Message Passing

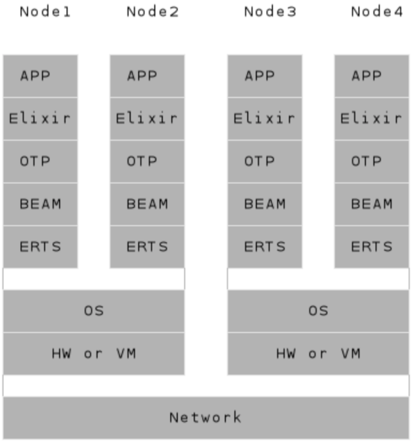
CS511

Interaction Models

- Previously
  - Shared memory (low-level, non-structured)
  - Semaphores (low-level, non-structured)
  - Monitors (popular, structured, encapsulate synchronization)
- So what's the problem with monitors?
  - Highly centralized (un/blocking processes, maintaining queues of blocked processes, encapsulating data)
  - For modern, distributed architectures, need for less centralized solution
  - Turn to interaction through communication rather than sharing

Erlang System

- Consists of a number of distributed Erlang runtime systems communicating with each other (instances of the VM)



Nodes and Processes in Erlang

- Each such runtime system is called a node
  - node name is an atom `name@host`
    - `name` is the name given by the user
    - `host` is the full host name if long names are used, or the first part of the host name if short names are used
- The name of a node may be consulted using `node()`

```
1> node().
nonode@nohost
```

Processes and Communication in Erlang

- A process in a node has
  - a process id (pid)

```
1> self().
<0.78.0>
```

  - its own memory (a mailbox, a heap and a stack); and
  - a process control block (PCB) with information about the process.
- Message passing between processes at different nodes, as well as links and monitors, are transparent when pids are used
  - Registered names, however, are local to each node.
- Format of a PID:
  - node id where process lives; 0 if node is local
  - process index itelf (index into process table)
  - serial which increases every time MAXPROCS has been reached.

The Message Passing Model

- No shared memory
  - A process sends a message
  - Another process receives the message
- Asynchronous communication model:

```
receive(Var);
send(PID,msg);
```

  - `receive` blocks until a message is available in the mailbox
  - `send(PID,msg)` is non-blocking; it sends message `msg` to process `PID`
- Erlang implements this model

A Simple Echo Server

- Process `echo` will receive a message and then send it back to the sender
- After that it will continue to wait for a new message
- It may be stopped by sending it the `stop` message

```
echo() ->
    receive
        {From, Msg} ->
            From ! {Msg},
            echo();
        stop -> true
    end.
```

- Processes are created using `spawn/1` and `spawn/3`

A Simple Echo Server (cont.)

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

echo() ->
    receive
        {From, Msg} ->
            From ! {Msg},
            echo();
        stop -> true
    end.

start() ->
    Pid = spawn(fun echo/0), % Returns pid of a new process
       % started by the application of echo/0 to []
    Token = "Hello Server!",     % Sending tokens to the server
    Pid ! {self(), Token},
    io:format("Sent ~s~n",[Token]),
    receive
       {Msg} ->
            io:format("Received ~s~n", [Msg])
    end,
    Pid ! stop.     % Stop server
```

A Simple Echo Server

```
1> echo:start( ).
Sent Hello Server!
Received Hello Server!
stop
```

If we export `echo/0` we can spawn from the interpreter:

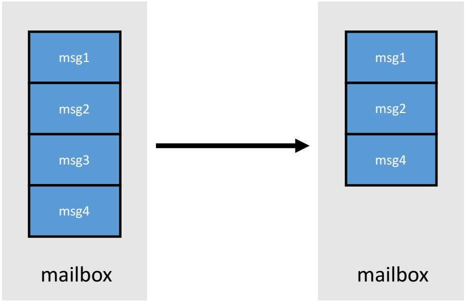
```
59> X=spawn(fun echo:echo/0).
<0.198.0>
60> X!{self(),"hello"}.
{<0.60.0>,"hello"}
61> X.
<0.198.0>
```

Note: the value of a send is the value of the message

Reacting to Multiple Messages

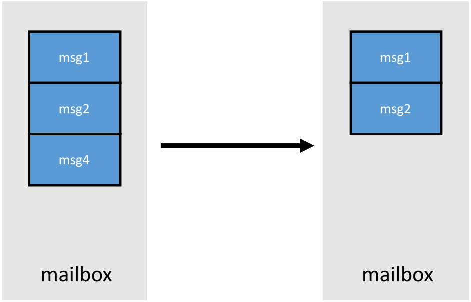
- Erlang “listens” for messages from different senders
- In which order will they be processed?
- Can we force an order?
- A receive statement tries to find a match as early in the mailbox as it can

```
receive
    msg3 -> 42
end
```



Reacting to Multiple Messages

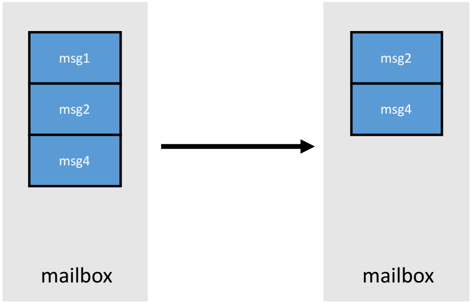
```
receive
    msg4 -> 42
end
```



Reacting to Multiple Messages

Waiting for multiple messages

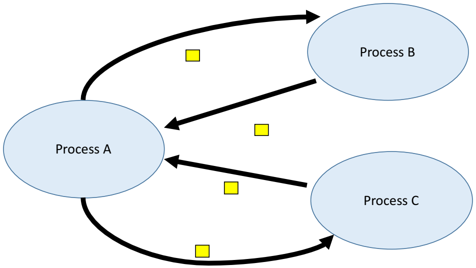
```
receive
    msg4 -> 42;
    _    -> 41
end
```



- The oldest message is tried against every pattern of the receive until one of them matches

Sources of Multiple Messages

Multiple messages can come from different processes



- How do we know who sent a message?
- Distinguish the source by Pids

Sources of Multiple Messages

```erlang
-module(echo2).
-export([start/0]).

echo() ->
    receive
     {From, Msg} ->
           timer:sleep(rand:uniform(100)),
           From ! {Msg},
           echo();
        stop ->
           true
    end.

% continued on next slide...
```

- `timer:sleep(N)` sleeps a process for `N` milliseconds
- `rand:uniform(N)` produces a random integer between 1 and N

Sources of Multiple Messages

```erlang
start() ->
    PidB = spawn(fun echo/0),
    PidC = spawn(fun echo/0),

    % sending tokens
    Token = 42,
    PidB ! {self(), Token},
    io:format("Sent~w~n",[Token]),
    Token2 = 41,
    PidC ! {self(), Token2},
    io:format("Sent~w~n",[Token2]),

    % receive message
    receive
       {Msg} ->
              io:format("Received ~w~n", [Msg])
    end,

    % stop echo-servers
    PidB ! stop,
    PidC ! stop.
```

Sources of Multiple Messages

- How do we know who sent a message?
- Distinguish the source by Pids

```
-module(echo2).
-export([start/0]).

echo() ->
    receive
     {From, Msg} ->
           timer:sleep(rand:uniform(100)),
           From ! {self(), Msg},
           echo();
        stop ->
           true
    end.

% continued on next slide...
```

Sources of Multiple Messages

```erlang
start() ->
    PidB = spawn(fun echo/0),
    PidC = spawn(fun echo/0),

    % sending tokens
    Token = 42,
    PidB ! {self(), Token},
    io:format("Sent~w~n",[Token]),
    Token2 = 41,
    PidC ! {self(), Token2},
    io:format("Sent~w~n",[Token2]),

    % receive messages
    receive
       {PidB, Msg} ->
              io:format("Received from B: ~w~n", [Msg]) ;
       {PidC, Msg} ->
              io:format("Received from C: ~w~n", [Msg])
    end,

    % stop echo-servers
    PidB ! stop,
    PidC ! stop.
```

Sources of Multiple Messages

```
11> echo2:start().
Sent42
Sent41
Received from B: 42
stop
12> echo2:start().
Sent42
Sent41
Received from B: 42
stop
13> echo2:start().
Sent42
Sent41
Received from C: 41
stop
14> echo2:start().
Sent42
Sent41
Received from B: 42
stop
```

Sources of Multiple Messages

Multiple messages can come from the same processes

- Send several messages of the same shape and continue computing
- When receiving the responses, how can the code match them to the appropriate request?
- BIF `make_ref` provides globally unique reference objects (references for short) different from every other object in the Erlang system including remote nodes
- References can be used to uniquely identify messages

Sources of Multiple Messages

```
-module(echo3).
-export([start/0]).

echo() ->
    receive
        {From, Ref, Msg} ->
            From ! {self(), Ref, Msg},
            echo();
        stop ->
            true
    end.

% continues in next slide...
```

Sources of Multiple Messages

```erlang
start() ->
   PidB = spawn(fun echo/0),
   % sending tokens
   Token = 42,
   Ref = make_ref(),
   PidB ! {self(), Ref, Token},
   io:format("Sent~w~n",[Token]),
   Token2 = 41,
   Ref2 = make_ref(),
   PidB ! {self(), Ref2, Token2},
   io:format("Sent~w~n",[Token2]),
   % receive messages
   receive
      {PidB, Ref2, Msg} ->
           io:format("Received 41? ~w~n", [Msg]) ;
      {PidB, Ref, Msg} ->
           io:format("Received 42? ~w~n", [Msg])

   end,

   % stop echo-servers
   PidB ! stop.
```

Selective Receive

- Clauses can have guards
- Guards must be composed of terminating functions (BIFs)

```
receive
  {Pid, Ref, N} when N>0 -> ...
```

Timeouts

```erlang
f(Pid) ->
    receive
        {Pid, Msg} -> Msg
    after 3000 ->
        timeout
end.
```

- The after part will be triggered if 3000 milliseconds have passed without receiving a message that matches the pattern.
- Other uses

```erlang
sleep(T) ->
    receive
    after T ->
       ok
end.

flush() ->
    receive
      _ -> flush()
    after 0 ->
      ok
end.
```

Exercise

- Implement a semaphore
- Use the `when` clause

Template that you can start from:

```erlang
-module(semaphore).
-compile(export_all).

make_semaphore(Permits) ->
spawn(?MODULE,semaphore,[Permits]).

% complete
```

- `?MODULE`: macro that refers to the name of the current module

A Semaphore

```erlang
-module(semaphore).
-compile(export_all).

make_semaphore(Permits) ->
    spawn(?MODULE,semaphore,[Permits]).

semaphore(0) ->
    receive
        {From,Ref,release} ->
            semaphore(1)
    end;
semaphore(P) when P>0 ->
    receive
        {From,Ref,release} ->
            From!{self(),Ref,ok},
            semaphore(P+1);
        {From,Ref,acquire} ->
            From!{self(),Ref,ok},
            semaphore(P-1)
    end.
```

- `semaphore` could be specified as a FSM

Semaphore - Print “a” before “b”

```erlang
start() ->
    S = make_semaphore(0),
    spawn(?MODULE,p1,[S]),
    spawn(?MODULE,p2,[S]).

release(S) ->  % could be included in semaphore module
    R = make_ref(),
    S!{self(),R,release},
    receive
        {S,R,ok} ->
            done
    end.

p1(S) ->
    io:format("a"),
    release(S).

p2(S) ->  %  acquire is inlined
    R = make_ref(),
    S!{self(),R,acquire},
    receive
        {S,R,ok} ->
            io:format("b")
    end.
```

Three Kinds of Exceptions

- Errors
  - Ends the execution in the current process and includes a stack trace of the last functions
  - Errors are the means for a function to stop its execution when you can't expect the calling code to handle what just happened
- Throws
  - Used for cases that the programmer can be expected to handle (`try...catch`).
- Exits
  - Same as errors except used to signal abnormal termination between processes.
  - More lightweight than errors in that stack trace not included

Note: `try...catch` actually can catch them all

Errors – Example

```
1> erlang:error(badarith).
** exception error: bad argument in an arithmetic expression
2> erlang:error(custom_error).
** exception error: custom_error
3> catch(1+a).
{'EXIT',{badarith,[{erlang,'+',[1,a],[]},
      {erl_eval,do_apply,6,[{file,"erl_eval.erl"},{line,681}]},
      {erl_eval,expr,5,[{file,"erl_eval.erl"},{line,434}]},
      {shell,exprs,7,[{file,"shell.erl"},{line,686}]},
      {shell,eval_exprs,7,[{file,"shell.erl"},{line,642}]},
      {shell,eval_loop,3,[{file,"shell.erl"},{line,627}]}]}}
```

Links

- Pid1 can be linked to Pid2 by calling `link(Pid2)`
    - Creates a two-way link
- Terminating processes emit exit signals to all linked processes, which can terminate as well or handle the exit in some way.
- This feature can be used to build hierarchical program structures where some processes are supervising other processes, for example, restarting them if they terminate abnormally.

Note: Some comments on monitors are present at the end of these set of slides

Example

```erlang
-module(linkmon).
-compile(export_all).

myproc() ->
    timer:sleep(2000),
    exit(reason).
```

In the shell:

```
> c(linkmon).
{ok,linkmon}
> self().
<0.79.0>
> spawn(fun linkmon:myproc/0).
<0.75.0>
> self().
<0.79.0>
> link(spawn(fun linkmon:myproc/0)).
true
** exception error: reason
> self().
<0.83.0>
```

Another Example

```erlang
chain(0) ->
  receive
    _ -> ok
  after 2000 ->
    exit("chain dies here")
  end;

chain(N) ->
  Pid = spawn(fun() -> chain(N-1) end),
  link(Pid),
  receive
    _ -> ok
  end.
```

In the shell:

```
1> c(linkmon).
{ok,linkmon}
2> link(spawn(linkmon, chain, [3])).
true
** exception error: "chain dies here"
```

Another Example (cont.)

```
[shell] == [3] == [2] == [1] == [0]
[shell] == [3] == [2] == [1] == *dead*
[shell] == [3] == [2] == *dead*
[shell] == [3] == *dead*
[shell] == *dead*
*dead, error message shown*
[shell] <-- restarted
```

- After the process running `linkmon:chain(0)` dies, the error is propagated down the chain of links until the shell process itself dies because of it.
- The crash could have happened in any of the linked processes
  - because links are bidirectional, you only need one of them to die for the others to follow suit.

On Number of Links and Linking

- Links cannot be stacked.
  - Calling `link/1` multiple times for the same two processes, will still create only one link between them
  - A single call to `unlink/1` will be enough to tear it down.
- `link(spawn(Function))` or `link(spawn(M,F,A))` happens in more than one step. In some cases, it is possible for a process to die before the link has been set up and then provoke unexpected behavior.
  - `spawn_link/1-3` spawns and links as an atomic operation

Trapping Exit Signals

- In order to be reliable, an application needs to be able to both kill and restart a process quickly.
  - Links convenient for the killing part but restarting is missing.
- When a linked process terminates, it terminates with an exit reason that is sent through a special message known as an exit signal
  - Eg. exit signal with exit reason `"chain dies here"`

```
exit("chain dies here")
```

Trapping Exit Signals

- The default behaviour when a process receives an exit signal with an exit reason other than normal, is to terminate and in turn emit exit signals with the same exit reason to its linked processes.
- System processes: normal processes, except they can convert exit signals to regular messages.
  - Done by calling `process_flag(trap_exit, true)` in a running process.
- Allows a process to react to exit signals

Chain Example Revisited

Chain example with a system process at the beginning

```
1> process_flag(trap_exit, true).
true
2> spawn_link(fun() -> linkmon:chain(3) end).
<0.49.0>
3> receive X -> X end.
{'EXIT',<0.49.0>,"chain dies here"}
```

Description of behavior:

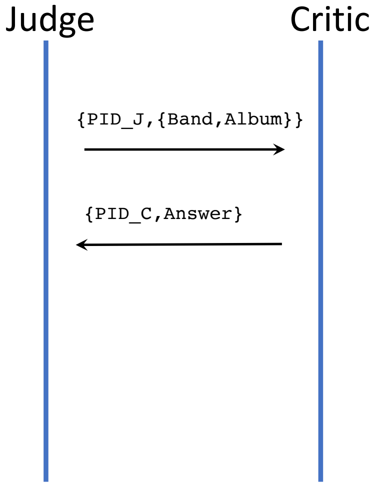
```
[shell] == [3] == [2] == [1] == [0]
[shell] == [3] == [2] == [1] == *dead*
[shell] == [3] == [2] == *dead*
[shell] == [3] == *dead*
[shell] <-- {'EXIT,Pid,"chain dies here"} -- *dead*
[shell] <-- still alive!
```

Kill Reason

- Acts as a special signal that can't be trapped.
- Ensures any process you terminate with it will be dead.
  - A last resort, when everything else has failed.
- As the kill reason can never be trapped, it needs to be changed to `killed` when other processes receive the message.
  - Otherwise, every other process linked to it would in turn die for the same kill reason and would in turn kill its neighbors, and so on.
  - This explains why `exit(kill)` looks like `killed` when received from another linked process.

```
> spawn_link(fun() -> exit(kill) end).
** exception exit: killed
```

MSC for Critic Example



Restarting Processes

```
start_critic() ->
    spawn(?MODULE, critic, []).

judge(Pid, Band, Album) ->
  Pid ! {self(), {Band, Album}},
    receive
      {Pid, Criticism} -> Criticism
      after 2000 ->
        timeout
  end.

critic() ->
  receive
    {From, {"Rage Against the Turing Machine", "Unit Testify"}} ->
      From ! {self(), "They are great!"};
    {From, {"System of a Downtime", "Memoize"}} ->
      From ! {self(), "They’re not Johnny Crash but they’re good."
    {From, {"Johnny Crash", "The Token Ring of Fire"}} ->
      From ! {self(), "Simply incredible."};
   {From, {_Band, _Album}} ->
      From ! {self(), "They are terrible!"}
  end,
  critic().
```

Restarting Processes

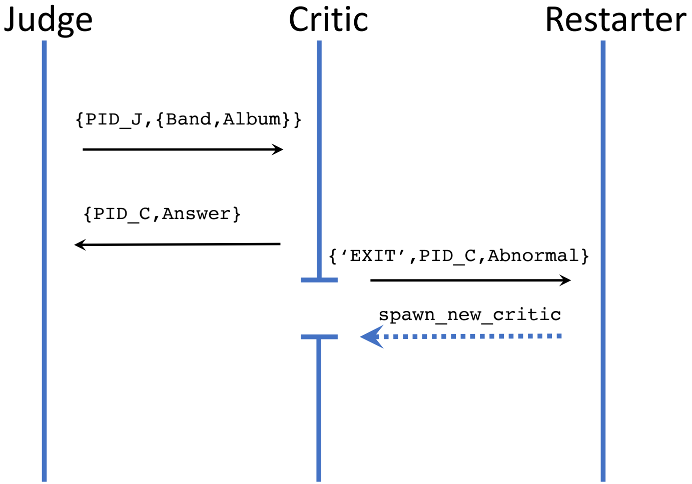
```
1> c(linkmon).
{ok,linkmon}
2> Critic = linkmon:start_critic().
<0.47.0>
3> linkmon:judge(Critic, "Genesis", "The Lambda Lies Down on Broad
"They are terrible!"
```

We now kill the `Critic` process

```
4> exit(Critic, solar_storm).
true
5> linkmon:judge(Critic, "Genesis", "A trick of the Tail Recursion
timeout
```

We need a "supervisor" process to keep critics alive

MSC for Critic Example



Restarting Processes

```erlang
start_critic2() ->
spawn(?MODULE, restarter, []).

restarter() ->
  process_flag(trap_exit, true),
  Pid = spawn_link(?MODULE, critic, []),
  receive
    {'EXIT', Pid, normal} -> % not a crash
      ok;
    {'EXIT', Pid, shutdown} -> % manual termination, not a crash
      ok;
    {'EXIT', Pid, _} ->
  restarter()
end.
```

Problem: Pid of the critic is part of internal state, it is not known

```
1> c(linkmon).
{ok,linkmon}
2> linkmon:start_critic2().
<0.48.0>
3> linkmon:judge(?????, "Genesis", "The Lambda Lies Down on Broadw
```

Restarting Processes

- We can name a process, using an atom, rather than use its pid via `erlang:register/2`
- If a process dies, it will automatically lose its name or you can also use `unregister/1`
- You can get a list of all registered processes with `registered/0` or a more detailed one with the shell command `regs()`.

```erlang
restarter() ->
  process_flag(trap_exit, true),
  Pid = spawn_link(?MODULE, critic, []),
  register(critic, Pid),
  receive
    {'EXIT', Pid, normal} -> % not a crash
      ok;
    {'EXIT', Pid, shutdown} -> % manual termination, not a crash
      ok;
    {'EXIT', Pid, _} ->
      restarter()
  end.
```

What about the judge?

Restarting a Process

```erlang
judge2(Band, Album) ->
  critic ! {self(), {Band, Album}},
  Pid = whereis(critic),
  receive
    {Pid, Criticism} -> Criticism
  after 2000 ->
    timeout
  end.
```

Restarting a Process

```
1> linkmon:start_critic2().
<0.58.0>
2> whereis(critic).
<0.59.0>
3> linkmon:judge2("Genesis", "A trick of the Tail Recursion").
"They are terrible!"
4> exit(whereis(critic),solar_storm).
true
5> linkmon:judge2("Genesis", "A trick of the Tail Recursion").
"They are terrible!"
6> whereis(critic).
<0.63.0>
```

Race Conditions due to Shared State

- `critic` is stored in a shared registry
- There are processes that read it such as `judge2`
- And processes that write to it such as `restarter`
- Race conditions are therefore possible

Race Conditions due to Shared State – Example 1

1. `critic ! Message`
2. critic receives
3. critic replies
4. critic dies
5. whereis fails
6. critic is restarted
7. code crashes

```erlang
judge2(Band, Album) ->
  critic ! {self(), {Band, Album}},
  %% critic dies at this point
  %% register still not updated
  Pid = whereis(critic), %% fails (returns undefined)
  receive
    {Pid, Criticism} -> Criticism  %% undefined!=Pid
  after 2000 ->
    timeout
  end.
```

Race Conditions due to Shared State – Example 2

1. `critic ! Message`
2. critic receives
3. critic replies
4. critic dies
5. critic is restarted
6. whereis picks up wrong pid
7. message never matches

```erlang
judge2(Band, Album) ->
  critic ! {self(), {Band, Album}},
  %% critic dies at this point
  %% register updated with new Pid
  Pid = whereis(critic), %% successful (but different Pid)
  receive
    {Pid, Criticism} -> Criticism  %% no match
  after 2000 ->
    timeout
  end.
```

- Both may be solved by replacing the use of `whereis` (and Pid matching) to that of reference matching

Adding References to Messages

```erlang
judge2(Band, Album) ->
  Ref = make_ref(),
  critic ! {self(), Ref, {Band, Album}},
  receive
    {Ref, Criticism} -> Criticism
  after 2000 ->
    timeout
  end.

critic2() ->
  receive
    {From, Ref, {"Rage Against the Turing Machine", "Unit Testify"
      From ! {Ref, "They are great!"};
    {From, Ref, {"System of a Downtime", "Memoize"}} ->
      From ! {Ref, "They're not Johnny Crash but they're good."};
    {From, Ref, {"Johnny Crash", "The Token Ring of Fire"}} ->
      From ! {Ref, "Simply incredible."};
    {From, Ref, {_Band, _Album}} ->
      From ! {Ref, "They are terrible!"}
  end,
  critic2().
```

Appendix: More on Exceptions

Appendix: Monitors

Revisiting Exceptions – How Processes Trap Them

- `spawn_link(fun() ->ok end)`
  - Untrapped Result: Nothing
  - Trapped Result: `{'EXIT', <0.61.0>, normal}`
  - The process exited normally, without a problem.
- `spawn_link(fun() ->exit(reason) end)`
  - Untrapped Result: `** exception exit: reason`
  - Trapped Result: `{'EXIT', <0.55.0>, reason}`
  - The process has terminated for a custom reason.
- `spawn_link(fun() ->exit(normal) end)`
  - Untrapped Result: Nothing
  - Trapped Result: `{'EXIT', <0.58.0>, normal}`
  - Emulates process terminating normally.

Revisiting Exceptions

- `spawn_link(fun() ->1/0 end)`
  - Untrapped Result:
    ```
    Error in process <0.44.0> with exit value: {badarith, [{erlang, '/',
    ```
  - Trapped Result:
    ```
    {'EXIT', <0.52.0>, {badarith, [{erlang, '/', [1,0]}]}
    ```
- `spawn_link(fun() ->erlang:error(reason) end)`
  - Untrapped Result:
    ```
    Error in process <0.47.0> with exit value: {reason, [{erlang, apply,
    ```
  - Trapped Result:
    ```
    {'EXIT', <0.74.0>, {reason, [{erlang, apply, 2}]]}}
    ```
  - Similar to 1/0.
- `spawn_link(fun() ->throw(rocks) end)`
  - Untrapped Result:
    ```
    Error in process <0.51.0> with exit value: {{nocatch, rocks}, [{erlan
    ```
  - Trapped Result:
    ```
    {'EXIT', <0.79.0>, {{nocatch, rocks}, [{erlang, apply, 2}]}}
    ```
  - Because the throw is never caught by a try ... catch, it bubbles up into an error, which in turn bubbles up into an EXIT. Without trapping exit, the process fails.

Revisiting Exceptions – the `exit/2` case

Allows a process to kill another one from a distance, safely

- `exit(self(), normal)`
  - Untrapped Result: `** exception exit: normal`
  - Trapped Result: `{'EXIT', <0.31.0>, normal}`
  - When not trapping exits, `exit(self(), normal)` acts the same as `exit(normal)`.
- `exit(spawn_link(fun() ->timer:sleep(50000) end), normal)`
  - Untrapped Result: nothing
  - Trapped Result: nothing
- `exit(spawn_link(fun() ->timer:sleep(50000) end), reason)`
  - Untrapped Result: `** exception exit: reason`
  - Trapped Result: `{'EXIT', <0.52.0>, reason}`

Revisiting Exceptions – the `exit/2` case

- `exit(spawn_link(fun() ->timer:sleep(50000) end), kill)`
  - Untrapped Result: `** exception exit: killed`
  - Trapped Result: `{'EXIT', <0.58.0>, killed}`
- `exit(self(), kill)`
  - Untrapped Result: `** exception exit: killed`
  - Trapped Result: `** exception exit: killed`
- `spawn_link(fun() ->exit(kill) end)`
  - Untrapped Result: `** exception exit: killed`
  - Trapped Result: `{'EXIT', <0.67.0>, kill}`

Monitors

- Special type of link with two differences
  - they are unidirectional,
  - can monitor via a registered name, and
  - they can be stacked.
- Allows a process to, unobtrusively, monitor another one
- Useful for when you have multiple libraries that you call and they all need to know whether a process is alive or not
  - You can stack links and remove them individually

Example

`erlang:monitor/2` sets up a monitor, where the first argument is the atom process and the second one is the pid

```
1> erlang:monitor(process, spawn(fun() -> timer:sleep(500) end)).
#Ref<0.0.0.77>
2> flush().
Shell got {'DOWN',#Ref<0.0.0.77>,process,<0.63.0>,normal}
ok
```

- When monitored process goes down, send message to monitor: `{'DOWN', MonitorReference, process, Pid, Reason}`.
- The reference allows you to demonitor the process.
  - Monitors are stackable, so it's possible to take more than one down.
  - References allow you to track each of them in a unique manner.

Example

Atomic function to spawn process while monitoring it:

```
3> {Pid, Ref} = spawn_monitor(fun() -> receive _ -> exit(boom) end
{<0.73.0>,#Ref<0.0.0.100>}
4> erlang:demonitor(Ref).
true
5> Pid ! die.
die
6> flush().
ok
```

- We demonitored the other process before it crashed hence no trace of it dying.