



UNIVERSITY OF
GOTHENBURG

Functional programming in Erlang

Lecture 6 of TDA384/DIT391

Principles of Concurrent Programming

Gerardo Schneider

Chalmers University of Technology | University of Gothenburg
SP1 2020/2021

Based on course slides by Carlo A. Furia and Sandro Stucki

Today's menu

What is Erlang?

Types

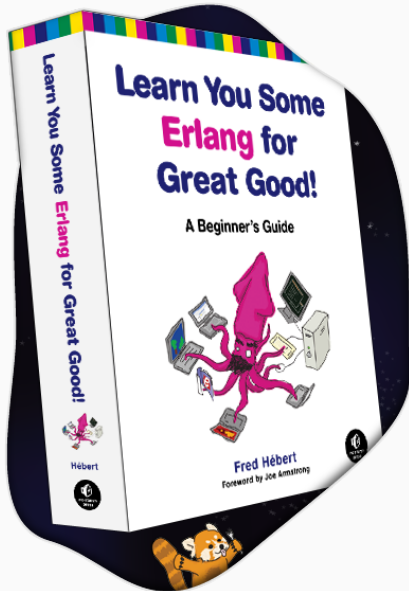
Expressions and patterns

Function definitions

Recursion

Impure and higher-order functions

Don't forget...



What is Erlang?

What is Erlang?

Erlang combines a **functional language** with **message-passing** features:

- The functional part is **sequential**, and is used to define the behavior of **processes**.
- The message-passing part is highly **concurrent**: it implements the **actor model**, where actors are Erlang processes.

This class covers the **functional/sequential** part of Erlang.

Erlang: a minimal history

- 1973 Hewitt and others develop the **actor model** – a formal model of concurrent computation
- 1985 Agha further refines the actor model

Erlang: a minimal history

- 1973 Hewitt and others develop the **actor model** – a formal model of concurrent computation
- 1985 Agha further refines the actor model
- Mid 1980s Armstrong and others at Ericsson prototype the first version of Erlang (based on the actor model)

Erlang: a minimal history

- 1973 Hewitt and others develop the **actor model** – a formal model of concurrent computation
- 1985 Agha further refines the actor model
- Mid 1980s Armstrong and others at Ericsson prototype the first version of Erlang (based on the actor model)



Erlang: a minimal history

- 1973 Hewitt and others develop the **actor model** – a formal model of concurrent computation
- 1985 Agha further refines the actor model
- Mid 1980s Armstrong and others at Ericsson prototype the first version of Erlang (based on the actor model)
- Late 1980s Erlang's implementation becomes efficient; Erlang code is used in production at Ericsson
- 1998 Ericsson bans Erlang, which becomes open-source
- Late 2000s Erlang and the actor model make a come-back in mainstream programming



Erlang in the real world

Erlang has made a significant **impact** in the **practice** of concurrent programming by making the formal actor model applicable to real-world scenarios.

Initially, Erlang was mainly used for **telecommunication software**:

- Ericsson's AXD301 switch – includes over one million lines of Erlang code; achieves “nine 9s” availability (99.9999999%)
- cellular communication infrastructure (services such as SMSs)

Recently, it has been rediscovered for Internet **communication apps**:

- WhatsApp's communication services are written in Erlang
- Facebook Chat (in the past)

Why Erlang?

We've faced many challenges in meeting the ever-growing demand for [the WhatsApp] messaging services, but [...] Erlang continues to prove its capability as a versatile, reliable, high-performance platform.

Rick Reed, 2014 –

That's 'Billion' with a 'B': Scaling to the next level at WhatsApp

The language itself has many pros and cons, but we chose Erlang to power [Facebook] Chat because its model lends itself well to concurrent, distributed, and robust programming.

Chris Piro, 2010 – Chat Stability and Scalability

What is a functional language?

Functional languages are based on elements quite **different from** those **imperative** languages are based on.

Imperative languages – such as Java – are based on:

- state – variables
- state modifications – assignments
- iteration – loops

Functional languages – such as Erlang – are based on:

- data – values
- functions on data – without side effects
- functional forms – function composition, higher-order functions

What is a functional language?

Functional languages are based on elements quite **different from** those **imperative** languages are based on.

Imperative languages – such as Java – are based on:

An imperative program is a sequence of state modifications on variables.

```
// compute  $x^n$ 
int power(int x, int n) {
    int result = 1;
    for (int i = n; i < n; i++)
        result *= x;
    return result;
}
```

Functional languages – such as Erlang – are based on:

A functional program is the side-effect-free application of functions on values.

```
% compute  $X^N$ 
power(X, 0) -> 1;
power(X, N) -> X * power(X, N-1).
```

In functional programs, variables store **immutable** values, which can be **copied** but not modified.

The Erlang shell

You can experiment with Erlang using its **shell**, which can evaluate expressions on the fly without need to define complete programs.

```
$ erl
Erlang R16B03 (erts-5.10.4) [source] [64-bit] [smp:2:2]

Eshell V5.10.4 (abort with ^G)
1> 1 + 2.                % evaluate expression '1 + 2'
3
2> c(power).            % compile file 'power.erl'
{ok,power}
3> power:power(2, 3).  % evaluate power(2, 3)
8
```

Notice you have to terminate all expressions with a period. Functions are normally defined in external files, and then used in the shell. Compilation targets bytecode by default.

Types

Types, dynamically

A **type** constrains:

1. The (kinds) of **values** that an expression can take
2. The **functions** that can be applied to expressions of that type

For example, the **integer** type:

1. includes integer values (1, -100, 234, ...), but not, say, decimal numbers (10.3, -4.3311, ...) or strings ("hello!", "why not", ...)
2. supports functions such as sum +, but not, say, logical **and**

Erlang is **dynamically typed**:

- programs do **not** use type **declarations**
- the type of an expression is only determined **at runtime**, when the expression is evaluated
- if there is a type mismatch (for example `3 + false`) expression evaluation **fails**

Erlang types include **primitive** and **compound** data types.

An overview of Erlang types

Erlang offers eight **primitive types**:

- Integers: arbitrary-size integers with the usual operations
- Atoms: roughly corresponding to identifiers
- Floats: 64-bit floating point numbers
- References: globally unique symbols
- Binaries: sequences of bytes
- Pids: process identifiers
- Ports: for communication
- Funs: function closures

And three + two **compound types** (a.k.a. type constructors):

- Tuples: fixed-size containers
- Lists: dynamically-sized containers
- Maps: key-value associative tables (a.k.a. dictionaries) – recent feature, experimental in Erlang/OTP R17
- Strings: syntactic sugar for sequences of characters
- Records: syntactic sugar to access tuple elements by name

Numbers

Numeric types include **integers** and **floats**. We will mainly use integers, which are arbitrary-size, and thus do not overflow.

EXPRESSION	VALUE	
3	3	explicit constant (“ term ”)
1 + 3	4	addition
1 - 3	-2	subtraction
4 * 2	8	multiplication
5 div 4	1	integer division
5 rem 3	2	integer remainder
5 / 4	1.25	float division
power (10,1000)	1000000000...	no overflow!
2#101	5	101 in base 2
16#A1	161	A1 in base 16

Atoms

Atoms are used to denote **distinguished values**; they are similar to symbolic uninterpreted constants. An atom can be:

- a sequence of alphanumeric characters and underscores, starting with a lowercase letter, or
- an arbitrary sequence of characters (including spaces and escape sequences) between single quotes

Examples of valid atoms:

```
x  
a_Longer_Atom  
'Uppercase_0k_in_quotes'  
'This is crazy!'  
true
```

Booleans

In Erlang there is **no Boolean type**; instead, the **atoms** `true` and `false` are conventionally used to represent Boolean values.

OPERATOR	MEANING
not	negation
and	conjunction (evaluates both arguments/eager)
or	disjunction (evaluates both arguments/eager)
xor	exclusive or (evaluates both arguments/eager)
andalso	conjunction (short-circuited/lazy)
orelse	disjunction (short-circuited/lazy)

Examples:

```
true or      (10 + false)  % error: type mismatch in second argument  
true orelse (10 + false)  % true: only evaluates first argument
```

Relational operators

Erlang's **relational operators** have a few syntactic differences with those of most other programming languages.

OPERATOR	MEANING
<	less than
>	greater than
<=	less than or equal to
>=	greater than or equal to
:=	equal to
/=	not equal to
==	numeric equal to
/=	numeric not equal to

Examples:

```
3 := 3      % true: same value, same type
3 := 3.0    % false: same value, different type
3 == 3.0    % true: same value, type not checked
```

Order between different types

Erlang defines an **order relationship** between values of **any type**.
When different types are compared, the following **order** applies:

number < atom < reference < fun < port < pid < tuple < map < list

Thus, the following inequalities hold:

```
3 < true           % number < atom
3 < false          % number < atom
999999999 < infinity % number < atom
10000000000000000 < epsilon % number < atom
```

When comparing **lists to lists** and **tuples to tuples**:

- tuple comparison is by size first;
- two tuples with the same size or two lists are compared element by element, and satisfy the comparison only if all (existing) pairs satisfy it.

Tuples

Tuples denote ordered **sequences** with a **fixed** (but arbitrary for each tuple instance) **number of elements**. They are written as comma-separated sequences enclosed in curly braces. Examples of valid tuples:

```
{ }                % empty tuple
{ 10, 12, 98 }
{ 8.88, false, aToM } % elements may have different types
{ 10, { -1, true } } % tuples can be nested
```

Functions on a tuple **T**:

FUNCTION	RETURNED VALUE
<code>element(N, T)</code>	Nth element of T
<code>setelement(N, T, X)</code>	a copy of T , with the Nth element replaced by X
<code>tuple_size(T)</code>	number of elements in T
<code>element(2, {a, b, c})</code>	% <i>b: tuples are numbered from 1</i>
<code>setelement(1, {a, b}, z)</code>	% <i>{z, b}</i>
<code>tuple_size({ })</code>	% <i>0</i>

Lists

Lists denote ordered **sequences** with a **variable** (but immutable for any list instance) **number of elements**. They are written as comma-separated lists enclosed in square brackets.

Examples of valid lists:

```
[ ]           % empty list
[ 10, 12, 98 ]
[ 8.88, false, {1, 2} ] % elements may have different type
[ 10, [ -1, true ] ]   % lists can be nested
```


List operators

Some useful functions on lists L :

FUNCTION	RETURNED VALUE
<code>length(L)</code>	number of elements in L
<code>[H L]</code>	a copy of L with H added as first (“head”) element
<code>hd(L)</code>	L ’s first element (the “head”)
<code>tl(L)</code>	a copy of L without the first element (the “tail”)
<code>L1 ++ L2</code>	the concatenation of lists $L1$ and $L2$
<code>L1 -- L2</code>	a copy of $L1$ with all elements in $L2$ removed (without repetitions, and in the order they appear in $L1$)

Operator `|` is also called `cons`; using it, we can define any list:

```
[1, 2, 3, 4] ::= [1 | [2 | [3 | [4 | []]]]]
```

```
hd([H | T]) ::= H
```

```
tl([H | T]) ::= T
```

```
% this is an example of --
```

```
[1, 2, 3, 4, 2] -- [1, 5, 2] ::= [3, 4, 2]
```

Strings

Strings are sequences of characters enclosed between **double quotation marks**. Strings are just syntactic sugar for lists of character codes.

String **concatenation** is implicit whenever multiple strings are juxtaposed without any operators in the middle.

Using strings ($\$c$ denotes the integer code of character c):

```
" " % empty string := empty list
"hello!"
"hello" "world" % := "helloworld"
"xyz" := [$x, $y, $z] := [120, 121, 122] % true
[97, 98, 99] % evaluates to "abc"!
```

Records

Records are ordered sequences with a **fixed number of elements**, where each element has an atom as **name**. Records are just syntactic sugar for **tuples** where positions are named.

```
% define 'person' record type
% with two fields: 'name' with default value "add name"
%                               'age' without default value (undefined)
-record(person, { name="add name", age })
% 'person' record value with given name and age
#person{name="Joe", age=55}
#person{age=35, name="Jane"} % fields can be given in any order
% when a field is not initialized, the default applies
#person{age=22} ::= #person{name="add name", age=22}
% evaluates to 'age' of 'Student' (of record type 'person')
Student#person.age
```

Erlang's shell does not know about records, which can only be used in **modules**. In the shell, `#person{age=7, name="x"}` is `{person, "x", 7}`.

Expressions and patterns

Variables

Variables are identifiers that can be **bound to values**; they are similar to constants in an imperative programming language. A variable **name** is a sequence of alphanumeric characters, underscores, and @, starting with an uppercase letter or an underscore.

In the **shell**, you can directly bind values to variable:

- Evaluating `Var = expr` binds the value of expression `expr` to variable `Var`, and returns such value as value of the whole **binding expression**
- Each variable can only be bound **once**
- To clear the binding of variable `Var` evaluate `f(Var)`
- Evaluating `f()` clears all variable bindings
- The anonymous variable `_` (“any”) is used like a variable whose value can be ignored

In **modules**, variables are used with pattern matching, which we present later.

Expressions and evaluation

Expressions are evaluated exhaustively to a **value** – sometimes called (ground) term: a number, an atom, a list, ...

The **order of evaluation** is given by the usual **precedence rules**; using **parentheses** forces the evaluation order to be inside-out of the nesting structure.

Some precedence rules to be aware of:

- **and** has higher precedence than **or**
- **andalso** has higher precedence than **orelse**
- when lazy (**andalso**, **orelse**) and eager (**and**, **or**) Boolean operators are mixed, they all have the same precedence and are left-associative
- ++ and -- are right-associative
- relational operators have lower precedence than Boolean operators; thus you have to use parentheses in expressions such as `(3 > 0) and (2 == 2.0)`

Precedence rules: examples

```
3 + 2 * 4           % is 11
3 + (2 * 4)         % is 11
(3 + 2) * 4         % is 20
true or false and false % is true
true orelse false andalso false % is true
true or false andalso false % is false
true orelse false and false % is true (why?)
```

Patterns

Pattern matching is a flexible and concise mechanism to **bind values to variables**. It is widely used in functional programming languages to define functions on data (especially lists); Erlang is no exception.

A **pattern** has the same structure as a term, but in a pattern some parts of the term **may** be replaced by free **variables**.

Examples of patterns:

3

A

{X, Y}

{X, 3}

[H | T]

[H | [2]]

Note that a pattern may contain bound variables; in this case, evaluating the pattern implicitly evaluates its bound variables.

Pattern matching

Pattern matching is the process that, given a pattern P and a term T , **binds the variables** in P to match the values in T according to P and T 's structure. If P 's structure (or type) cannot match T 's, pattern matching **fails**.

PATTERN = TERM	BINDINGS
3 = 3	none
A = 3	A: 3
A = B	if B is bound then A ::= B; otherwise fail
{X,Y} = 3	fail (structure mismatch)
{X,Y} = {1, 2}	X: 1, Y: 2
{X,Y} = {"a", [2,3]}	X: "a", Y: [2,3]
[H T] = [1,2]	H: 1, T: [2]
[H [2]] = [1,2]	H: 1
[F,S] = [foo,bar]	F: foo, S: bar
{X,Y} = [1,2]	fail (type mismatch)

Pattern matching: notation

Given a **pattern** P and a **term** T , we write $\langle P \triangleq T \rangle$ to denote the **pattern match of T to P** . If the match is successful, it determines bindings of the variables in P to terms. Given an expression E , we write

$$E\langle P \triangleq T \rangle$$

to denote the term obtained by applying the bindings of the pattern match $\langle P \triangleq T \rangle$ to the variables in E with the same names.

If the pattern match fails, $E\langle P \triangleq T \rangle$ is undefined.

Examples:

- $(X + Y)\langle\{X, Y\} \triangleq \{3, 2\}\rangle$ is 5
- $(T ++ [2])\langle[H|T] \triangleq [8]\rangle$ is [2]
- $H\langle[H|T] \triangleq []\rangle$ is undefined

The notation $E\langle P \triangleq T \rangle$ is not valid Erlang, but we use it to illustrate Erlang's semantics.

Multiple expressions

Multiple expressions E_1, \dots, E_n can be combined in a **compound expression** obtained by separating them using commas. Evaluating the compound expression entails evaluating all component expressions in the order they appear, and returning the **value** of the **last** component expression as the value of the whole compound expression. A single failing evaluation makes the whole compound expression evaluation **fail**.

```
3 < 0, 2.           % evaluates 3 < 0  
                    % returns 2
```

```
3 + true, 2.       % evaluates 3 + true  
                    % fails
```

```
R=10, Pi=3.14, 2*Pi*R. % binds 10 to R,  
                    % binds 3.14 to Pi  
                    % returns 62.8
```

Multiple expression blocks

Using **blocks** delimited by **begin...end**, we can introduce **multiple expressions** where **commas** would normally be interpreted in a different way.

This may be useful in function calls:

```
power(2, begin X=3, 4*X end) % returns power(2, 12)
```

Without **begin...end**, the expression would be interpreted as calling a function `power` with three arguments.

List comprehensions

List comprehensions provide a convenient syntax to define lists using pattern matching.

A list comprehension is an expression of the form

```
[ Expression || P1 <- L1, ..., Pm <-Ln, C1, ..., Cn ]
```

where each P_k is a pattern, each L_k is a list expression, and each C_k is a condition (a Boolean expression). Intuitively, each pattern P_k is matched to every element of L_k , thus determining a binding B ; if substituting all bound values makes all conditions evaluate to true, the value obtained by substituting all bound values in $Expression$ is accumulated in the list result; otherwise the binding is ignored.

```
[X*X || X <- [1, 2, 3, 4]]           % is [1, 4, 9, 16]
[X  || X <- [1, -3, 10], X > 0]     % is [1, 10]
[{A, B} || A <- [carl, sven], B <- [carlsson, svensson]]
% is [{carl, carlsson}, {carl, svensson},
%     {sven, carlsson}, {sven, svensson}]
```

Modules

A **module** is a **collection of function definitions** grouped in a **file**. Indeed, modules are the only places where functions can be defined – they cannot directly be defined in the shell. The **main elements** of a module are as follows:

```
-module(foo).    % module with name 'foo' in file 'foo.erl'
-export([double/1,up_to_5/0]). % exported functions
    % each f/n refers to the function with name 'f' and arity 'n'
-import(lists, [seq/2]). % functions imported from module 'lists'
    % function definitions:
double(X) -> 2*X.
up_to_5() -> seq(1, 5).    % uses imported lists:seq
```

Compiling and using a module in the shell:

```
1> c(foo).        % compile module 'foo' in current directory
{ok,foo}.        % compilation successful
2> foo:up_to_5(). % call 'up_to_5' in module 'foo'
[1,2,3,4,5]
```

Function definitions

Function definitions: basics

In Erlang, like every functional programming language, **functions** are the fundamental units of computation. A **function** defines how to map values to other values; unlike in imperative programming languages, most functions in Erlang have **no side effects**: they do not change the state of the program executing them (especially their arguments).

The basic definition of an n -argument function f (arity n), denoted by f/n , has the form:

$$\overbrace{f(P_1, \dots, P_n)}^{\text{head}} \rightarrow \overbrace{E}^{\text{body}}$$

- The function **name** f is an atom
- The function's formal **arguments** P_1, \dots, P_n are patterns
- The **body** E is an expression – normally including variables that appear in the arguments

```
identity(X) -> X.           % the identity function
sum(X, Y)   -> X + Y.      % the sum function
```


Examples of function definitions

The most fundamental definition of an n -argument function f (arity n), denoted by f/n , has the form:

$$f(P_1, \dots, P_n) \rightarrow E.$$

Some examples:

```
zero()      -> 0.           % integer zero
identity(X) -> X.          % identity
sum(X, Y)   -> X + Y.      % sum
head([H|_]) -> H.          % head
tail([_|T]) -> T.          % tail
second({_, Y}) -> Y.       % 2nd of pair
positives(L) -> [X || X <- L, X > 0]. % filter positive
```

Function call/evaluation

Given the definition of a function f/n :

$$f(P_1, \dots, P_n) \rightarrow E.$$

a **call expression** to f/n has the form:

$$f(A_1, \dots, A_n)$$

and is **evaluated** as follows:

1. for each $1 \leq k \leq n$, evaluate A_k , which gives a term T_k
2. for each $1 \leq k \leq n$, pattern match T_k to P_k
3. if all pattern matches are successful, the call expression evaluates to $E\langle P_1, \dots, P_n \triangleq T_1, \dots, T_n \rangle$
4. otherwise, the evaluation of the call expression fails

Examples of function calls

DEFINITIONS	CALLS	VALUE
<code>zero()</code> -> 0.	<code>zero()</code>	0
<code>identity(X)</code> -> X.	<code>identity({1,2,3})</code>	{1,2,3}
<code>sum(X, Y)</code> -> X + Y.	<code>sum(zero(), second({2,3}))</code>	3
<code>head([H _])</code> -> H.	<code>head([])</code>	fail
<code>tail([_ T])</code> -> T.	<code>head([3,4,5])</code>	3
<code>second({_, Y})</code> -> Y.	<code>tail([])</code>	fail
<code>positives(L)</code> -> [X X <- L, X > 0].	<code>positives([-2,3,-1,6,0])</code>	[3,6]

Function definition: clauses

Function definitions can include multiple **clauses**, separated by semicolons:

```
f(P11, ..., P1n) -> E1;  
f(P21, ..., P2n) -> E2;  
      ⋮  
f(Pm1, ..., Pmn) -> Em.
```

A **call expression** is evaluated against each clause in textual order; the first successful match is returned as the result of the call.

Therefore, we should enumerate clauses from more to less specific.

```
lazy_or(true, _) -> true;  
lazy_or(_, true) -> true;  
lazy_or(_, _)   -> false.
```



this function does not work as expected
unless this clause is listed last

Pattern matching with records

Pattern matching an expression R of record type rec

$$\#rec\{f_1=P_1, \dots, f_n=P_n\} = R$$

succeeds if, for all $1 \leq k \leq n$, field f_k in R 's evaluation – that is, $R\#name.f_k$ – matches to pattern P_k . If record type rec has fields **other** than f_1, \dots, f_n , they are **ignored** in the match.

Thanks to this behavior, using **arguments of record type** provides a simple way to **extend data** definitions **without** having to **change** the signature of all functions that use that datatype.

Flexible arguments with records: example

```
-record(error, {code}).  
error_message(#error{code=100}) -> io.format("Wrong address");  
error_message(#error{code=101}) -> io.format("Invalid username");  
...  
error_message(_) -> io.format("Unknown error").
```

If we want to add more information to the type `error`, we only have to change the record definition, and the clauses using the new information:

```
-record(error, {code, line_number}).  
error_message(#error{code=100}) -> io.format("Wrong address");  
error_message(#error{code=101}) -> io.format("Invalid username");  
...  
error_message(#error{code=C, line_number=L}) ->  
    io.format("Unknown error ~p on line ~p", [C, L]).
```

Compare this to the case where we would have had to change `error_message` from a unary to a binary function!

Function definition: guards

Clauses in function definitions can include any number of **guards** (also called **conditions**):

```
f(Pk1, ..., Pkn) when Ck1, Ck2, ... -> Ek;
```

A guarded clause is selected only if **all guards** Ck_1, Ck_2, \dots evaluate to **true** under the match, that is if $Ck_i \langle Pk_1, \dots, Pk_n \triangleq Tk_1, \dots, Tk_n \rangle$ evaluates to true for all guards Ck_i in the clause.

More generally, two guards can be separated by either a comma or a **semicolon**: commas behave like lazy **and** (both guards have to hold); semicolon behave like lazy **or** (at least one guard has to hold).

```
can_drive(Name, Age) when Age >= 18 -> Name ++ " can drive";  
can_drive(Name, _) -> Name ++ " cannot drive".
```

```
same_sign(X, Y) when X > 0, Y > 0; X < 0, Y < 0 -> true;  
same_sign(_, _) -> false.
```

Type checking – at runtime

Since Erlang is dynamically typed, there are cases where we have to **test** the **actual type** of an expression – for example, because a certain operation is only applicable to values of a certain type.

To this end, Erlang provides several **test functions** whose names are self-explanatory:

```
is_atom/1
is_boolean/1
is_float/1
is_integer/1
is_list/1
is_number/1
is_pid/1
is_port/1
is_tuple/1
```

Use these only when necessary: in most cases defining implicitly partial functions is enough.

Function definition: local binding

The expression **body** in a function definition can include **compound expressions** with **bindings**:

```
f(Pk1, ..., Pkn) -> V1=E1, ..., Vw=EW, Ek;
```

Such bindings are **only visible** within the function definition.

They are useful to define shorthands in the definition of complex expressions.

```
volume({cylinder, Radius, Height}) ->  
  Pi=3.1415,  
  BaseArea=Pi*Radius*Radius,  
  Volume=BaseArea*Height,  
  Volume.
```

If expressions (guard patterns)

ifs provide a way to express conditions alternative to guards (in fact, ifs are called – somewhat confusingly – guard patterns in Erlang). An **if expression**:

```
if
    C1 -> E1;
    ⋮
    Cm -> Em
end
```

evaluates to the expression E_k of the first guard C_k in textual order that evaluates to true; if no guard evaluates to true, evaluating the **if** expression fails.

```
age(Age) ->
    if Age > 21 -> adult;
       Age > 11 -> adolescent;
       Age > 2  -> child;
       true    -> baby end.
```

Case expressions

Cases provide an additional way to use pattern matching to define expressions. A **case expression**:

```
case E of
  P1 -> E1;
  ⋮
  Pm -> Em
end
```

evaluates to $E_k \langle P_k \triangleq T \rangle$, where E evaluates to T , and P_k is the first pattern in textual order that T matches to; if T matches no pattern, evaluating the **case** expression fails. Patterns may include **when** clauses, with the same meaning as in function definitions.

```
years(X) ->
  case X of {human, Age} -> Age;
            {dog, Age}   -> 7*Age;
            _            -> cant_say end.
```

Which one should I use?

Having several **different ways** of defining a function can be confusing. There are no absolute rules, but here are some **guidelines** that help you write idiomatic code:

- the first option to try is using pattern matching directly in a function's arguments, using different clauses for different cases
- if parts of a pattern expression depend on others, you may consider using **case** expressions to have nested patterns
- you do not need **if** expressions very often (but it's good to know what they mean, and sometimes they may be appropriate)

Recursion

Recursion in programming

Recursion is a **style of programming** where functions are defined in terms of themselves.

The **definition** of a **function** f is **recursive** if it includes a call to f (directly or indirectly).

```
% compute  $X^N$   
power(X, 0) -> 1;  
power(X, N) -> X * power(X, N-1).
```

↑
recursive call

Recursion in mathematics

Recursion is a **style of definition** where concepts are defined in terms of themselves.

The **definition** of a **concept** is **recursive** if it defines the concept in terms of an instance of the concept itself.

Definition of **natural numbers**:

- **0** is a natural number;
- if **n** is a natural number then **$n + 1$** is a natural number.



recursive/inductive definition

Recursion: from math to programming

Recursion in programming provides a natural way of implementing recursive definitions in mathematics.

Factorial of a nonnegative integer n :

$$n! \triangleq \underbrace{n \cdot (n-1) \cdot \dots \cdot 1}_{n \text{ terms}}$$

Recursion: from math to programming

Recursion in programming provides a natural way of implementing recursive definitions in mathematics.

Factorial of a nonnegative integer n :

$$n! \triangleq n \cdot \underbrace{(n-1) \cdot \dots \cdot 1}_{n \text{ terms}} = n \cdot \underbrace{(n-1) \cdot \dots \cdot 1}_{n-1 \text{ terms}}$$

Recursion: from math to programming

Recursion in programming provides a natural way of implementing recursive definitions in mathematics.

Factorial of a nonnegative integer n :

$$n! \triangleq \underbrace{n \cdot (n-1) \cdot \dots \cdot 1}_{n \text{ terms}} = n \cdot \underbrace{(n-1) \cdot \dots \cdot 1}_{n-1 \text{ terms}}$$

$$n! \triangleq \begin{cases} 1 & \text{if } 0 \leq n \leq 1 \leftarrow \text{base case} \\ n \cdot (n-1)! & \text{if } n > 1 \leftarrow \text{recursive/inductive case} \end{cases}$$

Recursion: from math to programming

Recursion in programming provides a natural way of implementing recursive definitions in mathematics.

Factorial of a nonnegative integer n :

$$n! \triangleq \begin{cases} 1 & \text{if } 0 \leq n \leq 1 \leftarrow \text{base case} \\ n \cdot (n-1)! & \text{if } n > 1 \leftarrow \text{recursive/inductive case} \end{cases}$$

```
factorial(N) when N =< 1 -> 1;           % base case
factorial(N)           -> N * factorial(N-1). % recursive case
```

↑
recursive call

How does recursion work?

- Each recursive call triggers an **independent evaluation** of the recursive function. (Independent means that it works on its own private copy of actual argument expressions.)
- When a recursive instance terminates evaluation, its value is used in the calling instance **for its own evaluation**.

entry $\xrightarrow{\text{call}}$ factorial(3)

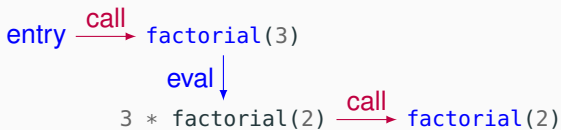
How does recursion work?

- Each recursive call triggers an **independent evaluation** of the recursive function. (Independent means that it works on its own private copy of actual argument expressions.)
- When a recursive instance terminates evaluation, its value is used in the calling instance **for its own evaluation**.

entry $\xrightarrow{\text{call}}$ factorial(3)
 eval ↓
 3 * factorial(2)

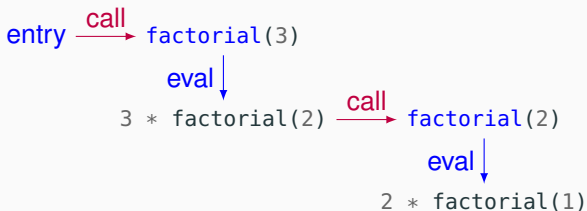
How does recursion work?

- Each recursive call triggers an **independent evaluation** of the recursive function. (Independent means that it works on its own private copy of actual argument expressions.)
- When a recursive instance terminates evaluation, its value is used in the calling instance **for its own evaluation**.



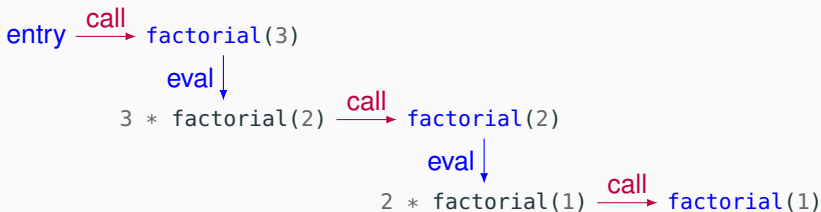
How does recursion work?

- Each recursive call triggers an **independent evaluation** of the recursive function. (Independent means that it works on its own private copy of actual argument expressions.)
- When a recursive instance terminates evaluation, its value is used in the calling instance **for its own evaluation**.



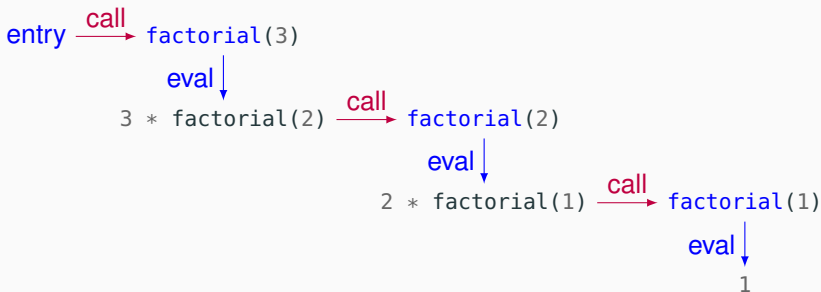
How does recursion work?

- Each recursive call triggers an **independent evaluation** of the recursive function. (Independent means that it works on its own private copy of actual argument expressions.)
- When a recursive instance terminates evaluation, its value is used in the calling instance **for its own evaluation**.



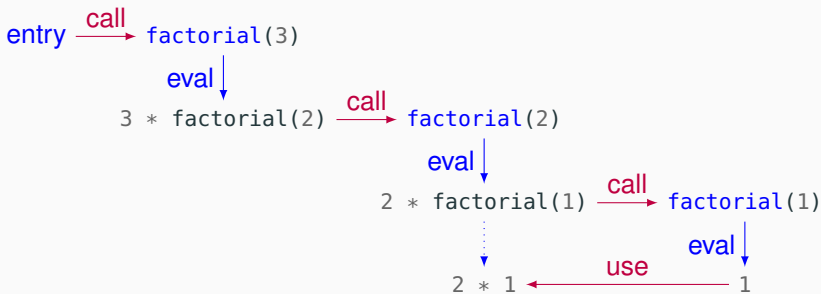
How does recursion work?

- Each recursive call triggers an **independent evaluation** of the recursive function. (Independent means that it works on its own private copy of actual argument expressions.)
- When a recursive instance terminates evaluation, its value is used in the calling instance **for its own evaluation**.



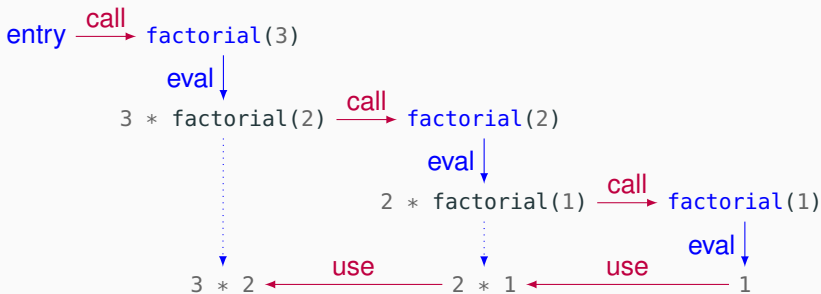
How does recursion work?

- Each recursive call triggers an **independent evaluation** of the recursive function. (Independent means that it works on its own private copy of actual argument expressions.)
- When a recursive instance terminates evaluation, its value is used in the calling instance **for its own evaluation**.



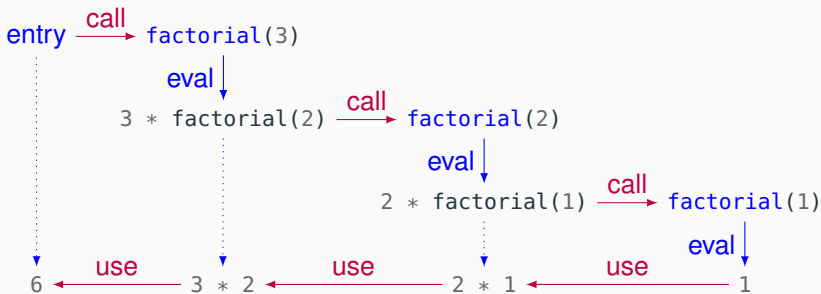
How does recursion work?

- Each recursive call triggers an **independent evaluation** of the recursive function. (Independent means that it works on its own private copy of actual argument expressions.)
- When a recursive instance terminates evaluation, its value is used in the calling instance **for its own evaluation**.



How does recursion work?

- Each recursive call triggers an **independent evaluation** of the recursive function. (Independent means that it works on its own private copy of actual argument expressions.)
- When a recursive instance terminates evaluation, its value is used in the calling instance **for its own evaluation**.



Recursion as a design technique

Recursion as a programming technique is useful to design programs using the **divide and conquer** approach:

To solve a **problem instance** P , **split** P into problem instances P_1, \dots, P_n chosen such that:

1. Solving P_1, \dots, P_n is **simpler** than solving P directly
2. The solution to P is a **simple combination** of the solutions to P_1, \dots, P_n

In functional programming, **recursion** goes hand in hand with **pattern matching**:

- **pattern matching** splits a function argument's into **smaller bits** according to the input's **structure**
- **recursive** function definitions define the **base cases directly**, and **combine** simpler cases into more complex ones

Recursive functions: sum of list

Define a function `sum(L)` that returns the **sum of all numbers** in `L`.

1. The base case (the simplest possible) is when `L` is empty:

`sum([]) -> 0`

2. Let now `L` be non-empty: a non empty list matches the pattern

`[H|T]`

- `H` is a single number, which we must add to the result
- `T` is a list, which we can sum by calling `sum` recursively

Recursive functions: sum of list

Define a function `sum(L)` that returns the **sum of all numbers** in `L`.

1. The base case (the simplest possible) is when `L` is empty:

```
sum([]) -> 0
```

2. Let now `L` be non-empty: a non empty list matches the pattern

`[H|T]`

- `H` is a single number, which we must add to the result
- `T` is a list, which we can sum by calling `sum` recursively

```
sum([])      -> 0;           % base case
sum([H|T])   -> H + sum(T). % recursive case
```

Recursive functions: sum of list

Define a function `sum(L)` that returns the **sum of all numbers** in `L`.

1. The base case (the simplest possible) is when `L` is empty:

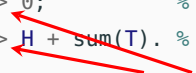
```
sum([]) -> 0
```

2. Let now `L` be non-empty: a non empty list matches the pattern

`[H|T]`

- `H` is a single number, which we must add to the result
- `T` is a list, which we can sum by calling `sum` recursively

```
sum([])      -> 0;           % base case
sum([H|T])   -> H + sum(T). % recursive case
```



can we switch the order of clauses?

To make the function more robust, we can skip over all non-numeric elements:

```
sum([])                -> 0;           % base case
sum([H|T]) when is_number(H) -> H + sum(T); % recursive case 1
sum([_|T])             -> sum(T).      % recursive case 2
```


Recursive functions: last list element

Define a function `last(L)` that returns the **last element** of `L`.

1. When `L` is empty, `last` is undefined, so we can ignore this case
2. The simplest case is then when `L` is one element: `last([E]) -> E`
3. Let now `L` be non-empty: a non empty list matches the pattern `[H|T]`
 - `E` is the first element, which we throw away
 - `T` is a list, whose last element we get by calling `last` recursively

```
last([E])    -> E;           % base case
last([_|T]) -> last(T).    % recursive case
```

Can `T` match the empty list?

Recursive functions: last list element

Define a function `last(L)` that returns the **last element** of `L`.

1. When `L` is empty, `last` is undefined, so we can ignore this case
2. The simplest case is then when `L` is one element: `last([E]) -> E`
3. Let now `L` be non-empty: a non empty list matches the pattern `[H|T]`
 - `E` is the first element, which we throw away
 - `T` is a list, whose last element we get by calling `last` recursively

```
last([E]) -> E;           % base case
last([_|T]) -> last(T).  % recursive case
```

Can `T` match the empty list? No, because neither of the clauses match the empty list. To make this explicit, we could write:

```
last([E|[]]) -> E;       % base case
last([_|T]) -> last(T).  % recursive case
```

Tail recursion

A **recursive function** f is **tail recursive** if the evaluation of f 's body evaluates the recursive call **last**.

% general recursive:

```
power(_, 0) ->  
    1;  
power(X, N) ->  
    X * power(X, N-1).
```

% tail recursive:

```
power(X, N) ->  
    power(X, N, 1).  
power(_, 0, Accumulator) ->  
    Accumulator;  
power(X, N, Accumulator) ->  
    power(X, N-1, X*Accumulator).
```

Tail-recursive functions are generally more efficient than general-recursive functions. When efficiency is **not an issue**, there is no need to use a tail-recursive style; but we will use tail-recursive functions extensively (and naturally) when implementing servers.

Tail recursion

A **recursive function** f is **tail recursive** if the evaluation of f 's body evaluates the recursive call **last**.

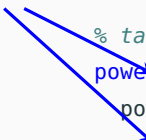
overloading: two functions `power/2` and `power/3`

% general recursive:

```
power(_, 0) ->
  1;
power(X, N) ->
  X * power(X, N-1).
```

% tail recursive:

```
power(X, N) ->
  power(X, N, 1).
power(_, 0, Accumulator) ->
  Accumulator;
power(X, N, Accumulator) ->
  power(X, N-1, X*Accumulator).
```



Tail-recursive functions are generally more efficient than general-recursive functions. When efficiency is **not an issue**, there is no need to use a tail-recursive style; but we will use tail-recursive functions extensively (and naturally) when implementing servers.

Impure and higher-order functions

Where are all the statements, assignments, loops?

Statements, assignments, and loops are not available as such in Erlang. Everything is an **expression** that gets **evaluated**.

- (side-effect free) expressions are used instead of statements
- (pure) functions return **modified copies** of their arguments instead of modifying the arguments themselves
- one-time bindings are used instead of assignments that change values to variables
- recursion is used instead of loops

The sparse presence of side effects helps make functional programs **higher level** than imperative ones.

Printing to screen

The expressions we have used so far have no side effects, that is they do not change the state but simply evaluate to a value. Not all expressions are side-effect free in Erlang. **Input/output** is an obvious exception: to print something to screen, we **evaluate** an expression call, whose side effect is printing.

% print the string Format, interpreting control sequences on Data
`io:format(Format, Data)`

CONTROL SEQUENCE	DATA
~B	integer
~g	float
~s	string
~p	any Erlang term
~n	line break

```
1> io:format("~s ~B. ~p~n~s ~B~n", ["line", 1, true, "line", 2]).  
line 1. true  
line 2
```

Exception handling

Erlang has an exception handling mechanism that is similar to a functional version of Java's **try/catch/finally** blocks.

```
try Expr of  
    Success1 -> Expr1;  
    ...  
catch  
    Error1:Fail1 -> Recov1;  
    ...  
after After end
```

- The **try** blocks behaves like a **case** block
- If evaluating **Expr** raises an exception, it gets pattern matched against the clauses in **catch** (**Errork**'s are error types, **Failk**'s are patterns, and **Recovk**'s are expressions)
- Expression **After** in the **after** clause always gets evaluated in the end (but does not return any value: used to close resources)

Exception handling: example

Function `safe_plus` tries to evaluate the sum of its arguments; if evaluation succeeds, it returns the result; if evaluation raises a `badarith` exception, it returns `false`.

```
safe_plus(X, Y) ->  
  try X + Y of  
    N -> N  
  catch  
    error:badarith -> false  
  end.
```

Example of using it:

```
1> safe_plus(2, 3).  
5  
2> safe_plus(2, []).  
false
```

Functions are values too

Functions are **first-class** objects in Erlang: they can be passed around like any other values, and they can be **arguments** of functions.

A function f/k defined in module m is passed as argument **fun** $m:f/k$.

This makes it easy to define functions that apply other functions to values following a pattern.

```
% apply function F to all elements in list L
```

```
map(F, []) -> [];
```

```
map(F, [H|T]) -> [F(H)|map(F,T)].
```

```
1> map(fun m:age/1, [12, 1, 30, 56]). % we defined age before  
[adolescent,baby,adult,adult]
```

A function that takes another function as argument is called **higher-order**.

Inline functions

Sometimes it is necessary to **define** a function **directly in an expression** where it is used. For this we can use **anonymous functions** – also called lambdas, closures, or funs (the last is Erlang jargon):

```
fun  
  (A1) -> E1;  
  ⋮  
  (An) -> En  
end
```

where each A_k is a sequence of patterns, and each E_k is a body.

```
% double every number in the list  
1> map(fun (X)->2*X end, [12, 1, 30, 56]).  
[24,2,50,112]
```

Working on lists

Module `lists` includes many useful predefined functions to work on lists. These are some you should know about – but check out the full module documentation at <http://erlang.org/doc/man/lists.html>.

```
all(Pred, List)    % do all elements E of List satisfy Pred(E)?
any(Pred, List)   % does any element E of List satisfy Pred(E)?
filter(Pred, List) % all elements E of List that satisfy Pred(E)
last(List)        % last element of List
map(Fun, List)    % apply Fun to all elements of List
member(Elem, List) % is Elem an element of List?
reverse(List)     % List in reverse order
seq(From, To)     % list [From, From+1, ..., To]
seq(From, To, I)  % list [From, From+I, ..., ~To]
```

Folds

Several functions compute their result by recursively accumulating values from a list:

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

We can generalize this pattern into a single higher-order function `fold(F, R, L)`: starting from an **initial value** `R`, combine all elements of **list** `L` using **function** `F` and accumulate the result.

```
fold(_, Result, [])    -> Result;
fold(F, Result, [H|T]) -> F(H, fold(F, Result, T)).
```

Folds

Several functions compute their result by recursively accumulating values from a list:

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

We can generalize this pattern into a single higher-order function `fold(F, R, L)`: starting from an **initial value** `R`, combine all elements of **list** `L` using **function** `F` and accumulate the result.

```
fold(_, Result, [])    -> Result;
fold(F, Result, [H|T]) -> F(H, fold(F, Result, T)).
```

Using `fold`, we can define `sum` and `len`:

```
sum(L) -> fold(fun (X,Y)->X+Y end, 0, L).  len(L) -> fold(fun (X,Y)->1+Y end, 0, L).
```

Erlang module `lists` offers functions `foldr/3` (which behaves like our `fold`) and `foldl/3` (a tail-recursive version of `fold`, with the same arguments).

These slides' license

© 2016–2019 Carlo A. Furia, Sandro Stucki



Except where otherwise noted, this work is licensed under the Creative Commons Attribution-ShareAlike 4.0 International License.

To view a copy of this license, visit

<http://creativecommons.org/licenses/by-sa/4.0/>.