A cartesian bicategory of polynomial functors in homotopy type theory

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In a nutshell

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- the category of polynomial functors is cartesian closed

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Our contributions:

- we have formalized polynomials in groupoids (or spaces) in HoTT/Agda
- we have shown that the resulting bicategory is cartesian closed
- we have provided a small axiomatization of the type $\mathbb{B}$ of natural numbers and bijections

Part I

Polynomial functors

Categorifying polynomials

A **polynomial** is a sum of monomials

$$P(X) = \sum_{0 \leq i < k} X^{n_i}$$

(no coefficients, but repetitions allowed)

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We can **categorify** this notion: replace natural numbers by elements of a set.

$$P(X) = \sum_{b \in B} X^{E_b}$$

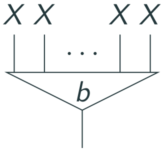
Polynomial functors

This data can be encoded as a **polynomial** P, which is a diagram in **Set**:

$$E \xrightarrow{p} B$$

where

- $b \in B$ is a monomial
- $E_b = p^{-1}(b)$ is the set of instances of X in the monomial b.



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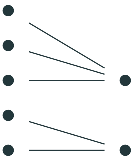
It induces a **polynomial functor**

$$\begin{aligned} [\![P]\!] : \mathbf{Set} &\to \mathbf{Set} \\ X &\mapsto \sum_{b \in B} X^{E_b} \end{aligned}$$

For instance, consider the polynomial corresponding to the function

$$E \xrightarrow{p} B$$



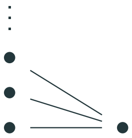
The associated polynomial functor is

$$\begin{aligned} [\![P]\!](X) &: \mathbf{Set} \to \mathbf{Set} \\ X &\mapsto X \times X \sqcup X \times X \times X \end{aligned}$$

Polynomial functors

For instance, consider the polynomial corresponding to the function

$$\mathbb{N} \xrightarrow{p} 1$$



The associated polynomial functor is

$$\llbracket P \rrbracket(X) : \textbf{Set} \to \textbf{Set}$$
$$X \mapsto X \times X \times X \times \dots$$

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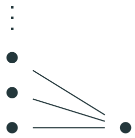

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$$\begin{aligned} [\![P]\!](X) : \mathbf{Set} &\to \mathbf{Set} \\ X &\mapsto X \times X \times X \times \ldots \end{aligned}$$

A polynomial is **finitary** when each monomial is a finite product.

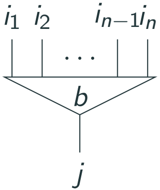
Polynomial functors: typed variant

We will more generally consider a "colored variant" of polynomials P

$$I \xleftarrow{s} E \xrightarrow{p} B \xrightarrow{t} J$$

this means that

- each monomial b has a color $t(b) \in J$,
- each occurrence of a variable $e \in E$ has a color $s(e) \in I$.



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It induces a **polynomial functor**

$$\llbracket P \rrbracket(X) : \mathbf{Set}^I \to \mathbf{Set}^J$$

$$(X_i)_{i \in I} \mapsto \left(\sum_{b \in t^{-1}(j)} \prod_{e \in p^{-1}(b)} X_{s(e)} \right)_{j \in J}$$

The category of polynomial functors

Proposition
The composite of two polynomial functors is again polynomial:

$$\mathbf{Set}^I \xrightarrow{[\![P]\!]} \mathbf{Set}^J \xrightarrow{[\![Q]\!]} \mathbf{Set}^K$$

$$[\![Q]\!] \circ [\![P]\!] = [\![Q \circ P]\!]$$

We can thus build a category **PolyFun** of sets and polynomial functors:

- an object is a set I,
- a morphism

  $$F : I \to J$$

  is a polynomial functor

  $$[\![P]\!] : \mathbf{Set}^I \to \mathbf{Set}^J$$

Polynomial vs polynomial functors

A *polynomial P*

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induces a *polynomial functor*

$$[\![P]\!] : \mathbf{Set}^I \to \mathbf{Set}^J$$

We have mentioned that composition is defined for polynomials. However, on polynomials, it is not strictly associative: we can build a *bicategory* **Poly** of sets an polynomial functors.

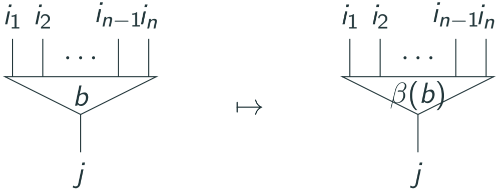
This suggests that 2-cells are an important part of the story!

Morphisms between polynomials

A morphism between two polynomials is

$$\begin{array}{ccccccc} I & \xleftarrow{s} & E & \xrightarrow{p} & B & \xrightarrow{t} & J \\ \| & & \downarrow{\scriptstyle \varepsilon} & \lrcorner & \downarrow{\scriptstyle \beta} & & \| \\ I & \xleftarrow[s']{} & E' & \xrightarrow[p']{} & B' & \xrightarrow[t']{} & J \end{array}$$

We send monomials to monomials, preserving typing and arities:



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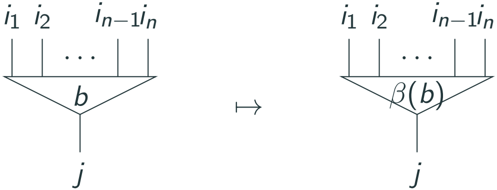

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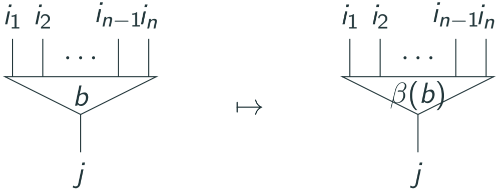

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In the following, we will restrict to the case where 2-cells are *equivalences*.

Morphisms between polynomial functors

A morphism between polynomial functors

$$[\![P]\!], [\![Q]\!] : \mathbf{Set}^I \to \mathbf{Set}^J$$

is a “suitable” natural transformation, and we can build a 2-category **PolyFun**.

Cartesian structure

The category **PolyFun** is cartesian. Namely, given two polynomial functors in **Poly**

$$P : I \to J \qquad\qquad Q : I \to K$$

i.e., in **Cat**,

$$[\![P]\!] : \mathbf{Set}^I \to \mathbf{Set}^J \qquad\qquad [\![Q]\!] : \mathbf{Set}^I \to \mathbf{Set}^K$$

we have, in **Cat**,

$$\langle P, Q \rangle : \mathbf{Set}^I \to \mathbf{Set}^J \times \mathbf{Set}^K \cong \mathbf{Set}^{J \sqcup K}$$

and the constructions preserve polynomiality: in **PolyFun**,

$$\langle P, Q \rangle : I \to (J \sqcup K)$$

Closed structure

For the closed structure, we can hope for the same: given, in **PolyFun**,

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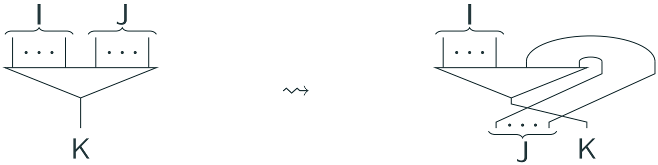
for LL-people: this looks like $!J \parr K$.

Closed structure

In terms of operations, the intuition behind the bijection

$$\mathbf{PolyFun}(I \sqcup J, K) \cong \mathbf{PolyFun}(I, \mathbf{Set}^J \times K)$$

is that we can formally transform operations as follows



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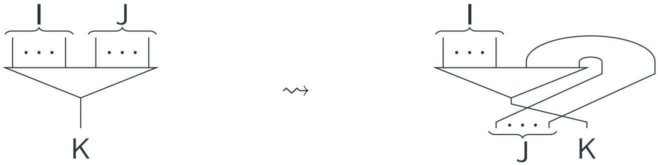

via

$$\mathbf{Set}^J \simeq \mathbf{Set}/J$$

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Finitary polynomial functors are also known as **normal functors** [Girard].

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Remark (Girard)
The 2-category **PolyFun** is not cartesian closed.

Failure of the cartesian closed structure

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which is induced by the polynomial

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which has two automorphisms

$$\begin{array}{ccccccc}
1 & \longleftarrow & 2 & \longrightarrow & 1 & \longrightarrow & 1 \\
\| & & {\scriptstyle \tau}\big\downarrow{\scriptstyle \mathrm{id}} \lrcorner & & \big\downarrow & & \| \\
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The equivalence fails:

$$\mathbf{PolyFun}(0 \sqcup 1, 1) \not\simeq \mathbf{PolyFun}(0, \mathbb{N}/1 \times 1)$$

(two elements on the left, one on the right)

Fixing the cartesian closed structure

The failure of the equivalence

$$\textbf{PolyFun}(0 \sqcup 1, 1) \not\simeq \textbf{PolyFun}(0, \mathbb{N}/1 \times 1)$$

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This suggests moving to **groupoids**!

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More precisely, we should replace $\mathbb{N}$ by the groupoid $\mathbb{B}$ of all symmetric groups.

Polynomial functors in groupoids

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Kock has identified that if we perform all the usual constructions up to homotopy (slice, pullbacks, etc.), we recover a suitable setting to define polynomial functors.

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Kock has identified that if we perform all the usual constructions up to homotopy (slice, pullbacks, etc.), we recover a suitable setting to define polynomial functors.

This requires properly defining and using all the usual constructions in a suitable 2-categorical sense.

Polynomial functors in groupoids

Given a polynomial P

$$E \xrightarrow{p} B$$

the induced polynomial functor

$$\begin{aligned} [\![P]\!] : \mathbf{Gpd} &\to \mathbf{Gpd} \\ X &\mapsto \int^{b \in B} E_b \end{aligned}$$

where E_b is the *homotopy fiber* of p at b and

$$\int^{b \in E} E_b = \sum_{b \in \pi_0(B)} X_b / \mathrm{Aut}(b)$$

where the quotient is to be taken 2-categorically / homotopically...

Part II

Formalization in Agda

Homotopy type theory

There is a framework in which everything is constructed *up to homotopy* for free: **homotopy type theory**.

In particular, there is a well-known notion of groupoid in this setting: a type with no non-trivial equalities between equalities.

Let's formally develop the theory of polynomials in this setting.

Formalizing polynomials

A polynomial

$$I \xleftarrow{s} E \xrightarrow{p} B \xrightarrow{t} J$$

is a **container**:

```
record Poly (I J : Type) : Type₁ where
  field
    Op : J → Type
    Pm : (i : I) → {j : J} → Op j → Type
```

We sometimes write

```
I ⇝ J = Poly I J
```

Composing polynomials

The polynomial functor induced by a polynomial `P` is

```
⟦_⟧ : I ⇝ J → (I → Type) → (J → Type)
⟦_⟧ P X j = Σ (Op P j) (λ c → (i : I) → (p : Pm P i c) → (X i))
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The composite of two polynomials is

```
_·_ : I ⇝ J → J ⇝ K → I ⇝ K
Op (P · Q) = ⟦ Q ⟧ (Op P)
Pm (_·_ P Q) i (c , a) = Σ J (λ j → Σ (Pm Q j c) (λ p → Pm P i (a j p)))
```

A bicategory

Theorem
We can build a pre-bicategory of types, polynomials and their morphisms.

Note: by univalence, we can use propositional equality for 2-cells, which simplifies the definition.

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Theorem
This bicategory is cartesian with $\sqcup$ as coproduct.

Defining the exponential

In order to define the 1-categorical closure, the plan was:

$$\mathbf{Set} \quad \rightsquigarrow \quad \mathbf{Set}_{\mathrm{fin}} \quad \rightsquigarrow \quad \mathbb{N}$$

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$$\mathbf{Set} \quad \rightsquigarrow \quad \mathbf{Set}_{\mathrm{fin}} \quad \rightsquigarrow \quad \mathbb{N}$$

For the 2-categorical closure the plan is

$$\mathbf{Gpd} \quad \rightsquigarrow \quad \mathbf{Gpd}_{\mathrm{fin}} \quad \rightsquigarrow \quad \mathbb{B}$$

Here, $\mathbb{B}$ is the groupoid with $n \in \mathbb{N}$ as objects and Σ_n as automorphisms on n.

Finite types

We write `Fin n` for the canonical finite type with `n` elements: its constructors are `0` to `n-1`.

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```
data Fin : ℕ → Set where
  zero : {n : ℕ}               → Fin (suc n)
  suc  : {n : ℕ} (i : Fin n) → Fin (suc n)
```

Finite types

The predicate of being **finite** is

```
is-finite : Type → Type
is-finite A = Σ ℕ (λ n → ∥ A ≃ Fin n ∥)
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```

(note that this is a *large* type)

Finitary polynomials

A polynomial is **finitary** when, for each operation, the total space of its parameters is finite:

```
is-finitary : (P : I ⇝ J) → Type
is-finitary P = {j : J} (c : Op P j) → is-finite (Σ I (λ i → Pm P i c))
```

A small model for finite types

The type of **integers** is

```
data ℕ : Type where
  zero : ℕ
  suc  : ℕ → ℕ
```

A small model for finite types

The type $\mathbb{B}$ is

```
data 𝔹 : Type where
  obj      : ℕ → 𝔹
  hom      : {n : ℕ} (α : Fin n ≃ Fin n) → obj n ≡ obj n
  id-coh   : (n : ℕ) → hom {n = n} ≃-refl ≡ refl
  comp-coh : {m n o : ℕ} (α : Fin m ≃ Fin n) (β : Fin n ≃ Fin o) →
             hom (≃-trans α β) ≡ hom α · hom β
```

(this is a small higher inductive type!)

A small model for finite types

The type $\mathbb{B}$ is

```
data 𝔹 : Type where
  obj      : ℕ → 𝔹
  hom      : {n : ℕ} (α : Fin n ≃ Fin n) → obj n ≡ obj n
  id-coh   : (n : ℕ) → hom {n = n} ≃-refl ≡ refl
  comp-coh : {m n o : ℕ} (α : Fin m ≃ Fin n) (β : Fin n ≃ Fin o) →
             hom (≃-trans α β) ≡ hom α · hom β
```

(this is a small higher inductive type!)

Theorem
FinType $\simeq$ $\mathbb{B}$.

The closure

We define

```
Exp : Type → Type₁
Exp I = I → Type
```

Theorem
Ignoring size issues, for polynomials we have

$$\mathtt{(I} \sqcup \mathtt{J)} \rightsquigarrow \mathtt{K} \quad \simeq \quad \mathtt{I} \rightsquigarrow \mathtt{(Exp\ J} \times \mathtt{K)}$$

The closure

We define

```
Exp : Type → Type₁
Exp I = Σ (I → Type) (λ F → is-finite (Σ I F))
```

Theorem
Ignoring size issues, for finitary polynomials we have

```
(I ⊔ J) ⇝ K  ≃  I ⇝ (Exp J × K)
```

The closure

We define

```
Exp : Type → Type₁
Exp I = Σ FinType (λ N → fst N → I)
```

Theorem
Ignoring size issues, for finitary polynomials we have

$$(I \sqcup J) \rightsquigarrow K \quad \simeq \quad I \rightsquigarrow (\mathrm{Exp}\ J \times K)$$

The closure

We define

```
Exp : Type → Type
Exp I = Σ 𝔹 (λ b → 𝔹-to-Fin b → A)
```

Theorem
For finitary polynomials we have

```
(I ⊔ J) ⇝ K  ≃  I ⇝ (Exp J × K)
```

The exponential

Note that

```
Exp : Type → Type
Exp I = Σ 𝔹 (λ b → 𝔹-to-Fin b → A)
```

is the free pseudo-commutative monoid!

Questions?