Erlang

An introduction

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Languages for Concurrency and Distribution

Erlang, in a slogan

Declarative (functional) language for concurrent and **distributed fault-tolerant** systems

Erlang

=

Functions + **Concurrency** + **Messages**

Basics

- **Dynamic typing**
- **Light-weight processes**
- Total separation between processes (**no sharing**, naturally enforced by **functional style**)
- (Fast) **Message passing**
- **Transparent distribution**

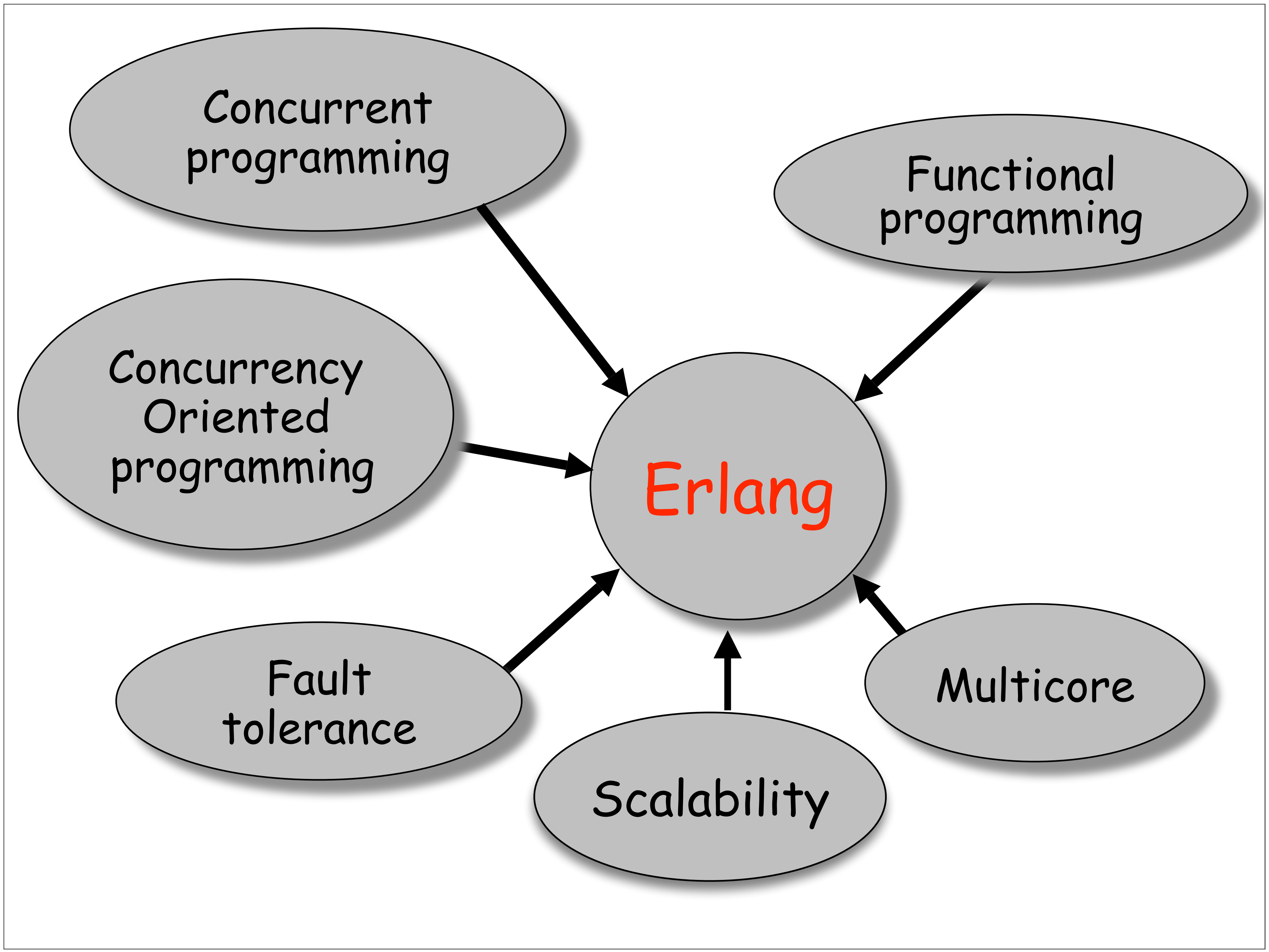
Where does it come from?

- Old language with modern design
  - Created in ’86 at Ericsson
  - Open sourced in ’98
  - “Programming with Erlang” published in ’07
  - Getting more and more popular … also in different incarnations (cfr. **Elixir**)

Intended domain

- Highly concurrent and distributed (hundreds of thousands of parallel activities)
- (Soft) real time
- Complex software (million of lines of code)
- High Availability (down times of minutes/year – never down)
- Continuous operation (years)
- Continuous evolution / In service upgrade

Principles


Concurrent programming
Functional programming
Concurrency Oriented programming
Erlang
Fault tolerance
Scalability
Multicore

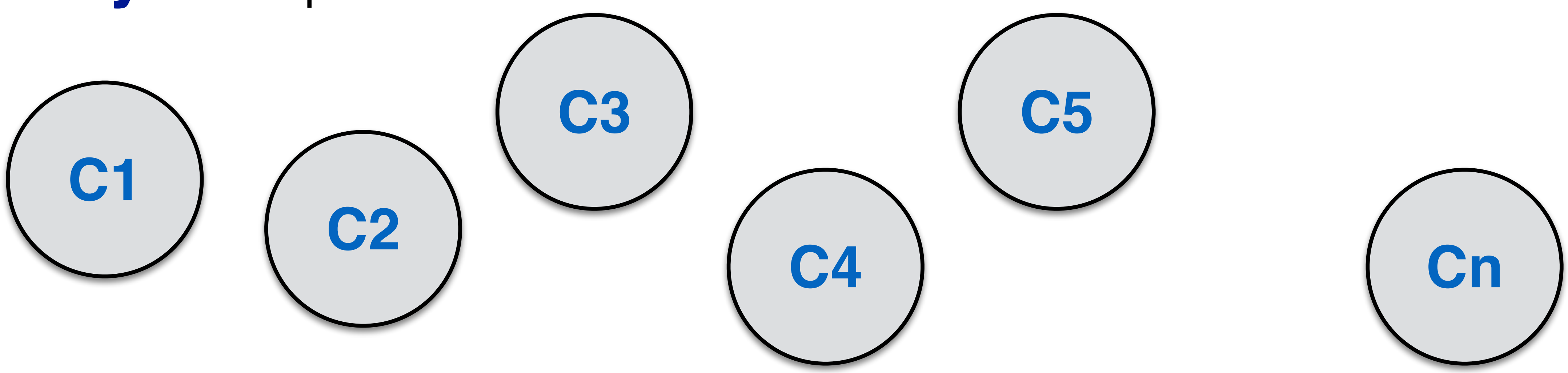
Fault tolerance

- To make a system **fault tolerant** you need at least …
- **two** computers (and some form of coordination)

- If one crashes, the other takes over

Fault tolerance

- To make a system **very fault tolerant** you need (at least) …
- **many** computers



- Which also addresses **scalability**

- **Concurrency**
- **Distribution**
- **Fault tolerance**
- **Scalability**

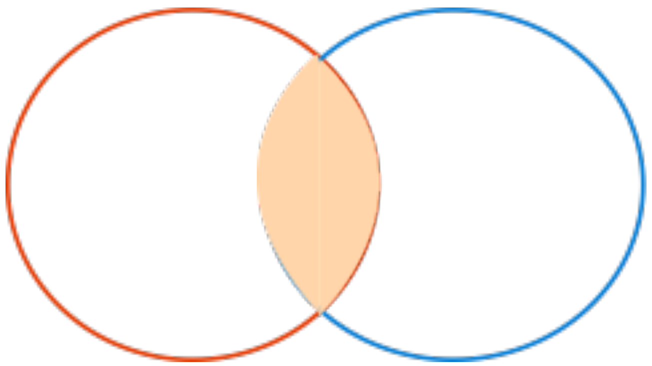
faces of the same coin
(inseparable)

Models of concurrency

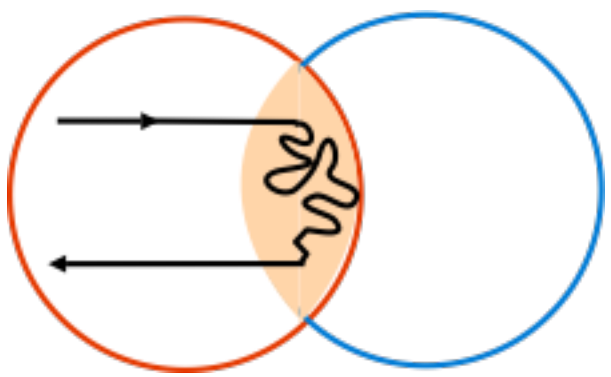
- **Shared memory**
  - Threads
  - Mutexes and locks
- **Message passing**
  - Processes
  - Messages

Shared Memory

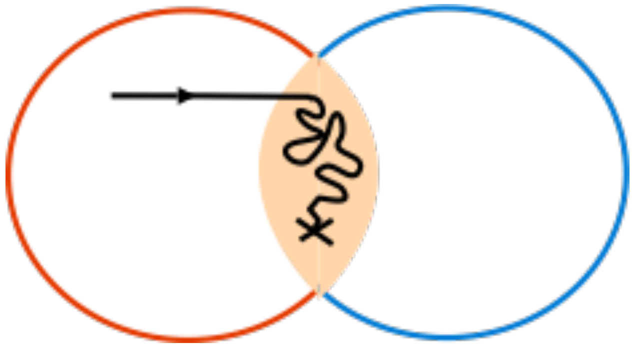
- **Problems**:



  - What if a thread **fails** in the critical section?



corrupted shared memory



  - Where do we (physically) locate the shared memory for **distributed systems**?

Message passing Concurrency

- **No sharing** (share by communicating)
- **No locks, mutexes** etc
- (Lots of) processes (fault tolerant, scalable) communicating via pure message passing

Concurrency oriented programming

- The world is **parallel** and **distributed**

- The observation of the **concurrency patterns** and **message channels** as a way of designing an application

- Concurrency seen as a **structuring paradigm** (without being shy at creating processes)

Concurrency oriented programming (COP)

Message from …

"My first message is that

concurrency

is best regarded as a

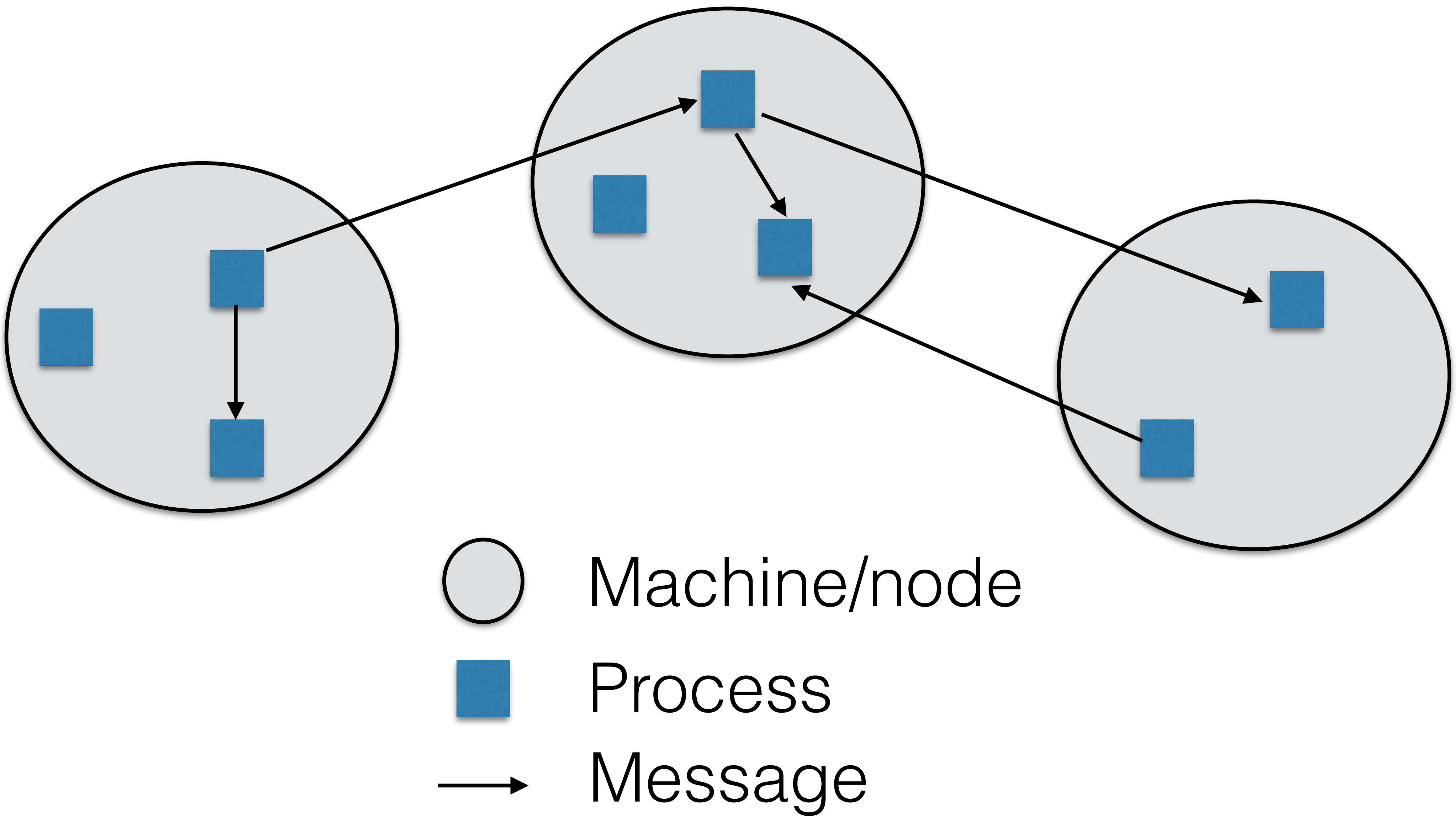
program structuring principle"

Sir Tony Hoare

Structured Concurrent Programming

Transparent distribution

- Abstract from physical locations



Functional programming

- **Programs** are **expressions**, **computation** is **evaluation**

  P1 → P2 → P3 .... → Value

- **No mutable state**
  - copy, not modify
  - essentially no side effects
- Nothing to lock and **automatic thread safety** when parallellized

Multicore (& co.) era

- Paradigm shift in CPU architecture
  - **Multi core**
    (easily up to 8 cores)
  - **GPU** - Graphical Processing Unit
  - NOC - Network on chip
    (up to 80 and more cores)

Hope

- Language and programming style exploiting parallelism
- **Ideally**: Make my program run **N times faster** on an **N core** CPU with
  - no changes to the program
  - no pain and suffering
- Can we have this? Somehow …

Erlang basics

Erlang

- Functional
- dynamic(ally typed)
- garbage collected
- eager
- compiled to Erlang runtime (BEAM instance)

Shell

- Can play most tricks in the **shell**!

```
Erlang/OTP 26 [erts-14.2.5] [source] [64-bit]
[smp:8:8] [ds:8:8:10] [async-threads:1] [jit] [dtrace]

Eshell V14.2.5 (press Ctrl+G to abort, type help().
for help)
1> help().
...
```

Expression

- Terminated with a period, evaluate to a value

```
1> 2 + 15.
17

2> 15 div 2.
7

3> 2#101010.
42

4> 16#AE.
174
```

Variables

- Start with **capital letter**
- Once "assigned", a variable is **immutable**
- "=" is **pattern matching**
  Compare (and possibly instantiate vars in the lhs)

```
1> Two = 2.
2

2> Two = 2.
2

3> Two = 3.
** exception error: no match of right hand side value 3
```

Modules

- Programs are organised in **modules**

```
-module(myMath).
-export([fac/1]).

fac(0) ->
    1;
fac(N) ->
    N * fac(N-1).
```

```
fac(5)  → 5*fac(5-1)    → 5*fac(4)
        → 5*4*fac(4-1)  → ...
```

Modules

- Some functions are exported, some others are not

```
-module(myMath).
-export([fac/1]).

add(X,0) -> X;
add(X,Y) -> add(X,Y-1)+1.

mul(X,0) -> 0;
mul(X,Y) -> add(mul(X,Y-1),X).

fac(0)   -> 1;
fac(N)   -> mul(N, fac(N-1)).
```

Compilation

- A module can be compiled (and loaded)

```
1> c(myMath).
{ok,myMath}
```

- And used …

```
2> myMath:fac(5).
120
3> myMath:fac(7).
5040
```

Besides integers

- **Atoms**: constants with their own name for value

```
1> my_atom.
my_atom
2> new_atom.
new_atom
```

- **Booleans**

```
1> true and false.
false
2> false or true.
true
3> true xor false.
true
```

```
4> not false.
true
5> not (true and true).
false
```

```
andalso / orelse
Lazy versions
```

Tuples

- **Syntax** {comp1, comp2, comp3}

```
1> X = 10, Y = 4.
4

2> Point = {X,Y}.
{10,4}


3> {First,_} = Point.
{10,4}


4> First.
10.
```

Tagged Tuples

- Tuples can be tagged for identifying their structure

```
1> P  = {point,{10,5}}.
{point,{10,5}}

2> CP = {colpoint, {{10,5},red}}.
{colpoint, {{10,5},red}}

3> {colpoint, Val} = P
** exception error: no match of right hand side
value {point,{10,5}}

4> {colpoint, Val} = CP
{colpoint,{{10,5},red}

5> Val.
{{10,5},red}
```

Temperature converter

- Temperatures denoted by pairs `{Unit, Value}` where `Unit` can be `c`(elsius), or `f`(ahrenheit)

```
-module(conv).
-export([convert/1]).

convert({c, X}) ->
    {f, 1.8 * X + 32};
convert({f, X}) ->
    {c, (X-32)/ 1.8}.
```

Temperature converter

```
2> conv:convert({f,100}).
{c,37.8}

3> conv:convert({c,100}).
{f,212.0}

4> conv:convert({k,2}).
** exception error: no function clause matching …)
```

Temperature converter, Reprise

```
-module(conv).
-export([convert/1]).

convert({c, X}) ->
    {f, 1.8 * X + 32};
convert({f, X}) ->
    {c, (X-32)/ 1.8}
convert(_) ->
    error.
```

Lists

- **Syntax** [elem1, elem2, elem3, ….]

- Any type of element

```
1> [1, 2, 3, {numbers,[4,5,6]}, 5.34, atom].
[1,2,3,{numbers,[4,5,6]},5.34,atom]
```

- Head and tail

```
11> hd([1,2,3,4]).
1
12> tl([1,2,3,4]).
[2,3,4]
```

Head/Tail, with matching

```
15> [ Head | Tail ] = [1,2,3,4].
[1,2,3,4]

16> Head.
1

17> Tail.
[2,3,4]


18> [NewHead | NewTail] = Tail.
[2,3,4]


19> NewHead.
2
```

Length

```
len([]) ->
    0;
len([_|T]) ->
    1+len(T).
```

- With **tail recursion**

```
% lentr(L, N)
lentr([],N) ->
    N;
lentr([_|T],N) ->
    lentr(T,N+1).

lentr(L) ->
    lentr(L,0).
```

More list ops

- Concatenation, subtraction

```
5> [1,2,3] ++ [4,5].
[1,2,3,4,5]

6> [1,2,3,4,5] -- [1,2,3].
[4,5]

7> [2,4,2] -- [2,4].
[2]

8> [2,4,2] -- [2,4,2].
[]
```

Comprehension

- Doubling

```
1> [2*N || N <- [1,2,3,4]].
[2,4,6,8]
```

- Get the even

```
2> [X || X <- [1,2,3,4,5,6,7,8,9,10], X rem 2 =:= 0].
[2,4,6,8,10]
```

- Sum

```
5> [X+Y || X <- [1,2], Y <- [2,3]].
[3,4,4,5]
```

Quicksort

```
-module(quicksort).
-export([qsort/1, triqsort/1]).

qsort([]) ->
    [];

qsort([Pivot|Rest]) ->
             qsort([ X || X <- Rest, X < Pivot])
          ++ [Pivot]
          ++ qsort([ Y || Y <- Rest, Y >= Pivot]).
```

```c
void QuickSort(int list[], int beg, int end)
{
    int piv; int tmp;
    int  l,r,p;

    while (beg < end)
    {
        l = beg; p = (beg + end) / 2; r = end;
        piv = list[p];
        while (1)
        {
            while ((l <= r) && ((list[l] - piv) <= 0 )) l++;
            while ((l <= r) && ((list[r] - piv) > 0 )) r--;
            if (l > r) break;
            tmp = list[l]; list[l] = list[r]; list[r] = tmp;
            if (p==r) p=l;
            l++; r--;
        }
        list[p] = list[r]; list[r] = piv;
        r--;
        if ((r - beg) < (end - l))
        {
            QuickSort(list, beg, r);
            beg = l;
        }
        else
        {
            QuickSort(list, l, end);
            end = r;
        }
    }
}
```

If

- Sugar for (conditional) pattern matching

```
test(X,Y) ->
    if
      X < Y    -> -1;
       X == Y   ->  0;
       X > Y    ->  1
    end.
```

```
test(X,Y) when X < Y ->
    -1;
test(X,X) ->
    0;
test(X,Y) when X > Y ->
    1.
```

Case

- Sugar for (conditional) pattern matching

```
insert(X,Set) ->
    case lists:member(X,Set) of
        true  -> Set;
        false -> [X|Set]
    end.
```

Types?

- **Dynamically typed**
- Types inferred runtime (type errors are possible)
- **Type test** functions

  is_atom/1, is_binary/1, is_bitstring/1, is_boolean/1

- **Type conversion** functions

  atom_to_list/1, list_to_atom/1, integer_to_list/1 …

Higher-order

- Functions are first class values

```
1> Double = fun(X) -> X * 2 end.
#Fun<erl_eval.6.54118792>
2> Double(3).
6.
```

- Profitably used as function arguments

Map, filter ...

- Apply to all elements of a list

```
map(Fun, [First|Rest]) ->  [Fun(First)|map(Fun,Rest)];
map(Fun, []) ->            [].
```

- Filter only elements satisfying a predicate

```
filter(Pred, L)

filter(_, []) -> [];
filter(Pred, [H|T]) ->
    case Pred(H) of
        true  -> [H|filter(Pred, T)];
        false -> filter(Pred, T)
    end.
```

Example

- Convert a list of temperatures

```
1> Temps = [{"Milan", {c,10}}, {"Turin", {c,12}},... ]
2> Fun   = fun(X) ->
               {City,Temp} = X,
               {City,conv:convert(Temp)} end.

3> map(Fun, Temps)
```

```
4> [{"Milan",{f,50.0}},{"Turin",{f,53.6}}, ...]
```

Example

- Keep only warm temperatures

```
1> Temps = [{"Milan", {c,10}}, {"Turin", {c,12}}, … ]
2> Pred  = fun(X) ->
               {City,{c,Temp}} = X,
               Temp >= 12 end.

3> filter(Fun, Temps)
```

```
4> [{"Turin", {c,12}}, …]
```

Erlang: Concurrency

Processes

- Basic **structuring concept** for concurrency (everything is a process)
- Execute a **function** on some **parameters**
- Strongly **isolated** (no sharing)
- Identified by an **identifier** (id or name), that can be passed (and cannot be forged)

Messages

- Processes communicate through **asynchronous message passing** (with known companions)
- Messages are atomic (delivered or not)
- Messages are sent to a process and kept in a **message queue** (the **mailbox**)
- A process can be informed about the status of other processes (detect a **failure**)

General structure

- Processes typically sit in an **infinite loop**
  - **get** a message
  - **process** the message
  - start over
- The mailbox can be accessed **selectively**

Actor model

- **Everything is an actor** and actors execute **concurrently**
- Actors can
    - **send** messages to other actors, **asynchronously** (**mailing**);
    - designate the **behaviour** for the messages received
    - **create** new actors;
- An actor can **communicate** only with actors whose **address is known**, and **addresses can be passed**

Creating processes

```
spawn(Module, Exported_Function, Arg_List)
```

- Create a new **process** executing
  - a **function**
  - **exported** by some module
  - on a **list of arguments**
- Returns a **pid**, uniquely identifying the process

Tick

```
-module(tick).
-export([start/0, tick/2]).

tick(Msg, 0) ->
    done;

tick(Msg, N) ->
    io:format("Here is tick saying \"~p\" ~B times~n",
              [Msg,N]),
    tick(Msg, N - 1).

start() ->
    spawn(tick, tick, [yup, 3]),
    spawn(tick, tick, [yap, 2]).
```

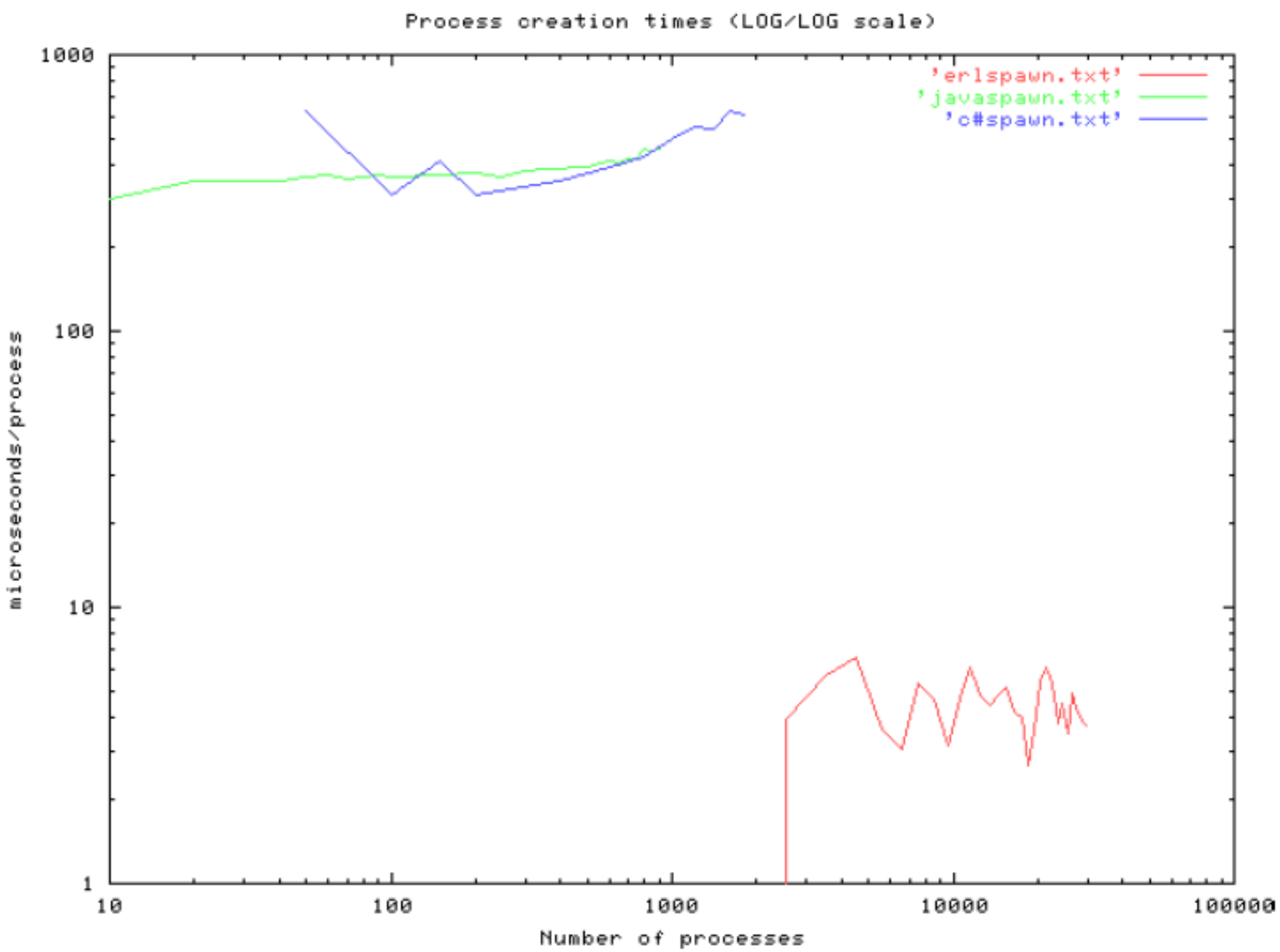
Tick tock … run

```
7> tick:start().
Here is tick saying "yup" 3 times
Here is tick saying "yap" 2 times
Here is tick saying "yup" 2 times
Here is tick saying "yap" 1 times
Here is tick saying "yup" 1 times


8>
```

Fast spawning

- Lightweight (not 1-1 with system threads)



Fast spawning

- **Goroutines**: Managed by the runtime, lightweight threads multiplexed over a number of system threads (green threads)
- **Erlang processes**: managed by the Beam VM, multiplexed over a thread pool, no shared memory (green processes)
- **Java**:
  - **Java Threads** are (although not defined by the specification) platform threads, heavy (1Mb memory footprint)
  - **Java Virtual Threads** (since Java 21), lightweight threads, multiplexed over a thread pool, shared memory very similar to goroutines, but possibly heavier

Communication

- Asynchronous message passing
- **Messages** are valid **Erlang terms** (lists, tuples, integers, atoms, **pids**, …)
- Each process has a **message queue**
- A message can be **sent** to a process (non blocking)
- A process can **selectively receive** messages on its queue (blocking)

Send and receive

- **Send**

```
pid ! msg
```

- **Receive**

```
receive
  msg_pattern1 ->
                 action1;
  msg_pattern2 ->
                  action2;
  ...
end
```

Multiplier: server

```
-module(mulServer).
-export([start/0, mul_server/0]).

mul_server() ->
    receive
        {X, Y, Pid} ->
            Pid ! X*Y,
            mul_server();

        stop ->
            io:format("Server stopping ... ", [])
    end.
```

Multiplier: server (concurrent)

```
-module(mulServerConc).
-export([start/0, mul_server/0]).

mul_server() ->
    receive
        {X, Y, Pid} ->
            spawn(fun() -> Pid ! X*Y end.),
            mul_server();

        stop ->
            io:format("Server stopping ... ", [])
    end.
```

Multiplier: client

```
start() ->
    Server = spawn(proc2, mul_server, []),
    Server ! {2, 2, self()},
    Server ! {2, 4, self()},
    receive
        P1 ->
            io:format("Product 2*2 = ~B~n", [P1])
    end,

    receive
        P2 ->
            io:format("Product 2*4 = ~B~n", [P2])
    end,

    Server!stop.
```

Problems

- Receive for concurrent server can be out of order
- What if we want different binary operations (e.g., sum and product)
- Messages not of the right format are kept in the mailbox
- Everyone knowing the server can shut it down
- The Client could wait for the answer indefinitely

MultiplierAdder: server

```
-module(mulAddServer).
% messages are of the kind {Op, X, Y, Pid}
mul_add_server() ->
    receive
        {mul, X, Y, Pid} ->
            spawn(fun() -> Pid ! X*Y.),
            mul_add_server();

        {add, X, Y, Pid} ->
            spawn(fun() -> Pid ! X+Y.),
            mul_add_server();

        stop ->
            io:format("Server stopping ...", [])
    end.
```

mulAddSever.erl

Careful with the mailbox

- What if the server gets wrongly formatted messages?

```
# However, as messages not matched by receive are left in the
# mailbox, it is the programmer's responsibility to make sure
# that the system does not fill up with such messages.
```

- Do something with **unmatched messages**
- Try to avoid unmatched messages offering a **communication interface**

Process unmatched messages

```
-module(mulAddServer).
% messages are of the kind {Op, X, Y, Pid}
mul_add_server() ->
    receive
        {mul, X, Y, Pid} -> … ;
        {add, X, Y, Pid} -> … ;
        stop -> … ;
        …
        M -> do st. with message M (e.g., log error)
    end.
```

mulAddSever1.erl

Offer an interface

```
-module(mulAddServer).

mul(Server, X,Y) ->
    Server ! {mul, X, Y, self()}.

add(Server, X,Y) ->
    Server ! {add, X, Y, self()}.

mul_add_server() ->
    receive
        {mul, X, Y, Pid} -> … ;
        {add, X, Y, Pid} -> … ;
        stop -> … ;
  end.
```

mulAddSever2.erl

Registering

- Processes can be registered

```
register(Alias, Pid)
```

- Useful for **restarting behaviours** (node visibility)

- Alias can be unregistered (done automatically when aliased process dies)

```
unregister(Alias)
```

Timing out

- A receive can be exited after some time:

```
receive
    Msg1 ->
        action1;
    Msg2 ->
        action2
    …

    after Time ->
        action after timeout
```

- Example

Multiplier, again

- The server (mul_server) is registered (as ‘multiplier’)

- Accessible to clients knowing the name

- The server can be stopped ‘only by the creator’ (secret = creator pid … not very secret)

- The client sends and gets 'signed' messages and possibly timeouts if answer takes too long.

`mulServerReg.erl`

Multiplier, again

- The server (mul_server) is registered (as **multiplier**) when started

```
start() ->
  Server = spawn(mulServerReg, mul_server, [self()]),
  register(multiplier, Server),
```

- Known as `multiplier` in the node

- Pid of the creator is passed to the server, to be kept in the “server state”

Server

```
mul_server(Creator) ->

   receive
        % mul message: provide answer 'signed'
        %              with an id
        {Id, Pid, X, Y} ->
            spawn(fun() -> Pid ! {Id, X*Y} end),
            mul_server(Creator);

        % stop message (only by creator)
        {Creator, stop} ->
            io:format("Server stopping ...~n", []);

        % stop message, not from creator
        {Pid, stop} ->
             io:format("Process \"~w\" not allowed
                        to stop ...~n", [Pid]),
             mul_server(Creator)
   end.
```

Client

```
client() ->
    % first message
    Id1 = crypto:strong_rand_bytes(5),
    Msg1 = {Id1, self(), 2, 2},
    multiplier ! Msg1,

    receive
        {Id1,P1} ->
            out_result(Msg1,P1)
    after
        10 ->
            out_result(Msg1,fail)
    end,

    multiplier ! {self(), stop },
```

Robustness

- Abnormal termination is normal: "**Let it crash"** philosophy
- Primitives allows to “**link**” processes in a way that processes in the same group are notified of abnormal (error) events
- The structuring can be **hierarchical** allowing for layered applications: workers, controllers, supervisors

Links and monitors

- A process can be **linked to** or **monitor** another process

- A process can **exit**
  - **normally**
    run out of code or `exit(normal)`
  - **abnormally**
    error or `exit(Reason)`

Links

- (Bidirectional) link between caller and pid

```
link(Pid)
```

- When a process exits, linked processes receive a **signal**, carrying **pid** and **exit reason**

- By default
  - **normal exits** ignored
  - **abnormal exits** **kill** the receiving process.

    propagate the error signal to the links of the killed process

Links, more control

- A process can become a **supervisor process** (also called **system process**)

```
process_flag(trap_exit, true).
```

- The **exit signal** is caught as a **message**

```
{'EXIT',Pid, Reason}
```

Links, more control

- E.g., in the process **`start`** (see before)

```
start() ->
  process_flag(trap_exit, true),

  Server = spawn(mulServerReg, mul_server, [self()]),
  link(Server),
  register(multiplier, Server),

  ...
  receive
     {'EXIT', Server, Reason} ->
           % depending on reason, possibly
           % restart the server
```

Example

- A server that gets messages consisting of a **function** and **its arguments**
- Execute the **function** on the arguments as a **“supervised” servant**, keeping a list of the unfinished tasks
- For each servant, get the result and provides it to the corresponding client.
- In case of abnormal exit of the servant, retry

`hierarchy.erl`

Example: servant

```
% Given a function and some arguments
% - executes the functions on the arguments
% - or randomly fails (75% of the times)
servant(F, Args, Server) ->
    case rand:uniform(4) of

        % regular execution, notify the server
        % providing the result
        1 ->
            Server ! {answ, {self(), F(Args)}};

        % failure
        _ ->
            exit(went_wrong)
    end.
```

Example: server

```
% The server keeps in its state
% - Creator: the pid of the creator
% - WaitingList: list of requests being processed of
%   the kind {Servant,Client,F,Args} including
%   Servant's pid, client's pid, request data

server(Creator, WaitingList) ->

    % Supervisor process: traps the exit signals
    process_flag(trap_exit, true),

    receive
      % (1) client request
      % (2) normal termination from servant
      % (3) error message from servant
      % (4) stop request from creator
      % (5) stop request from non creator
     end.
```

Example: server

```
% (1) client request
{req, {Client, F, Args}} ->

   % spawn and link at the same time (atomic)
   Servant = spawn_link(hierarchy, servant, [F, Args, self()]),
   server(Creator, [{Servant,Client,F,Args} | WaitingList]);




% (2) normal termination from servant
{answ, {Servant, Result}} ->

    {_,Client,F,Args} = lists:keyfind(Servant,1,WaitingList),
    Client ! {answ, {Client, F,Args}, Result},
    server(Creator, WaitingList--[{Servant,Client,F,Args}]);
```

Example: server

```
% (3) error message from servant
{'EXIT', Servant, went_wrong } ->
    {_,Client,F,Args} = lists:keyfind(Servant,1,WaitingList),
    io:format("Servant ~w went wrong, retrying ...~n", [Servant]),
    NewServant = spawn_link(hierarchy, servant, [F, Args, self()]),
    server(Creator, (WaitingList--[{Servant,Client,F,Args}])
                                    ++ [{NewServant,Client,F,Args}] );

% (4) stop request from creator
{Creator, stop} ->
   io:format("Server stopping ...~n", []),
   exit(normal) ;

% (5) stop request not from creator
{Pid, stop} ->
   io:format("Process \"~w\" not allowed ...~n", [Pid]),
   server(Creator,WaitingList)
```

Example: creator

```
start() ->

    % create and register the the server
    Server = spawn(hierarchy, server, [self(),[]]),
    register(pserver, Server),

    % accessible to some client, without getting the pid
    spawn(hierarchy, client, []),

    % wait a bit and stops the server
    timer:sleep(1000),
    pserver ! {self(),stop}.
```

Example: client

```
client() ->
    % first message
    Msg1 = {self(), fun([X,Y]) -> X*Y end, [1,2]},
    pserver ! {req, Msg1},

    % wait for result, possibly timing out
    receive
        {answ, Msg1, R1} ->
            out_result(product,R1)
    after
        10 ->
            out_result(product,fail)
    end,

    ...
```

Exercise

- Modify the system as follows:
  - The server creates a servant for each request
  - In case of normal termination, the servant itself send the result to the client
  - In case of abnormal termination of the servant, the server is notified and a new servant is created

Monitors

- Create a “**unidirectional” link**:
  current process monitors the process Pid

```
monitor(process, Pid)
```

- On exits the monitor process gets a message

```
{'DOWN', MonitorReference, process, Pid, Reason}
```

Distribution

- **Distributed Erlang**
    - Processes run in various Erlang nodes, same intranode primitives
    - Applications running in a **distributed trusted environment** (cluster)
- **Socket-based distribution**
    - TCP/IP sockets to communicate in an untrusted environment
    - less flexibile, but more secure

Distributed Erlang

- Actors are spread on different **nodes**

- **Node A** can communicate with **Node B** if they share a cookie (**magic cookie**) and know each other name

- Start a node (with cookie)

```
erl -sname name      -setcookie cookie % same host
erl -name name@host -setcookie cookie % across hosts
```

Connections

- Node in Erlang are loosely connected
- **Connecting nodes**

```
net_kernel:connect_node(NodeName)
```

  Also implicitly established at first connection attempt

- Connections are **transitive**
- If a node goes down, all connections to it are removed.

Connections

```
erl -sname node1@host -setcookie "a"
erl -sname node2@host -setcookie "a"
erl -sname node3@host -setcookie "a"

node1> nodes().
[]
node1> net_kernel:connect_node('node2@host').
True

node1> nodes().
['node2@host']

node2> net_kernel:connect_node('node3@host').
True

node1> nodes().
['node2@host', 'node3@host']
```

Distributing

- Lifting to the cluster level works reasonably smoothly
  - primitives like spawn, link, monitor etc. has additional node parameter, e.g.

```
spawn(Node, Module, Exported_Function, Arg List)
```

  - registered names are local to nodes, hence pid must be used (or see **global** module)
  - when spawning a process at a node, the code must be available at that node

Example

- The previous example, of a server getting a list of tasks to execute modified as follows:
    - client, server and slaves on different nodes
    - the server monitors the slaves, on fail it retries on a (possibly) different node

`distributed.erl`

Example: server

```
% The server keeps in its state
% - Creator: the pid of the creator
% - WaitingList: list of requests being processed of
%   the kind {Servant,Client,F,Args} including
%   Servant's pid, client's pid, request data
% - Slaves: list of slave nodes, first in the list is
%           next to use, and then reinserted as last

server(Creator, WaitingList, Slaves) ->

    % Supervisor process: traps the exit signals
    process_flag(trap_exit, true),
```

Example: server

```
% (1) client request
{req, {Client, F, Args}} ->

  % get the next slave
   [Slave|SlavesRest] = Slaves,

   % spawn and link at the same time (atomic)
   Servant = spawn_link(Slave, distributed, servant,
                                               [F, Args, self()]),
   server(Creator,
          [{Servant,Client,F,Args} | WaitingList],
          SlavesRest++[Slave]);
```

Example: server

```
% (3) error message from callback
{'EXIT', Servant, went_wrong } ->
    % get the next slave
    [Slave|SlavesRest] = Slaves,

    {_,Client,F,Args} = lists:keyfind(Servant,1,WaitingList),
    NewServant = spawn_link(Slave, distributed, servant,
                                              [F, Args, self()]),
    server(Creator,
           WaitingList--[{Servant,Client,F,Args}]
                       ++[{NewServant,Client,F,Args}],
           SlavesRest++[Slave]);
```

Socket-based distribution

- Standard (low level) socket interface (gen_tcp module)
  - Server: listen, accept
  - Client: connect
  - send, recv

Open Telecom Platform (OTP)

- A set of design principles
- A set of libraries
- Developed and used by Ericsson to build large-scale, fault-tolerant, distributed applications with pre-designed skeletons and patterns (server, fsm, event …)

gen_server

- Need to implement a number of callbacks
  - **`init`** (set up, initialise the state)
  - **`handle_cast`** (asynchronous call without a reply, determining a state change)
  - **`handle_call`** (synchronous call with a reply)
  - **`terminate`**
  - **…**

Example

- Multiplier realised with **gen_server**

`mulGenServer.erl`

```erlang
-module(mulGenServer).

% declare that the gen_server behaviour is implemented
-behaviour(gen_server).

-export([go/0,client/0]).
-export([start/0, mul/2, stop/0]).
-export([init/1, handle_call/3, handle_cast/2,
         handle_info/2, terminate/2]).
```

```erlang
%%% INTERFACE

% Create the server, registered locally as multiplier, calling init
% with parameter self() (the pid of the creator)
start() ->
    gen_server:start({local, multiplier}, ?MODULE, [self()], []).

% multiplication: synchronous call
mul(X,Y) ->
    gen_server:call(multiplier, {mul, X, Y}).

% stop request, asynchronous call passing the pid of the caller
% (better implemented as terminate message, just to have an example of
% cast)
stop() ->
    gen_server:cast(multiplier, {stop, self()}).
```

```
%%% CALLBACKS

% initialization: establish the initial state
init([Creator]) ->
    {ok, [Creator]}.

% multiplication handle
% IN:   message, sender, server state
% OUT:  reply atom, reply content, new state
handle_call({mul,X,Y}, _From, [Creator]) ->
    {reply, X*Y, [Creator]}.

% stop handle
handle_cast({stop, From}, [Creator]) ->
    if From =:= Creator ->
       {stop, normal, [Creator]};
             From =/= Creator ->
       io:format("Invalid shutdown req (pid ~w)~n",[From]),
             {noreply, [Creator]}
    end.
```

```erlang
% handling termination
terminate(normal, [Creator]) ->
    io:format("Server created by: ~w properly
terminated~n",[Creator]).

% other messages
handle_info(Msg, [Creator]) ->
    io:format("Unexpected message: ~p~n",[Msg]),
    {noreply, [Creator]}.
```

Dynamic Code Loading

- Built-in in Erlang
- A **module** can exist in **two variants** in a system: **current** and **old**
- **When** a module is **loaded** into the system for the first time, the code becomes '**current**'.
- If then a **new instance** is **loaded**, the previous instance becomes 'old' and the new one 'current'.

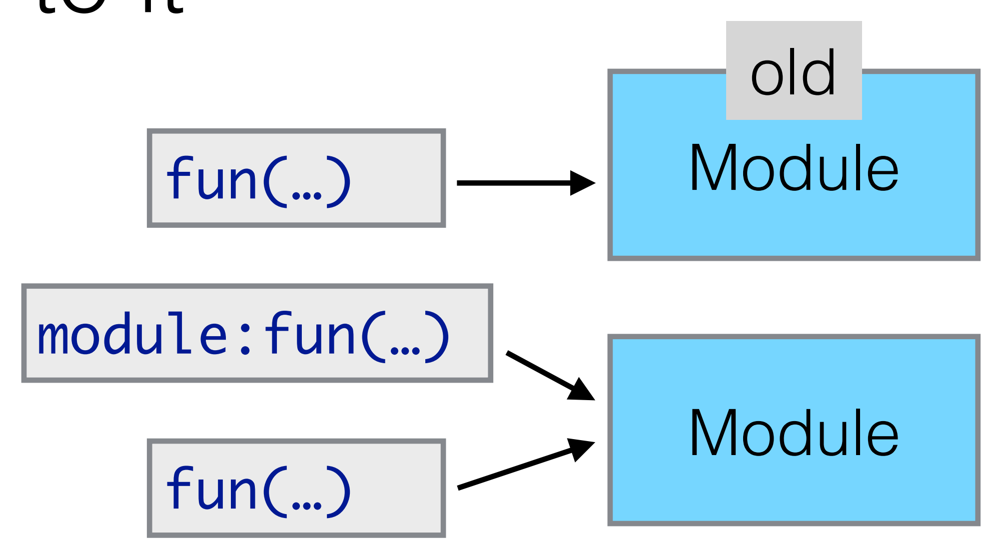
Dynamic Code Loading

- Two possible ways of referencing a function
  - Name only: still refers to the old version

```
fun(…)
```

  - Fully qualified: refers to the current version code, subsequent calls refers to it

```
module:fun(…)
```




```
hotSwap.erl
```

Example

- **Controller**:
  - **new**: create new **loop** process, return pid
  - Supervises **termination** of loop processes and communicate reason
- **Loop:**
  - **ver:** get version
  - **upd:** update to new version
  - **stop:** stop

Dynamic Code Loading

- Dangerous
- Higher-level abstractions provided in OTP

Concluding …

- Concurrency Oriented Programming (~ actor model)
- Emphasis on
  - Encapsulation with focus on computing entities (state + reaction to messages)
  - Transparent Distribution
  - Fault tolerance (supervisor trees and let it crash philosophy)
  - Scalability (multiple instances on multiple nodes)
  - Continuous Operation (hot-swapping)

Not perfect (as everything in the world)

- A bit oldish/low level syntax and design choices … alternatives Elixir, Clojure, …
- Untyped … (Scala, Akka)
- Identifying communication channels with computing entities possibly cumbersome (see msg tagging/signing)
- Primitive security model (restricting access to a node / process capabilities)
- Message passing only is good, but can be heavy when supporting the sharing of large data sets

Still you can make cool apps