Erlang
and Functional Programming

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Outline

Functional programming features, its use in the message-passing model, the Erlang language, addressing distribution, scalability, fault tolerance

- Functional Programming: Principles and concurrency
- Introducing Erlang
- The Actor Model
- Going concurrent & distributed, actually

Functional Programming: Principles and Concurrency

Programming Paradigms

A paradigm is a “pattern”, a “way” of *something*, usually of *thinking*.

A programming paradigm is a way of programming:
it influences structure, performance, etc. of a program
and *our ability to reason about it and the problems it solves*.

We focus on two broad (ampi) programming paradigms:

imperative - sequences of commands drive the control flow
functional - no state mutation,
computation as *evaluation* of expressions/functions

Imperative Programming

Computation is intended as a sequence of commands that operate on *state information*: the **effect** of the **execution** of a **statement** is a **modification of the program state**.

The adoption of certain program organization rules led to more specific paradigms: “structured”, “procedural”, “object oriented”...


```
if x>0: result = 15/3
else: result = 2*3
result = result - 1
```

Information *updates* lead to the solution

I linguaggi di programmazione imperativi sono un paradigma di programmazione che si concentra sulla descrizione dettagliata di come un programma dovrebbe raggiungere uno stato specifico (es. il C)

Functional Programming

Typical trait: **lack of state** during computation.
A computation is a **sequence of expressions** resulting from the **evaluation** (and subsequent **substitution**) of sub-expressions.

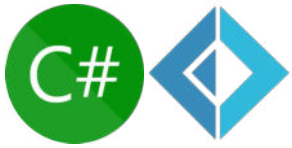
No side-effect in “ideal” computations: the only result is the computed value - even if, in practice, at least I/O is required!


```
   (15/3 if x>0 else 2*3) - 1
⇒  (5 if 7>0 else 6) - 1
⇒  5 - 1
⇒  4
```

Evaluation + substitution

Functional Programming Adoption

Ideas used in functional programming have found application also in new languages, as well as languages grounded on other paradigms. Some examples:



Concepts in Functional Programming

Some popular concepts in functional programming
are not present or are unusual in imperative languages - among them:

- Referential integrity / pure functions
- Lack of state
- Eager / lazy evaluation
- First-class functions & Higher-order functions
- Primary role of recursion
- Use of recursive data structures - lists

Nelle prossime slide esploreremo questi concetti uno per volta...

Expression & Referential Transparency

Computations are seen as *evaluation of expressions*;

an expression is said **referentially transparent** if it can be replaced by its value *with no change in the program behavior*.

Thus, such an expression has **no side effects**.

A **function** is said ***pure*** if its calls are referentially transparent, thus it has no side-effect - a potential target for *memo-ization*.

Whenever ref. transp. holds, it is possible to formally reason on the program as a *rewriting system* (objects + rules to modify them)
➜ useful for automatic verification, optimizations, parallelization, etc.

Una funzione si dice "pura" se soddisfa due condizioni principali:

- Referential Transparency: Per ogni insieme di argomenti, restituisce sempre lo stesso risultato. Ciò significa che l'output della funzione dipende solo dai suoi input e non da uno stato esterno.

- Assenza di Effetti Collaterali: Non modifica lo stato esterno del programma. Cioé NON modifica variabili globali, variaibli esterne o parametri passati per riferimento.

Lack of State

In principle, state information is not kept ➜ no *mutable* variables.

According to this approach, the classical *assignment operation* is not supported in functional programs.

A “variable” (symbolic name) is **immutable**:
once it is bound to a value, such a binding never changes.

We can create new variables, but we cannot modify existing ones.

Typically, *garbage collection* is used to get rid of what cannot be used any more in the computation

Eager vs. Lazy Evaluation

In computations, evaluation of expressions (mainly for function arguments) can be carried out, in different languages/situations, according to different strategies:

Eager evaluation - an expression is evaluated as soon as it is encountered; usually adopted in *call-by-value* and *call-by-reference* semantics of function argument passing.

Lazy evaluation - expression evaluation is postponed to the time its value will be really needed; for actual parameters in functions, this leads to the *call-by-need* argument passing semantics.

First-class & Higher-order Functions

Functions can be handled in the program *as any other value*: so, they can be ordinarily passed as arguments to functions, and can be returned by functions: they are “first-class citizens.”

Higher-order functions are those that can accept functions as arguments and can return functions as result.

As a returned function may depend on actual parameters of the function that generated it, such values have to be kept: this leads to the notion of *closures*.

Erlang uses high-order functions as a prime means of abstraction

Use of Recursion

As it is known, recursion and iteration have the same expressive power.

Without the help of state variables, recursion represents the only way to support the repetition of specific computations.

Example, ***in Python***: (factorial)

```
def it_fact(n):
    res = 1 #base case
    while n>1:
        res *= n
        n -= 1
    return res
```

⇔

```
def rc_fact(n, res=1):
    #res acts as an "accumulator"
    if n <= 1:
        return res #base case
    return rc_fact(n-1, res*n)
```

Tail recursion: for dealing with *performance problems* and *stack limits*.

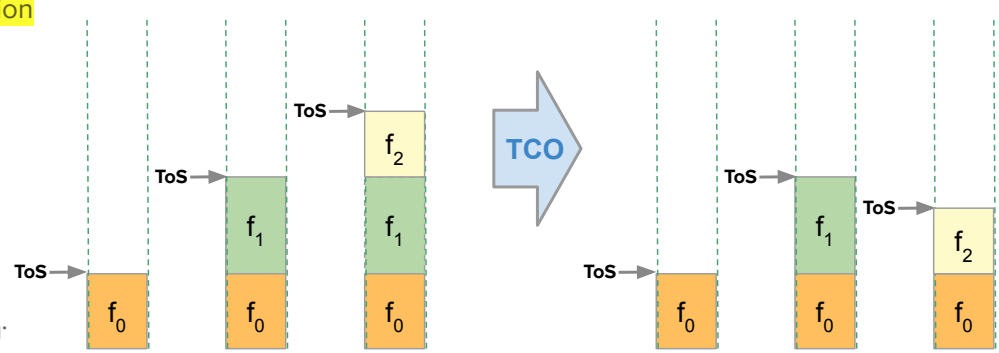
La tail recursion (ricorsione di coda) è una tecnica di programmazione in cui una funzione ricorsiva effettua la sua chiamata ricorsiva finale come ultima operazione, senza ulteriori calcoli o operazioni da eseguire dopo la chiamata ricorsiva. Questo consente all'interprete o al compilatore di ottimizzare l'uso della memoria, riutilizzando il frame dello stack corrente invece di allocarne uno nuovo per ogni chiamata ricorsiva.

Aside: Tail Call Optimization

Tail recursion can be efficiently handled adopting the so-called "tail call optimization" to avoid excessive growth of the call stack.

Trick: whenever the *last executed* operation within a function call is another function call, we can **substitute** the caller's frame with the callee's frame - no need to keep both!

Example:
f_1 is called inside f_0;
f_2 is called as last op in f_1.



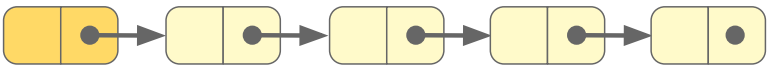
Use of Recursive Data Structures

Primary role of recursion ➜ widespread (diffuso) use of recursive data structures.

No side effects ➜ no arrays in the language: they keep state info!

Immutable data: inefficiency? ➜ low-level tricks allow data reuse

Basic data structure in most functional languages ➜ **single linked list**

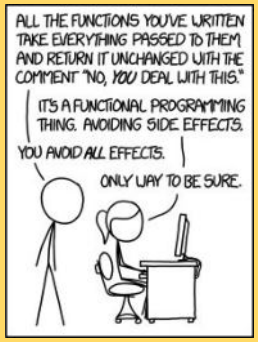


It can be managed *recursively* by telling apart:
the first *element* (head), and the rest (tail) as *a list itself*.

!!! the head is an (single) element, the tail is a list

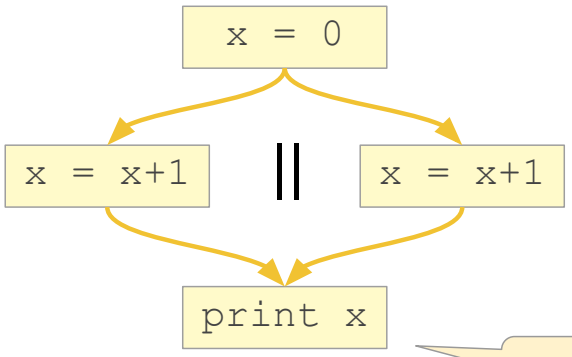
Pause for Thought

No Side-Effects: What Benefits?



Addressing Concurrency (I)

Main problem in concurrent computations: *data races*



1 ? or maybe 2 ?

The problem is related to *data mutability*.

Similar considerations apply to issues related to *visibility of updates* (memory consistency models)

Addressing Concurrency (II)

Dealing with *mutable* state requires **synchronization**, which limits resource utilization. In imperative languages, concurrent computations must be explicitly specified.

Synchronization code - locking, etc. - is often error-prone (e.g. deadlock) and hampers parallel executions

In pure functional programming:
no state, no side-effects!

No shared mutable state ➜ No problem in concurrent access

➜ Thread-safe computations (no critical races)

Simple approach to parallelization:
sub-expressions can be evaluated *in parallel*

Addressing Concurrency (III)

But, in practice:

> "The trouble is that *essentially all the interesting applications of concurrency involve the deliberate and controlled mutation of shared state* [...]. The right solution, therefore, is to provide mechanisms which allow the safe mutation of shared state."
>
> Cit. from paper "Concurrent Haskell", in POPL 1996

Side effects cannot be avoided in practical programming,
and encapsulation can be used also in concurrent settings:
A "process" can be considered as a basic program component,
and a way to make processes interact has to be provided.

What about Message Passing?

Il passaggio di messaggi è una tecnica di comunicazione tra processi.
Invece di condividere la memoria, i processi comunicano inviandosi messaggi.

Message Passing can be used also in a functional landscape,
with "processes" used as basic components.

Notably, here "processes" refer to *abstract entities*, which could be mapped onto actual computational units, possibly distributed ones.

The Erlang language, built according to the functional programming vision, adopts this vision of concurrency, with "processes" exchanging messages and reacting to receptions of messages.

In principle, concurrent programs written according to this paradigm could be (mostly transparently) run over parallel/distributed platforms.

Introducing Erlang

Erlang è un linguaggio di programmazione funzionale ideale per sviluppare sistemi concorrenti, distribuiti e fault-tolerant. Originariamente sviluppato da Ericsson per i sistemi di telecomunicazioni, è particolarmente adatto per applicazioni che richiedono alta disponibilità e gestione di molte connessioni simultanee, come i sistemi di messaggistica e chat in tempo reale. Grazie al suo modello di attori, Erlang eccelle nella gestione della concorrenza e del parallelismo, permettendo di sfruttare al meglio i sistemi multi-core.

Il linguaggio offre un robusto modello di gestione degli errori, con processi leggeri che possono essere monitorati e riavviati automaticamente, garantendo alta affidabilità per applicazioni mission-critical. Inoltre, Erlang facilita la costruzione di sistemi distribuiti e scalabili, permettendo di aggiungere facilmente nuovi nodi per gestire carichi di lavoro crescenti.

Erlang: Simple Language Suited (adatto a) to...

- Concurrent apps with fine-grained parallelism
- Network servers, Distributed systems
- Middleware machinery:
  - Distributed databases
  - Message queue servers
- Soft real-time apps; Monitoring, control, and testing tools

The need to address large-scale apps led to → elixir

We'll present only the basic features of the language

System Overview (I)

Erlang code is executed by **ERTS** (Erlang Run-Time System), via an intermediate language (so compilation is needed); bytecode is run **over a dedicated virtual machine** (BEAM).

Also an implementation over JVM exists (Erjang)

Each Erlang code file (.erl) contains a basic application block (*module*).

Modules are *compiled* (➔ .beam files), and *loaded* by BEAM

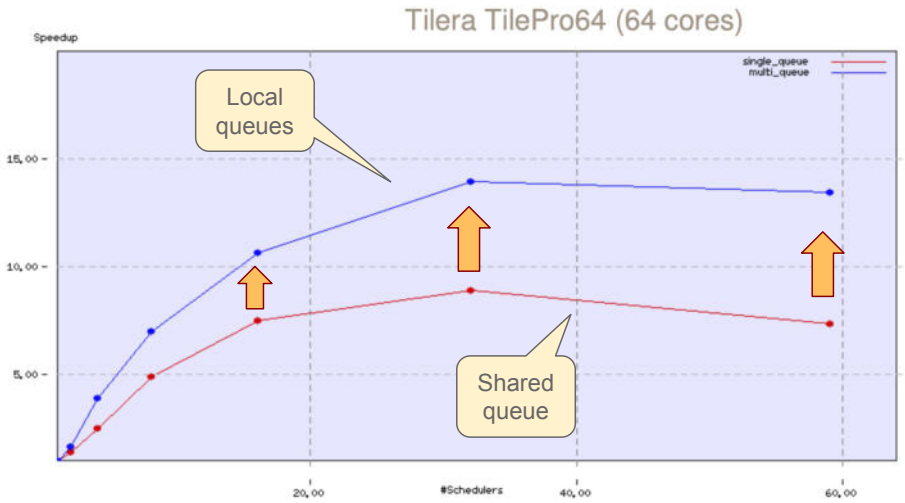
BEAM: one single OS process ➔ concurrency aspects managed **internally**. It uses its own 1+ schedulers (one per CPU core) to distribute the execution of Erlang processes over the "supporting" threads (one per core).

ATTENTION: Erlang processes ≠ OS processes/threads !!!

Interlude 😀 - BEAM Exploits SMP

The BEAM process scheduling has been improved by using one separate process queue per scheduler.

Work stealing is used to improve load balancing.



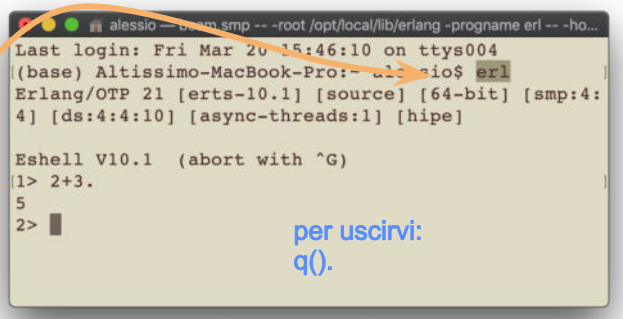
System Overview (II)

ERTS has garbage collection facilities to handle dynamic memory.

Users can interact with the system by means of the Erlang shell (`erl`).

Compilation+loading can be issued from the shell (`c(Mod)`).

Modules can be *replaced* also as the app is running!



Shell ("repl"): Expressions are evaluated, but functions cannot be defined.(nella shell)
Functions exported by modules can be accessed after module loading.

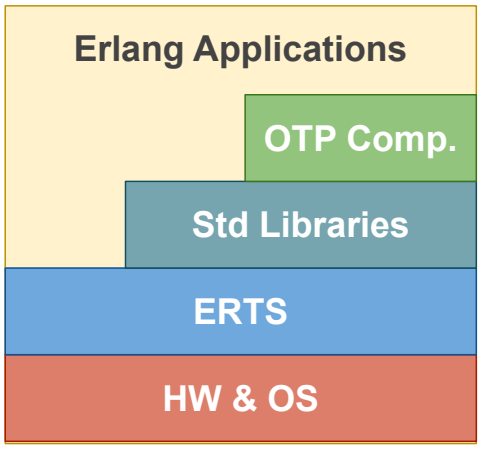
System Overview (III)

Erlang apps are independent of HW/OS, so distributed portions can naturally interact.

Processes can be spawn on different nodes, and inter-process communication is transparent w.r.t placement on nodes.

OTP (Open Telecom Platform) is a set of tools/components/libraries/patterns to boost the development of Erlang apps.

OTP acts as middleware for Erlang apps.



Predictable Prelude: Expressions etc.

An Erlang program is basically made of **expressions**.

The program is run by **evaluating** such expressions, one after the other.

The simplest expression: **term**, i.e. a piece of data of any data type, which can be written by its literal. It evaluates to ("returns") the term itself.

Expressions can be made of **sub-expressions** combined by **operators**: All subexpressions are evaluated *before* an expression itself is evaluated, unless explicitly stated otherwise.

A **variable** is an expression. If a variable is bound to a value, the evaluation of the variable is such a value.

Starting Up: Expressions, Numbers

In the shell, an expression must be terminated by "." + a whitespace char! Multiple subsequent expressions must be separated by ","

Two types of numeric literals:

- Integers
- Floats

Two Erlang-specific notations:

- `base#value` for ints in any base
- `$char` ASCII/Unicode codepoint for `char`

```
1> 1+2.
3
2> 1+2, 2+3.
5
3> 7 rem 3.
1
4> 2.3*1.1.
2.53
5> 16#A5F2.
42482
6> $A.
65
```

Variables (so to speak)...

Starting with a capital letter, or underscore (_) - mandatory!

Erlang is ***dynamically typed*** - no static type indication for variables.

A variable can be **bound to a value only once** (a.k.a. “single assignment”), so it actually “doesn’t vary.”

Variables are bound to values by means of **pattern matching** (see later).

A *pattern* is structured like a term, but includes *unbounded variables*.

The anonymous variable (only _) can be used when a variable is required but its value can be ignored.

Pivotal Concept: Pattern Matching

Idea: attempt to make a (right-side) pattern and a (left-side) term *identical*, by possibly binding (to proper values) the unbound variables in the pattern.

Trivial case: use of **match operator “ = ”**

Other cases of occurrence of pattern matching:

- Evaluation of a function call
- `case- receive- try-`expressions

If the matching fails, a run-time error occurs.

```
1> A.
** 1: variable 'A' is
unbound **
2> A = 2.
2
3> {A, B} = {0, 1}.
** exception error: no match
of right hand side value
{0,1}
4> {A, B} = {2, 1}.
{2,1}
5> B.
1
```

In Erlang, il pattern matching è utilizzato in vari contesti, come l'assegnazione di variabili, le clausole delle funzioni, le espressioni case e i messaggi tra processi.

Basic Data Types

- **Number** (int, float)
- **Atom**
- no Boolean: instead, atoms `true` and `false`
- Bit string
- Reference (unique term in ERTS)
- **Fun** (a.k.a. “lambda”)
- Port Identifier
- **Pid** (to identify a process)

Compound data types:

- **Tuple** - with fixed number of terms
- Record - syntactic sugar for tuple (with named fields), not available in the shell
- **List** - with variable number of terms
- **String** - actually, a list of ints
- Map - with a variable number of key-value associations

atoms

Atoms are used to represent **constant values**, so that an atom value is unique within the program.

They resemble (assomigliano) enumerated types in C/Java.

The value of an atom is just the atom.

Atoms start with **lowercase letters**, followed by alphanumeric chars plus _ and @.

Otherwise, they can be delimited by single quotes ‘_‘, with any char inside.

```
1> lion.
lion
2> Animal = lion.
lion
3> Animal = tiger.
** exception error: no match of
right hand side value tiger
4> {zoo, Animal1, Animal2} = {zoo,
'zebra joe', 'monkey bob'}.
{zoo,'zebra joe','monkey bob'}
5> Animal1.
'zebra joe'
6> Animal2.
 'monkey bob'
```

{ Tuples }

A *tuple* is a compound data type with a *fixed* number of terms (*elements*).

Tuples are used to group up items; similar to structs in C, without named fields.

Delimiters: curly brackets - braces; elements separated by commas.

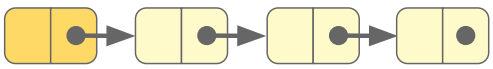
Values can be extracted from tuples by using pattern matching.

"Named" variant of tuples: *records*.

! nel leggere questi esempi, distingui le variabili (iniziale masiucola) dagli atoms (iniziale minuscola)

```
1> {alan,turing}.
{alan,turing}
2> Logician = {alonso, church,
{birthyear, 1903}}.
{alonso,church,{birthyear,1903}}
3> {Name,church,{birthyear,1903}}
= Logician.
{alonso,church,{birthyear,1903}}
4> Name.
alonso
5> {_, Lastname, _} = Logician.
{alonso,church,{birthyear,1903}}
6> Lastname.
church
```


[Lists]



A *list* is a compound data type to store an *arbitrary* number of terms (*elements*).

Delimiters: square brackets; comma-separated elements.

Empty list: `[]`

Not-empty list: head (elem) and tail (list): `[H|T]`

"cons"

Note: `[E1,...,EN]` is thus equivalent to `[E1|[...|[EN|[]]]]`

Values can be extracted from lists by using pattern matching, also in the form `[H|T]`.

```
1> L1 = [bob, 42, {4,2}].
[bob,42,{4,2}]
2> L2 = [3 | L1].
[3,bob,42,{4,2}]
3> [X|Y] = L1.
[bob,42,{4,2}]
4> X.
bob
5> Y.
[42,{4,2}]
6> [X,Z,W] = L1.
[bob,42,{4,2}]
7> W.
{4,2}
8> length(L1).
3
```

++ := per concatenare liste

! the head is an (single) element, the tail is a list

Come concatenare 2 liste:
- uso "++" se devo effetivamente concatenare due liste
- uso "[Elem|L] se Elem è un nuovo (singolo) elemento che voglio aggiungere alla lista

Built-in Functions (BIFs)

BIF := acronimo di Built-In Function (funzione incorporata).
Queste sono funzioni predefinite che fanno parte del runtime system di Erlang e sono disponibili per essere utilizzate direttamente nel codice Erlang.

```
1> date().
{2022,10,10}
2> time().
{10,11,42}
3> Tup = {lion,rhino,ostrich}.
{lion,rhino,ostrich}
4> element(2,Tup).
rhino
5> Lis = tuple_to_list(Tup).
[lion,rhino,ostrich]
6> length(Lis).
3
7> io:format("hello~n").
hello
ok
```

NB: questa è una tupla

++ := per concatenare liste

Some operations cannot be developed using the basic Erlang constructs, or at least not in a very efficient way.

For this reason, several “built-in” functions (within BEAM) have been made available; some are “auto-imported.”

They are typically used for system access, data conversion, efficient handling of compound data, I/O, etc.

List Comprehensions

Compact notation for generating elements in a list according to specified rules.

`[ Expr || Qualif1, … QualifN ]`

Idea: qualifiers specify what values to consider, and such values will be used in `Expr` to construct list elements.

Qualifiers:

- Generators - `Pattern <- ListExpr`
- Filters - expr. that evaluate to `true/false`
- Bit string generators - not discussed here

=/= (diverso)

```
1> L1 = [1,2,3,4,5].
[1,2,3,4,5]
2> [ X*X || X <- L1 ].
[1,4,9,16,25]
3> [ X || X <- L1, X rem 2 =/= 0].
[1,3,5]
4> L2 = [0,1].
[0,1]
5> [ {X,Y} || X<-L2, Y<-L2 ].
[{0,0},{0,1},{1,0},{1,1}]
6> L3 = [a,{3,1},0,{2,2},L1].
[a,{3,1},0,{2,2},[1,2,3,4,5]]
7> [ X+Y || {X,Y}<-L3 ].
[4,4]
```

↓ è l'operatore modulo (%)

↑ pensa alla virgola come un AND logico (&&)

La sintassi {X, Y} <- L3 indica che stiamo cercando di estrarre (solo) tuple {X, Y} dalla lista L3.

Per ogni tupla {X, Y} trovata, stiamo calcolando la somma X + Y e aggiungendo il risultato alla nuova lista.

In Erlang, le list comprehensions possono essere utilizzate non solo a partire da liste già esistenti, ma anche con qualsiasi struttura che supporta l'iterazione, come tuple, stringhe e generatori che producono liste.
Tuttavia, è comunque necessario iterare su una struttura "di partenza", sia che questa venga creata manualmente sia che venga generata da una funzione.

What about Strings?

No special data type for strings;
A string can be represented as *list of integers*, each element corresponding to a Unicode codepoint.

(Strings can be represented also as *binaries*, but this is not discussed here.)

Special syntax for strings handling: "double quote" delimiters are used.

```
1> S1 = "Hello".
"Hello"
2> S2 = S1 ++ " World!". %str-list concat
"Hello World!"
3> S2 ++ [10].    %10: newline
"Hello World!\n"
4> S2 ++ [-3].
[72,101,108,108,111,32,87,111,114,108,100,
33,-3]
5> S3 = "\x{2200} e \x{2208} A \x{2a01}
B".
[8704,32,101,32,8712,32,65,32,10753,32,66]
6> io:format("~ts~n",[S3]).
∀ e ∈ A ⨁ B
ok
```

- ~t è un direttore di formato che specifica il tipo di argomento successivo, che in questo caso è una stringa (s sta per stringa).
- ~n è un carattere di nuova riga che aggiunge un ritorno a capo dopo la stringa.

Modules

A module, contained in a .erl file, is the **basic unit of code**.

It contains *metadata* (for the module itself), plus *functions*.

Most important metadata:

- module name (same as file)
- what functions can be called from outside the module (i.e. what functions are *exported* - *"APIs"*).

Modules **have to be compiled**.

```
-module(myfirstmod).
%% API
-export([sayhello/0,addinc/2]).
          functions that can be called from
              outside the module

add(X,Y) ->
  X+Y.

%% not exported!
addinc(X) ->
  X+1.
addinc(X,Y) ->
  add(addinc(X), Y).

sayhello() ->
   io:format("Hello World!~n").
```

myfirstmod.erl

Compiling & Using Modules

ls() := restituisce una lista di moduli che sono stati compilati e caricati nella sessione corrente

```
1> ls().
myfirstmod.erl
ok
2> compile:file("myfirstmod.erl").
{ok,myfirstmod}
3> c(myfirstmod).
{ok,myfirstmod}
4> ls().
myfirstmod.beam     myfirstmod.erl
ok
```

From the command line ➜

```
erlc [flags] myfirstmod.erl
```

From inside a module or the repl ➜

```
compile:file("myfirstmod.erl")
```

From the repl ➜ `c(myfirstmod)`

Functions in a module
can be used *externally* with the syntax: `mymodule:myfunction(...)`

Importing specific functions: `-import(mymodule, [myfunct/1 …]`

Functions - Basics

"A function clause consists of a clause head and a clause body, separated by ->"
In Erlang, una "clause" è una clausola o una regola all'interno di una funzione.
Una funzione Erlang può avere più clausole, ciascuna delle quali rappresenta una possibile corrispondenza per gli argomenti passati a quella funzione.

Function declaration (only in a module):

sequence of ***function clauses***, ~~separated by ",~~ ~~and terminated by ";~~
separated by ";" and terminated by "."

J-th function clause:

```
Name(PattJ1,...,PattJN) [when GuardSeqJ] -> BodyJ
```

Function ***name***: atom Function ***arguments***: patterns

Within a module, a function is identified by the couple name/arity.

Clause ***body***: sequence of expressions separated by ",";
a clause evaluates to the value of the last expression in its body.

Functions - Example Def/Call

shapes.erl

```
-module(shapes).
-export([area/1]).

area({square,Side}) ->
  Side*Side;
area({circle,Radius}) ->
  Radius*Radius*3.1415;
area({triangle,B,H}) ->
  B*H/2.
```

la funz area ha 3 clauses

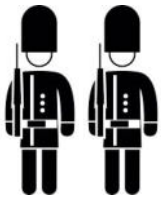
NB: il primo parametro atteso è un atom, il secondo una variabile

...

shell

":" specifies the *module* containing the *exported function* to use

```
1> c(shapes).  %compile module
{ok,shapes}
2> shapes:area({square,3.2}).
10.240000000000002
3> shapes:area({circle,3.2}).
32.168960000000006
4> shapes:area({triangle,3.2, 2}).
3.2
5> shapes:area({rectangle,3.2, 2}).
** exception error: no function
   clause matching
shapes:area({rectangle,3.2,2}) (...)
```

Guards

Generally speaking, a guard is a boolean expression that affects the way a program is executed.

In Erlang, guards can be used *to increase the power of pattern matching*, in particular in heads of function clauses.

Formally: a *guard* is a sequence of *guard expressions*; the set of guard expressions is a subset of valid Erlang expressions (see docs).

Attention: *No user-defined function is allowed in guards* (to be sure to avoid side-effects.)

```
sign(X) when is_number(X), X>0 ->
  1;
sign(X) when is_number(X), X==0 ->
  0;
sign(X) when is_number(X) ->
  -1;
sign(_) -> argerror.
```


WE NEED TO BE GOOD AT EXPLOITING ERLANG'S TWO MAIN ELEMENTS:
- **pattern matching**
- **guards**

solo se queste due non bastanno allora poi mi metto ad usare i costrutti come il case e l'if

“Case” Expressions...

Sometimes, instead of relying on pattern matching on many clauses, it may be convenient using *case expressions*.

```
case Expr of
   P1 [when C1] -> E1;
   ⋮
   Pn [when Cn] -> En
end
```

[when C_i] è una guardia opzionale che può essere aggiunta per applicare condizioni aggiuntive al pattern matching

Semantics: expression `Expr` is evaluated to T, and patterns `P1` ... `Pn` are sequentially matched against T. As soon as a match occurs and the (optional) relative guard is true, the corresponding `E` is evaluated, and the return value of `E` becomes the return value of the case expression.

!!! - No matching pattern with a true guard sequence ➔
➔ `case_clause` run-time error (to avoid this, catch-all clauses are often used.)

il costrutto *case* viene utilizzato per fare il pattern matching su un'espressione e selezionare il ramo di esecuzione corrispondente. Tuttavia, se nessun pattern coincide e non è presente una clausola generica di "cattura tutto", il sistema genererà un errore a tempo di esecuzione chiamato "case_clause run-time error".

Per evitare questo tipo di errore, è spesso buona pratica includere una clausola di "cattura tutto" alla fine del blocco case. Una clausola di cattura tutto ha la forma _ -> ..., dove _ è un underscore che funziona come un jolly, corrispondendo a qualsiasi valore.

esempi:

```
-module(my_module).
-export([my_function/1]).

my_function(X) ->
    case X of
        0 -> "Zero";
        1 -> "One";
        2 -> "Two";
        _ -> "Other"
    end.
```

qui Expr è la var stessa, che poi confronto con i vari valori che può assumere

```
maxElem([]) -> undefined;
maxElem([X]) -> X;
maxElem([H | T]) ->
    Max = maxElem(T),
    case H > Max of
        true -> H;
        false -> Max
    end.
```

qui Expr è una condizione, che poi verifico nel case

... and “If” Expressions

Another conditional expression is provided: “if”
- to be used in case the resulting term must depend only on guards.

```
if
   Guard1 -> E1;
   ⋮
   Guardn -> En
end
```

Semantics: Guards `Guard1` ... `Guardn` are sequentially checked; as soon as a guard succeeds, the value of the whole if expression is the return value of the relative E expression sequence.
No guard succeeds ➔ `if_clause` run-time error.
Note: “if” clauses are usually called “branches.”

!!! - “**`if`**” in Erlang is an expression; to avoid a possible exception, often a final `true` guard is inserted.

Esattamente come prima, qui userò la clausola "true" per scegliere un comportamento di default (nel caso le altre guard non dovessero bastare)

```
check_value(X) ->
    if
        X > 0 ->
            io:format("~p is greater than 0~n", [X]);
        X == 0 ->
            io:format("~p is equal to 0~n", [X]);
        true ->
            io:format("~p is less than 0~n", [X])
    end.
```

CURIOSITÀ MIE:

FUNCTION MAP

In Erlang, the lists:map/2 function is used to apply a given function to each element of a list and return a new list containing the results. The function takes two arguments:
- Fun: the function to apply to each element of the list
- List: the list of values to apply the function to

IO:FORMAT VS IO:WRITE

In Erlang, io:fwrite/2 and io:format/2 are both functions used for formatted output to the console or a file. The main difference between the two functions is that io:fwrite/2 returns the number of characters written to the output, while io:format/2 returns the atom ok.

#IO:FORMAT PARAMETERS

format(Format, Arguments)

! arguments must be passed in a list (even if this means often using lists with only one element).

You can find the complete list at this link:
https://erlang.org/documentation/doc-5.3/lib/stdlib-1.12/doc/html/io.html

~s : per stringhe standard
~ts : per stringhe Unicode (liste di caratteri Unicode o binari)
~p : per stampare un termine (term) in modo leggibile per l'utente
~n (opp. \n) : per andare a capo
~w : simile a ~p, ma ~w non limita la lunghezza dell'output, mentre ~p potrebbe fare delle limitazioni per rendere l'output più leggibile

Looping? What?

Repeating calculations in functional languages is usually performed **by means of recursion**: *no basic looping construct is provided!*

Recursion is particularly suited to work on lists.

Iteration: seen as a particular type of recursion

This recursive function mimics the “for” behavior:
It implements LINEAR ITERATIVE execution

The use of **tail recursion** improves the execution performance, and makes extensive looping actually feasible.

```
-module(helloworld).
-export([forhw/1,start/0]).

forhw(0) -> done;
forhw(N) ->
   io:fwrite("Hello~n"),
   forhw(N-1).

start() ->
   forhw(5).
```

!! questa forhw, non è una keyword. Infatti qui non esiste un costrutto for, siamo noi che lo "costruiamo" sfruttando la ricorsione.

Example: Looping over a List

```
-module(showlist).
-export([scanl/1,start/0]).

scanl(L) -> scanl(L,0).

scanl([], Index) -> Index;
scanl([H|T], Index) ->
   io:fwrite("~w: ~w~n",[Index,H]),
   scanl(T,Index+1).

start() ->
   X = [10,2,7,4],
   scanl(X).
```

The “Head-Tail” structure of a list helps us work *recursively* on the data structure.

Just in case, additional “state variables” can be added in *helper* functions.

Usually, helper functions are not exported, to promote module-level encapsulation.

scanl/**2** is a helper function,
with the additional argument
used to indicate the position in the list

Having Fun with Funs

Le *fun* non sono funzioni "normali" (come quelle viste prima) ma sono funzioni lambda.
Le "fun" offrono maggiore flessibilità e possono essere utili in situazioni in cui si desidera passare funzioni come argomenti o restituirle da altre funzioni.

lavorano con funzioni come parametri o valori restituiti

Higher-order functions work with functions as parameters/returned values.

A data type for functions is needed: in Erlang, it is called "**fun**".

General syntax of an *anonymous* function ➜

```
fun(Arg1, … ArgN) ->
  FunBody
end
```

Like "lambda" in Python and other languages

Multi-clause `funs` can be defined as well, e.g.:

```
1> TempConv = fun({cel,C}) -> {far, 32 + C*9/5};
1>              ({far,F}) -> {cel, (F-32)*5/9}
1>            end.
#Fun<erl_eval.6.128620087>
2> TempConv({cel,22}).
{far,71.6}
3> TempConv({far,0}).
 {cel,-17.77777777777778}
```

qui "far" e "cel" sono atom (e non variabili), lo si nota dalla iniziale minuscola.

Non farti fregare dalle "{}" di questo esempio, qui ci sono perché la Fun di esempio ha come I/O delle tuple.

↑ Fun usata nella shell

Syntax to refer to values of NAMED functions

```
fun Module:Function/Arity
```


sono molto simili alle funzione lamba in Python:
In Python, una "funzione lambda" è una funzione anonima, cioè una funzione definita senza un nome.

In Erlang una "variabile" può contenere una funzione. Le funzioni in Erlang possono essere assegnate a variabili, passate come argomenti ad altre funzioni e restituite da funzioni. Le funzioni anonime, chiamate "fun", sono particolarmente utili per questo scopo.

```
erlang
% Definire una funzione anonima e assegnarla a una variabile
Fun = fun(X) -> X * X end.

% Utilizzare la variabile per chiamare la funzione
Result = Fun(5). % Result sarà 25

% Passare la funzione come argomento a un'altra funzione
lists:map(Fun, [1, 2, 3, 4]). % Risultato sarà [1, 4, 9, 16]
```

Funs for Building Control Abstractions

A control abstraction has to refer to an operation to be executed according to some given rules.

The way to apply the rules can be specified *by a function*, and the generic operation *by a Fun as parameter*. E.g.:

questo codice stampa: [2, 4, 6, 8, 10]

```
-module(mycontrols).
-export([myfor/3, test/0]).

myfor(Max,Max,Oper) -> [Oper(Max)];
myfor(I,Max,Oper) ->
    [Oper(I) | myfor(I+1, Max, Oper)].

test() -> myfor(1,5,fun(X) -> 2*X end).
```

↑ Fun passata come argomento nel codice

```
1> mycontrols:test().
[2,4,6,8,10]
2> mycontrols:myfor(1,3,fun(Z)->Z*Z/2 end).
[0.5,2.0,4.5]
3>
```

↑ Fun passata come argomento dalla shell

Example: Filtering a List

In Erlang, a predicate typically refers to a function or expression that evaluates to a boolean value (either true or false).

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

is_even(X)-> case (X rem 2) of
    0 -> true;
    _ -> false
  end.

test() -> myfilter(fun is_even/1,
[1,2,3,4,5]).
```

NB: posso passare una funzione come argomento anche se questa non è una Fun

In this case, a *predicate* is used as the first argument for "myfilter/2".

Inside "test/0," function "is_even/1" (actually, a predicate) is passed as the actual parameter for "myfilter."

The *anonymous variable* "_" is used to match anything, when we don't care about the match

The standard module **lists** contains several functions to operate on lists (and *lists:filter* as well)

Example: Returning a Function

Functions can be returned by functions as well.

In the example, **fcomp** returns the composition of two functions (with arity 1) passed as input.

```
-module(mymod).
...
fcomp(F,G) ->
  fun(X) -> F(G(X)) end.
...
```

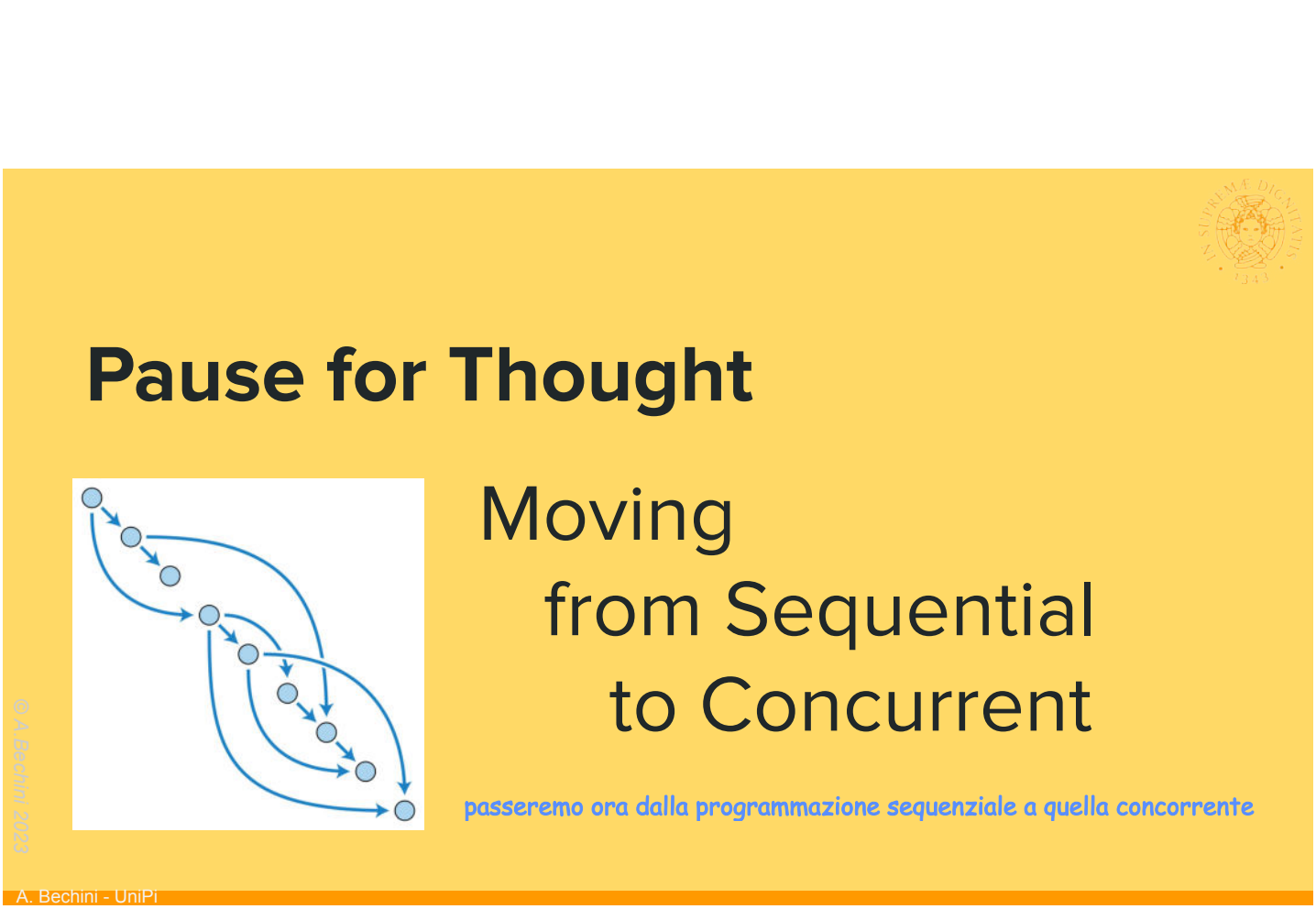
↑ restituire una Fun

shell

Qui passo 2 Fun come parametri. fcomp() poi mi restituirà una Fun come output, che io "salvo" in "Myf1"

Function values as params

```
1> Myf1 = mymod:fcomp(fun(X)->X*X end,
fun(X)->X+1 end).
#Fun<mymod.1.70048917>
2> Myf2 = mymod:fcomp(fun(X)->X+1 end,
fun(X)->X*X end).
#Fun<mymod.1.70048917>
3> io:format("~p\n",[Myf1(5)]).
36
ok
4> io:format("~p\n",[Myf2(5)]).
26
ok
```



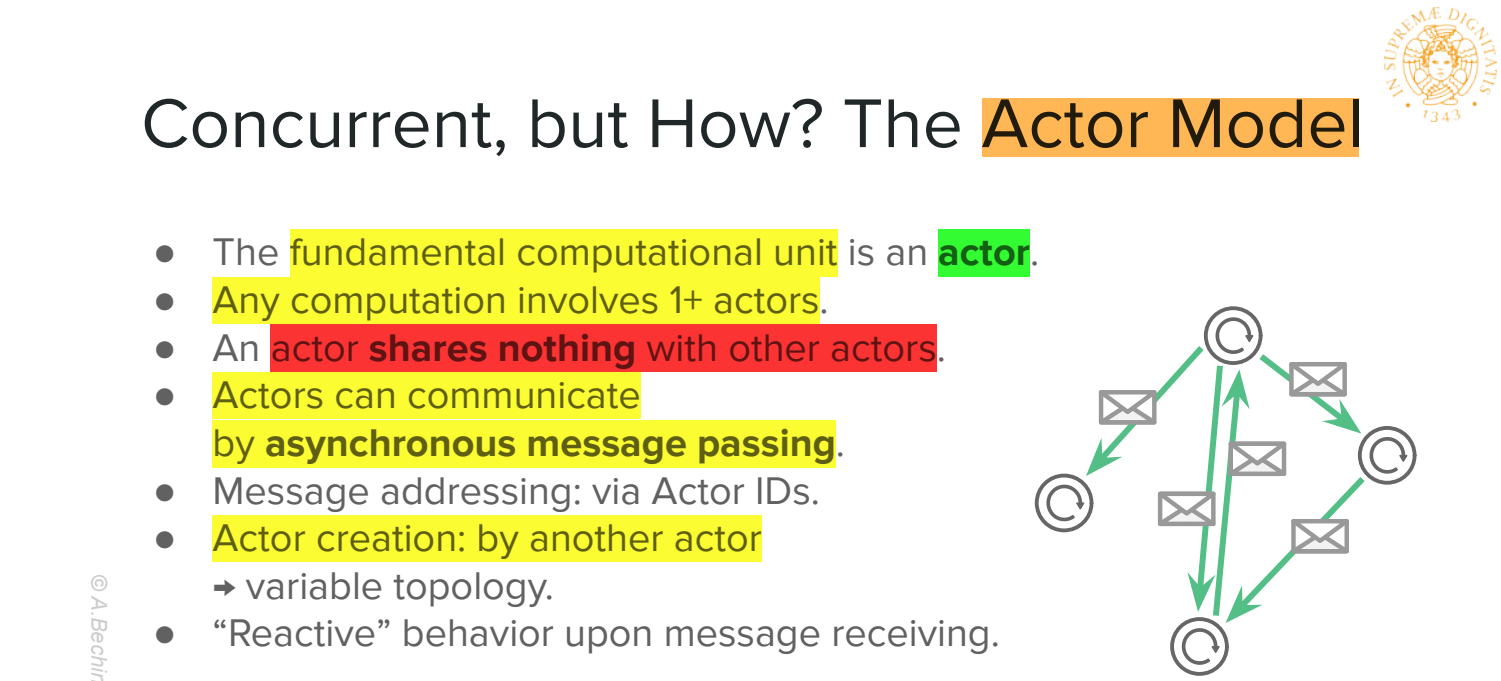
Pause for Thought

Moving from Sequential to Concurrent

passeremo ora dalla programmazione sequenziale a quella concorrente

Erlang Concurrency & Distribution

Concurrent, but How? The Actor Model



- The fundamental computational unit is an **actor**.
- Any computation involves 1+ actors.
- An actor **shares nothing** with other actors.
- Actors can communicate by **asynchronous message passing**.
- Message addressing: via Actor IDs.
- Actor creation: by another actor ➜ variable topology.
- "Reactive" behavior upon message receiving.

Every actor can react upon receiving a message in a way defined by itself.

Re-acting Actors

Actor's *behavior*: what an actor does in processing a received message.

Possibilities: upon receiving a message, an actor can concurrently:

- send a finite number of messages to other actors;
- create a finite number of new actors;
- designate the behavior to be used for the next message it receives.

In practice, we have to better specify how the overall receive operation has to be structured.

BIF := acronimo di Built-In Function (funzione incorporata).
Queste sono funzioni predefinite che fanno parte del runtime system di Erlang e sono disponibili per essere utilizzate direttamente nel codice Erlang.

Erlang Ingredients for Concurrency

Erlang follows a version of the actor model; actors are named "processes".
! Don't confuse Erlang's processes with OS processes.

In the language, only three *concurrent* constructs are required, namely for:

1. Creating processes → **`spawn(...)`** BIF, with arguments that identify a function (+ actual argument values) that corresponds to the process body; **`spawn(...)`** returns the process **PID**, used as its address;
2. Sending messages → **`!`** "bang" operator. e.g. **`self()!emptymessage.`**
3. Receiving messages → **`receive ... end`**, which applies pattern matching (as for **`case ... end`**) to select the message to be received/processed.

`self()` returns the PID of the current process

PID
In Erlang, un PID (Process Identifier) è formato da tre parti <Node.ID.Serial>.
Queste parti permettono di distinguere tra vari processi non solo all'interno di un singolo nodo ma anche tra diversi nodi in un sistema distribuito.

- Node: nodo in cui il processo è in esecuzione. (Nei sistemi distribuiti, i nodi sono identificati da nomi univoci, come node@hostname.)
- ID: identificatore numerico unico del processo all'interno del nodo.
- Serial: campo utilizzato per distinguere tra processi che potrebbero aver avuto lo stesso ID in passato.

In termini di rappresentazione, un PID viene visualizzato come tre parti perché la rappresentazione visibile ("<0.123.0>") non include esplicitamente il campo di Creation. Tuttavia, internamente Erlang mantiene questa informazione.
- Creation: numero che viene incrementato ogni volta che il nodo è riavviato. Serve a distinguere tra processi creati prima e dopo il riavvio del nodo.

Spawning of Processes

- Se voglio lavorare con le Fun (funzioni anonime) uso spawn/1
- Se voglio lavorare con le funzioni "normali", allora uso spawn/3

```
-module(test).
-export([body/2]).
body(X,Y) ->
   io:format("~w+~w=~w~n",[X,Y,X+Y]).
```

```
1> F=fun(X,Y)->io:format("~w+~w=~w~n",
[X,Y,X+Y]) end.
#Fun<erl_eval.12.128620087>
2> [spawn(fun()->F(A,A+1)end)||A<-[3,4]].
3+4=7
4+5=9
[<0.134.0>,<0.135.0>]
3> spawn(test,body,[1,2]).
1+2=3
<0.137.0>
```

Per ogni elemento A nella lista [3, 4], viene creato un nuovo processo con spawn che esegue la Fun.

Qui la list comprehension restituisce una lista di PIDs dei processi creati

questo esempio è un po' strano da leggere perché usa una list comprehension. Vengono creati 2 processi.

A process body can be specified by

- *Fun*: **`spawn/1`**. Arg: a `fun()`.
- *Function* ("MFA"): **`spawn/3`**. Args: Module, Function (atoms), and the list of function Args. Used for dynamic code loading.

EXPORTED function

Returned Pid: what node (0: local), and a process counter - in two parts.

Process end: at its body function ends.

Each process has its own "dictionary" (BIFs: `get`, `put`, `get_keys`, `erase`).

Possibly, "write once"

La funz spawn restituisce il Pid del processo spawnato

The Pid is a special data structure made of 3 parts.
First part indicate on what node the process reside, the other 2 parts are dedicated to the process

Quando avvii due shell Erlang separate sulla stessa macchina, ognuna di esse rappresenta un nodo Erlang indipendente (ovviamente si troveranno sulla stessa macchina).

COME FARE PER LAVORARE CON DUE PROCESSI NELLO STESSO NODO

- Opzione 1: Usare una singola shell

```
%% Creare un processo
Pid1 = spawn(fun() -> receive Msg -> io:format("Process 1 received: ~p~n", [Msg]) end end).

%% Creare un altro processo
Pid2 = spawn(fun() -> receive Msg -> io:format("Process 2 received: ~p~n", [Msg]) end end).

%% Inviare un messaggio a Pid1
Pid1 ! hello.

%% Inviare un messaggio a Pid2
Pid2 ! world.
```

- Opzione 2: Usare più shell connesse allo stesso nodo

```
%% Avvio il nodo Erlang principale:
erl -sname mynode

%% In un'altra shell del terminale, connettiti allo stesso nodo:
% L'opzione -remsh permette di collegare una shell remota a un nodo Erlang già esistente.
In questo modo, puoi avere più shell connesse allo stesso nodo
erl -sname mynode_remsh -remsh mynode@hostname
```

Messages, and Sending thereof

degli stessi

In Erlang, communication is performed by asynchronous signalling (most common signals: ***messages***).

A message has a *recipient* (by Pid) and a *content*.

destinatario

contenuto

Content: *any* Erlang term.

What *ordering guarantee*?
Only point-to-point FIFO, for all signals.

(il mittente può inviare un msg e immediatamente proseguire con altre operazioni, senza aspettare che il msg sia effettivamente ricevuto o elaborato dal destinatario)

Non-blocking send: The expression

syntax for send: `Pid ! Msg`

recipient

content

evaluates Msg to term T, *sends* it to process Pid, and *returns* T.

Send is right-associative: e.g.

e grazie al fatto che ritorna T possiamo:

```
Pid2 ! Pid1 ! Pid0 ! examplemsg
```

atom `examplemsg` is sent to `Pid0`, `Pid1`, `Pid2`

questo è un esempio di come possiamo inviare lo stesso messaggio a più processi

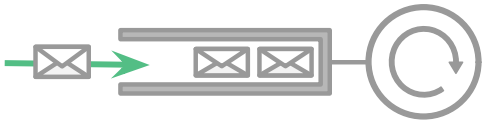
...and Other Signals...

- Exit
- Link/Unlink
- Monitor/Demonitor

Signals to a terminated receiver: possibly trigger other signals (typically, are silently ignored).

Receive Machinery

Every process has a mailbox (queue) to hold incoming messages.



A mailbox can be inspected by the BIF `process_info(Pid, messages)`

To extract messages from the mailbox: *receive expression*

```
receive
   P1 [when C1] -> E1;
   ⋮
   Pn [when Cn] -> En
end
```

[when C_] è una guardia opzionale che può essere aggiunta per applicare condizioni aggiuntive al pattern matching

By sequentially going through the clauses, it is selected the oldest term T (message) in the mailbox that:

- matches a pattern Pk , and
- satisfies condition Ck.

...and the message is removed from the mailbox!

If such a term T exists, Ek (evaluated to Tk) is returned;

otherwise, evaluation **blocks** until a suitable message arrives.

Se un messaggio non rispetta alcun pattern di ricezione specificato nell'istruzione receive, questo rimarrà nella mailbox del processo e NON viene rimosso.
Vedremo tra qualche slide come ovviare a questo problema...

Example: Ping Pong (code)

```
-module(pp).
-export([start/0, alice/2, bob/0]).

alice(0, Other_PID) ->
  Other_PID ! finished, %terminates bob
  io:format("Alice finished~n");
alice(N, Other_PID) ->
  Other_PID ! {ping_msg, self()},
  receive
    pong_msg ->
      io:format("Alice received pong~n")
  end,
  alice(N - 1, Other_PID). %last call opt.

...
```

```
...

bob() ->
  receive
    finished ->
      io:format("  Bob finished~n");
    {ping_msg, Other_PID} -> %pttrn with Pid
      io:format("  Bob received ping~n"),
      Other_PID ! pong_msg,
      bob()    %last call optimization!
  end.

start() ->
  Bob_PID = spawn(?MODULE, bob, []),
  spawn(?MODULE, alice, [2, Bob_PID]).
```

MACRO: current module

Con questo codice, solo il PID del processo 'alice' viene restituito: In Erlang, una funzione restituisce solo l'ultimo valore valutato. Per restituire entrambi i PID, è necessario mettere esplicitamente i PID in una struttura dati come una tupla o una lista.

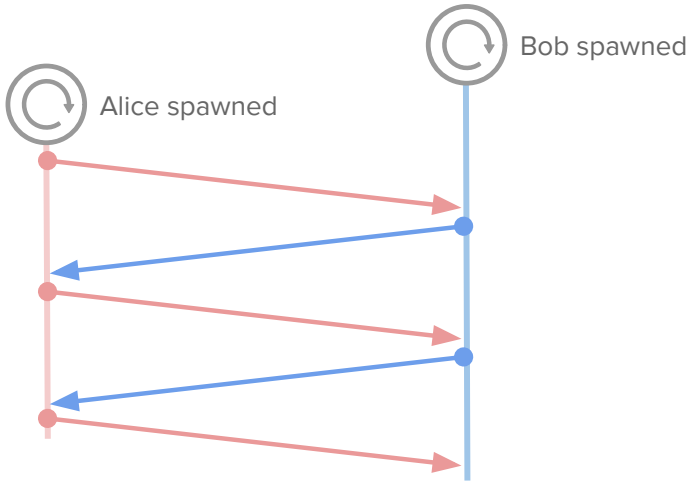

```
-module(test).
-export([start/0, alice/2, bob/0]).

alice(0, Other_PID) ->
  Other_PID ! finished,
  io:format("Alice finished~n");
alice(N, Other_PID) ->
  Other_PID ! {ping_msg, self()},
  receive
    pong_msg ->
      io:format("A - Alice received pong~n")
  end,
  alice (N-1, Other_PID).

bob() ->
  receive
    finished ->
      io:format("B - Bob finished~n");
    {ping_msg, Other_PID} ->
      io:format("B - Bob received ping~n"),
      Other_PID ! pong_msg,
      bob()
  end.

start() ->
  Bob_PID = spawn(?MODULE, bob, []),
  Alice_PID = spawn(?MODULE, alice, [2, Bob_PID]),
  {Bob_PID, Alice_PID}. % Restituisce una tupla con entrambi i PID.
```

In questo esempio in totale avremo 3 processi: quello di partenza ed i due creati con la spawn/3.
Ovviamente i tre avranno PID diversi.

Example: Ping Pong (run)

```
1> pp:start().
  Bob received ping
Alice received pong
  Bob received ping
Alice received pong
Alice finished
  Bob finished
<0.79.0>
2>
```

...what Pid is this???



è il Pid di Alice, questo perché nel codice è l'ultima azione svolta prima del '.'

Basic Client-Server (I)

A *server process* is intended to perform (repeatedly) the following operations:

1. Wait for a request;
2. As it comes, compute the answer, and
3. Reply back with the answer.

The basic code can be arranged as indicated aside:

The used msg structuring: just for the sake of clarity → { PID, { *<payload>* } }

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

start() -> spawn(?MODULE, loop, []).

loop() ->
  receive
    {From, {plus, X, Y} } ->
      From ! {self(), X+Y},
      loop();
    {From, {minus, X, Y} } ->
      From ! {self(), X-Y},
      loop()
  end.
```

Msg body with {Sender, opID, params}

Different "services"

Reply back, with sender ID as well

For dynamic code loading: `server:loop()`

Basic Client-Server (II)

il client dove conoscere:
- il PID del server
- l'operazione da eseguire
- gli operandi da fornire

```
-module(client).
-export([start/4, body/4]).

start(ServID, OpID, X, Y) ->
  spawn(?MODULE, body, [ServID,opID,X,Y]).

body(ServID, OpID, X, Y) ->
  ServID ! {self(), {OpID, X, Y}},
  receive
    {ServID, Result} ->
      io:format("Result: ~p~n", [Result])
  end.
```

Only replies from the server are received!

Basic operations for a client:

1. Send out a request to a server;
2. Receive back the reply.

← Basic code indicated aside.

shell

```
1> S = server:start().
<0.77.0>
2> C = client:start(S, plus, 2, 2).
<0.79.0>
Result: 4
3> exit(S, kill).
true
```

! notiamo che quando runniamo il server, non si "blocca" la shell. Il server potrà comunque stampare sulla shell.

Requested service: sum

Command to kill a running process

NB: Anche se già conosco il PID del server, me lo faccio comunque inviare nei messaggi così da poter controllare (tramite il pattern matching) se un incoming msg è stato inviato dal server o dal qualcun altro.

Basic Client-Server (III)

```
-module(client).
-export([start/4, body/4]).

start(ServID, OpID, X, Y) ->
  spawn(?MODULE, body, [ServID,opID,X,Y]).

rpc(ServID, Msg) ->
  ServID ! {self(), Msg},
  receive
    {ServID, Result} -> Result
  end.

body(ServID, OpID, X, Y) ->
  Result = rpc(ServID, {OpID, X, Y} ),
  io:format("Result: ~p~n", [Result]).
```

Often, communication details **can be abstracted away** within functions, e.g. on client side:

(praticamente l'invio e la ricezione dei messaggi con il server li vado a mettere in una funzione apposita)

shell

```
1> S = server:start().
<0.77.0>
2> C = client:start(S, plus, 2, 2).
<0.79.0>
Result: 4
3> exit(S, kill).
true
```

Same as before

RPC := Remote Procedure Call, cioè invio una richiesta (ad un server) ed aspetto la risposta

Basic Client-Server (IV)

At server side, we should deal also with incoming messages with unexpected format which, otherwise, would clutter (ingombrerebbero) the server mailbox!

```
...
start() -> spawn(?MODULE, loop, []).

loop() ->
  receive
    {From, {plus, X, Y} } ->
      From ! {self(), X+Y},
      loop();
    ...
    stop ->
      ok;
    _Unexpected ->
      loop()
  end.
```

per "spegnere" il server basta non richiamare la funzione loop()

! _Unexpected è un nome di variabile come un altro. Quello che otteniamo è che qualsiasi messaggio che non è dei tipi precedenti verrà "catturato" da questa var, in quanto ogni messaggio è comunque una var.

Trick to terminate a running process (a.k.a. "poison pill")

"Catch-all" clause: Just discard messages with wrong format

(vado a "sprecare" il msg in arrivo, senza di fatto utilizzarlo)

Receive Glitches & Timeouts

In some unexpected situations, a blocking receive operation may hamper (ostacolare) the program progression.
This may happen, e.g., in presence of server crashes. (lì abbiamo rpc() in attesa di ricevere un msg, che non sta arrivando a causa del crash del server)

```
1> S = server:start().
<0.77.0>
2> exit(S, kill).
true
3> client:rpc(S,{plus, 1,2}).
```

SHELL BLOCKED!

```
receive
  P1 when C1 -> E1;
  ⋮
  Pn when Cn -> En
after Delay -> ExprDel
end
```

Possible solution:
a TIMED version of receive;
in case no message is received by a given timeout (in millisecs), a dedicated expression is evaluated instead.

Example with Timeout = 0

Also a timeout of 0 milliseconds may be useful.

Example:
a function to flush all the messages in the mailbox.

Recursively, it tries to match (and "consume") any message; if no message is present, the 0 timeout terminates the recursive calls.

```
flush_messages() ->
  receive
    _Any ->
      flush_messages()
  after 0 ->
    true
  end.
```

Questa funzione viene chiamata quando si vuole flushare la mailbox.
Se non mettessi la "after 0", in caso di mailbox vuota, il programma si bloccherebbe sulla receive, noi invece vogliamo andare avanti...

The value `infinity` can be used for a timeout as well;
it makes sense when the delay value has to be calculated/decided, and one of the possible options is having no timeout al all.

Semantics of Receive, Detailed (I)

1. Entering a receive statement, start a timer (only if "after" is present).
2. Take the first message in the mailbox, and try to match it against the first pattern, then the second pattern, and so on. As soon as a match occurs, the message is removed from the mailbox, and the relative expressions are evaluated.
3. In case of no match for the first message in the mailbox, it is removed from the mailbox and put into a ***"save queue."*** Then, the second message in the mailbox is tried. This procedure is repeated until:
   a. a matching message is found, or
   b. all the messages have been examined.

Semantics of Receive, Detailed (II)

4. If none of the messages matches, then **the process is suspended**, and will be rescheduled for execution at the time another message is put in the mailbox. When a new message arrives, the messages in the save queue are not rematched; only the new message is matched.
5. As a message match occurs, then all messages previously stored in the save queue are moved back to the mailbox*, keeping their order of arrival. The timer (if any) is cleared.
6. If the timer elapses when we are waiting for a message, then evaluate the relative expressions; move all the saved messages back to the mailbox, keeping their order of arrival.

because of the blocking nature of the receive operation

* questo perché l'aver processato un messaggio potrebbe aver reso vera qualche condizione che prima era falsa

Publishing of Processes

we can assign a symbolic name to processes

! Quando registri un processo con un nome utilizzando la register(), il processo può poi essere recuperato solo all'interno dello stesso nodo.

In Erlang, a Pid can be *published* (in a system repository), so to make any process in the system able to communicate with the relative process.

Such a process is called a *registered process*.

Only special-purpose processes should be registered!

Registration operations: by four BIFs

- **`register`**`(AnAtom, Pid)` - Register the process `Pid` with the name `AnAtom`.
- **`unregister`**`(AnAtom)` - Remove any registrations associated with `AnAtom`.
- **`whereis`**`(AnAtom) -> Pid | undefined`-
  Lookup for the `Pid` of the `AnAtom` process
- **`registered`**`() -> [AnAtom::atom()]` Return a list of all registered processes.

A registered process is automatically unregistered as it dies

From the shell: **`regs()`** for a nice view

Quando posso usare la atom registrata "da sola" senza usare la whereis() ?
Per evitare errori stupidi, questa cosa falla solo come primo operando del bang (!), per tutti gli altri utilizzi, salva la whereis() in una variabile e poi usa la var.

Example: Registered Server

We can show how to deal with registered processes using the code developed before for basic server & client:

"send" can use the server name (an atom) as destination

Reply message (as flushed out of the mailbox)

In rpc, the PID is required for the selective receive

Server registration

```
1> S = server:start().
<0.77.0>
2> register(calc_server, S).
true
3> calc_server ! { self(),
{plus,1,1} }.
{<0.75.0>,{plus,1,1}}
4> flush().
Shell got {<0.77.0>,2}
ok
5> client:rpc(whereis(calc_server),
{minus, 10,7} ).
3
```

flush() is a function used in the shell (interactive mode) to flush out all the messages currently in the message queue. The function reads and displays all the messages present in the message queue of the shell process.

Keeping State at Server, Functionally

Often a service offered by a server has to exploit *state information*.

How to keep state in a server loop? Functionally speaking, in 1+ parameter(s).

Example: *a server that keeps the count of the number of executed loops.*

The required state is initially obtained as a parameter (N), and the next recursive call makes use, for such a parameter, of a new calculated value (N+1).

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

start() -> spawn(?MODULE, loop, [0]).

loop(N) ->
  io:format("Loop nr.~p ~n", [N]),
  receive
    {From, {plus, X, Y} } ->
      From ! {self(), {X+Y, N} },
      loop(N+1);
    ... <other receive clauses>
  end.
```

Going Distributed, Actually

Erlang Distributed Applications

In Erlang, distributed programming is enabled by the possibility to spawn processes on remote nodes and machines.

There exist two main ways to develop distributed programs:

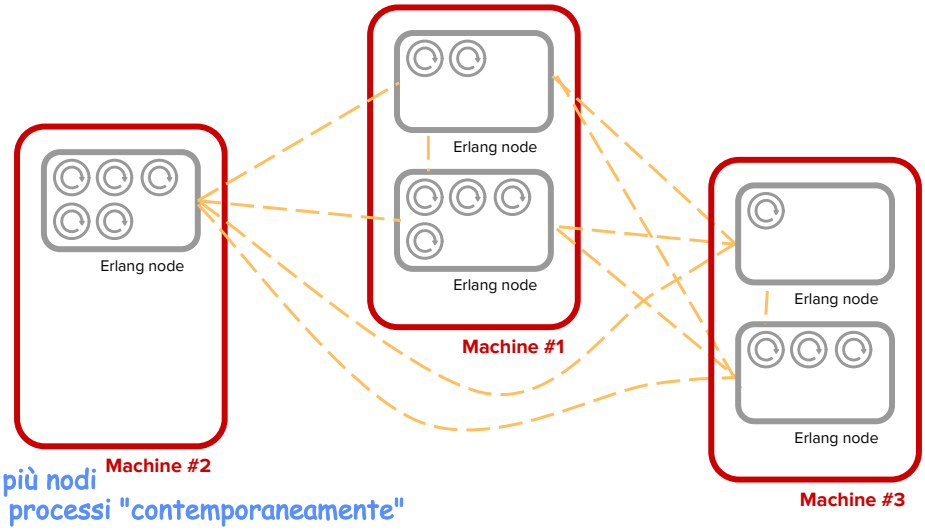
- **Distributed Erlang** - programs run on *Erlang nodes*, i.e. separate full-featured Erlang systems, with their own set of processes. We can spawn a process on any node, and processes can interact across nodes using the usual message-passing constructs.
- **Socket-based distribution** - more secure, to get more control on what a remote "client" can do in a node. We'll skip this part in our description.

- the second is more flexibile and you can get more control on what a remote client can do
- the first abstract more datails so we will focus on it.

! TCP is used for these communications

Nodes and Machines

1+ Erlang nodes can be hosted on a machine.



una macchina può hostare più nodi
ogni nodo può eseguire più processi "contemporaneamente"

Node Naming and Addressing

ora che i nodi si trovano su macchine diverse, il solo PID non basta più… (vedi slide 42)

Nodes must be given **unique** names, to be located and contacted.

Form of node names: `Name@Host`

Host: available DNS entries, + /etc/hosts

Two name types:

- Long names: with fully qualified domain names
- Short names: host w/o a "." (without)

Only one type can be used in a single cluster.

Optional

```
erl -sname ale@localhost
    shortname
(ale@localhost)1>
```

EPMD (Erlang Port Mapper Daemon, on port 4369) runs on each of the machines in the Erlang cluster, acting as a name server, enabling contacts across nodes.

si comporta da "name server", cioè mantiene le associazioni nomi-nodi

prima di inviare un messaggio ad un certo nodo, dobbiamo prima "connettere" il nodo sorgente con il nodo destinatario.
Due nodi si connettono la prima volta che provano a comunicare.

Connecting Nodes

Interaction between two nodes is possible only after a connection has been setup.

```
erl -sname tom@localhost
(tom@localhost)1>
```

Nodes get connected the 1st time they “try” to communicate: e.g.

Another way:
`net_adm:ping(Node)`

```
erl -sname ale@localhost
(ale@localhost)1> net_kernel:connect_node(tom@localhost).
true
(ale@localhost)1> nodes().
[tom@localhost]
```

nodes() restituisce una lista dei nodi a cui siamo collegati

“Transitive connections”: If node X connects to node Y, by default it obtains also the connection with all the nodes Y is connected to.

► net_adm:ping/1:
Questa funzione viene utilizzata per verificare se un nodo Erlang è raggiungibile o meno. Non è strettamente una funzione per stabilire una connessione permanente tra i nodi.

► net_kernel:connect_node/1:
Questa funzione viene utilizzata per stabilire una connessione permanente tra due nodi Erlang. Una volta stabilita la connessione, i due nodi possono comunicare tra loro.

In sintesi, net_adm:ping/1 è più orientato alla verifica dell'accessibilità e alla verifica se un nodo è "vivo", mentre net_kernel:connect_node/1 è utilizzato per stabilire una connessione permanente tra due nodi per consentire la comunicazione tra di essi.

Going Distributed, Gradually

According to Joe Armstrong’s suggestion, it is recommendable refining a distributed application in three steps:

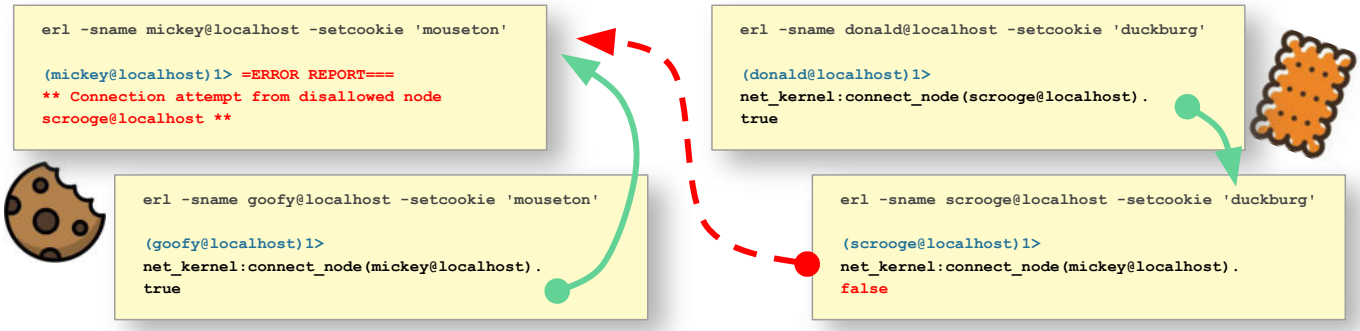
1. Write and test the program in a single, ordinary Elang system
2. Test the program on two Erlang nodes on the same machine
3. Test the program on two Erlang nodes on two distinct machines

Keep your own Cookie!

Quando "attivo" un nodo, imposto un cookie.
Quando un altro nodo vorrà connettersi ad esso, potrà farlo solo se ha lo stesso cookie impostato dal primo nodo.

Nodes of different clusters on the same HW must be kept separated.

Simple solution: one special value (cookie) is shared by all the nodes of the same cluster. Nodes with different cookies are not allowed to connect.



Spawning, Remotely

Processes can be spawned on remote nodes by means of `spawn/2` and `spawn/4`: they behaves like classical `spawn/1` and `3`, but the node name must be added as 1st argument.

This is useful to:

- spawn remote servers
- execute remote commands
- ...

!!! l'output viene rediretto sul nodo che ha spawnato il processo

notiamo che fino ad ora, il primo numero del Pid era 0, il fatto che ora non è più zero ci indica che è su di un altro host

node() is a built-in function that returns the name of the local node

Infatti, se un sistema è distribuito i PID hanno una "forma diversa":
<0.42.0> - Questo è un PID in un sistema non distribuito.
<node@hostname, 0.42.0> - Questo è un PID in un sistema distribuito.

Communicating, Remotely

Send: `Expr1` must evaluate to a pid (remote...), ~~a registered name~~, or a tuple `{RegisteredProcName, NodeName}`.

```
Expr1 ! Expr2
```

sto indicando il processo ed in quale nodo è
(questo perché nel RegisteredProcName non è incluso il nome del nodo, nei PID invece sì)

Receive: as usual.

```
(mickey@localhost)1> net_adm:ping(goofy@localhost).
Pong
(mickey@localhost)2> {goofyshell,goofy@localhost} !
{hello, self()}.
{hello,<0.82.0>}

(mickey@localhost)3> flush().
Shell got hello_back
ok
```

```
(goofy@localhost)1> register(goofyshell, self()).
true

(goofy@localhost)2> receive {hello, Friend} ->
Friend ! hello_back end.
hello_back

(goofy@localhost)3> Friend.
<8135.82.0>
```

! basta che il RegisteredProcName sia registrato sulla macchina che riceve il messaggio, non deve essere registrato anche dal sender

Rispondere ad un messaggio remoto è più semplice rispetto all'invio. Sfrutteremo il fatto che il sender ci manda il suo PID ed a noi basta quello per rispondere. Il codice della receive è infatti uguale a quello che avevamo quando non avevamo a che fare con nodi remoti.

Notare che i due Pid mostrati nell'esempio sono in realtà lo stesso Pid, infatti cambia soltanto l'host ma la seconda parte è uguale

Come fa la shell (del nodo) di sinistra a conoscere il processo registrato dalla shell (del nodo) di destra?
In teoria, non dovrebbe essere possibile. Tuttavia, per questo esempio, è possibile che il demone Erlang sia stato configurato in modo che la visibilità delle registrazioni non sia limitata ai singoli nodi, ma sia estesa a tutti i nodi presenti sulla stessa macchina.

Modules to Support Distribution

Modules provided to support distributed Erlang programs:

`net_kernel` - to connect/disconnect nodes, to switch a node to distributed/non-distributed, to control heartbeat...

`global` - a *global* process registry; ➔ use `global:send(Name, Msg)`; handles name conflicts

`rpc` - functions to execute commands on remote nodes ➔ `rpc:call(Node,Mod,Funct,Args)` returns *locally* whatever is returned by the function executed remotely; `rpc:call/5` w/ timeout; support to *promises* for asynchronous computing

OTP - Open Telecom Platform

OTP is a collection of supporting tools and libraries for boosting development of Erlang programs.

Central concept for application development: OTP *behavior*.

A behavior encapsulates common behavioral patterns, i.e. it is an *application framework* to be parameterized by a *callback* module.

Idea:

- Non-functional issues → **Behavior**
- Specific Functional issues → **Callback (custom)**

I behaviors forniscono una struttura e un insieme di regole che guidano lo sviluppo di determinati tipi di componenti nel sistema Erlang. Sono particolarmente utili per affrontare problemi comuni in modo coerente.

Aside: 😕 What's a "Callback" ???

Sometimes, the term "callback function" is used in a confusing way.

Regardless (indipendentemente da) of the specific programming language:

a **callback function** is just a function f_c passed (somehow...) by a *caller* to a *called* function, so that in turn f_c could be called/executed *later*.

Important: the actual callback function must be identified via actual arguments, and sometimes also according to **naming conventions**.

Two different types of callbacks:

- *Synchronous* callbacks - executed before the called function will return
- *Deferred* callbacks - executed after; *used for event handling*, GUIs, etc.

Una callback function è una funzione che viene passata come argomento a un'altra funzione e che viene invocata (o "richiamata") all'interno di quella funzione per completare una qualche operazione.

Parameterizing a Server - Behavior

Si tratta di separare la logica generica del server dalla logica specifica dell'applicazione che il server deve gestire.

Specific functionality must be defined apart in module `Mod`, which must contain `init()` and `handle(Req, State)`.

```
-module(server_0).
-export([start/2, rpc/2]).

start(Name, Mod) ->
  register(Name, spawn(fun()-> loop(Name, Mod, Mod:init()) end)).

rpc(Name, Req) ->
  Name ! {self(), Req},
  receive {Name, Response} -> Response
  end.

loop(Name, Mod, State) ->
  receive
    {From, Req} ->
      {Response, NewState} = Mod:handle(Req, State),
      From ! {Name, Response},
      loop(Name, Mod, NewState)
  end.
```

Module with required request-handling function

Keep: Name, Mod, and (evolving) state

Standard API to get a service

To be computed: Response & updated state

- in init() i have to specify how to calculate the initial state
- in handle() i have to specify how to calculate the response and the NewState given the response and the current state

Parameterizing a Server - Callback

Here we specify a server that receives one number per request, and returns the average of all the values received so far.

```
-module(avg_server).
-export([init/0, handle/2, get_avg/1]).
-import(server_0, [rpc/2]).

% client routines
get_avg(X) -> rpc(calc_avg, X).

% callback routines
init() -> {0, 0}. % total: 0; # of reqs: 0

handle(X, {Total, Times}) ->
  NewTotal = Total + X,
  NewTimes = Times + 1,
  {NewTotal/NewTimes, {NewTotal, NewTimes}}.
```

Server name to be registered

Initial state

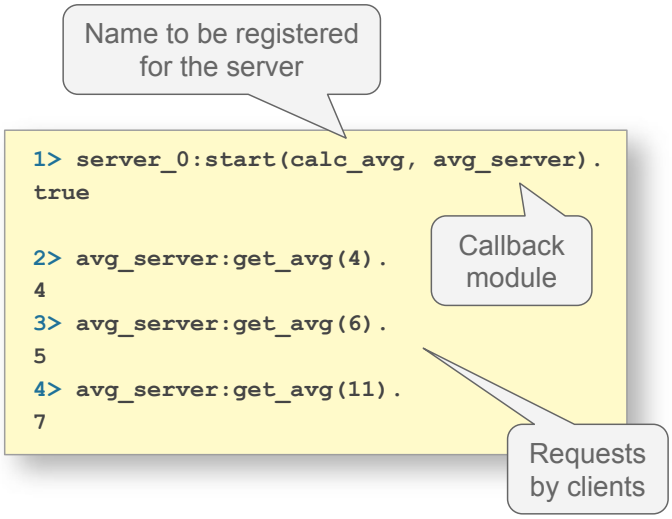
State info: Total, and # of calls

Standard API to get a service

Returns a tuple with response and updated state

Abbiamo riorganizzato il codice della media che abbiamo già visto in un esercizio, separando il "behavior" dalla specifica logica dell'applicazione. In questo modo il behavior può essere riutilizzato per implementare server che devono svolgere altri calcoli, in quanto il behavior implementa solo le funzioni di base che sono richieste ad un server, indipendentemente da cosa questo deve svolgere.

Setup & Use the Custom Server



Server setup: call `start/2` from the behavior, providing:

- standard name for server
- reference to the callback module.

The server is used via client routines, defined in the callback module.

Focus on: *callback module*.

! notare che alla funzione passo solo il nome del modulo, infatti l'applicazione si aspetta di trovare al suo interno la funzione init() e la handle()

questa slide ci mostra come passare ciò abbiamo implementato nel modulo avg_server (quello cioè in cui scriviamo la logica della nostra applicazione) al modulo behavior.
Notiamo quindi che basta passare un modulo diverso, per creare facilmente un server con altre funzionalità.

OTP gen_server

The OTP behavior gen_server adopts the previously described approach.

To build up a server, gen_server must be paired to a callback module with standard API, to deal with any possible piece of required functionality (initialization, handling of rpcs, handling of “casts”, termination, etc.).

The callback module must specify `-behaviour(gen_server).`

gen_server module	callback module
`gen_server:start, start_link, start_monitor`	`mod:init/1`
`gen_server:stop`	`mod:terminate/2`
`gen_server:call, send_request, multi_call`	`mod:handle_call/3`
`gen_server:cast, abcast`	`mod:handle_cast/3`
others	

se voglio usare il behavior gen_server, queste solo le funzioni che dovrò implementare nel mio callback module

OTP gen_server Example

A practical example is present in the lab exercises.

Data Storing: ETS & DETS

ets and **dets** are system modules to store Erlang terms.

Both provide {*key-value*} lookup tables: ETS on memory, DETS on disk.

Tables are collection of tuples; the first element acts as key.

- Sets - no duplicate keys; also “ordered sets” are available
- Bags - duplicate keys allowed, but not tuples; in “duplicate bags” also duplicate tuples can be present.

Operations: creation/opening, insertion, lookup, disposal.

Further details on documentation pages.

Integrated Data Management: Mnesia

ets and **dets** are system modules to store Erlang terms.

Erlag programs that need efficient and more complex data management can rely on an integrated Data Base System: **Mnesia**.

It can store any kind of Erlang data structure.

In a mnesia db, data is organized in tables; query language capabilities (as in SQL) are available in ordinary Erlang syntax.

Mnesia provide transaction support as well.

Dealing with Errors in Erlang

Handling of Runtime Errors in Erlang

è destinato a sostenere

Erlang is intended to support the development of fault-tolerant systems, thus **runtime** errors must be handled (i.e., detected, corrected, etc.).

Specific mechanisms have been introduced for different scenarios:

- **Error Handling in SEQUENTIAL programs** - we need to understand when, within a process, something goes wrong (a function "crashes"), and to specify what to do in such exceptional cases.
- **Error Handling in CONCURRENT programs** - we need to deal with errors at the process level, in collection of processes. In case of a process crash, we want another process may detect the event, and take over the job of the crashed process.

Typical case in fault-tolerant systems

Raising Exceptions, Explicitly

An error can be explicitly generated with these BIFs (one per error type):

- **error(Why)** - used for denoting *severe errors* ("crashing errors"), i.e. programmatically *emulated internal errors*
- **throw(Why)** - an exception is generated, and the caller might want to catch it.
- **exit(Why)** - used to terminate (kill) the (current) process.

gravi

a.k.a. ***generated errors***

"Why" denotes a term to describe the relative reason.

Erlang provides two ways to catch exceptions:

- **Try ... catch** expressions
- **Catch** expressions

NOTE:
They are expressions, as it always happens in Erlang!

Motto: “Let It Crash!”

In designing a fault-tolerant system, we assume that errors will occur, processes will crash, machines will fail.

In Erlang, the focus is in the cure, not on prevention!

The behavior of a function should always be described in terms of *valid* input values; anomalous cases should automatically determine exception raising.
It is up to the caller handling the exception.

In applications with many processes, we can let a faulty process die, but *we should be able to correct the error in another process*.

Faremo quindi in modo da avere un processo che "controlli" gli altri così da reagire qualora qualcuno di questi fallisca

Trapping Exceptions with try...catch

It is adopted a trapping mechanism alike the one present in other languages, but designed according to a “functional structure.”

Note: tail recursion is not admitted in the protected exception.

The “of” part is optional...

```
try ExprList
catch
    TypeOfError:ExcPattern -> Expr1
end.
```

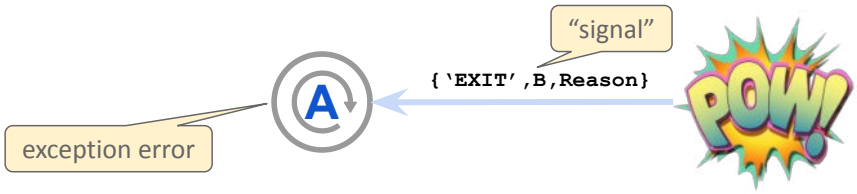
“Protected” expression

```
try Expr of
    OkPattern1 [Guards] -> Expr1;
    OkPattern2 [Guards] -> Expr2
catch
    TypeOfError:ExcPattern1 -> Expr3;
    TypeOfError:ExcPattern2 -> Expr4
after  %like “finally” in other langs
    Expr5
end.
```

error|throw|exit

Links between Processes

A special relationship between processes can be set up, to let us terminate a set of related processes in case one of them would fail.
BIF: link/1, and spawn_link/1-3



Once a process is 'linked' with another, the relationship between them is bidirectional (the first is linked to the second, and the second is linked to the first in the exact same way).

Trapping Signals

The exit signals seen so far make the recipient die.

How to trap them? Making the recipient a *system process*!

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

Any exit signal to a system process is converted to a regular message. Upon receiving it, we can decide what to do - maybe, restarting the dead process!

- Special case: `kill` reason ➜ never trapped; an ultimate weapon!
- The recipient of "`killed`" will send out the "`killed`" reason instead: Why?
  dato che il segnale kill è transitivo (cioè un processo che ricevo questo segnale lo trasmette agli altri processi linkati a lui) potrebbe accadere che se tutti i processi sono linkati tra loro, il segnale di kill arriverebbe a tutti terminando così tutti i processi

Process Monitoring

A more flexible kind of relationship can be set up via monitor/2-3, and spawn_monitor/1-3.

```
monitor(process, Pid)
spawn_monitor(Pid2)
```

Differently from links, monitors

- are unidirectional; i link invece erano bidirezionali
- can be stacked (1+ instances per ordered pair).

As a monitored process goes down, the monitoring process receives a message whose pattern is `{'DOWN', MonitorRef, process, Pid, Reason}.`

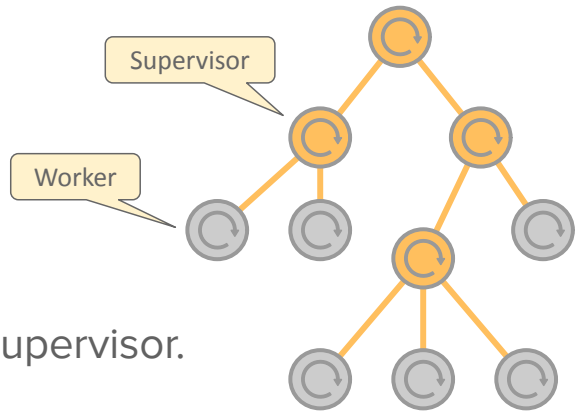
Così che il processo possa decidere cosa fare sulla base delle informazioni ricevute.

Supervisors and Supervision Trees

Links & monitors are used to implement supervision of a process by another one.

Organizing an application according to a supervision tree let us get full control over it.

One specific OTP behavior is aimed at providing a robust/flexible implementation of a supervisor.



DOMANDE

► se la ricorsione occupa più memoria? alla fine perchè l'abbiamo scelta? l'unico motivo è favorire la concorrenza tra processi?
Non usa tutta sta memoria in più come mi penso io, questo grazie alle ottimizzazioni sull'uso della memoria durante la ricorsione. Poi ovviamente un po' di memoria in più verrà usata, ma amen, preferiamo usare più memoria ma non avere problemi di conflitti tra processi.

► quando abbiamo visto i loop, richiamare il loop era l'ultima cosa che facevamo. Nei server invece richiamiamo il loop prima della end. Quindi quella funzione non si chiude mai... ?
La end non conta come istruzione, quindi effettivamente la funzione "si chiude" e quindi abbiamo la "Tail Call Optimization".

► la register, whereis ecc... si possono usare solo nella shell Erlang oppure anche nel codice (quindi a cavallo tra più funzioni)? O meglio, mi sembra si possa fare, ma "è giusto"?
Le posso usare dove voglio, poi ovviamente nella realtà server e client non sono nella stessa macchina quindi non potrei fare register nella funzione server e whereis in quella client.

► net_adm:ping or net_kernel:connect_node
Lui dice che non sa che differenza c'è, le usa gli gira.

► slide 42, come fa la shell di sinistra a conoscere il Pid di "goofyshell", c'è un qualcosa di condiviso?
Semplicemente in quell'esempio funziona perché i due nodi girano nella stessa macchina. Se invece fossero stati in macchine diverse allora probabilmente non avrebbe funzionato.
(Poi lui disse roba strana per farlo funzionare lo stesso, ma …)