

Where do ultracategories come from?

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joint work with Joshua Wrigley

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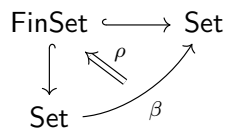
CT, Brno, Czech Republic

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Compact Hausdorff spaces and the ultrafilter monad

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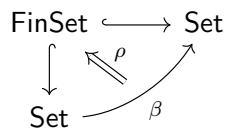
1. they are algebras for the *ultrafilter monad* $\langle \beta, \eta, \mu \rangle$ on $\mathbf{Set}$;
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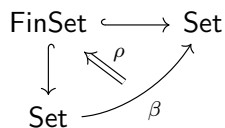
In *no-iteration form*, the monad $\langle \beta, \eta, \mu \rangle$ can be equivalently described by

- ▶ a function $\eta_X: X \rightarrow \beta X$ for each set X ,
 - ▶ and a function $(-)^*: \mathbf{Set}(Y, \beta X) \rightarrow \mathbf{Set}(\beta Y, \beta X)$ for each pair of sets X, Y ,
- satisfying equations.

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satisfying equations. In the same spirit, a β -algebra K is equivalently described by a function

$$(-)^K: \mathbf{Set}(Y, K) \longrightarrow \mathbf{Set}(\beta Y, K)$$

for each set Y , satisfying equations. Intuitively, $h^K(\nu) \in K$ is the *topological limit* of a family $h: Y \rightarrow K$ of points of K with respect to the ultrafilter $\nu \in \beta Y$.

Ultracategories

Ultracategories were introduced by Makkai as categories endowed with structure meant to abstract the notion of **ultraproducts** from model theory. Different definitions exist, but the core is that of a category C with a functor

$$(-)^C: [Y, C] \longrightarrow [\beta Y, C]$$

for each set Y , which Makkai calls a *pre-ultracategory*. Intuitively, $h^C(\nu)$ is the ‘ultraproduct’ of a family $h: Y \rightarrow C$ of objects of C with respect to the ultrafilter $\nu \in \beta Y$.

Makkai, *Stone duality for first-order logic*, 1987

Lurie, *Ultracategories*, 2018

Main example

$\text{Mod}(\mathbb{T})$, for a coherent theory $\mathbb{T}$, is an ultracategory: $(-)^{\text{Mod}(\mathbb{T})}$ maps a tuple $(M_y)_{y \in Y}$ of models and an ultrafilter $\nu \in \beta Y$ to the actual ultraproduct $\prod_\nu M_y$.

Our contribution

Question

Ultracategories categorify compact Hausdorff spaces. Can we make an axiomatisation of the notion of ultracategory emerge just as naturally, i.e. as

1. algebras for a pseudomonad on $\mathbf{CAT}$,
2. whose underlying pseudofunctor is universally-induced by $\beta: \mathbf{Set} \rightarrow \mathbf{Set}$?

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“[Both Makkai’s and Lurie’s definitions of an ultracategory are] very heavy, and come together with axioms whose choice seems quite arbitrary.”

Di Liberti, *The geometry of coherent topoi and ultrastructures*, 2022

“Ultraproducts are categorically inevitable.”

Leinster, *Codensity and the ultrafilter monad*,
2018

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Earlier work in this direction tries to tackle the problem directly, by defining suitable pseudomonads on $\mathbf{CAT}$.

Marmolejo, *Ultraproducts and continuous families of models*, 1995

Rosolini, *Ultracompletions*, talk at CT2024

Hamad, *Ultracategories as colax algebras for a pseudo-monad on $\mathbf{CAT}$* , 2025

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Our answer

We will make an axiomatisation emerge by putting ultracategories in the context of *relative monad theory*. The starting point is that Lurie's definition is *almost* that of a **colax algebra** for a **relative 2-monad** over $\mathbf{CAT}$.

Altenkirch, Chapman, Uustalu, *Monads need not be endofunctors*, 2015

Fiore, Gambino, Hyland, Winskel, *Relative pseudomonads, Kleisli bicategories and substitution monoidal structures*, 2018

Relative 2-monads

Definition

Let $J: \mathcal{B} \rightarrow \mathbf{CAT}$ be a 2-functor.

A *J*-relative 2-monad on $\mathbf{CAT}$ is given by

1. a category Tb , for each $b \in \mathcal{B}$,
2. a functor $\eta_b: Jb \rightarrow Tb$ for each $b \in \mathcal{B}$,
3. and a functor $(-)^*: [Jb, Tb'] \rightarrow [Tb, Tb']$ for each pair $b, b' \in \mathcal{B}$,

satisfying the conditions:

- a. $\eta_b^* = \text{id}_{Tb}$,
- b. $f^* \circ \eta_b = f$,
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The relative ultrafilter 2-monad

If J is 2-fully-faithful, every 2-monad $\langle T, \eta, (-)^* \rangle$ on $\mathcal{B}$ yields a J -relative 2-monad $\langle JT, J\eta, J(-)^* J^{-1} \rangle$ on $\mathbf{CAT}$. In particular, considering the inclusion $\mathbf{Set} \hookrightarrow \mathbf{CAT}$, the ultrafilter monad $\beta: \mathbf{Set} \rightarrow \mathbf{Set}$ yields the *relative ultrafilter 2-monad* $\beta: \mathbf{Set} \rightarrow \mathbf{CAT}$.

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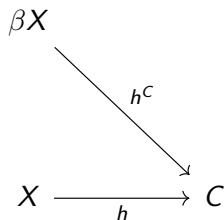
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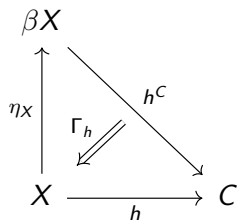
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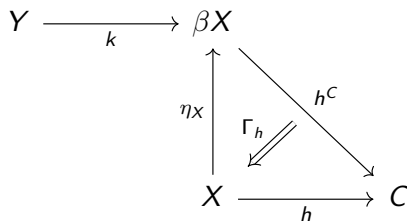
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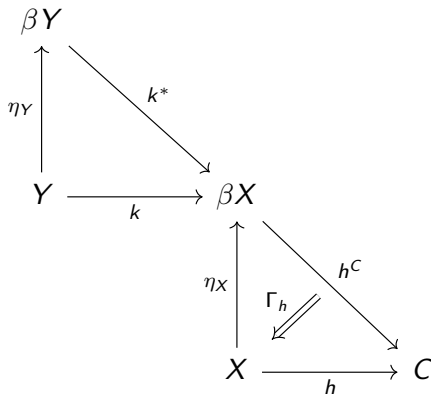
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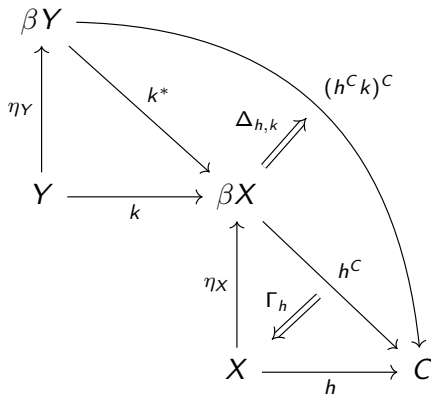
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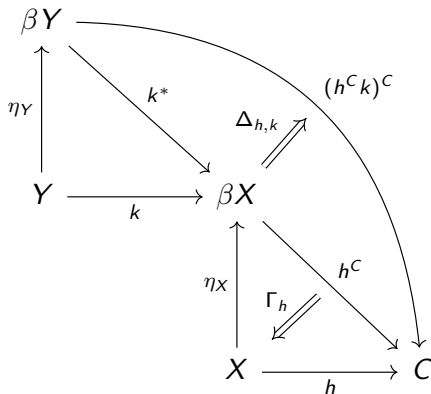
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Remark

Lurie's definition is the same, but he also requires each counitor Γ_h and some coassociators $\Delta_{h,k}$ to be invertible.

However:

- ▶ **ultrafunctors** coincide with *pseudomorphisms*;
- ▶ **left ultrafunctors** coincide with *colax morphisms*.

Left oplax Kan extensions

For a weak ultracategory C , the functors $(-)^C: [X, C] \rightarrow [\beta X, C]$ define a *lax transformation*

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where, for 2-functors $F, G: \mathcal{B} \rightarrow \mathcal{A}$, a lax transformation $\sigma: F \Rightarrow G$ is given by

- ▶ a 1-cell $\sigma_b: Fb \rightarrow Gb$ for each $b \in \mathcal{B}$,
- ▶ and a 2-cell

$$\begin{array}{ccc} Fb & \xrightarrow{\sigma_b} & Gb \\ Ff \downarrow & \swarrow \sigma_f & \downarrow Gf \\ Fb' & \xrightarrow{\sigma_{b'}} & Gb' \end{array}$$

for each 1-cell $f: b \rightarrow b'$ in $\mathcal{B}$,

satisfying some coherence and naturality conditions. Reversing the 2-cells we obtain an *oplax* transformation.

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For 2-functors $J, T: \mathcal{B} \rightarrow \mathcal{A}$, a *left oplax Kan extension* of T along J is a 2-functor $\tilde{T}: \mathcal{A} \rightarrow \mathcal{A}$ such that for all $a, a' \in \mathcal{A}$ there are natural isomorphisms:

$$\mathbf{Lax}[\mathcal{B}^{\mathrm{op}}, \mathbf{CAT}] (\mathcal{A}(J-, a), \mathcal{A}(T-, a')) \cong \mathcal{A}(\tilde{T}a, a')$$

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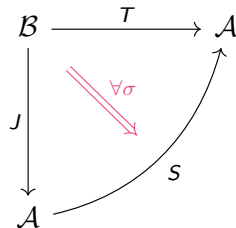
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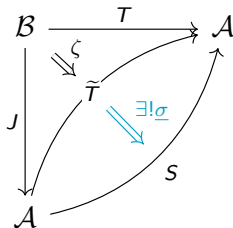
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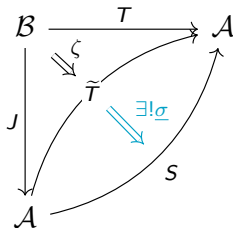
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$$\mathbf{Str}[\mathcal{A}, \mathcal{A}](\tilde{T}, S) \cong \mathbf{Oplax}[\mathcal{B}, \mathcal{A}](T, S \circ J)$$



The main result

Theorem (T. & Wrigley)

Let $\langle T, \eta, (-)^* \rangle$ be a J -relative 2-monad on $\mathbf{CAT}$. Suppose that:

1. J is 2-fully-faithful,
2. $\mathcal{B}$ has a terminal object 1 that is preserved by J ,
3. $\mathcal{B}$ has oplax colimits of shape $(Jb)^{\text{op}}$ for $b \in \mathcal{B}$, which J preserves.

The left oplax Kan extension $\tilde{T}$ of T along J carries the structure of a pseudomonad on $\mathbf{CAT}$ such that the 2-categories $\text{ColaxAlg}_J(T)$ and $\text{ColaxAlg}(\tilde{T})$ are isomorphic.

T. and Wrigley, *Ultracategories via Kan extensions of relative monads*, 2025

Left oplax Kan extensions in CAT

For $\mathcal{A} = \mathbf{CAT}$, left oplax Kan extensions exist and we can describe them explicitly. For concreteness, we describe here the extension of $\beta: \mathbf{Set} \rightarrow \mathbf{CAT}$ along $\mathbf{Set} \hookrightarrow \mathbf{CAT}$.

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If C is a weak ultracategory, recall that each functor $h: X \rightarrow C$ extends to a functor $h^C: \beta X \rightarrow C$. The corresponding colax $\tilde{\beta}$ -algebra functor $\tilde{\beta}C \rightarrow C$ then maps

$$(X, h: X \rightarrow C, \nu \in \beta X) \mapsto h^C(\nu).$$

A pseudomonad structure on $\tilde{\beta}$

In the case of $\beta: \mathbf{Set} \rightarrow \mathbf{CAT}$, the inclusion $\mathbf{Set} \hookrightarrow \mathbf{CAT}$:

1. is fully-faithful,
2. preserves the terminal object 1;
3. preserves small coproducts.

A pseudomonad structure on $\tilde{\beta}$

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Therefore, $\tilde{\beta}$ carries the structure of a pseudomonad $\langle \tilde{\beta}, \eta^\sharp, \mu^\sharp \rangle$ on $\mathbf{CAT}$, which we now describe.

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For an element $x \in X$, write $h(x) = (Y_x, k_x: Y_x \rightarrow C, \theta_x \in \beta Y_x) \in \tilde{\beta}C$.

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$$\mu_C^\sharp(X, h: X \rightarrow \tilde{\beta}C, \nu \in \beta X) = (\textcolor{violet}{Y}, -, -).$$

For an element $x \in X$, write $h(x) = (Y_x, k_x: Y_x \rightarrow C, \theta_x \in \beta Y_x) \in \tilde{\beta}C$.

1. Let $\textcolor{violet}{Y}$ be the coproduct $\coprod_{x \in X} Y_x$,
with inclusions $\{i_x: Y_x \hookrightarrow \textcolor{violet}{Y}\}_{x \in X}$.

A pseudomonad structure on $\tilde{\beta}$

In the case of $\beta: \mathbf{Set} \rightarrow \mathbf{CAT}$, the inclusion $\mathbf{Set} \hookrightarrow \mathbf{CAT}$ satisfies our assumptions. Therefore, $\tilde{\beta}$ carries the structure of a pseudomonad $\langle \tilde{\beta}, \eta^\sharp, \mu^\sharp \rangle$ on $\mathbf{CAT}$, which we now describe.

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A pseudomonad structure on $\tilde{\beta}$

In the case of $\beta: \text{Set} \rightarrow \text{CAT}$, the inclusion $\text{Set} \hookrightarrow \text{CAT}$ satisfies our assumptions. Therefore, $\tilde{\beta}$ carries the structure of a pseudomonad $\langle \tilde{\beta}, \eta^\sharp, \mu^\sharp \rangle$ on CAT , which we now describe.

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$$\mu_C^\sharp(X, h: X \rightarrow \tilde{\beta}C, \nu \in \beta X) = (\textcolor{violet}{Y}, k: \textcolor{green}{Y} \rightarrow \textcolor{teal}{C}, \textcolor{brown}{q}^*(\nu)).$$

For an element $x \in X$, write $h(x) = (Y_x, k_x: Y_x \rightarrow C, \theta_x \in \beta Y_x) \in \tilde{\beta}C$.

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with inclusions $\{i_x: Y_x \hookrightarrow \textcolor{violet}{Y}\}_{x \in X}$.
2. Let $k: \textcolor{green}{Y} \rightarrow \textcolor{teal}{C}$ be the unique functor
determined by $\{k_x: Y_x \rightarrow C\}_{x \in X}$,
i.e. $k(y \in Y_x) := k_x(y)$.
3. The functor $q: X \rightarrow \beta Y$ defined by $x \mapsto \beta i_x(\theta_x)$ extends to a functor
 $q^*: \beta X \rightarrow \beta Y$, so that we can consider $\textcolor{brown}{q}^*(\nu) \in \beta Y$. Concretely, for $S \subseteq Y$,

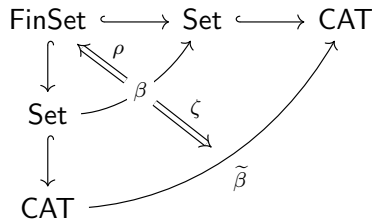
$$S \in q^*(\nu) \iff \{x \in X \mid S \cap Y_x \in \theta_x\} \in \nu$$

Weak ultracategories II

Applying our result to the relative ultrafilter 2-monad, we conclude that weak ultracategories are pseudomonadic over CAT.

Corollary

Weak ultracategories are the colax algebras for the pseudomonad $\tilde{\beta}$ on CAT where:



- ▶ $\beta: \mathbf{Set} \rightarrow \mathbf{Set}$ is the right Kan extension of $\mathbf{FinSet} \hookrightarrow \mathbf{Set}$ along itself;
- ▶ $\tilde{\beta}: \mathbf{CAT} \rightarrow \mathbf{CAT}$ is the left oplax Kan extension of $\beta: \mathbf{Set} \rightarrow \mathbf{CAT}$ along $\mathbf{Set} \hookrightarrow \mathbf{CAT}$.

Future directions

- ▶ We can apply our result to other monads of interest: in particular, the *upper prime filter monad* $B: \mathbf{Pos} \rightarrow \mathbf{Pos}$ whose algebras are **compact ordered spaces**. *Prime categories*, i.e. the colax algebras for the *relative upper prime filter 2-monad* $B: \mathbf{Pos} \rightarrow \mathbf{CAT}$, are then the colax algebras for $\tilde{B}: \mathbf{CAT} \rightarrow \mathbf{CAT}$.
 - Connections with *positive model theory*
 - Towards a Priestley-like duality for first-order logic

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- ▶ We can apply our result to other monads of interest: in particular, the *upper prime filter monad* $B: \mathbf{Pos} \rightarrow \mathbf{Pos}$ whose algebras are **compact ordered spaces**. *Prime categories*, i.e. the colax algebras for the *relative upper prime filter 2-monad* $B: \mathbf{Pos} \rightarrow \mathbf{CAT}$, are then the colax algebras for $\tilde{B}: \mathbf{CAT} \rightarrow \mathbf{CAT}$.
 - Connections with *positive model theory*
 - Towards a Priestley-like duality for first-order logic
- ▶ Assuming they exist, left oplax Kan extensions along $J: \mathcal{B} \rightarrow \mathcal{A}$ determine a 2-adjunction

$$\begin{array}{ccc} & \widetilde{(-)} & \\ \text{Oplax } [\mathcal{B}, \mathcal{A}] & \xrightarrow{\quad} & \mathbf{Str} [\mathcal{A}, \mathcal{A}] \\ & \underset{J^*}{\xleftarrow{\quad}} & \\ & \perp & \end{array}$$

Can we find sufficient hypotheses on $\mathcal{A}$ to obtain an abstract ‘unrelativisation’ procedure for J -relative pseudomonads?

- Connections with *skew-monoidal 2-categories* and monoidal 2-functors

Thank you!

Ultracategories via Kan extensions of relative monads,
Umberto Tarantino and Joshua Wrigley, 2025, arXiv:2506.09788

Weak ultracategories are ultracategories

Lurie's ultracategories are a (proper) subclass of weak ultracategories.

However, Lurie's ultrafunctors and left ultrafunctors coincide with pseudomorphisms and colax morphisms, so that we have 2-fully-faithful embeddings:

$$\mathbf{Ult} \hookrightarrow \mathbf{WeakUlt}^{\text{pseudo}} \quad \mathbf{Ult}^{\text{L}} \hookrightarrow \mathbf{WeakUlt}^{\text{colax}}$$

This ensures that weak ultracategories are a good axiomatisation of ultracategories.

Theorem (Lurie)

For a small pretopos P , the evaluation functor $\text{ev}: P \rightarrow [\text{Mod}(P), \text{Set}]$ induces equivalences of categories:

1. $P \simeq \mathbf{WeakUlt}^{\text{pseudo}}(\text{Mod}(P), \text{Set});$
2. $\text{Sh}(P) \simeq \mathbf{WeakUlt}^{\text{colax}}(\text{Mod}(P), \text{Set}).$

In particular, $\text{Mod}: \text{Pretop}^{\text{op}} \hookrightarrow \mathbf{WeakUlt}^{\text{pseudo}}$ is 2-fully-faithful.

Left oplax Kan extensions in CAT

For $\mathcal{A} = \text{CAT}$, left oplax Kan extensions exist and we can describe them explicitly. For concreteness, consider $\beta: \text{Set} \rightarrow \text{CAT}$. For a category C :

- ▶ objects of $\tilde{T}C$ are triples $(b \in \mathcal{B}, h: Jb \rightarrow C, \nu \in Tb)$;
- ▶ morphisms $(b, h, \nu) \rightarrow (b', h', \nu')$ in $\tilde{T}C$ are triples of
 1. a 1-cell $f: b' \rightarrow b$ in $\mathcal{B}$,
 2. a natural transformation $\alpha: h \circ Jf \Rightarrow h'$,
 3. and an arrow $\varphi: \nu \rightarrow Tf(\nu')$ in Tb ,

modulo the equivalence relation generated by $(f, \alpha_f, \varphi_f) \sim (g, \alpha_g, \varphi_g)$ if there exists a 2-cell $\sigma: f \Rightarrow g$ in $\mathcal{B}$ such that

$$\begin{array}{ccc}
 Jb' & \xrightarrow{Jf} & Jb \\
 \downarrow J\sigma & & \downarrow \alpha_f \\
 Jb' & \xrightarrow{Jg} & Jb \\
 \downarrow \alpha_g & & \downarrow \\
 C & & C
 \end{array}
 \quad (1)$$

(The diagram shows a commutative square with curved arrows h' and h from Jb' and Jb to C , and a 2-cell σ between Jf and Jg .)

$$\begin{array}{ccc}
 \nu & \xrightarrow{\varphi_f} & Tf(\nu') \\
 \downarrow \varphi_g & (2) & \downarrow (T\sigma)_{\nu'} \\
 \nu & \xrightarrow{\varphi_g} & Tg(\nu')
 \end{array}$$

(The diagram shows a commutative square with curved arrows φ_f and φ_g from ν to $Tf(\nu')$ and $Tg(\nu')$, and a 2-cell σ between f and g .)

A pseudomonad structure on $\tilde{T}$

Under our assumptions, $\tilde{T}$ carries the structure of a pseudomonad $\langle \tilde{T}, \eta^\sharp, \mu^\sharp \rangle$ on CAT.

- ▶ On objects, the unit $\eta_C^\sharp: C \rightarrow \tilde{T}C$ maps $c \in C$ to $(1_B, c: 1_{\text{CAT}} \rightarrow C, \eta_{1_B}(*))$.
- ▶ On objects, the multiplication $\mu_C^\sharp: \tilde{T}^2 C \rightarrow \tilde{T}C$ acts by

$$\mu_C^\sharp(b, h: Jb \rightarrow \tilde{T}C, \nu) = (\ell, a: J\ell \rightarrow C, Q^*\nu).$$

For an object $x \in Jb$, write $h(x) = (Rx, a_x: JRx \rightarrow C, \nu_x)$.

For an arrow $g: x \rightarrow y \in Jb$, write $h(g) = (Rg, \gamma_g: a_x \circ JRg \Rightarrow a_y, \psi_g)$.

1. Let $\ell \in \mathcal{B}$ be the oplax colimit of $R: (Jb)^{\text{op}} \rightarrow \mathcal{B}$, with universal cocone:
2. As J preserves oplax colimits and C is an oplax cocone of $JR: (Jb)^{\text{op}} \rightarrow \text{CAT}$

$$\begin{array}{ccc} Rx & \xleftarrow{Rg} & Ry \\ & \searrow \lambda_g & \swarrow \\ c_x & & c_y \end{array} \quad \text{with universal cocone to } \ell$$

$$\begin{array}{ccc} JRx & \xleftarrow{JRg} & J Ry \\ & \searrow \gamma_g & \swarrow \\ a_x & & a_y \end{array} \quad \text{with universal cocone to } C$$

there is a universal functor $a: J\ell \rightarrow C$.

3. The map $x \mapsto T_{c_x}(\nu_x)$ lifts to a functor $Q: Jb \rightarrow T\ell$, which extends to a functor $Q^*: Tb \rightarrow T\ell$ via the monad structure of T , so that we can consider $Q^*\nu \in T\ell$.