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**Theoretical Foundation of
Functional Language with Inductive Constructions
that compiles to Pure Type System**

Technical Article

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Kyiv 2016

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1 Introduction

1.1 Verifiable Functional Compiler

This article describes the frontend language **Exe** along with its categorical semantic that compiles to a pure type system minimal core **Om** — the non-recursive subset of dependent type theory from which you can extract: LLVM code, untyped lambda code with erased type information, or even *System F_ω* programs. As a top-level task we expect to produce lean verifiable functional compiler pipeline, but as an milestone task we just produce concise working prototype in Erlang language.

1.2 General Purpose Functional Language Exe

General purpose function language with functors, lambdas on types, recursive algebraic types, higher order functions and embedded process calculus with corecursion, free monad for effects encoding. This language will be called Exe and dedicated to be high level general purpose functional programming language frontend to small core of dependent type system without recursion called Om. This language indended to be useful enough to encode KVS, N2O and BPE applications.

1.3 Intermediate Language Om

An intermediate Om language is base on Henk [1] languages described first by Erik Meyer and Simon Peyton Jones in 1997. Leter on in 2015 Morte impementation of Henk design appeared in Haskell, using Boem-Berrarducci encoding of non-recursive lamda terms. It is based only on π , λ and *apply* constructions, one axiom and four deduction rules. The design of Om language resemble Henk and Morte both design and implementation. This language indended to be small, conside, easy provable and clean and produce verifiable peace of code that can be distributed over the networks and compiled at target with safe linkage.

1.4 Target Erlang VM and LLVM platforms

This works expect to compile to limited target platforms. For now Erlang, Haskell and LLVM is awaiting. Erlang version is expected to be useful both on LING and BEAM Erlang virtual machines.

2 General Purpose Language

2.1 Category Theory, Programs and Functions

Category theory is widely used as an instrument for mathematicians for software analysis. Category theory could be treated as an abstract algebra of functions. Let's define an Category formally: **Category** consists of two lists: the one is morphisms (arrows) and the second is objects (domains and codomains of arrows) along with associative operation of composition and unit morphism that exists for all objects in category.

The formation axioms of objects and arrows are not given here and autopostulating yet. Formation axioms will be introduced during exponential definition. Objects A and B of an arrow $f : A \rightarrow B$ are called **domain** and **codomain** respectively.

Intro axioms – associativity of composition and left/right unit arrow compositions show that categories are actually typed monoids, which consist of morphisms and operation of composition. There are many languages to show the semantic of categories such as commutative diagrams and string diagrams however here we define here in proof-theoretic manner:

$$\begin{array}{c}
 \frac{\Gamma \vdash f : A \rightarrow B \quad \Gamma \vdash g : B \rightarrow C}{\Gamma \vdash g \circ f : A \rightarrow C} \qquad \frac{}{\Gamma \vdash id_A : A \rightarrow A} \\
 \\
 \frac{\Gamma \vdash f : B \rightarrow A \quad \Gamma \vdash g : C \rightarrow B \quad \Gamma \vdash h : D \rightarrow C}{\Gamma \vdash (f \circ g) \circ h = f \circ (g \circ h) : D \rightarrow A} \qquad \frac{\Gamma \vdash f : A \rightarrow B}{\Gamma \vdash f \circ id_A = f : A \rightarrow B} \\
 \\
 \frac{}{\Gamma \vdash id_B \circ f = f : A \rightarrow B}
 \end{array}$$

Composition shows an ability to connect the result space of the previous evaluation (codomain) and the arguments space of the next evaluation (domain). Composition is fundamental property of morphisms that allows us to chain evaluations.

1. $A : *$
2. $A : *, B : * \implies f : A \rightarrow B$
3. $f : B \rightarrow C, g : A \rightarrow B \implies f \circ g : A \rightarrow C$
4. $(f \circ g) \circ h = f \circ (g \circ h)$
5. $A \implies id : A \rightarrow A$
6. $f \circ id = f$
7. $id \circ f = f$

2.2 Algebraic Types and Cartesian Categories

After composition operation of construction of new objects with morphisms we introduce operation of construction cartesian product of two objects A and B of a given category along with morphism product $\langle f, g \rangle$ with a common domain, that is needed for full definition of cartesian product of $A \times B$.

This is an internal language of cartesian category, in which for all two selected objects there is an object of cartesian product (sum) of two objects along with its \perp terminal (or \top coterminial) type. Exe languages is always equiped with product and sum types.

Product has two eliminators π with an common domain, which are also called projections of an product. The sum has eliminators i with an common codomain. Note that eliminators π and i are isomorphic, that is $\pi \circ \sigma = \sigma \circ \pi = id$.

$$\begin{array}{c}
\frac{\Gamma x : A \times B}{\Gamma \vdash \pi_1 : A \times B \rightarrow A; \Gamma \vdash \pi_2 : A \times B \rightarrow B} \\
\\
\frac{\Gamma \vdash a : A \quad \Gamma \vdash b : B}{\Gamma \vdash (a, b) : A \times B} \\
\\
\frac{}{\Gamma \vdash \perp} \\
\\
\frac{\Gamma \vdash a : A \quad \Gamma \vdash b : B}{\Gamma \vdash a \mid b : A \otimes B} \\
\\
\frac{\Gamma x : A \otimes B}{\Gamma \vdash \beta_1 : A \rightarrow A \otimes B; \Gamma \vdash \beta_2 : B \rightarrow A \otimes B}
\end{array}$$

The \perp type in Haskell is used as **undefined** type (empty sum component presented in all types), that is why Hask category is not based on cartesian closed but CPO [26]. The \perp type has no values. The \top type is known as unit type or zero tuple () often used as an default argument for function with zero arguments. Also we include here an axiom of morphism product which is given during full definition of product using commutative diagram. This axiom is needed for applicative programming in categorical abstract machine. Also consider co-version of this axiom for $[f, g] : B + C \rightarrow A$ morphism sums.

$$\begin{array}{c}
\frac{\Gamma \vdash f : A \rightarrow B \quad \Gamma \vdash g : A \rightarrow C \quad \Gamma \vdash B \times C}{\Gamma \vdash \langle f, g \rangle : A \rightarrow B \times C} \\
\\
\begin{array}{c}
\pi_1 \circ \langle f, g \rangle = f \\
\pi_2 \circ \langle f, g \rangle = g \\
\langle f \circ \pi_1, f \circ \pi_2 \rangle = f \\
\langle f, g \rangle \circ h = \langle f \circ h, g \circ h \rangle \\
\langle \pi_1, \pi_2 \rangle = id
\end{array}
\end{array}$$

2.3 Exponential, λ -calculus and Cartesian Closed Categories

Being an internal language of cartesian closed category, lambda calculus except variables and constants provides two operations of abstraction and applications which defines complete evaluation language with higher order functions, recursion and corecursion, etc.

To explain functions from the categorical point of view we need to define categorical exponential $f : A^B$, which are analogue to functions $f : A \rightarrow B$. As we already defined the products and terminals we could define an exponentials with three axioms of function construction, one eliminator of application with apply a function to its argument and axiom of currying the function of two arguments to function of one argument.

$$\begin{array}{c}
\frac{\Gamma x : A \vdash M : B}{\Gamma \vdash \lambda x . M : A \rightarrow B} \\
\\
\frac{\Gamma f : A \rightarrow B \quad \Gamma a : A}{\Gamma \vdash \text{apply } f \ a : (A \rightarrow B) \times A \rightarrow B} \\
\\
\frac{\Gamma \vdash f : A \times B \rightarrow C}{\Gamma \vdash \text{curry } f : A \rightarrow (B \rightarrow C)}
\end{array}
\qquad
\begin{array}{l}
\text{apply} \circ \langle (\text{curry } f) \circ \pi_1, \pi_2 \rangle = f \\
\text{curry } \text{apply} \circ \langle g \circ \pi_1, \pi_2 \rangle = g \\
\text{apply} \circ \langle \text{curry } f, g \rangle = f \circ \langle \text{id}, g \rangle \\
(\text{curry } f) \circ g = \text{curry } (f \circ \langle g \circ \pi_1, \pi_2 \rangle) \\
\text{curry } \text{apply} = \text{id}
\end{array}$$

2.4 λ -language

$$\begin{array}{l}
\text{Objects : } \perp \mid \rightarrow \mid \times \\
\text{Morphisms : } \text{id} \mid f \circ g \mid \langle f, g \rangle \mid \text{apply} \mid \lambda \mid \text{curry}
\end{array}$$

2.5 Functors, Λ -calculus

Functor comes as a notion of morphisms in categories whose objects are categories. Functors preserve compositions of arrows and identities, otherwise it would be impossible to deal with categories. One level up is notion of morphism between categories whose objects are Functors, such morphisms are called natural transformations. Here we need only functor definition which is needed as general type declarations.

$$\begin{array}{c}
\frac{\Gamma \vdash f : A \rightarrow B}{\Gamma \vdash F f : (A \rightarrow B) \rightarrow (F a \rightarrow F b)} \\
\\
\frac{\Gamma \vdash \text{id}_A : A \rightarrow A}{\Gamma \vdash F \text{id}_A = \text{id}_{FA} : F A \rightarrow F A} \\
\\
\frac{\Gamma \vdash f : B \rightarrow C, g : A \rightarrow B}{\Gamma \vdash F f \circ F g = F(f \circ g) : F A \rightarrow F C}
\end{array}$$

We start thinking of functors on dealing with typed theories, because functors usually could be seen as higher order type con

2.6 Algebras

F-Algebras gives us a categorical understanding recursive types. Let $F : C \rightarrow C$ be an endofunctor on category C . An F-algebra is a pair (C, ϕ) , where C is an object and $\phi : F C \rightarrow C$ an arrow in the category C . The object C is the carrier and the functor F is the signature of the algebra. Reversing arrows gives us F-Coalgebra.

$$\begin{array}{ccc}
 F C & \xrightarrow{\varphi} & C \\
 F f \downarrow & & \downarrow f \\
 F D & \xrightarrow{\psi} & D
 \end{array}
 \qquad
 \begin{array}{ccc}
 C & \xrightarrow{\varphi} & F C \\
 f \downarrow & & \downarrow F f \\
 D & \xrightarrow{\psi} & F D
 \end{array}$$

$$f \circ \varphi = \psi \circ F f \qquad \psi \circ f = F f \circ \varphi$$

2.7 Initial Algebras

A F-algebra $(\mu F, in)$ is the initial F-algebra if for any F-algebra (C, φ) there exists a unique arrow $\llbracket \varphi \rrbracket : \mu F \rightarrow C$ where $f = \llbracket \varphi \rrbracket$ and is called catamorphism. Similar a F-coalgebra $(\nu F, out)$ is the terminal F-coalgebra if for any F-coalgebra (C, φ) there exists unique arrow $\llbracket \varphi \rrbracket : C \rightarrow \nu F$ where $f = \llbracket \varphi \rrbracket$

$$\begin{array}{ccc}
 F \mu F & \xrightarrow{in} & \mu F \\
 F \llbracket \varphi \rrbracket \downarrow & & \downarrow \llbracket \varphi \rrbracket \\
 F C & \xrightarrow{\varphi} & C
 \end{array}
 \qquad
 \begin{array}{ccc}
 C & \xrightarrow{\phi} & F C \\
 \llbracket \varphi \rrbracket \downarrow & & \downarrow F \llbracket \varphi \rrbracket \\
 \nu F & \xrightarrow{out} & F \nu F
 \end{array}$$

$$f \circ in = \varphi \circ F f \equiv f = \llbracket \varphi \rrbracket \qquad out \circ f = F f \circ \varphi \equiv f = \llbracket \varphi \rrbracket$$

2.8 Recursive Types

As was shown by Wadler [2] we could deal with recursive equations having three axioms: one $fix : (A \rightarrow A) \rightarrow A$ fixedpoint axiom, and axioms $in : F T \rightarrow T$ and $out : T \rightarrow F T$ of recursion direction. We need to define fixed point as axiom because we can't define recursive axioms. This axioms also needs functor axiom defined earlier.

$$\frac{\Gamma \vdash M : F (\mu F)}{\Gamma \vdash in_{\mu F} M : \mu F}
 \qquad
 \frac{\Gamma \vdash M : A \rightarrow A}{\Gamma \vdash fix M : A}$$

$$\frac{\Gamma \vdash M : \mu F}{\Gamma \vdash out_{\mu F} M : F (\mu F)}$$

2.9 Inductive Types

There are two types of recursion: one is least fixed point (as $F_A X = 1 + A \times X$ or $F_A X = A + X \times X$), in other words the recursion with a base (terminated with a bounded value), lists and trees are examples of such recursive structures (so we call induction recursive sums); and the second is greatest fixed point or recursion without base (as $F_A X = A \times X$) — such kind of recursion on infinite lists (codata, streams, coinductive types) we can call recursive products.

As we know there are several ways to appear for variable in recursive algebraic type. Least fixpoint are known as an recursive expressions that have a base of recursion. Both recursive and corecursive datatypes could be encoded using Böhm-Berarducci encoding as an non-recursive definitions of folds that include in identity signature all the constructor components of (co)inductive type.

2.10 Nat

2.11 Lists

The data type of lists over a given set A can be represented as the initial algebra $(\mu L_A, in)$ of the functor $L_A(X) = 1 + (A \times X)$. Denote $\mu L_A = List(A)$. The constructor functions $nil : 1 \rightarrow List(A)$ and $cons : A \times List(A) \rightarrow List(A)$ are defined by $nil = in \circ inl$ and $cons = in \circ inr$, so $in = [nil, cons]$. Given any two functions $c : 1 \rightarrow C$ and $h : A \times C \rightarrow C$, the catamorphism $f = \llbracket [c, h] \rrbracket : List(A) \rightarrow C$ is the unique solution of the equation system:

$$\begin{cases} f \circ nil = c \\ f \circ cons = h \circ (id \times f) \end{cases}$$

where $f = foldr(c, h)$. Having this the initial algebra is presented with functor $\mu(1 + A \times X)$ and morphisms $sum [1 \rightarrow List(A), A \times List(A) \rightarrow List(A)]$ as catamorphism. Using this encoding the base library of List will have following form:

$$\begin{cases} foldr = \llbracket [f \circ nil, h] \rrbracket, f \circ cons = h \circ (id \times f) \\ len = \llbracket [zero, \lambda a n \rightarrow succ\ n] \rrbracket \\ (++) = \lambda xs\ ys \rightarrow \llbracket [\lambda(x) \rightarrow ys, cons] \rrbracket(xs) \\ map = \lambda f \rightarrow \llbracket [nil, cons \circ (f \times id)] \rrbracket \end{cases}$$

2.12 Inductive Encoding and List Module

```
inductive list : (A : *) → * :=
  (nil : list A)
  (cons : A → list A → list A)
```

$$\begin{cases} list = \lambda ctor \rightarrow \lambda cons \rightarrow \lambda nil \rightarrow ctor \\ cons = \lambda x \rightarrow \lambda xs \rightarrow \lambda list \rightarrow \lambda cons \rightarrow \lambda nil \rightarrow cons\ x\ (xs\ list\ cons\ nil) \\ nil = \lambda list \rightarrow \lambda cons \rightarrow \lambda nil \rightarrow nil \end{cases}$$

```
record lists : (A B : *) :=
  (len : list A → integer)
  ((++): list A → list A → list A)
  (map : (A → B) → (list A → list B))
  (filter : (A → bool) → (list A → list A))
```

$$\begin{cases} len = foldr (\lambda x\ n \rightarrow succ\ n)\ 0 \\ (++) = \lambda ys \rightarrow foldr\ cons\ ys \\ map = \lambda f \rightarrow foldr (\lambda x\ xs \rightarrow cons\ (f\ x)\ xs)\ nil \\ filter = \lambda p \rightarrow foldr (\lambda x\ xs \rightarrow if\ p\ x\ then\ cons\ x\ xs\ else\ xs)\ nil \\ foldl = \lambda f\ v\ xs \rightarrow foldr (\lambda x\ g \rightarrow (\lambda \rightarrow g\ (f\ a\ x)))\ id\ xs\ v \end{cases}$$

2.13 Process Calculus

The π -calculus of processes by Robert Milner is basic formalism for distributed computational theory and its implementations. From origin times of CSP developed by Hoare, Milner significantly evolved the theory and adopted it to contemporary telecommunication requirements, such as handovers in mobile networks.

2.14 Model

Core Axioms

We announce process and a fundamental function type of a special signature with protocol Σ and state X .

$$\begin{array}{c}
 \frac{\Gamma \vdash E, \Sigma, X \quad \Gamma \vdash action : \Sigma \times X \rightarrow \Sigma \times X}{\Gamma \vdash spawn\ action : \pi(\Sigma, X)} \\
 \\
 \frac{\Gamma \vdash pid : \pi(\Sigma, X) \quad \Gamma \vdash msg : \Sigma}{\Gamma \vdash join\ msg\ pid : \Sigma \times \pi_{\Sigma} \xrightarrow{\bullet} \Sigma; \Gamma \vdash send\ msg\ pid : \Sigma \times \pi_{\Sigma} \rightarrow \Sigma} \\
 \\
 \frac{\Gamma \vdash L : A + B, R : X + Y \quad \Gamma \vdash M : A \rightarrow X, N : B \rightarrow Y}{\Gamma \vdash receive\ L\ M\ N : L \xrightarrow{\bullet} R}
 \end{array}$$

Process Algebra

Алгебра процесів визначає базові операції мультиплексування двох чи декількох протоколів в рамках одного процесу (добуток), а також паралельного та повністю ізольованого запуску включно зі стеком та областю пам'яті (сума) на віртуальній машині.

$$\begin{array}{ll}
 \oplus & : \quad \pi \parallel \pi \\
 \otimes & : \quad \pi \mid \pi
 \end{array}$$

2.15 Intuitionistic Type Theory

Розбудовуючи певний фреймворк чи систему конструктивними методами так чи інакше доведеться зробити певний вибір у мові та способі кодування. Так при розробці теорії абстрактної алгебри в Coq були використані поліморфні індуктивні структури [?]. Однак Agda та Idris використовують для побудови алгебраїчної теорії типи класів, а у Idris взагалі відсутні поліморфірні індуктивні структури та коіндуктивні структури. В Lean теж відсутні коіндуктивні структури проте повністю реалізована теорія НоТТ на нерекурсивних поліморфних структурах що об'єднує основні чотири класи математичних теорій: логіка, топологія, теорія множин, теорія типів. Як було показано Стефаном Касом [25], одна з стратегій імплементації типів класів — це використання поліморфних структур. Хоча в Lean також підтримуються типи класів нами була вибрана стратегія імплементації нашої теорії з використаннями нерекурсивних індуктивних структур, що дозволить нам оперувати з персистентними структурами на низькому рівні. Крім того такий спосіб кодування ієрархій повністю відповідає семантиці Erlang, де немає типів класів, а дані передаються запаковані в кортежі-структури.

2.16 Logic and Quantification

Далі йдуть квантори \forall та \exists які теж виражаються як конструкції типів:

$$\frac{\Gamma x : A \vdash B \quad \Gamma \vdash A}{\Gamma \vdash \Pi(x : A)B} \qquad \frac{\Gamma \vdash a : A \quad \Gamma x : A \vdash B \quad \Gamma b : B(x = a)}{\Gamma \vdash (a, b) : \Pi(x : A)B}$$

$$\frac{\Gamma x : A \vdash B \quad \Gamma \vdash A}{\Gamma \vdash \Sigma(x : A)B} \qquad \frac{\Gamma \vdash a : A \quad \Gamma x : A \vdash B \quad \Gamma b : B(x = a)}{\Gamma \vdash (a, b) : \Sigma(x : A)B}$$

$$\frac{\Gamma \vdash x : A \quad \Gamma \vdash x' : A}{\Gamma \vdash Id_A(x, x')}$$

рефлексивність	:	$Id_A(a, a)$
підстановка	:	$Id_A(a, a') \rightarrow B(x = a) \rightarrow B(x = a')$
симетричність	:	$Id_A(a, b) \rightarrow Id_A(b, a)$
транзитивність	:	$Id_A(a, b) \rightarrow Id_A(b, c) \rightarrow Id_A(a, c)$
конгруентність	:	$(f : A \rightarrow B) \rightarrow Id_A(x, x') \rightarrow Id_B(f(x), f(x'))$

3 Intermediate Language

3.1 Om Language Definition

Om resemble both the Henk theory of pure type system and λC calculus of constructions and Morte Core Specification

```

EXPR :=
  | "\"      "(" LABEL ":" EXPR ")" "arrow" EXPR
  | "\"/"    "(" LABEL ":" EXPR ")" "arrow" EXPR
  |          EXPR      "arrow" EXPR
  |          LABEL
  | "*"
  | "[]"
  | "("      EXPR ")"

```

During forward pass we stack applications (except typevars), then on reaching close paren ")" we perform backward pass and stack arrows, until nearest unstacked open paren "(" appeared (then we just return control to the forward pass).

We need to preserve applies to typevars as they should be processes lately on rewind pass, so we have just typevars bypassing rule. On the rewind pass we stack lambdas by matching arrow/apply signatures where $\text{typevar}(x)$ is an introduction of variable "x" to the Gamma context.

$$\begin{aligned}
 & \text{apply} : (A \rightarrow B) \times A \rightarrow B \\
 & \text{lambda} : \text{arrow} (\text{app} (\text{typevar } x) , A) B
 \end{aligned}$$

3.2 Abstract Syntax Tree

```

E  :=  K
      |  x
      |  EE
      |   $\lambda(x : E) \rightarrow E$ 
      |   $\Pi(x : E) \rightarrow E$ 

```

3.3 Prelude

```
inductive unit: * :=
  (make: () -> unit)

inductive option: (A:*) -> * :=
  (none: () -> option A)
  (some: A -> option A)

inductive product: (A:*) -> (B:*) -> * :=
  (make: (a:A) -> (b:B) -> prod A B)

inductive sum: (A:*) -> (B:*) -> * :=
  (make: (a:A) -> (b:B) -> sum A B)

inductive list: (A:*) -> * :=
  (nil: () -> list A)
  (cons: A -> list A -> list A)

inductive eq: (A:*) -> A -> A -> * :=
  (refl: (x:A) -> eq A x x)

inductive exists: (A:*) -> (A -> *) -> * :=
  (exists-intro: (P: A -> *) -> (x:A) -> P x -> exists A P)
```

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