:benchmark(pqsort3, L).
232.18068
```

What is copied here?

```
pqsort3(L) -> pqsort3(5, L).

pqsort3(0, L) -> qsort(L);
pqsort3(_, []) -> [];
pqsort3(D, [P|Xs]) ->
  Par = self(),
  Ref = make_ref(),
  spawn_link(fun () ->
               Gs = [X || X <- Xs, P < X],
               Par ! {Ref, pqsort3(D-1, Gs)}
             end),
  pqsort3(D-1, [X || X <- Xs, X =< P])
  ++ [P]
  ++ receive {Ref, Ys} -> Ys end.
```

terms in variables that the closure needs access to are copied to the heap of the spawned process

A parallel sort with less copying

```
pqsort3(L) -> pqsort3(5, L).

pqsort3(0, L) -> qsort(L);
pqsort3(_, []) -> [];
pqsort3(D, [P|Xs]) ->
  Par = self(),
  Ref = make_ref(),
  Gs = [X || X <- Xs, P < X],
  spawn_link(fun () ->
                 Par ! {Ref, pqsort3(D-1, Gs)}
             end),
  pqsort3(D-1, [X || X <- Xs, X =< P])
  ++ [P]
  ++ receive {Ref, Ys} -> Ys end.
```

copy only the part of the list that the process needs to sort