The Polynomial Abacus

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TOPOS INSTITUTE

Workshop on Polynomial Functors
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Outline

Abacus for the Glass Bead Game

There is a story by Herman Hesse, called *The Glass Bead Game*.

- It depicts a monastic community of thinkers, led by a “game master”.
- The game is played on an instrument involving strings of glass beads.

Like a rap battle or poetry slam, the game is played to express deep ideas.

- Players represent connections between math, music, philosophy, etc.
- The moving glass beads weave these subjects together in harmony.
- To play well is to contemplate and communicate profound insights.

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I loved the idea of the book, but something was missing.

- Hesse only roughly describes the instrument—the abacus—itself.
- What sort of combinatorial object is capable of this grand scope?

To my lights, Poly can serve as an abacus; I hope to justify that to you.

Approximate plan for tutorial

Today:

- Introduce Poly and its combinatorics (how the abacus works);
- Discuss its pleasing properties and monoidal structures;
- Present the framed bicategory $\mathbb{P}$.

Wednesday:

- Recall $\mathbb{P}$ and discuss some properties of it;
- Consider applications: dynamical systems, data, and deep learning;
- Conclude with a summary.

Outline

Poly for experts

What I'll call the category Poly has many names.

- The free completely distributive category on one object;
- The free coproduct completion of $\mathsf{Set}^{\mathsf{op}}$;
- The full subcategory of $[\mathsf{Set}, \mathsf{Set}]$ spanned by functors that preserve connected limits;
- The full subcategory of $[\mathsf{Set}, \mathsf{Set}]$ spanned by coproducts of repr'bles;

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- The category of *typed sets* and colax maps between them.
  - Objects: pairs (I, τ), where $I \in \mathsf{Set}$ and $\tau \colon I \to \mathsf{Set}$.
  - Morphisms $(I, \tau) \xrightarrow{\varphi} (I', \tau')$: pairs $(\varphi_1, \varphi^\sharp)$, where

$$\begin{tikzcd} I \arrow[rr, "\varphi_1"] \arrow[dr, "\tau"'] & {} \arrow[d, phantom, "\Leftarrow\varphi^\sharp"] & I' \arrow[dl, "\tau'"] \\ & \mathsf{Set} & \end{tikzcd}$$

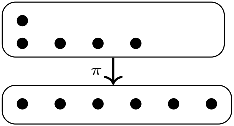
But let's make this easier.

What is a polynomial?

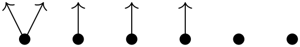
Algebraic

$$y^2 + 3y + 2$$

Bundle



Corolla forest



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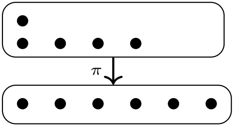

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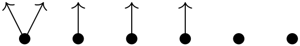

One could repurpose this machine to represent $15y^{5\times 2} \in \mathsf{Poly}$.

Terminology woes

Issue: prior terminology from computer science doesn't fit my conception.

$$p \coloneqq y^3 + y^2 + y^2 + 1$$

- Container terminology from Abbott: "shapes and positions".
  - `data p Y = Foo Y Y Y | Bar Y Y | Baz Y Y | Qux`
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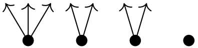

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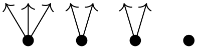
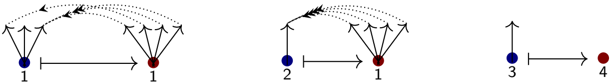


- Hard decision but I'll say positions and directions. Reasons:
  - Dynamical systems: position = point, direction = vector.
  - Categories: position = object, direction = morphism.
  - Terminal coalgebra trees: position = label, direction = arrow.

Combinatorics of polynomial morphisms

Let $p \coloneqq y^3 + 2y$ and $q \coloneqq y^4 + y^2 + 2$

A morphism $p \xrightarrow{\varphi} q$ delegates each p-position to a q-position, passing back directions:



Example: how to think of

- $y^2 + y^6 \to y^{52}$?
- $p \to y$ for arbitrary p ?

The category of polynomials

Easiest description: Poly $=$ "sums of representables functors Set $\to$ Set".

- For any set S, let $y^S := \mathsf{Set}(S, -)$, the functor *represented* by S.
- Def: a polynomial is a sum $p = \sum_{i \in I} y^{p[i]}$ of representable functors.
- Def: a morphism of polynomials is a natural transformation.

Notation

We said that a polynomial is a sum of representable functors

$$p \cong \sum_{i \in I} y^{p[i]}.$$

But note that $I \cong p(1)$. So we can write

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Here's a derivation of the combinatorial formula for morphisms:

$$\begin{aligned} \mathsf{Poly}(p, q) = \mathsf{Poly}\left(\sum_{i \in p(1)} y^{p[i]}, \sum_{j \in q(1)} y^{q[j]}\right) &\cong \prod_{i \in p(1)} \mathsf{Poly}\left(y^{p[i]}, \sum_{j \in q(1)} y^{q[j]}\right) \\ &\cong \prod_{i \in p(1)} \sum_{j \in q(1)} \mathsf{Set}(q[j], p[i]) \end{aligned}$$

"For each $i \in p(1)$, a choice of $j \in q(1)$ and a function $q[j] \to p[i]$."

Notation for the abacus

For any polynomial $p \in \mathsf{Poly}$, I'll use the following sort of notation

$$\begin{array}{r|c|}\cline{2-2} p[-] & \quad \\ \cline{2-2} p(1) & \quad \\ \cline{2-2}\end{array}$$

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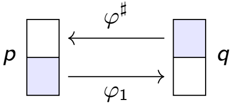

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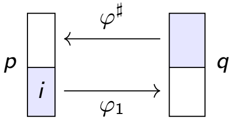

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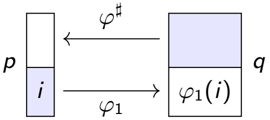

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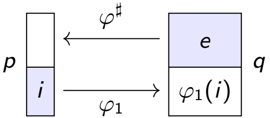

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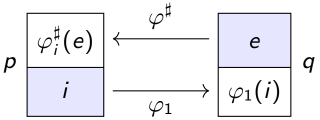

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$$p \quad \begin{tikzcd} \boxed{\varphi_i^\sharp(e)} & \boxed{e} \arrow[l, "\varphi^\sharp"'] \\ \boxed{i} \arrow[r, "\varphi_1"'] & \boxed{\varphi_1(i)} \end{tikzcd} \quad q$$

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But this notation will really come in handy later in handling composition.

Pleasing aspects of Poly

Here are some properties enjoyed by Poly:

- Poly contains two copies of Set and one copy of $\mathsf{Set}^{\mathsf{op}}$.
  - Sets A can be represented as a constant or linear: $A, Ay \in \mathsf{Poly}$.
  - Sets A can be op-represented as representables $y^A \in \mathsf{Poly}$.
  - Each of these inclusions is full and has at least one adjoint.

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- Poly has all coproducts and limits (extensive), and is Cartesian closed;
  - These agree with coproducts, limits, closure in " $\mathsf{Set}^{\mathsf{Set}}$ ".
  - 0 is initial, 1 is terminal, $+$ is coproduct, $\times$ is product.
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- Poly has coequalizers, though these differ from coeq's in " Set^{Set} ".
- Poly has two factorization systems: epi-mono, vertical-cartesian.

Monoidal structures on Poly

There are many monoidal structures on Poly.

- It has a coproduct $(0, +)$ structure.
- Day convolution can be applied to any SMC structure $(I, \cdot)$ on Set.
  - The result is a distributive monoidal structure $(y^I, \odot)$ on Poly.
  - In the case of $(0, +)$, the result is the product $(1, \times)$.
  - In the case of $(1, \times)$, the result is $(y, \otimes)$.

$$p \times q \cong \sum_{i \in p(1)} \sum_{j \in q(1)} y^{p[i]+q[j]} \qquad \text{and} \qquad p \otimes q \cong \sum_{i \in p(1)} \sum_{j \in q(1)} y^{p[i] \times q[j]}.$$

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There's one more monoidal product, which will be of great interest.

Composition monoidal structure $(\mathsf{Poly}, y, \triangleleft)$

The composite of two polynomial functors is again polynomial.

- Let's denote the composite of p and q by $p \triangleleft q$.
- Example: if $p := y^2$, $q := y + 1$, then $p \triangleleft q \cong y^2 + 2y + 1$.
- This is a monoidal structure, but not symmetric. $(q \triangleleft p \cong y^2 + 1)$
- The identity functor y is the unit: $p \triangleleft y \cong p \cong y \triangleleft p$.

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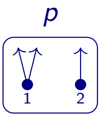
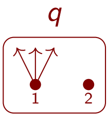
Why the we weird symbol $\triangleleft$ rather than $\circ$?

- We want to reserve $\circ$ for morphism composition.
- The notation $p \triangleleft q$ represents trees with p under q.

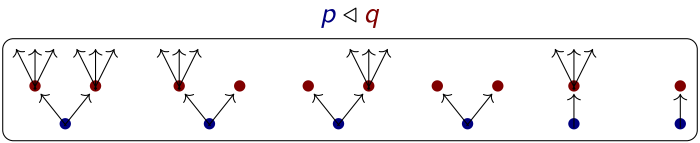
Composition given by stacking trees

Suppose $p := y^2 + y$ and $q := y^3 + 1$.





Draw the composite $p \triangleleft q$ by stacking q-trees on top of p-trees:



You can also read it as q feeding into p, which is how composition works.

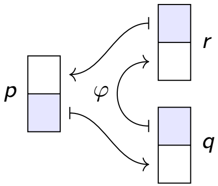
Maps to composites

The abacus pictures are most useful for maps $p \to q_1 \triangleleft \cdots \triangleleft q_k$.

- A map $\varphi \colon p \to q \triangleleft r$ is an element of

$$\varphi \in \mathrm{Poly}(p, q \triangleleft r) \cong \prod_{i \in p(1)} \sum_{j \in q(1)} \prod_{e \in q[j]} \sum_{k \in r(1)} \prod_{f \in r[k]} \sum_{d \in p[i]} 1.$$

We could write it with our abacus pictures:



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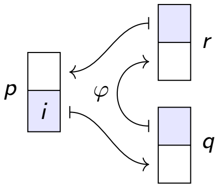

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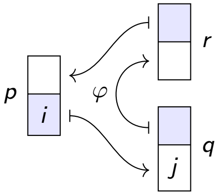

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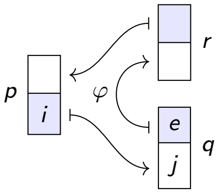

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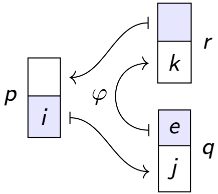
We could write it with our abacus pictures:



Maps to composites

The abacus pictures are most useful for maps $p \to q_1 \triangleleft \cdots \triangleleft q_k$.

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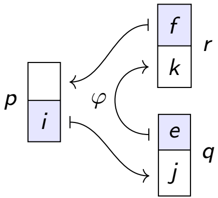

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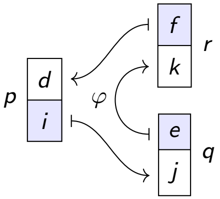

These will come in handy when asking if two such φ, ψ are equal.

Comonoids in $(\mathsf{Poly}, y, \triangleleft)$

In any monoidal category $(\mathcal{M}, I, \otimes)$, one can consider comonoids.

- A comonoid is a triple (m, ϵ, δ) satisfying certain rules, where
  - $m \in \mathcal{M}$ is an object, the *carrier*,
  - $\epsilon\colon m \to I$ is a map, the *counit*, and
  - $\delta\colon m \to m \otimes m$ is a map, the *comultiplication*.

In $(\mathsf{Poly}, y, \triangleleft)$, comonoids are exactly categories![1]

[1] Ahman-Uustalu. "Directed Containers as Categories". *MSFP 2016*.

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In $(\mathsf{Poly}, y, \triangleleft)$, comonoids are exactly categories![1]

- If $\mathcal{C}$ is a category, the corresponding comonoid has carrier

$$\mathfrak{c} := \sum_{i \in \mathsf{Ob}(\mathcal{C})} y^{\mathcal{C}[i]}$$

  where $\mathcal{C}[i]$ is the set of morphisms in $\mathcal{C}$ that emanate from i.
- The counit $\epsilon \colon \mathfrak{c} \to y$ assigns to each object an identity.
- The comult $\delta \colon \mathfrak{c} \to \mathfrak{c} \triangleleft \mathfrak{c}$ assigns codomains and composites.

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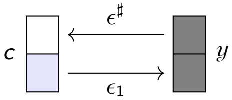
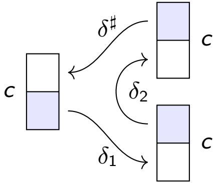
The abacus in action

We can understand the Ahman-Uustalu result combinatorially.

- Let (c, ϵ, δ) be a comonoid, where $\epsilon\colon c \to y$ and $\delta\colon c \to c \triangleleft c$.





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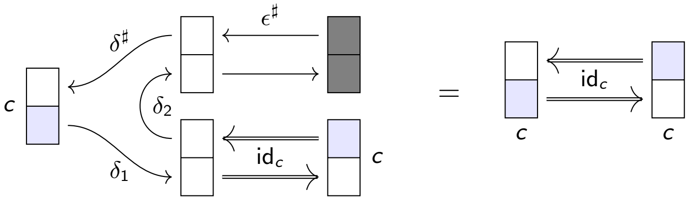

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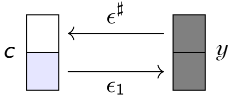

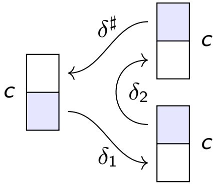

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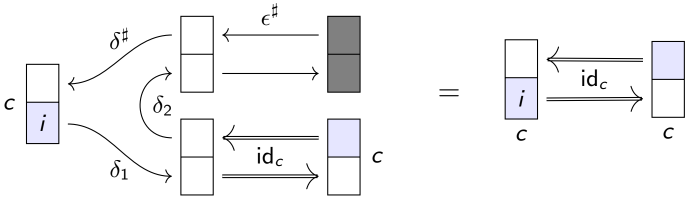

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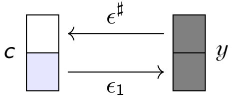

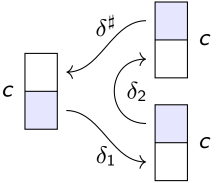

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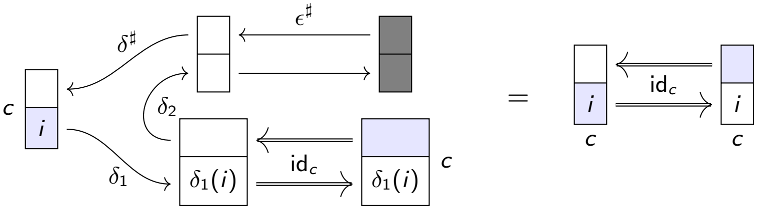

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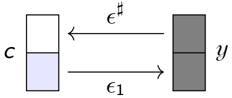

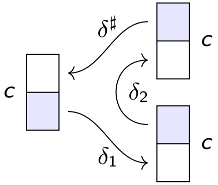

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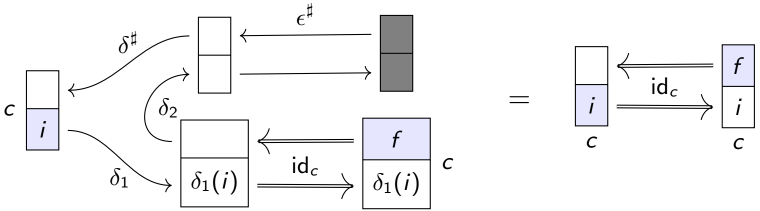

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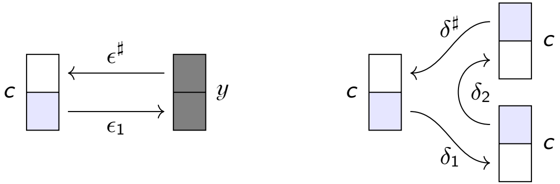

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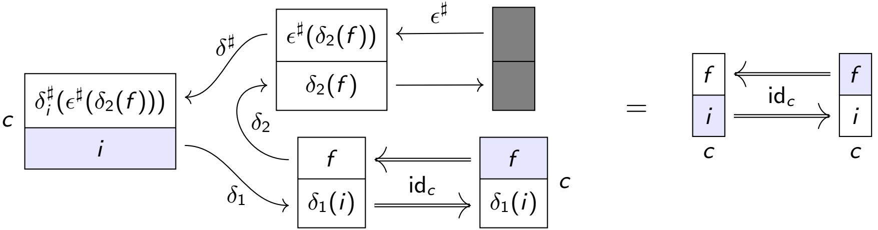
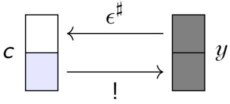


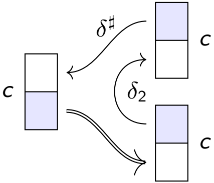
Equation: $\forall i \in c(1), \delta_1(i) = i \wedge \forall f \in c[i], \delta_i^\sharp(f, \epsilon^\sharp(\delta_2(f))) = f.$

Making sense of the results

We want to make sense of the set-theoretic equations from the abacus.

- For example, we found out that $\delta_1(i) = i$ for all $i \in c(1)$, so...





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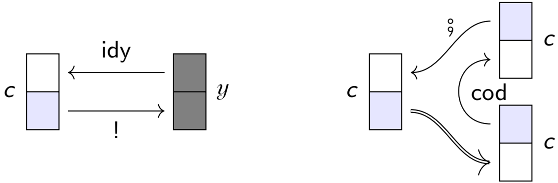

- To make sense of the other equations, let's rename $\epsilon^\sharp, \delta_2$, and $\delta^\sharp$.
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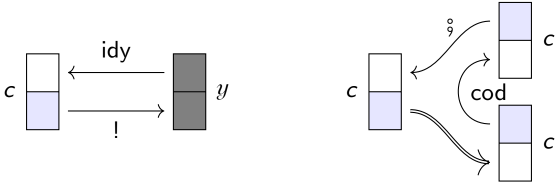

- To make sense of the other equations, let's rename $\epsilon^\sharp, \delta_2$, and $\delta^\sharp$.
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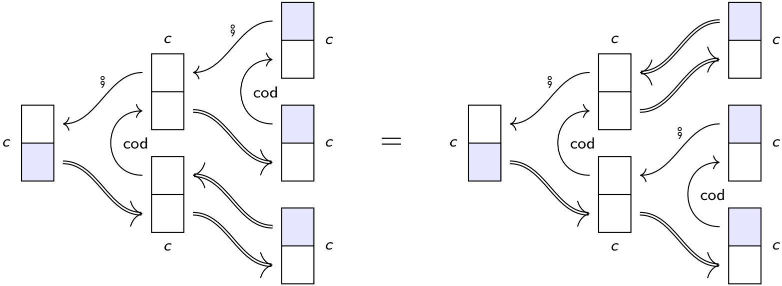
  - Then the previous equation says: $f ⨟ \text{idy}(\text{cod}(f)) = f$.
  - The other unitality eq'n gives: $\text{cod}(\text{idy}(i)) = i$ and $\text{idy}(i) ⨟ f = f$.
  - The associativity eq'n gives: $\text{cod}(f ⨟ g) = \text{cod}(g)$ and $(f ⨟ g) ⨟ h = f ⨟ (g ⨟ h)$.

A brief glance at associativity



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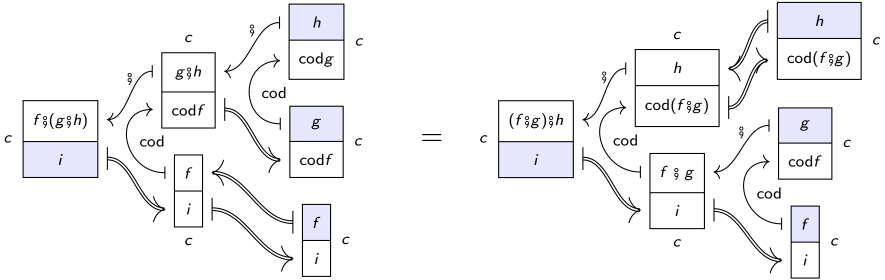

Let's fill it in and read off the abacus:

$$\forall i \in c(1), i = i \wedge$$
$$\forall f \in c[i], \mathrm{cod} f = \mathrm{cod} f \wedge$$
$$\forall g \in c[\mathrm{cod} f], \mathrm{cod} g = \mathrm{cod}(f ⨾ g) \wedge$$
$$\forall h \in c[\mathrm{cod} g], f ⨾ (g ⨾ h) = (f ⨾ g) ⨾ h.$$

Comonoid maps are "cofunctors"

In Poly, comonoids are categories, but their morphisms aren't functors.

- A comonoid morphism $\varphi\colon \mathscr{C} \nrightarrow \mathscr{D}$ is called a *cofunctor*.
- It includes a Poly map on carriers. For each object $i \in \mathfrak{c}(1)$, we get:
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  - for each emanating $f \in \mathfrak{d}[j]$, an emanating $\varphi_i^\sharp(f) \in \mathfrak{c}[i]$.
  - Rules: $\varphi^\sharp$ preserves ids and comps, and φ_1 preserves cods.
- Denote this by $\mathbf{Cat}^\sharp := \mathrm{Comon}(\mathbf{Poly}) =$ (cat'ys and cofunctors).

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Example: what is a cofunctor $\mathcal{C} \overset{\varphi}{\nrightarrow} y^{\mathbb{Q}}$?

- It is trivial on objects $i \in \mathrm{Ob}(\mathcal{C})$. Passing back morphisms gives:
- ... a map $\varphi^\sharp_i(q)\colon i \to i_{+q}$ emanating from i for each $q \in \mathbb{Q}$, s.t....
- ... $\varphi^\sharp_i(0) = \mathrm{id}_i$, so $i_{+0} = i$, and $\varphi^\sharp_i(q) \mathbin{⨟} \varphi^\sharp_{i_{+q}}(q') = \varphi^\sharp_i(q+q')$.

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"That's a strange sort of structure to put on a category!"

- Cofunctors offer a whole new world to explore. Think "vector fields".
- The natural co-transformations between them are even wilder.

$\mathsf{Cat}^\sharp$: examples and facts

Here are some examples of the polynomial $\mathfrak{c}$ carrying a category $\mathcal{C}$.

- $\mathfrak{c}$ never has constant part: every object needs an outgoing arrow.
- The following are equivalent:
  - the comonoid structure maps ϵ, δ are cartesian;
  - $\mathfrak{c} = Oy$ is a linear polynomial;
  - $\mathcal{C}$ is a discrete category, with $\mathrm{Ob}(\mathcal{C}) = O$.
- $\mathfrak{c} = y^M$ is representable iff $M \in \mathbf{Set}$ carries a monoid.
- If $\mathcal{C} = \boxed{\overset{1}{\bullet} \to \overset{2}{\bullet} \to \cdots \to \overset{N}{\bullet}}$ then $\mathfrak{c} = y^N + y^{N-1} + \cdots + y$.

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Other facts about $\mathsf{Cat}^\sharp$:

- Coproducts in $\mathsf{Cat}^\sharp$ and in Cat agree; carrier is $\mathfrak{c} + \mathfrak{d}$.
- $\mathsf{Cat}^\sharp$ has finite products (Niu), and they're very interesting.
- $\mathsf{Cat}^\sharp$ inherits $\otimes$ from Poly, and $\mathfrak{c} \otimes \mathfrak{d}$ is the usual categorical product.

Cofree comonoids

To any polynomial p, we can associate the *cofree comonoid* on p.

- That is, the forgetful functor $\mathsf{Cat}^\sharp \to \mathsf{Poly}$ has a right adjoint.
- I'll give an explicit description on the next slide.
- There's a standard construction for this type of thing.

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- Starting with $p \in \mathsf{Poly}$, we first copoint it by multiplying by y.
- That is, py is the universal thing mapping to p and y.
- We get $\mathfrak{c}_p$ by taking the limit of the following diagram in Poly:

$$\mathfrak{c}_p := \lim \left(y \longleftarrow py \Longleftarrow py \triangleleft py \Lleftarrow py \triangleleft py \triangleleft py \;\overset{\longleftarrow}{\underset{\longleftarrow}{\Longleftarrow}}\; \cdots \right)$$

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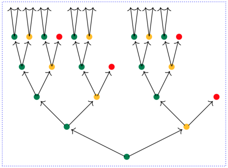
For us, a main use of $\mathfrak{c}_p$ is an equivalence $\mathfrak{c}_p$-$\mathsf{Set} \cong p$-Coalg.

- A coalgebra $S \to p(S)$ corresponds to $\mathfrak{c}_p \to \mathsf{Set}$ with elements S.
- For example, the object set $\mathfrak{c}_p(1)$ is the terminal p-coalgebra.

The cofree comonoid $\mathfrak{c}_p$ via p-trees

Comonoids in Poly are categories, so $\mathfrak{c}_p$ is a category; which one?

- It's actually free on a graph, but the graph is very interesting.
- The vertex-set $\mathfrak{c}_p(1)$ of the graph is the set of p-trees.
  - A p-tree is a possibly infinite tree t, where each node...
  - ...is labeled by a position $i \in p(1)$ and has $p[i]$-many branches.
  - Example object $t \in \mathfrak{c}_p(1)$, where $p = \{{\color{orange}\bullet}, {\color{green}\bullet}\}y^2 + \{{\color{red}\bullet}\} \cong 2y^2 + 1$:



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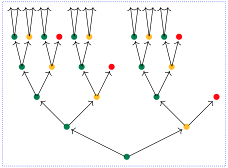

- For any vertex $t \in \mathfrak{c}_p(1)$, an arrow $a \in \mathfrak{c}_p[t]$ emanating from t is...
- ...a finite path from the root of t to another node in t.
- Its codomain is the p-tree sitting at the target node (its root).
- Identity arrow = length-0 path; composition = path concatenation.

Imagine the whole graph $\mathfrak{c}_p$: every possible "destiny" is included.

Bicomodules in $(\mathsf{Poly}, y, \triangleleft)$

Given ~~comonoids~~ categories $\mathscr{C}, \mathscr{D}$, a $(\mathscr{C}, \mathscr{D})$-bicomodule is another kind of map.

- It's a polynomial m, equipped with two morphisms in Poly

$$\mathfrak{c} \triangleleft m \xleftarrow{\lambda} m \xrightarrow{\rho} m \triangleleft \mathfrak{d}$$

each cohering naturally with the comonoid structure ϵ, δ for $\mathfrak{c}, \mathfrak{d}$.

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  each cohering naturally with the comonoid structure ϵ, δ for $\mathfrak{c}, \mathfrak{d}$.
- I denote this $(\mathcal{C}, \mathcal{D})$-bicomodule m like so:

$$\mathfrak{c} \triangleleft\!\xrightarrow{\;m\;}\!\triangleleft \mathfrak{d} \qquad \text{or} \qquad \mathcal{C} \triangleleft\!\xrightarrow{\;m\;}\!\triangleleft \mathcal{D}$$

  - The $\triangleleft$'s at the ends help me remember the how the maps go.
  - Maybe it looks like it's going the wrong way, but hold on.

Bicomodules are parametric right adjoints

Garner explained[2] that bicomodules $m \in {}_{\mathcal{C}}\mathrm{Mod}_{\mathcal{D}}$, which we've denoted

$$\mathcal{C} \triangleleft\!\xrightarrow{\;m\;}\!\triangleleft\ \mathcal{D} \qquad \text{or} \qquad \mathfrak{c} \triangleleft\!\xrightarrow{\;m\;}\!\triangleleft\ \mathfrak{d}$$

can be identified with parametric right adjoint functors (prafunctors)

$$\mathcal{D}\text{-Set} \xrightarrow{M} \mathcal{C}\text{-Set}.$$

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- From this perspective the arrow points in the expected direction.
- Assuming Garner's result, check: ${}_{\mathcal{C}}\mathrm{Mod}_{0} \cong \mathcal{C}\text{-Set}$.

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Prafunctors $\mathcal{C} \triangleleft\!\longleftarrow\!\triangleleft\ \mathcal{D}$ generalize profunctors $\mathcal{C} \nrightarrow \mathcal{D}$:

- A profunctor $\mathcal{C} \nrightarrow \mathcal{D}$ is a functor $\mathcal{C} \to (\mathcal{D}\text{-Set})^{\mathsf{op}}$
- A prafunctor $\mathcal{C} \triangleleft\!\longleftarrow\!\triangleleft\ \mathcal{D}$ is a functor $\mathcal{C} \to \mathrm{Coco}\big((\mathcal{D}\text{-Set})^{\mathsf{op}}\big)$...
- ...where Coco is the free coproduct completion.

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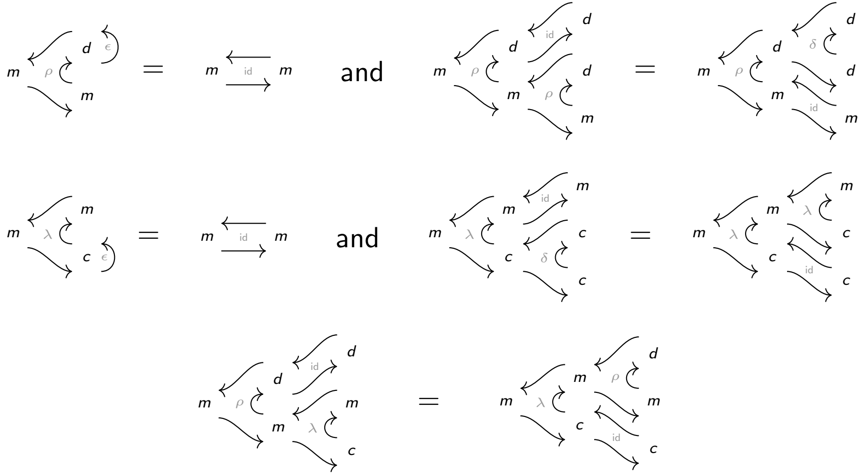
Let's ask the abacus

To prove that bicomodules $\mathfrak{c} \mathrel{\triangleleft\!\!\overset{m}{\longleftarrow}\!\!\triangleleft} \mathfrak{d}$ are prafunctors ${}_{\mathfrak{d}}\mathrm{Mod}_0 \to {}_{\mathfrak{c}}\mathrm{Mod}_0$:

- Write out the bicomodule equations and run the abacus.



Interpreting the abacus

By running the abacus and interpreting the results, we find the following.

- A left comodule $\mathfrak{c} \triangleleft m \xleftarrow{\lambda} m$ can be identified with a functor $\mathfrak{c} \to \mathbf{Poly}$.

$$m \cong \sum_{i \in \mathfrak{c}(1)} \sum_{x \in m_i} y^{m[x]}$$

- The right comodule conditions on $m \xrightarrow{\rho} m \triangleleft d$ say that each $m[x]$ …
- … is not just a set, it's the set of elements for a copresheaf on $\mathfrak{d}$!

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When we add the coherence condition, it all falls into place.

- The idea is that each $i \in \mathfrak{c}(1)$ functorially gets a set m_i and...
- ... each $x \in m_i$ gets a $\mathfrak{d}$-set with elements $m[x]$.
- The prafunctor $\mathfrak{d}$-Set $\to$ $\mathfrak{c}$-Set associated to m takes any $\mathfrak{d}$-set N, ...
- ... hom's in the $m[x]$'s, and adds them up to get a $\mathfrak{c}$-set.

We'll understand this better semantically when we get to applications.

Getting acquainted with bicomodules

Here are some facts, just to get you acquainted with $\mathfrak{c} \overset{m}{\triangleleft\!\!\longrightarrow\!\!\triangleleft} \mathfrak{d}$.

- If $\mathfrak{d} = 0$ then carrier $m \in \mathsf{Poly}$ is constant, i.e. $m = M$ for $M \in \mathsf{Set}$.
- If carrier $m = M$ is constant, then m factors as $\mathfrak{c} \overset{M}{\triangleleft\!\!\longrightarrow\!\!\triangleleft} 0 \overset{!}{\triangleleft\!\!\longrightarrow\!\!\triangleleft} \mathfrak{d}$.

Getting acquainted with bicomodules

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- The following cat'ies are isomorphic and all are equivalent to $\mathfrak{c}$-Set:
  - Cartesian cofunctors over $\mathfrak{c}$ = Discrete opfibrations over $\mathfrak{c}$.
  - The constant left $\mathfrak{c}$-comodules, i.e. with constant carrier $m = M$.
  - The linear left $\mathfrak{c}$-comodules, i.e. with linear carrier $m = My$.
  - The representable right $\mathfrak{c}$-comodules, i.e. with carrier y^M.

Bicomodule composition

If you've ever tried to compose prafunctors; this might look familiar.

$$
\begin{tikzcd}
 & & \bullet \arrow[rr] \arrow[d] \arrow[drr, phantom, "\text{comma}"] & & \bullet \arrow[r] \arrow[d] & \bullet \arrow[dd] \\
 & & \bullet \arrow[rr] \arrow[dl] \arrow[dr, phantom, "\text{comma}"] & & \bullet \arrow[dl] \arrow[d] \arrow[r, phantom, "\text{dist.}"] & {} \\
 & \bullet \arrow[rr] \arrow[dl] & & \bullet \arrow[d] \arrow[r, phantom, "\text{pb}"] & \bullet \arrow[r] \arrow[dl] & \bullet \arrow[d] \\
\mathfrak{e} & & & \mathfrak{d} & & \mathfrak{c}
\end{tikzcd}
$$

But in Poly, it's just given by the usual bicomodule composition.

- The composite of $\mathfrak{c} \overset{m}{\lhd\!\!\longleftarrow\!\!\lhd} \mathfrak{d} \overset{n}{\lhd\!\!\longleftarrow\!\!\lhd} \mathfrak{e}$, is carried by the equalizer:

$$m \lhd_{\mathfrak{d}} n \xrightarrow{eq} m \lhd n \rightrightarrows m \lhd \mathfrak{d} \lhd n$$

- This has a natural $(\mathfrak{c}, \mathfrak{e})$-structure, because $\lhd$ preserves conn. limits.
- It's amazing to see the combinatorics handle all this complexity.

The framed bicategory $\mathbb{P}$

Poly comonoids, cofunctors, and bicomodules form a framed bicategory $\mathbb{P}$.

$$\begin{tikzcd}
\mathfrak{c} \arrow[d, "\varphi"'] \arrow[dr, phantom, "\Downarrow\alpha"] & \mathfrak{d} \arrow[l, "m"'] \arrow[d, "\psi"] \\
\mathfrak{c}' & \mathfrak{d}' \arrow[l, "m'"]
\end{tikzcd}$$

- It's got a ton of structure, e.g. two monoidal structures, $+, \otimes$.
- It's actually not too hard to describe.

Here are some facts about ${}_{\mathcal{C}}\mathsf{Mod}_{\mathcal{D}}$ for categories $\mathcal{C}, \mathcal{D}$.

- ${}_{\mathcal{C}}\mathsf{Mod}_0 \cong \mathcal{C}$-Set, copresheaves on $\mathcal{C}$.
- ${}_1\mathsf{Mod}_{\mathcal{D}} \cong \mathsf{Coco}\big((\mathcal{D}\text{-Set})^{\mathsf{op}}\big)$.
- ${}_{\mathcal{C}}\mathsf{Mod}_{\mathcal{D}} \cong \mathsf{Cat}(\mathcal{C}, {}_1\mathsf{Mod}_{\mathcal{D}})$.

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There's a factorization system on $\mathbb{P}$:

- Every $m \in {}_{\mathfrak{c}}\mathsf{Mod}_{\mathfrak{d}}$ can be factored as $m \cong f \circ p$,

$$\mathfrak{c} \xleftarrow{f} \mathfrak{c}' \xleftarrow{p} \mathfrak{d}$$

where f "is" a discrete opfibration and p "is" a profunctor.

Gambino-Kock's framed bicategory $\mathbb{P}\mathrm{oly}$

In Gambino-Kock, the authors construct a framed bicategory $\mathbb{P}\mathrm{oly}_{\mathsf{Set}}$.

- Its vertical category is Set.
- A horizontal map $I \to J$ is J-many polynomials in I-many variables.
- 2-cells are natural transformations between polynomial functors.

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This is a full subcategory $\mathbb{P}\mathsf{oly} \subseteq \mathbb{P}$.

- Objects in $\mathbb{P}$ are categories; those in $\mathbb{P}$oly are the discrete categories.
- Verticals in $\mathbb{P}$ are cofunctors; $\mathsf{Set}(I, I') \cong \mathsf{Cat}^\sharp(Iy, I'y)$.
- Horizontals in $\mathbb{P}$ are prafunctors; between discretes, these are poly's.
- In both, 2-cells are the natural transformations.

The comonoid theory $\mathbb{P}$ of (one-variable) Poly includes all of $\mathbb{P}$oly.

Adjunctions in $\mathbb{P}$

The map $\_\mathrm{Mod}_0 \colon \mathbb{P}^{\mathrm{op}} \to \mathbb{C}\mathrm{at}$ is locally fully faithful; i.e....

- ...for categories $\mathcal{C}, \mathcal{D}$, only some functors $m \colon \mathcal{D}\text{-Set} \to \mathcal{C}\text{-Set}$ count...
- ... as bimodules $\mathcal{C} \xleftarrow{m} \mathcal{D}$, but for those m, n that do...
- ... the bimodule maps $m \Rightarrow n$ are exactly the natural transformations.

Thus it is easy to say when $\mathcal{C} \xleftarrow{m} \mathcal{D}$ has an adjoint in $\mathbb{P}$, namely if...

- ...the induced $\mathcal{D}\text{-Set} \xrightarrow{m} \mathcal{C}\text{-Set}$ has an adjoint $\mathcal{C}\text{-Set} \xrightarrow{m'} \mathcal{D}\text{-Set}$ and...
- ... m' is in $\mathbb{P}$! (i.e. the adjoint m' needs to preserve connected limits).

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Both functors $\mathcal{C} \xrightarrow{F} \mathcal{D}$ and cofunctors $\mathcal{C} \overset{\varphi}{\nrightarrow} \mathcal{D}$ induce adjunctions in $\mathbb{P}^{\mathrm{op}}$.

- The pullback and right Kan extension along F are adjoint $\Delta_F \dashv \Pi_F$.
- The companion and conjoint of φ are adjoint $\Sigma_\varphi \dashv \Delta_\varphi$.
- A dopf F is both a functor and a cofunctor, and the Δ's coincide.

Note that cofunctors $\mathcal{C} \nrightarrow \mathcal{D}$ induce interesting maps between toposes:

- Whereas geometric morphisms $\mathcal{C}\text{-Set} \leftrightarrows \mathcal{D}\text{-Set}$ preserve finite limits...
- ... cofunctors induce adjunctions that preserve connected limits.

Operads as monads in $\mathbb{P}$

In any framed bicategory, notation from $\mathbb{P}$, a monad $(\mathcal{C}, m, \eta, \mu)$ consists of

- An object $\mathcal{C}$, the *type*
- a bicomodule $\mathcal{C} \triangleleft\!\xrightarrow{m}\!\triangleleft\ \mathcal{C}$, the *carrier*
- a 2-cell $\eta\colon \mathrm{id}_c \Rightarrow m$, the *unit*
- a 2-cell $\mu\colon m \circ m \Rightarrow m$, the *multiplication*
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In $\mathbb{P}$, these generalize operads in a number of ways:

- When $\mathcal{C} \cong I$ is discrete, η, μ are cartesian, you get colored operads.[3]
- Relaxing discreteness of $\mathcal{C}$, the domain of a morphism can be...
- ... a diagram, rather than a mere set, of objects.
- Relaxing "iso" condition, composites and ids can have "weird" arities.

[3] Not quite the standard definition of operad, but no less elegant: the input to a morphism is a set, rather than a list of objects. You can also talk about standard (list-based) operads and their generalizations within the $\mathbb{P}$ setting; see Gambino-Kock.

"Categories = monads in $\mathbb{S}$pan" in $\mathbb{P}$

It is well-known that "categories are monads in $\mathbb{S}$pan." Let O be a set.

- A prafunctor $Oy \overset{m}{\triangleright\!\!\longrightarrow\!\!\triangleright} Oy$ acts as a span iff it's a left adjoint.
- If a monad m has a right adjoint $Oy \overset{c}{\triangleleft\!\!\longleftarrow\!\!\triangleleft} Oy$, then c is a comonad.
- Now, since the vertical part of $\mathbb{P}$ is already Comon(Poly),
- … c has a canonical comonoid structure $\mathfrak{c}$, equipped with $\mathfrak{c} \nrightarrow Oy$.
- This map $\mathfrak{c} \nrightarrow Oy$ is identity on objects because c was right adjoint.
- Thus we see internally how m induces a category $\mathfrak{c}$ with object-set O.

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Here's how functors and cofunctors look in this perspective:

$$\begin{tikzcd} Oy \arrow[r, "m"] \arrow[d] \arrow[dr, phantom, "\Downarrow"] & Oy \arrow[d] \\ O'y \arrow[r, "m'"'] & O'y \end{tikzcd} \quad \text{vs.} \quad \begin{tikzcd} Oy \arrow[d] \arrow[dr, phantom, "\Downarrow"] & Oy \arrow[l, "c"'] \arrow[d] \\ O'y & O'y \arrow[l, "c'"] \end{tikzcd}$$

Grothendieck sites give $\mathbb{P}$-monads

Every Grothendieck site $(\mathcal{C}^{\mathsf{op}}, J)$ has an associated monad m_J in $\mathbb{P}$.

- A J-sheaf is an m_J-algebra, but not all m_J-algebras are J-sheaves.
- An m_J-algebra gives formula for gluing, but no uniqueness guarantee.

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To each Grothendieck top'y J, we need (m, η, μ) where $\mathcal{C} \triangleleft\!\xrightarrow{m}\!\triangleleft\ \mathcal{C}$.

- The topology J assigns to each $V \in \mathcal{C}$ a set J_V, "covering families"...
- ... and each $F \in J_V$ is assigned a subfunctor $S_F \subseteq \mathcal{C}[V]$.
- From this data we define $m \in \mathsf{Poly}$:

$$m := \sum_{V \in \mathsf{Ob}(\mathcal{C})} \sum_{F \in J_V} y^{S_F}.$$

The Grothendieck top'y axioms endow the bimodule and monad structure.

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An algebra structure $m \circ P \xrightarrow{h} P$ assigns a section $h_V(F, s) \in P_V$ to each V-covering family F and matching family s of sections.

$$\begin{tikzcd} \mathcal{C} & \mathcal{C} \arrow[l, "m"'] \arrow[d, phantom, "\Downarrow h"] & 0 \arrow[l, "P"'] \arrow[ll, bend left, "P"] \\ & {} & \end{tikzcd}$$

Outline

Bringing the abacus out of the monastery

I hope it's now clear that we've got a well-oiled machine:

- Poly and $\mathbb{P}$ have excellent formal properties, and
- we can see how they work using very concrete calculations.

Our next job is to take this shiny abacus out for a spin.

- How do I see Poly as appropriate for the Glass Bead Game?
- We can use this instrument to talk about many aspects of the world.

Moore machines

Definition

Given sets A, B, an (A, B)-*Moore machine* consists of:

- a set S, elements of which are called *states*,
- a function $r\colon S \to B$, called *readout*, and
- a function $u\colon S \times A \to S$, called *update*.

It is *initialized* if it is equipped also with

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Dynamics: an (A, B)-Moore machine (S, r, u, s_0) is a "stream transducer":

- Given a list/stream $[a_0, a_1, \ldots]$ of A's...
- let $s_{n+1} := u(s_n, a_n)$ and $b_n := r(s_n)$.
- We thus have obtained a list/stream $[b_0, b_1, \ldots]$ of B's.

Moore machines as maps in Poly

We can understand Moore machines $A - \boxed{S} - B$ in terms of polynomials.

- A Moore machine $r\colon S \to B$ and $u\colon S \times A \to S$ is:
  - A function $S \to B \times S^A$, i.e. a By^A-coalgebra.
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A *p-coalgebra* allows different input-sets at different positions.

- For arbitrary $p \in \mathsf{Poly}$ we can interpret a map $\varphi\colon S \to p \triangleleft S$ as:
  - a readout: every state $s \in S$ gets a position $i := \varphi_1(s) \in p(1)$
  - an update: for every direction $d \in p[i]$, a next state $\varphi_2(s, d) \in S$.

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  - an update: for every direction $d \in p[i]$, a next state $\varphi_2(s, d) \in S$.

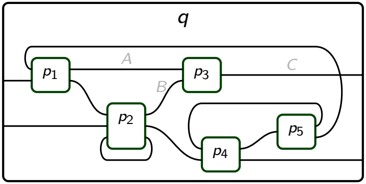
Even more general: a functor $S\colon \mathcal{C} \to \mathsf{Set}$ for any category $\mathcal{C}$.

- This generalizes the above, because $p\text{-}\mathsf{Coalg} \cong \mathfrak{c}_p\text{-}\mathsf{Set}$.
- Imagine its elements (c, s) as states; each reads out its object $c \in \mathcal{C}$...
- ... and for any morphism $f\colon c \to c'$, it can be updated to $(c', s.f)$.

We'll call any of these things *dynamical systems*.

Wiring diagrams

We can have a bunch of dynamical systems interacting in an open system.



(φ)

Each box represents a monomial, e.g. $p_3 = Cy^{AB} \in \mathbf{Poly}$.

- The whole interaction, p_1 sending outputs to p_2 and p_3, etc....
- ... is captured by a map of polynomials $\varphi\colon p_1 \otimes \cdots \otimes p_5 \to q$.
  - Given the positions (outputs) of each p_i, we get an output of q...
  - ... and when given an input of q, each p_i gets an input.

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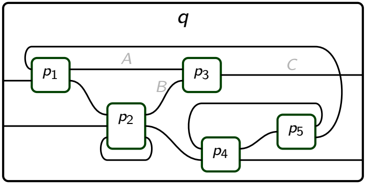

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    - Given the positions (outputs) of each p_i, we get an output of q...
    - ... and when given an input of q, each p_i gets an input.
- Now each subsystem can be endowed with a coalgebra $S_i \to p_i \triangleleft S_i$.
- We tensor and compose to give $S \to q \triangleleft S$, where $S := S_1 \times \cdots \times S_5$.

So φ applied to dynamics in $p_1, \ldots, p_5$ gives dynamics in q.

More general interaction

The whole picture above represents one morphism in Poly.

- Let's suppose the company chooses who it wires to; this is its *mode*.
- Then both suppliers have interface Wy for $W \in \mathsf{Set}$.
- Company interface is $2y^W$: two modes, each of which is W-input.
- The outer box is just y, i.e. a closed system.

So the picture represents a map $Wy \otimes Wy \otimes 2y^W \to y$.

- That's a map $2W^2y^W \to y$.
- Equivalently, it's a function $2W^2 \to W$. Take it to be evaluation.
- In other words, the company's choice determines which $w \in W$ it receives.

Other sorts of dynamical systems

Dynamical systems are usually defined as actions of a monoid T.

- Discrete: $\mathbb{N}$, reversible: $\mathbb{Z}$, real-time: $\mathbb{R}$.
- If T is a monoid and S is a set, a T-action on S is equivalently...
- ... a functor $S\colon T \to \mathsf{Set}$, as in our general definition above.

Other sorts of dynamical systems

Dynamical systems are usually defined as actions of a monoid T.

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Summary: Poly can encode dynamical systems and rewiring diagrams.

Categorical databases

One view on databases is that they're basically just copresheaves.

$$\mathcal{C} := \boxed{\begin{tikzcd} \underset{\bullet}{\text{Employee}} \arrow[loop left, "\text{Mngr}"] \arrow[r, shift left, "\text{WorksIn}"] & \underset{\bullet}{\text{Department}} \arrow[l, shift left, "\text{Admin}"] \end{tikzcd} \quad \text{Department.Admin.WorksIn} = \text{id}_{\text{Department}}}$$

A functor $I \colon \mathcal{C} \to \mathbf{Set}$ (i.e. $\mathcal{C} \xleftarrow{I} 0$) can be represented as follows:

Employee	**WorksIn**	**Mngr**
♡	P9	♡
T****	bLue	orca
orca	bLue	orca

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But where's the data? What are the employees names, etc.?

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More realistically, data should include *attributes* and look like this:

Employee	**FName**	**WorksIn**	**Mngr**
♡	Alan	P9	♡
T****	Dani	bLue	orca
orca	Sara	bLue	orca

Department	**DName**	**Secr**
bLue	Sales	T****
P9	IT	♡

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P9	IT	♡

- Assign a copresheaf $T\colon \mathrm{Ob}(\mathcal{C}) \to \mathrm{Set}$, e.g. $T(\text{Employee}) = \text{String}$.
- Using the canonical cofunctor $\mathcal{C} \nrightarrow \mathrm{Ob}(\mathcal{C})$, attributes are given by α:

$$\begin{tikzcd} \mathcal{C} \arrow[d, "|"] \arrow[r, phantom, shift right=6, "\Downarrow\alpha"] & 0 \arrow[l, "I"'] \arrow[d, equal] \\ \mathrm{Ob}(\mathcal{C}) & 0 \arrow[l, "T"] \end{tikzcd}$$

Data migration

The framed bicategory structure of $\mathbb{P}$ is very useful in databases.

- We hinted at this in the last slide, adding attributes via a cofunctor.
- But so-called *data migration functors* are precisely prafunctors.

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A prafunctor $\mathcal{C} \triangleleft\!\xrightarrow{P}\!\triangleleft\ \mathcal{D}$ in ${}_{\mathcal{C}}\mathbf{Mod}_{\mathcal{D}}$ can be understood as follows.

- First, it's a functor $\mathcal{C} \to {}_1\mathbf{Mod}_{\mathcal{D}}$, so what's an object in ${}_1\mathbf{Mod}_{\mathcal{D}}$?
- We said it's a formal coproduct of formal limits in $\mathcal{D}$.
- A formal limit in $\mathcal{D}$ is called a *conjunctive query* on $\mathcal{D}$.
- So a prafunctor $1 \triangleleft\!\xrightarrow{Q}\!\triangleleft\ \mathcal{D}$ is a disjoint union of conjunctive queries.
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Example: if $\mathcal{D} = \left(\overset{\text{City}}{\bullet} \xrightarrow{\text{in}} \overset{\text{State}}{\bullet} \xleftarrow{\text{in}} \overset{\text{County}}{\bullet} \right)$, a duc-query might be...

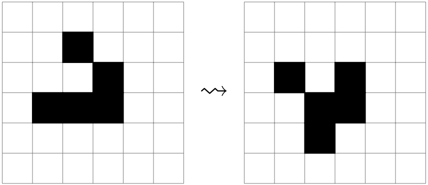
$$(\text{City} \times_{\text{State}} \text{City}) + (\text{City} \times_{\text{State}} \text{County}) + (\text{County} \times_{\text{State}} \text{County})$$

A general bimodule $P \in {}_{\mathcal{C}}\mathsf{Mod}_{\mathcal{D}}$ is a $\mathcal{C}$-indexed duc-query on $\mathcal{D}$.

Cellular automata

Cellular automata are like Moore machines, except with no internal state.

- Here's a picture of a *glider* from Conway's Game of Life:



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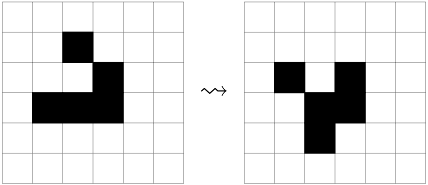

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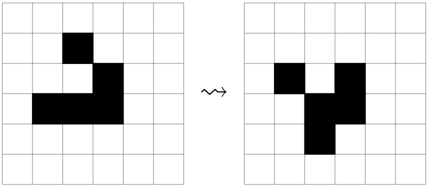

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- Each square has neighbors; think of the grid as a graph $A \rightrightarrows V$.
- Each square can be in one of two states: white or black.
- The state at any square is updated according to a formula, e.g.

  If the square is ■ and has 2 or 3 ■ neighbors, it stays ■.
  If the square is □ and has 3 ■ neighbors, it turns ■.
  Otherwise it turns / remains □.

Cellular automata as algebras in $\mathbb{P}$

How do we encode this in $\mathbb{P}$?

- We encode the graph $A \rightrightarrows V$ as a prafunctor $Vy \xleftarrow{g} Vy$
    - Each $v \in V$ queries its neighbors (and itself).
    - The carrier of the prafunctor for GoL is $g := Vy^9$.
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- We encode the color-set for each node as a prafunctor $Vy \triangleleft\!\xleftarrow{C}\!\triangleleft\; 0$
  - In GoL, each $v \in V$ gets the set 2; i.e. $C := 2V$.
- We encode the update formula as a map u of prafunctors

$$\begin{tikzcd} Vy & Vy \arrow[l, "g"'] \arrow[d, phantom, "\Downarrow u"] & 0 \arrow[l, "C"'] \arrow[ll, bend left=50, "C"] \\ & {} & \end{tikzcd}$$

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- We encode the update formula as a map u of prafunctors
- And we encode the initial color setup as a point $V \xrightarrow{i} C$:

$$\begin{tikzcd}
Vy & Vy \arrow[l, "g"'] \arrow[d, phantom, "\Downarrow u"] & 0 \arrow[l, "C"'] \arrow[l, bend right, "V"'] \arrow[ll, bend left=60, "C"] \\
& {} &
\end{tikzcd}$$

From here you can iteratively “run” the cellular automaton.

Running the cellular automaton

$$
\begin{tikzcd}[column sep=large]
Vy & Vy \arrow[l, "g"'] & Vy \arrow[l, "g"'] & Vy \arrow[l, "g"'] \arrow[r, phantom, "\Downarrow i"] & 0 \arrow[l, "C"] \arrow[l, bend right, "V"'] \arrow[ll, bend right=40, "V"'] \arrow[lll, bend right=45, "V"'] \arrow[llll, bend right=50, "V"'] \arrow[ll, bend left=40, "C"] \arrow[lll, bend left=45, "C"] \arrow[llll, bend left=50, "C"] \arrow[l, phantom, shift right=6, "\cong"] \arrow[ll, phantom, shift right=10, "\cong"] \arrow[lll, phantom, shift right=14, "\cong"] \arrow[l, phantom, shift left=6, "\Downarrow u"] \arrow[ll, phantom, shift left=10, "\Downarrow u"] \arrow[lll, phantom, shift left=14, "\Downarrow u"]
\end{tikzcd}
$$

Use that $Vy \xleftarrow{V} 0$ is terminal and $Vy \xleftarrow{g} Vy$ preserves terminals.

What is deep learning?

In *Backprop as functor*[4] "deep learning" is expressed in terms of SMCs.

- Objects are Euclidean spaces $\mathbb{R}^n$; monoidal product is $\times$.
- A morphism $\mathbb{R}^m \rightsquigarrow \mathbb{R}^n$ consists of
  - Another Euclidean space $\mathbb{R}^p$, *parameter space*,
  - A function $I\colon \mathbb{R}^p \times \mathbb{R}^m \to \mathbb{R}^n$, *implement*
  - A function $U\colon \mathbb{R}^p \times \mathbb{R}^m \times \mathbb{R}^n \to \mathbb{R}^p \times \mathbb{R}^m$, *update and backprop*
- Explanation:
  - The update takes an (inp, outp) pair and updates the parameter.
  - Without backprop, morphism composition cannot be defined.

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- Explanation:
  - The update takes an (inp, outp) pair and updates the parameter.
  - Without backprop, morphism composition cannot be defined.
- Typically, I and U have very particular forms.
  - I is usu. a composite of linear maps and logistic-like maps.
  - U is usu. gradient descent along a "loss covector" $\ell \in T^*(\mathbb{R}^n) \cong \mathbb{R}^n$.

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Deep learning in Poly

The best-known methods use calculus, but the structure is set-theoretic.

$\mathsf{Learn}(A, B) := \{(P, I, U) \mid P \in \mathsf{Set}, I \colon P \times A \to B, U \colon P \times A \times B \to P \times A\}$

We can see this inside of Poly:

$$\mathsf{Learn}(A, B) \cong [Ay^A, By^B]\text{-}\mathsf{Coalg}$$

That is, it's the cat'y of dynamical systems in $[Ay^A, By^B]$, where recall

$$[Ay^A, By^B] \cong \sum_{\varphi \colon Ay^A \to By^B} y^{AB}$$

An (A, B)-learner is thus a set P and a map $P \to [Ay^A, By^B] \triangleleft P$.

Learners' languages

For any polynomial p, the category p-Coalg forms a topos.

- Indeed, letting $\mathfrak{c}_p$ be the cofree comonoid on p,...
- ...there is an equivalence p-Coalg $\cong \mathfrak{c}_p$-Set.
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In particular, the topos p-Coalg has an internal type theory and logic.

- The logic describes constraints on dynamical systems.
- A proposition ϕ is any subobject of the terminal p-coalgebra:
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Gradient descent-backprop is a proposition in $[\mathbb{R}^m y^{\mathbb{R}^m}, \mathbb{R}^n y^{\mathbb{R}^n}]$-Coalg.

- That is, it is a constraint on $(\mathbb{R}^m, \mathbb{R}^n)$-learners.
- It has a very particular flavor: it can be checked in one timestep.

But the logic is much more expressive. We'll leave that for a later time.

Outline

Summary

Poly is a category of remarkable abundance.

- It's completely combinatorial.
  - Calculations using "the abacus" are concrete.
  - Much is already familiar, e.g. $(y+1)^2 \cong y^2 + 2y + 1$.
- It's theoretically beautiful.
  - Comonoids are categories.
  - Coalgebras are copresheaves.
- It's got a wide scope of applications.
  - Databases and data migration.
  - Dynamical systems and cellular automata.
  - Deep learning and its generalizations.

Thank you for your time; questions and comments welcome.