Elixir's Set-Theoretic Type System

Robert Ellen

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Summary

> Q: ..., A: "A static type system!"
> rich history of static type systems for BEAM languages
> R&D project to build the definitive static type system for Elixir
> gradual semantic subtyping with innovations for Elixir's features
> gradual introduction into production Elixir compiler

Disclaimer

> I am not a student of programming language / type theory
> mistakes are my own
> check out the paper and references

The Erlang Ecosystem

What is the Erlang Ecosystem?

A group of languages, libraries, frameworks, and applications that are implemented on top of the Erlang virtual machine, the BEAM.
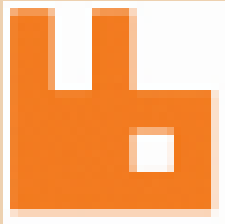
Languages include:
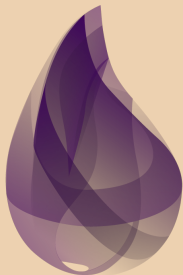
...plus dozens more

What is the Erlang Ecosystem?

Libraries and frameworks include:

OTP

What is the Erlang Ecosystem?

Built around a shared value in:

> massive concurrency
> fault-tolerance
> simplicity
> acknowledging the errors will occur so let's deal with them
  – "Let it crash"–have a plan to restart sub-systems when they crash

A brief history of Erlang

A brief history of Erlang

covered in my 2013 talk, but tonight...

A brief history of Erlang

A brief history of Erlang

> developed in the mid 1980s at Ericsson
> to run on next generation telephone switches
- concurrent, fault-tolerant, distributed, soft real-time
- strong, dynamically typed, impure, functional, simple
- reports of 1200k LOC and "nine nines" of uptime on the AXD301 switch
- reports of market penetration of > 50% in mobile telephony switches
> solved web-scale in the '80s

The BEAM and OTP

The BEAM

> Erlang's virtual machine / runtime system
> lightweight processes, SMP, low-latency IO, soft realtime, minimal locks
> multi-generational, per-process garbage collector
> asynchronous, location-transparent, message passing IPC
> hot-code-loading
> powerful REPL and introspection tools
> new JIT compiler (BEAM bytecode to machine code)

The OTP libraries

> Erlang's "standard library"
> dozens of modules providing various typical stdlib stuff
> core of which are for supervision trees
>> – `gen_server` - actors / workers
>> – supervisors - handling starting/stopping/restarting `gen_servers`

supervision trees
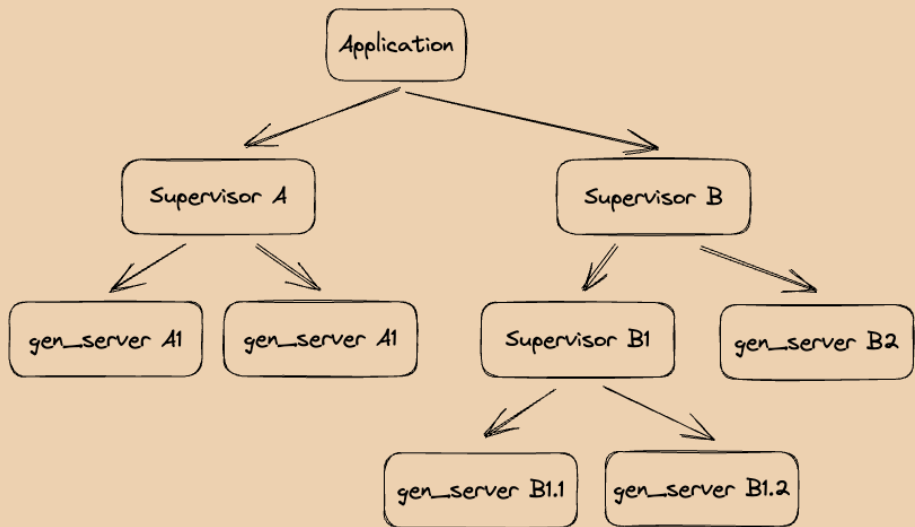
Brief history of Elixir

> created by José Valim starting in 2012
> inspired by Erlang, Ruby, and, to a lesser extent, Lisp
> like Erlang, the language is quite stable, imminent release of v1.18
> has gone from web applications to embedded systems and numerical analysis and ML/AI

Features of Elixir

> Ruby-like syntax while retaining most of Erlang's semantics
  - ..., immutable data, HoF, side-effects anywhere, dynamically-typed, ...
> interoperate with Erlang
> hygienic macros
> ad-hoc polymorhism with protocols
> highly ergonomic build tool: `mix`
> modern package manager: `hex`
> excellent unit test tool: exunit
> opinionated formatter
> did I mention dynamically-typed?

Typing BEAM languages

Marlow & Wadler - 1997

"We can stop waiting for functional languages to be used in practice–that day is here!"

> threw away Hindley-Milner: $U = V$ – this would not work with existing Erlang codebases
> opted for strictly more general "semantic sub-typing" instead: $U \subseteq V$
> this approach developed by Aiken & Wimmers 1993

eqWAlizer

> Developed by Meta for WhatsApp
> set-theoretic gradual typing
> https://github.com/WhatsApp/eqwalizer

Static analysis tools

> rely on the Erlang Typespec notation - not checked by compiler
> dialyzer
  – success-typing based on whole-program analysis
  – will only fail if it can prove there's a problem (no false positives)
  – Linhahl & Sagonas, 2006
> gradualizer - gradual set-theoretic-inspired typing

Typed BEAM languages with alternate semantics

> Hamler - PureScript for the BEAM
> Caramel - ML for the BEAM
> Gleam - Rust/Ocaml/Elm inspired - HM type system
  – see my May 2024 talk
> ...

Elixir's set-theoretic type system

Elixir's set-theoretic type system

A research and development project to gradually introduce a static type system to Elixir.

Requirements

> no modification to the syntax of Elixir expressions
> gradual typing
> extract maximum type information from patterns and guards
> mode to emit warnings when explicitly using gradual typing
> type annotations across language before advanced features
> initially - typing does not modify the compilation of Elixir code

Features of the type system

> semantic subtyping hence set-theoretic
> parametric polymorphism with local type inference
>> – type variables
>> – requires some type annotations–but not everywhere
> use patterns and guards
> typing maps in all use-cases
> gradual typing
> strong arrows
> typing ad-hoc polymorphism

Semantic subtyping

> establish subtyping relationships between types based on the semantic
  meaning of values of the types
> semantic meaning derived from treating types as sets, values as set members
> set operations on types: union, intersection, and negation

Semantic subtyping

> - in comparison to Hindley-Milner, relax $U = V$ to $U \subseteq V$
> - strictly more general–an extension to HM
> - Frish et. al. referencing Aiken & Wimmers (also ref. by Marlow & Wadler)
> - good idea because dynamically-typed languages variables can hold different types at run-time: hence union-ing

Subtyping in type checking

> subtyping is a means to typechecking programs due to "subsumption"

$$\frac{e{:}T_1 \quad T_1{<:}T_2}{e{:}T_2}$$

> given some expression e and types T_1 and T_2, if the type of e is T_1 and T_1 is a subtype of T_2 then e can be considered to also be of type T_2

Set-theoretic reasoning and type annotations

> the notation is based on Erlang/Elixir typespec

```
integer(), boolean(), binary(), float(), ... # indivisible types

atom(), :foo, # divisible types

list(element()) # element() is a concrete type

container(a) when a: term() # a is a type variable

%{required(:name) ⇒ binary(), ... }
# a map that must have at least a key :name of value binary()

%{required(:name) ⇒ binary(), required(:age) ⇒ integer()}
# a map that can have only :name and :age keys
```

Set-theoretic reasoning and type annotations

> special types

```
term() # top type

none() # bottom type

dynamic() # any type
```

Set-theoretic reasoning and type annotations

```
# union
integer() or boolean()

# intersection
# say we have these typespec types
@type person :: %{:name ⇒ binary(), :age ⇒ integer()}
@type school_record :: %{:school ⇒ binary(), :gpa ⇒ float()}
# and we want a student() type
person() and school_record()

# negation
not integer()

# combinations - e.g. all atoms except true, false, nil
atom() and not(boolean() or nil)
```

Set-theoretic reasoning and type annotations

`term() ` $\equiv$ ` not none()`

`none() ` $\equiv$ ` not term()`

`boolean() and integer() ` $\equiv$ ` none()`

Set-theoretic reasoning and type annotations

> type annotation of functions with $ - only reserved symbol left unused!
> function arguments comma-separated
> function application →

```
$ (integer(), integer()) → integer()
def add(x,y), do: x + y
```

Set-theoretic reasoning and type annotations

> function types are set-theoretic too

```
$ integer() → integer()
def negate(x) when is_integer(x), do: -x

$ (integer(), integer()) → integer()
def subtract(a, b) when is_integer(a) and is_integer(b) do
  a + negate(b)
end
```

Set-theoretic reasoning and type annotations

> function types are set-theoretic too: let's expand negate to `boolean()`

```
$ (integer() or boolean()) → (integer() or boolean())
def negate(x) when is_integer(x), do: -x
def negate(x) when is_boolean(x), do: not x
```

Set-theoretic reasoning and type annotations

```
$ (integer() or boolean()) → (integer() or boolean())
def negate(x) when is_integer(x), do: -x
def negate(x) when is_boolean(x), do: not x

Type warning:
  | def subtract(a, b) when is_integer(a) and is_integer(b) do
  |   a + negate(b)
        ^ the operator + expects integer(), integer() as arguments
          but the second argument can be integer() or boolean()
```

Set-theoretic reasoning and type annotations

```
$ (integer() or boolean()) → (integer() or boolean())
def negate(x) when is_integer(x), do: -x
def negate(x) when is_boolean(x), do: not x

Type warning:
  | def subtract(a, b) when is_integer(a) and is_integer(b) do
  |   a + negate(b)
        ^ the operator + expects integer(), integer() as arguments
          but the second argument can be integer() or boolean()

# a more precise (and correct in regards to subtract) type
$ (integer() → integer()) and (boolean() → boolean())

# negate is in the set of functions integer() → integer()
# and the set of functions boolean() → boolean()
```

Polymorphic with local type inference

> type variables: a, b - no parentheses
> local type inference
  – functions must have type annotations
  – types are inferred for arguments and return types

Polymorphic with local type inference

```
$ (list(a), a → b) → list(b) when a: term(), b: term()
def map([], _), do: []
def map([x | xs], f), do:  [f.(x) | map(xs, f)]

x = map([1, 2, 3], &double/1)
# type system infers type of double and x
# a and b are infered to be integers
```

Guards and pattern-matching

> Elixir has rich run-time testing of types
> the type system can type captured variables and variables in guards

```
def elem_at([x | rest] = xs, pos) when is_integer(pos) do ...
```

Guards and pattern-matching

> "type narrowing" can check exhaustiveness of case expressions
> type system is conservative: case branches must handle xs being any map or list

```
def elem_at(xs, pos) when is_map(xs) or is_list(x) do
  case xs do
    %{} → # get for map
    [] → # get for list
    _ → # redundant
  end
end
```

Maps as "records" and "dictionaries"
> maps can represent records, dictionaries, and structs

```
ashley = %{name: "Ashley", age: 42}
# %{required(:name)⇒ binary(),
#    required(:age) ⇒ integer()}


words = "The Elixir Type System ... "
word_count = wc(words) # :: %{optional(binary()) ⇒ integer()}
word_count["Elixir"] # 42

defstruct [:id , name: "", age: 0]
# %{
#    :__struct__ ⇒ :"User",
#    :id ⇒ term(),
#    :name ⇒ binary(),
#    :age ⇒ integer()
# }
```

Maps as "records" and "dictionaries"

> the type system treats maps as open or closed
>   – open means there are potentially unknown keys
> strict or dynamic access changes type inference

```
user.first_name # user :: %{:first_name ⇒ term(), ... }

middle = person["middle_name"]
# person :: %{optional("middle_name") ⇒ term(), ... } ⇒ %{ ... }
# middle :: binary() or nil

ashley = %{name: "Ashley", age: 42}
# ashley :: %{:name ⇒ binary(), :age ⇒ integer()}
```

Maps as "records" and "dictionaries"

> subtyping maps feels like structural subtyping...

```
ashley = %{name: "Ashley", age: 42}
# %{:name ⇒ binary(), :age ⇒ integer()}

ashley_at_school = %{name: "Ashley", age: 42, gpa: 6.75}
#  %{:name ⇒ binary(),
#    :age ⇒ integer(),
#    :gpa ⇒ float()}

def enroll(%{name: _, age: _} = person) do  ...
```

> but the type system innovates semantic subtyping to handle maps in all cases
  – Castagna 2023

Gradual typing with `dynamic()`

> as per requirements, avoid boiling the ocean in existing codebases
> gradual typing: see TypeScript, gradualizer
> a type that "materialises" into any other type
> a type that can be the subtype and supertype of any other type
>> – `term()` can only be the later, so need a new type
> `dynamic()`

Gradual typing with `dynamic()`

> "sound gradual typing" - Siek & Taha 2006
> in the presence of dynamic typing, partial static typing still works
> a static type annotation/inference guarantees an expression either:
> - never returns
> - returns a value of the static type
> - emits a runtime exception
> necessitates the addition of runtime checks to the compiled program
> Elixir innovation: as per requirements, no change to the compiled program

Halting `dynamic()` propagation

> VM and programmer type checks halt the propagation of `dynamic()`
> functions with these checks are referred to as "strong arrows"

```
$ integer() → integer()
def id_strong(x) when is_integer(x), do: x

$ integer() → integer()
def id_weak(x), do: x

# due to "weak" vs "strong" arrows, the following
# is an acceptable type annotation for `ids(x)`
$ dynamic() → {dynamic(), integer()}
def ids(x), do: {id_weak(x), id_strong(x)}
```

"Solving" the expression problem with protocols

> "ad-hoc" polymorphism akin to typeclasses
> the type system will union all implementations of `String.Chars` to define a type `String.Chars.t()`

```
defmodule MyNewType do
  defstruct [:data]
end

defimpl String.Chars, for: MyNewType do
  def to_string(value) do ... end
end
```

"Solving" the expression problem with protocols

> combines with parametric polymorphism
> please say it is so!

```
# functory.ex
$ Functory.t(a), (a → b) → Functory.t(b)
    when a: term(),  b: term()
def map(xs, f)
...
# my_struct.ex
defimpl Functory, for: MyStruct do
  def map(xs, f) do ... end
end
```

Gradually introducing the system

> don't discount the chance of a deal-breaker in prod code taking them back to the drawing board
> phased approach to introducing the experimental system into production Elixir compiler
>> – local inference of some Elixir types: v1.17
>> – type all Elixir data types and add typing of (and use information inferred from) pattern matching and guards: v1.18
>> – type annotations for functions: v1.?

Demo time!

Conclusion

> Static Type Systems Now! (or soon)
> innovations on semantic subtyping / set-theoretic type
> incremental release–stick with dialyzer for now and hope for a migration tool

References

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Thank you

I'll post slides somewhere (luma/discord/?) soon.

For my other talks as well...