A COINTUITIONISTIC ADJOINT LOGIC

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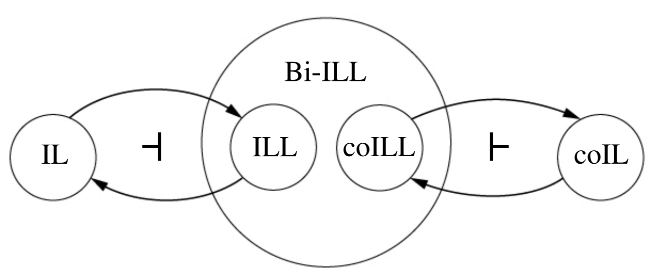
Abstract.

1. Introduction

Bi-intuitionistic logic (BINT) is a conservative extension of intuitionistic logic with perfect duality. That is, BINT contains the usual intuitionistic logical connectives such as true, conjunction, and implication, but also their duals false, disjunction, and coimplication. One leading question with respect to BINT is, what does BINT look like across the three arcs – logic, typed λ-calculi, and category theory – of the Curry-Howard-Lambek correspondence? A non-trivial (does not degenerate to a poset) categorical model of BINT is currently an open problem. This paper is the first of two that will provide an answer to this open problem.

BINT can be seen as a mixing of two worlds: the first being intuitionistic logic (IL), which is modeled categorically by a cartesian closed category (CCC), and the second being the dual to intuitionistic logic called cointuitionistic logic (coIL), which is modeled by a cocartesian coclosed category (coCCC). Crolard [4] showed that combining these two categories into the same category results in it degenerating to a poset, that is, there is at most one morphism between any two objects. However, this degeneration does not occur when both logics are linear. We propose that these two worlds need to be separated, and then mixed in a control way using the modalities from linear logic. This separation can be ultimately achieved by an adjoint formalization of bi-intuitionistic logic. This formalization consists of three worlds instead of two: the first is intuitionistic logic, the second is linear bi-intuitionistic (Bi-ILL), and the third is cointuitionistic logic. They are then related via two adjunctions as depicted by the following diagram:



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The adjoint between IL and ILL is known as a LNL model of ILL, and is due to Benton [2]. However, the dual to LNL models which would amount to the adjoint between coILL and coIL has yet to appear in the literature.

The main contribution of this paper is the definition and study of the dual to Benton's LNL models as models of cointuitionistic logic called dual LNL models. Bellin [1] was the first to propose the dual to Bierman's [3] linear categories which he names dual linear categories as a model of cointuitionistic linear logic. We conduct a similar analysis to that of Benton for dual LNL models by showing that dual LNL models are dual linear categories (Section 2.2.2), and that from a dual linear category we may obtain a dual LNL model (Section 2.2.3). Following this we give the definition of bi-LNL models by combining our dual LNL models with Benton's LNL models to obtain a categorical model of bi-intuitionistic logic (Section 2.3), but we leave its analysis and correspond logic to a future paper. Finally, we give the definition of dual LNL logic and a term assignment (Section 3 and Section 5 respectively).

2. The Adjoint Model

Suppose $(\mathcal{I}, 1, \times, \rightarrow)$ is a cartesian closed category, and $(\mathcal{L}, \top, \otimes, \multimap)$ is a symmetric monoidal closed category. Then relate these two categories with a symmetric monoidal adjunction $\mathcal{I} : \mathsf{F} \dashv \mathsf{G} : \mathcal{L}$ (Definition **??**), where F and G are symmetric monoidal functors. The later point implies that there are natural transformations $\mathsf{m}_{X,Y} : \mathsf{F}X \otimes \mathsf{F}Y \longrightarrow \mathsf{F}(X \times Y)$ and $\mathsf{n}_{A,B} : \mathsf{G}A \times \mathsf{G}B \longrightarrow \mathsf{G}(A \otimes B)$, and maps $\mathsf{m}_\top : \top \longrightarrow \mathsf{F}1$ and $\mathsf{n}_1 : 1 \longrightarrow \mathsf{G}\top$ subject to several coherence conditions; see Definition **??**. Furthermore, the functor F is strong which means that $\mathsf{m}_{X,Y}$ and $\mathsf{m}_\top$ are isomorphisms. This setup turns out to be one of the most beautiful models of intuitionistic linear logic called an formally a LNL model due to Benton [2]. In fact, the linear modality of-course can be defined by $!A = \mathsf{F}(\mathsf{G}(A))$ which defines a symmetric monoidal comonad using the adjunction; see Section 2.2 of [2]. This model is much simpler than other known models, and resulted in a logic called LNL logic which supports mixing intuitionistic logic with linear logic.

Taking the dual of the previous model results in what we call dual LNL models. They consist of a cocartesian coclosed category, $(C, 0, +, -)$, a symmetric monoidal coclosed category, $(\mathcal{L}', \perp, \oplus, \bullet\!\!-)$, where $\bullet\!\!-$: $\mathcal{L}' \times \mathcal{L}' \longrightarrow \mathcal{L}'$ is left adjoint to parr, and a symmetric monoidal adjunction $\mathcal{L}' : H \dashv\perp : C$. We will show that dual LNL models are a simplification of dual linear categories as defined by Bellin [1] in much of the same way that adjoint models are a simplification of linear categories. In fact, we will define Girard's exponential why-not by $?A = J(H(A))$, and hence, is the monad induced by the adjunction.

2.1. Symmetric (co)Monoidal Categories.

We now introduce the necessary definitions related to symmetric monoidal categories that our model will depend on. Most of these definitions are equivalent to the ones given by Benton [2], but we give a lesser well-known definition for symmetric co-monoidal functors due to Bellin [1]. In this section we also introduce distributive categories, the notion of cocloser, and finally, the definition of bilinear categories. The reader may wish to simply skim this section, but refer back to it when they encounter a definition or result they do not know.

Definition 1. A **symmetric monoidal category (SMC)** is a category, $\mathcal{M}$, with the following data:

- An object $\top$ of $\mathcal{M}$,
- A bi-functor $\otimes : \mathcal{M} \times \mathcal{M} \longrightarrow \mathcal{M}$,

- The following natural isomorphisms:

$$\begin{aligned}\lambda_A &: \top \otimes A \longrightarrow A\\ \rho_A &: A \otimes \top \longrightarrow A\\ \alpha_{A,B,C} &: (A \otimes B) \otimes C \longrightarrow A \otimes (B \otimes C)\end{aligned}$$

- A symmetry natural transformation:

$$\beta_{A,B} : A \otimes B \longrightarrow B \otimes A$$

- Subject to the following coherence diagrams:

$$\begin{tikzcd}
((A \otimes B) \otimes C) \otimes D \arrow[r, "\alpha_{A,B,C} \otimes \mathsf{id}_D"] \arrow[d, "\alpha_{A\otimes B,C,D}"] & (A \otimes (B \otimes C)) \otimes D \arrow[dd, "\alpha_{A,B\otimes C,D}"] \\
(A \otimes B) \otimes (C \otimes D) \arrow[d, "\alpha_{A,B,C\otimes D}"] & \\
A \otimes (B \otimes (C \otimes D)) & A \otimes ((B \otimes C) \otimes D) \arrow[l, "\mathsf{id}_A \otimes \alpha_{B,C,D}"']
\end{tikzcd}$$

$$\begin{tikzcd}
(A \otimes B) \otimes C \arrow[r, "\alpha_{A,B,C}"] \arrow[d, "\beta_{A,B} \otimes \mathsf{id}_C"] & A \otimes (B \otimes C) \arrow[r, "\beta_{A,B\otimes C}"] & (B \otimes C) \otimes A \arrow[d, "\alpha_{B,C,A}"] \\
(B \otimes A) \otimes C \arrow[r, "\alpha_{B,A,C}"] & B \otimes (A \otimes C) \arrow[r, "\mathsf{id}_B \otimes \beta_{A,C}"] & B \otimes (C \otimes A)
\end{tikzcd}$$

$$\begin{tikzcd}
(A \otimes \top) \otimes B \arrow[rr, "\alpha_{A,\top,B}"] \arrow[dr, "\rho_A"'] & & A \otimes (\top \otimes B) \arrow[dl, "\lambda_B"] \\
& A \otimes B &
\end{tikzcd}
\qquad
\begin{tikzcd}
A \otimes B \arrow[d, "\beta_{A,B}"'] \arrow[dr, "\mathsf{id}_{A\otimes B}"] & \\
B \otimes A \arrow[r, "\beta_{B,A}"'] & A \otimes B
\end{tikzcd}$$

$$\begin{tikzcd}
\top \otimes A \arrow[rr, "\beta_{\top,A}"] \arrow[dr, "\lambda_A"'] & & A \otimes \top \arrow[dl, "\rho_A"] \\
& A &
\end{tikzcd}$$

Categorical modeling implication requires that the model be closed; which can be seen as an internalization of the notion of a morphism.

Definition 2. A **symmetric monoidal closed category (SMCC)** is a symmetric monoidal category, $(\mathcal{M}, \top, \otimes)$, such that, for any object B of $\mathcal{M}$, the functor $- \otimes B : \mathcal{M} \longrightarrow \mathcal{M}$ has a specified right adjoint. Hence, for any objects A and C of $\mathcal{M}$ there is an object $B \multimap C$ of $\mathcal{M}$ and a natural bijection:

$$\mathsf{Hom}_{\mathcal{M}}(A \otimes B, C) \cong \mathsf{Hom}_{\mathcal{M}}(A, B \multimap C)$$

We call the functor $\multimap: \mathcal{M} \times \mathcal{M} \longrightarrow \mathcal{M}$ the internal hom of $\mathcal{M}$.

Symmetric monoidal closed categories can be seen as a model of intuitionistic linear logic with a tensor product and implication. What happens when we take the dual? First, we have the following result:

Lemma 3 (Dual of Symmetric Monoidal Categories)**.** If $(\mathcal{M}, \top, \otimes)$ is a symmetric monoidal category, then $\mathcal{M}^{\mathsf{op}}$ is also a symmetric monoidal category.

The previous result follows from the fact that the structures making up symmetric monoidal categories are isomorphisms, and so naturally taking their opposite will yield another symmetric monoidal category. To emphasize when we are thinking about a symmetric monoidal category in the opposite we use the notion $(\mathcal{M}, \perp, \oplus)$ which gives the suggestion of $\oplus$ corresponding to a disjunctive tensor product which we call the *cotensor* of $\mathcal{M}$. The next definition describes when a symmetric monoidal category is coclosed.

Definition 4. A **symmetric monoidal coclosed category (SMCCC)** is a symmetric monoidal category, $(\mathcal{M}, \perp, \oplus)$, such that, for any object B of $\mathcal{M}$, the functor $- \oplus B : \mathcal{M} \longrightarrow \mathcal{M}$ has a specified left adjoint. Hence, for any objects A and C of $\mathcal{M}$ there is an object $C \bullet\!\!- B$ of $\mathcal{M}$ and a natural bijection:

$$\mathsf{Hom}_{\mathcal{M}}(C, A \oplus B) \cong \mathsf{Hom}_{\mathcal{M}}(C \bullet\!\!- B, A)$$

We call the functor $\bullet\!\!- : \mathcal{M} \times \mathcal{M} \longrightarrow \mathcal{M}$ the internal cohom of $\mathcal{M}$.

A symmetric monoidal category is a category with additional structure subject to several coherence diagrams. Thus, an ordinary functor is not enough to capture this structure, and hence, the introduction of symmetric monoidal functors.

Definition 5. Suppose we are given two symmetric monoidal closed categories $(\mathcal{M}_1, \top_1, \otimes_1, \alpha_1, \lambda_1, \rho_1, \beta_1)$ and $(\mathcal{M}_2, \top_2, \otimes_2, \alpha_2, \lambda_2, \rho_2, \beta_2)$. Then a **symmetric monoidal functor** is a functor $F : \mathcal{M}_1 \longrightarrow \mathcal{M}_2$, a map $m_{\top_1} : \top_2 \longrightarrow F\top_1$ and a natural transformation $m_{A,B} : FA \otimes_2 FB \longrightarrow F(A \otimes_1 B)$ subject to the following coherence conditions:

$$\begin{tikzcd}
(FA \otimes_2 FB) \otimes_2 FC \arrow[r, "\alpha_{2FA,FB,FC}"] \arrow[d, "m_{A,B} \otimes \mathsf{id}_{FC}"] & FA \otimes_2 (FB \otimes_2 FC) \arrow[d, "\mathsf{id}_{FA} \otimes m_{B,C}"] \\
F(A \otimes_1 B) \otimes_2 FC \arrow[d, "m_{A \otimes_1 B, C}"] & FA \otimes_2 F(B \otimes_1 C) \arrow[d, "m_{A, B \otimes_1 C}"] \\
F((A \otimes_1 B) \otimes_1 C) \arrow[r, "F\alpha_{1A,B,C}"] & F(A \otimes_1 (B \otimes_1 C))
\end{tikzcd}$$

$$\begin{tikzcd}
\top_2 \otimes_2 FA \arrow[r, "\lambda_{2FA}"] \arrow[d, "m_{\top_1} \otimes \mathsf{id}_{FA}"] & FA \\
F\top_1 \otimes_2 FA \arrow[r, "m_{\top_1, A}"] & F(\top_1 \otimes_1 A) \arrow[u, "F\lambda_{1A}"]
\end{tikzcd}
\qquad
\begin{tikzcd}
FA \otimes_2 \top_2 \arrow[r, "\rho_{2FA}"] \arrow[d, "\mathsf{id}_{FA} \otimes m_{\top_1}"] & FA \\
FA \otimes_2 F\top_1 \arrow[r, "m_{A, \top_1}"] & F(A \otimes_1 \top_1) \arrow[u, "F\rho_{1A}"]
\end{tikzcd}$$

$$\begin{tikzcd}
FA \otimes_2 FB \arrow[r, "\beta_{2FA,FB}"] \arrow[d, "m_{A,B}"] & FB \otimes_2 FA \arrow[d, "m_{B,A}"] \\
F(A \otimes_1 B) \arrow[r, "F\beta_{1A,B}"] & F(B \otimes_1 A)
\end{tikzcd}$$

The following is dual to the previous definition.

Definition 6. Suppose we are given two symmetric monoidal closed categories $(\mathcal{M}_1, \perp_1, \oplus_1, \alpha_1, \lambda_1, \rho_1, \beta_1)$ and $(\mathcal{M}_2, \perp_2, \oplus_2, \alpha_2, \lambda_2, \rho_2, \beta_2)$. Then a **symmetric comonoidal functor** is a functor $F : \mathcal{M}_1 \longrightarrow \mathcal{M}_2$, a map $m_{\perp_1} : F\ \perp_1 \longrightarrow \perp_2$ and a natural transformation $m_{A,B} : F(A \oplus_1 B) \longrightarrow FA \oplus_2 FB$ subject to the following coherence conditions:

$$\begin{tikzcd}
F((A \oplus_1 B) \oplus_1 C) \arrow[r, "m_{A\oplus_1 B,C}"] \arrow[d, "F\alpha_{A,B,C}"] & F(A \oplus_1 B) \oplus_2 FC \arrow[d, "m_{A,B} \oplus_2 \mathsf{id}_{FC}"] \\
F(A \oplus_1 (B \oplus_1 C)) \arrow[d, "m_{A,B\oplus_1 C}"] & (FA \oplus_2 FB) \oplus_2 FC \arrow[d, "\alpha_{FA,FB,FC}"] \\
FA \oplus_2 F(B \oplus_1 C)) \arrow[r, "\mathsf{id}_{FA} \oplus_2 m_{B,C}"] & FA \oplus_2 (FB \oplus_2 FC)
\end{tikzcd}$$

$$\begin{tikzcd}
F(\perp_1 \oplus_1 A) \arrow[r, "m_{\perp_1,A}"] \arrow[d, "F\lambda_{1A}"] & F\ \perp_1 \oplus_2 FA \arrow[d, "m_{\perp_1} \oplus \mathsf{id}_{FA}"] \\
FA \arrow[r, "\lambda_2^{-1}{}_{FA}"] & \perp_2 \oplus_2 FA
\end{tikzcd}
\qquad
\begin{tikzcd}
F(A \oplus_1 \perp_1) \arrow[r, "m_{A,\perp_1}"] \arrow[d, "F\rho_{1A}"] & FA \oplus_2 F\ \perp_1 \arrow[d, "\mathsf{id}_{FA} \oplus m_{\perp_1}"] \\
FA \arrow[r, "\rho_2^{-1}{}_{FA}"] & FA \oplus_2 \perp_2
\end{tikzcd}$$

$$\begin{tikzcd}
F(A \oplus_1 B) \arrow[r, "m_{A,B}"] \arrow[d, "F\beta_{1A,B}"] & FA \oplus_2 FB \arrow[d, "\beta_{2FA,FB}"] \\
F(B \oplus_1 A) \arrow[r, "m_{B,A}"] & FB \oplus_2 FA
\end{tikzcd}$$

Naturally, since functors are enhanced to handle the additional structure found in a symmetric monoidal category we must also extend natural transformations, and adjunctions.

Definition 7. Suppose $(\mathcal{M}_1, \top_1, \otimes_1)$ and $(\mathcal{M}_2, \top_2, \otimes_2)$ are SMCs, and (F, m) and (G, n) are a symmetric monoidal functors between $\mathcal{M}_1$ and $\mathcal{M}_2$. Then a **symmetric monoidal natural transformation** is a natural transformation, $f : F \longrightarrow G$, subject to the following coherence diagrams:

$$\begin{tikzcd}
FA \otimes_2 FB \arrow[r, "m_{A,B}"] \arrow[d, "f_A \otimes_2 f_B"] & F(A \otimes_1 B) \arrow[d, "f_{A\otimes_1 B}"] \\
GA \otimes_2 GB \arrow[r, "n_{A,B}"'] & G(A \otimes_1 B)
\end{tikzcd}
\qquad
\begin{tikzcd}
F\top_1 \arrow[rr, "f_{\top_1}"] & & G\top_1 \\
& \top_2 \arrow[ul, "m_{\top_1}"] \arrow[ur, "n_{\top_1}"'] &
\end{tikzcd}$$

Definition 8. Suppose $(\mathcal{M}_1, \perp_1, \oplus_1)$ and $(\mathcal{M}_2, \perp_2, \oplus_2)$ are SMCs, and (F, m) and (G, n) are a symmetric comonoidal functors between $\mathcal{M}_1$ and $\mathcal{M}_2$. Then a **symmetric comonoidal natural transformation** is a natural transformation, $f : F \longrightarrow G$, subject to the following coherence diagrams:

$$
\begin{tikzcd}
F(A \oplus_1 B) \arrow[r, "m_{A,B}"] \arrow[d, "f_{A \oplus_1 B}"'] & FA \oplus_2 FB \arrow[d, "f_A \oplus_2 f_B"] \\
G(A \oplus_1 B) \arrow[r, "n_{A,B}"'] & GA \oplus_2 GB
\end{tikzcd}
\qquad
\begin{tikzcd}
\perp_2 & & G \perp_1 \arrow[ll, "n_{\perp_1}"'] \\
& F \perp_1 \arrow[ul, "m_{\perp_1}"] \arrow[ur, "f_{\perp_1}"'] &
\end{tikzcd}
$$

Definition 9. Suppose $(\mathcal{M}_1, \top_1, \otimes_1)$ and $(\mathcal{M}_2, \top_2, \otimes_2)$ are SMCs, and (F, m) is a symmetric monoidal functor between $\mathcal{M}_1$ and $\mathcal{M}_2$ and (G, n) is a symmetric monoidal functor between $\mathcal{M}_2$ and $\mathcal{M}_1$. Then a **symmetric monoidal adjunction** is an ordinary adjunction $\mathcal{M}_1 : F \dashv G : \mathcal{M}_2$ such that the unit, $\eta_A : A \to GFA$, and the counit, $\varepsilon_A : FGA \to A$, are symmetric monoidal natural transformations. Thus, the following diagrams must commute:

$$
\begin{tikzcd}
FGA \otimes_2 FGB \arrow[r, "m_{GA,GB}"] \arrow[d, "\varepsilon_A \otimes_1 \varepsilon_B"'] & F(GA \otimes_1 GB) \arrow[d, "Fn_{A,B}"] \\
A \otimes_2 B & FGA \otimes_2 FGB \arrow[l, "\varepsilon_{A \otimes_1 B}"']
\end{tikzcd}
\qquad
\begin{tikzcd}
F\top_1 \arrow[r, "Fn_{\top_2}"] & FG\top_2 \arrow[d, "\varepsilon_{\top_1}"] \\
\top_2 \arrow[u, "m_{\top_1}"] \arrow[r, equal] & \top_2
\end{tikzcd}
$$

$$
\begin{tikzcd}
GFA \otimes_1 GFB \arrow[d, "n_{FA,FB}"'] & A \otimes_1 B \arrow[l, "\eta_A \otimes_1 \eta_B"'] \arrow[d, "\eta_{A \otimes_1 B}"] \\
G(FA \otimes_2 FB) \arrow[r, "m_{A,B}"] & GF(A \otimes_1 B)
\end{tikzcd}
\qquad
\begin{tikzcd}
G\top_2 \arrow[r, "Gm_{\top_1}"] & GF\top_1 \\
\top_1 \arrow[u, "n_{\top_2}"] \arrow[r, equal] & \top_1 \arrow[u, "\eta_{\top_1}"']
\end{tikzcd}
$$

Definition 10. Suppose $(\mathcal{M}_1, \perp_1, \oplus_1)$ and $(\mathcal{M}_2, \perp_2, \oplus_2)$ are SMCs, and (F, m) is a symmetric comonoidal functor between $\mathcal{M}_1$ and $\mathcal{M}_2$ and (G, n) is a symmetric comonoidal functor between $\mathcal{M}_2$ and $\mathcal{M}_1$. Then a **symmetric comonoidal adjunction** is an ordinary adjunction $\mathcal{M}_1 : F \dashv G : \mathcal{M}_2$ such that the unit, $\eta_A : A \to GFA$, and the counit, $\varepsilon_A : FGA \to A$, are symmetric comonoidal natural transformations. Thus, the following diagrams must commute:

$$
\begin{tikzcd}
A \oplus_1 B \arrow[r, "\eta_{A \oplus_1 B}"] \arrow[d, "\eta_A \oplus_1 \eta_B"'] & GF(A \oplus_1 B) \arrow[d, "Gm_{A,B}"] \\
GFA \oplus_1 GFB & G(FA \oplus_2 FB) \arrow[l, "m_{FA,FB}"']
\end{tikzcd}
\qquad
\begin{tikzcd}
GF \perp_1 \arrow[r, "Gm_{\perp_1}"] & G \perp_2 \arrow[d, "n_{\perp_2}"] \\
\perp_1 \arrow[u, "\eta_{\perp_1}"] \arrow[r, equal] & \perp_1
\end{tikzcd}
$$

$$
\begin{tikzcd}
FG(A \oplus_2 B) \arrow[r, "Fn_{A,B}"] \arrow[d, "\varepsilon_{A \oplus_2 B}"'] & F(GA \oplus_1 GB) \arrow[d, "m_{GA,GB}"] \\
A \oplus_2 B & FGA \oplus_2 FGB \arrow[l, "\varepsilon_A \oplus_2 \varepsilon_B"']
\end{tikzcd}
\qquad
\begin{tikzcd}
FG \perp_2 \arrow[r, "\varepsilon_{\perp_2}"] \arrow[d, equal] & \perp_2 \\
FG \perp_2 \arrow[r, "Fn_{\perp_2}"] & F \perp_1 \arrow[u, "m_{\perp_1}"']
\end{tikzcd}
$$

We will be defining, and making use of the why-not exponentials from linear logic, but these correspond to a symmetric comonoidal monad. In addition, whenever we have a symmetric comonoidal adjunction, we immediately obtain a symmetric comonoidal monad on the left, and a symmetric comonoidal monad on the right.

Definition 11. A **symmetric comonoidal monad** on a symmetric monoidal category C is a triple (T,η,μ), where (T,n) is a symmetric comonoidal endofunctor on C, $\eta_A : A \longrightarrow TA$ and $\mu_A : T^2A \to TA$ are symmetric comonoidal natural transformations, which make the following diagrams commute:

$$\begin{tikzcd}
T^3A \arrow[r, "\mu_{TA}"] \arrow[d, "T\mu_A"'] & T^2A \arrow[d, "\mu_A"] \\
T^2A \arrow[r, "\mu_A"'] & TA
\end{tikzcd}
\qquad
\begin{tikzcd}
& TA & \\
TA \arrow[ur, equal] \arrow[r, "\eta_{TA}"'] & T^2A \arrow[u, "\mu_A"] & TA \arrow[ul, equal] \arrow[l, "T\eta_A"]
\end{tikzcd}$$

The assumption that η and μ are symmetric comonoidal natural transformations amount to the following diagrams commuting:

$$\begin{tikzcd}
A \oplus B \arrow[r, "\eta_A \oplus \eta_B"] \arrow[d, "\eta_A"'] & TA \oplus TB \\
T(A \oplus B) \arrow[ur, "\mathsf{n}_{A,B}"'] &
\end{tikzcd}
\qquad
\begin{tikzcd}
\perp \arrow[r, "\eta_\perp"] \arrow[dr, equal] & T\perp \arrow[d, "\mathsf{n}_\perp"] \\
& \perp
\end{tikzcd}$$

$$\begin{tikzcd}
T^2(A \oplus B) \arrow[r, "T\mathsf{n}_{A,B}"] \arrow[d, "\mu_{A\oplus B}"'] & T(TA \oplus TB) \arrow[r, "\mathsf{n}_{TA,TB}"] & T^2A \oplus T^2B \arrow[d, "\mu_A \oplus \mu_B"] \\
T(A \oplus B) \arrow[rr, "\mathsf{n}_{A,B}"] & & TA \oplus TB
\end{tikzcd}
\qquad
\begin{tikzcd}
T^2\perp \arrow[r, "T\mathsf{n}_\perp"] \arrow[d, "\mu_\perp"'] & T\perp \arrow[d, "\mathsf{n}_\perp"] \\
T\perp \arrow[r, "\mathsf{n}_\perp"'] & \perp
\end{tikzcd}$$

Finally, the dual concept of a symmetric comonoidal comonad.

Definition 12. A **symmetric comonoidal comonad** on a symmetric monoidal category C is a triple (T,ε,δ), where (T,m) is a symmetric comonoidal endofunctor on C, $\varepsilon_A : TA \longrightarrow A$ and $\delta_A : TA \to T^2A$ are symmetric comonoidal natural transformations, which make the following diagrams commute:

$$\begin{tikzcd}
TA \arrow[r, "\delta_A"] \arrow[d, "\delta_A"'] & T^2A \arrow[d, "T\delta_A"] \\
T^2A \arrow[r, "\delta_{TA}"] & T^3A
\end{tikzcd}
\qquad
\begin{tikzcd}
& TA \arrow[dl, equal] \arrow[d, "\delta_A"] \arrow[dr, equal] & \\
TA & T^2A \arrow[l, "\varepsilon_{TA}"] \arrow[r, "T\varepsilon_A"'] & TA
\end{tikzcd}$$

The assumption that ε and δ are symmetric monoidal natural transformations amount to the following diagrams commuting:

$$
\begin{tikzcd}
T(A \oplus B) \arrow[r, "\mathsf{m}_{A,B}"] \arrow[dr, "\varepsilon_{A\oplus B}"'] & TA \oplus TB \arrow[d, "\varepsilon_A \oplus \varepsilon_B"] \\
& A \oplus B
\end{tikzcd}
\qquad
\begin{tikzcd}
T\perp \arrow[rr, "\varepsilon_\perp"] \arrow[dr, equal] & & \perp \\
& T\perp \arrow[ur, "\mathsf{m}_\perp"'] &
\end{tikzcd}
$$

$$
\begin{tikzcd}
T(A \oplus B) \arrow[rr, "\mathsf{m}_{A,B}"] \arrow[d, "\delta_{A\oplus B}"] & & TA \oplus TB \arrow[d, "\delta_A \oplus \delta_B"] \\
T^2(A \oplus B) \arrow[r, "T\mathsf{m}_{A,B}"'] & T(TA \oplus TB) \arrow[r, "\mathsf{m}_{TA,TB}"'] & T^2A \oplus T^2B
\end{tikzcd}
\qquad
\begin{tikzcd}
T\perp \arrow[r, "\mathsf{m}_\perp"] \arrow[d, "\delta_\perp"] & \perp \\
T^2\perp \arrow[r, "T\mathsf{m}_\perp"] & T\perp \arrow[u, "\mathsf{m}_\perp"]
\end{tikzcd}
$$

2.2. **A Mixed Linear/Non-Linear Model for Co-Intuitionistic Logic.** Benton [2] showed that from a LNL model it is possible to construct a linear category, and vice versa. Bellin [1] showed that the dual to linear categories are sufficient to model co-intuitionistic linear logic. We show that from the dual to a LNL model we can construct the dual to a linear category, and vice versa, thus, carrying out the same program for co-intuitionistic linear logic as Benton did for intuitionistic linear logic.

Combining a symmetric monoidal coclosed category with a cocartesian coclosed category via a symmetric comonoidal adjunction defines a dual LNL model.

Definition 13. A **mixed linear/non-linear model for co-intuitionistic logic (dual LNL model)**, $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$, consists of the following:

i. a symmetric monoidal coclosed category $(\mathcal{L}, \perp, \oplus, \bullet\!\!-)$,
ii. a cocartesian coclosed category $(C, 0, +, -)$, and
iv. a symmetric comonoidal adjunction $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$, where $\eta_A : A \longrightarrow \mathsf{JH}A$ and $\varepsilon_R : \mathsf{HJ}R \longrightarrow R$ are the unit and counit of the adjunction respectively.

It is well-known that an adjunction $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$ induces a monad $\mathsf{H};\mathsf{J} : \mathcal{L} \longrightarrow \mathcal{L}$, but when the adjunction is symmetric comonoidal we obtain a symmetric comonoidal monad, in fact, $\mathsf{H};\mathsf{J}$ defines the linear exponential why-not denoted $?A = \mathsf{J}(\mathsf{H}A))$. By the definition of dual LNL models we know that both H and J are symmetric comonoidal functors, and hence, are equipped with natural transformations $\mathsf{h}_{A,B} : \mathsf{H}(A \oplus B) \longrightarrow \mathsf{H}A + \mathsf{H}B$ and $\mathsf{j}_{R,S} : \mathsf{J}(R+S) \longrightarrow \mathsf{J}R \oplus \mathsf{J}S$, and maps $\mathsf{h}_\perp : \mathsf{H}\perp \longrightarrow 0$ and $\mathsf{j}_0 : \mathsf{J}0 \longrightarrow \perp$. We will make heavy use of these maps throughout the sequel.

Compare this definition with that of Bellin's dual linear category from [1], and we can easily see that the definition of dual LNL models – much like LNL models – is more succinct.

Definition 14. A **dual linear category**, $\mathcal{L}$, consists of the following data:

i. A symmetric monoidal coclosed category $(\mathcal{L}, \oplus, \perp, \bullet\!\!-)$ with
ii. a symmetric co-monoidal monad $(?, \eta, \mu)$ on $\mathcal{L}$ such that
   a. each free ?-algebra carries naturally the structure of a commutative $\oplus$-monoid. This implies that there are distinguished symmetric monoidal natural transformations $\mathsf{w}_A : \perp \longrightarrow ?A$ and $\mathsf{c}_A : ?A \oplus ?A \longrightarrow ?A$ which form a commutative monoid and are ?-algebra morphisms.

b. whenever $f : (?\,A, \mu_A) \longrightarrow (?\,B, \mu_B)$ is a morphism of free ?-algebras, then it is also a monoid morphism.

2.2.1. *A Useful Isomorphism.* One useful property of Benton's LNL model is that the maps associated with the symmetric monoidal left adjoint in the model are isomorphisms. Since dual LNL models are dual we obtain similar isomorphisms with respect to the right adjoint.

Lemma 15 (Symmetric Comonoidal Isomorphisms)**.** Given any dual LNL model $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$, then there are the following isomorphisms:

$$\mathsf{J}(R+S) \cong \mathsf{J}R \oplus \mathsf{J}S \quad \text{and} \quad \mathsf{J}0 \cong \perp$$

Furthermore, the former is natural in R and S.

Proof. Suppose $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$ is a dual LNL model. Then we can define the following family of maps:

$$\mathsf{j}^{-1}_{R,S} := \mathsf{J}R \oplus \mathsf{J}S \xrightarrow{\eta} \mathsf{JH}(\mathsf{J}R \oplus \mathsf{J}S) \xrightarrow{\mathsf{Jh}_{A,B}} \mathsf{J}(\mathsf{HJ}R + \mathsf{HJ}S) \xrightarrow{\mathsf{J}(\varepsilon_R + \varepsilon_S)} \mathsf{J}(R+S)$$

$$\mathsf{j}^{-1}_0 := \perp \xrightarrow{\eta} \mathsf{JH}\perp \xrightarrow{\mathsf{Jh}_\perp} \mathsf{J}0$$

It is easy to see that $\mathsf{j}^{-1}_{R,S}$ is natural, because it is defined in terms of a composition of natural transformations. All that is left to be shown is that $\mathsf{j}^{-1}_{R,s}$ and j^{-1}_0 are mutual inverses with $\mathsf{j}_{R,S}$ and j_0; for the details see Appendix A.1. □

Just as Benton we also do not have similar isomorphisms with respect to the functor H. One fact that we can point out, that Benton did not make explicit – because he did not use the notion of symmetric comonoidal functor – is that j^{-1} makes J also a symmetric monoidal functor.

Corollary 16. Given any dual LNL model $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$, the functor $(\mathsf{J}, \mathsf{j}^{-1})$ is symmetric monoidal.

Proof. This holds by straightforwardly reducing the diagrams defining a symmetric monoidal functor, Definition 5, to the diagrams defining a symmetric comonoidal functor, Definition 6, using the fact that j^{-1} is an isomorphism. □

2.2.2. *Dual LNL Model Implies Dual Linear Category.* The next result shows that any dual LNL model induces a symmetric comonoidal monad.

Lemma 17 (Symmetric Comonoidal Monad)**.** Given a dual LNL model $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$, the functor, $? = H; J$, defines a symmetric comonoidal monad.

Proof. Suppose (H, h) and (J, j) are two symmetric comonoidal functors, such that, $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$ is a dual LNL model. We can easily show that $?\,A = \mathsf{JH}A$ is symmetric monoidal by defining the following maps:

$$\mathsf{r}_\perp := ?\perp = \mathsf{JH}\perp \xrightarrow{\mathsf{Jh}_\perp} \mathsf{J}0 \xrightarrow{\mathsf{j}_\perp} \perp$$

$$\mathsf{r}_{A,B} := ?(A \oplus B) = \mathsf{JH}(A \oplus B) \xrightarrow{\mathsf{Jh}_{A,B}} \mathsf{J}(\mathsf{H}A + \mathsf{H}B) \xrightarrow{\mathsf{j}_{\mathsf{H}A,\mathsf{H}B}} \mathsf{JH}A \oplus \mathsf{JH}B = ?\,A \oplus ?\,B$$

The fact that these maps satisfy the appropriate symmetric comonoidal functor diagrams from Definition 6 is obvious, because symmetric comonoidal functors are closed under composition.

We have a dual LNL model, and hence, we have the symmetric comonoidal natural transformations $\eta_A : A \longrightarrow \mathsf{J}\mathsf{H}A$ and $\varepsilon_R : \mathsf{H}\mathsf{J}R \longrightarrow R$ which correspond to the unit and counit of the adjunction respectfully. Define $\mu_A := \mathsf{J}\varepsilon_{\mathsf{H}A} : \mathsf{J}\mathsf{H}\mathsf{J}\mathsf{H}A \longrightarrow \mathsf{J}\mathsf{H}A$. This implies that we have maps $\eta_A : A \longrightarrow\ ?A$ and $\mu_A :\ ??A \longrightarrow\ ?A$, and thus, we can show that $(?, \eta, \mu)$ is a symmetric comonoidal monad. All the diagrams defining a symmetric comonoidal monad hold by the structure given by the adjunction. For the complete proof see Appendix A.2. $\square$

Lemma 18 (Right Weakening and Contraction)**.** Given a dual LNL model $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$, then for any $?A$ there are distinguished symmetric comonoidal natural transformations $\mathsf{w}_A : \perp\ \longrightarrow\ ?A$ and $\mathsf{c}_A :\ ?A \oplus ?A \longrightarrow\ ?A$ that form a commutative monoid, and are $?$-algebra morphisms with respect to the canonical definitions of the algebras $?A$, $\perp$, $?A \oplus ?A$.

Proof. Suppose (H, h) and (J, j) are two symmetric comonoidal functors, such that, $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$ is a dual LNL model. Again, we know $?A = H; J : \mathcal{L} \longrightarrow \mathcal{L}$ is a symmetric comonoidal monad by Lemma 17.

We define the following morphisms:

$$\mathsf{w}_A := \perp \xrightarrow{\mathsf{j}_\perp^{-1}} \mathsf{J}0 \xrightarrow{\mathsf{J}\diamond_{\mathsf{H}A}} \mathsf{J}\mathsf{H}A =\!=\ ?A$$

$$\mathsf{c}_A :=\ ?A \oplus ?A =\!= \mathsf{J}\mathsf{H}A \oplus \mathsf{J}\mathsf{H}A \xrightarrow{\mathsf{j}^{-1}_{\mathsf{H}A,\mathsf{H}A}} \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \xrightarrow{\mathsf{J}\,\nabla_{\mathsf{H}A}} \mathsf{J}\mathsf{H}\mathsf{A} =\!=\ ?A$$

The remainder of the proof is by carefully checking all of the required diagrams. Please see Appendix A.3 for the complete proof. $\square$

Lemma 19 (?-Monoid Morphisms)**.** Suppose $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$ is a dual LNL model. Then if $f : (?A, \mu_A) \longrightarrow (?B, \mu_B)$ is a morphism of free ?-algebras, then it is a monoid morphism.

Proof. Suppose $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$ is a dual LNL model. Then we know $?A = \mathsf{J}\mathsf{H}A$ is a symmetric comonoidal monad by Lemma 17. Bellin [1] remarks that by Maietti, Maneggia de Paiva and Ritter's Proposition 25 [5], it suffices to show that $\mu_A :\ ??A \longrightarrow\ ?A$ is a monoid morphism. For the details see the complete proof in Appendix B. $\square$

Finally, we may now conclude the following corollary.

Corollary 20. Every dual LNL model is a dual linear category.

2.2.3. *Dual Linear Category implies Dual LNL Model.*

- The Eilenberg-Moore category, $\mathcal{L}^?$, has as objects all ?-algebras, $(A, h_A :\ ?A \longrightarrow A)$, and as morphisms all ?-algebra morphisms.
- The Kleisli category, $\mathcal{L}_?$, is the full subcategory of $\mathcal{L}^?$ of all free ?-algebras $(?A, \mu_A :\ ??A \longrightarrow\ ?A)$.

Suppose $\mathcal{L}$ is a dual linear category, then the previous three categories are related by a pair of adjunctions:

$$\begin{tikzcd}
\mathcal{L} \arrow[r, bend left, "F"] \arrow[d, equal] & \mathcal{L}^? \arrow[l, bend left, "U"] \\
\mathcal{L} \arrow[r, bend left, "F"] & \mathcal{L}_? \arrow[l, bend left, "U"] \arrow[u, "i"']
\end{tikzcd}$$

The functor $F(A) = (?A, \mu_A)$ is the free functor, and the functor $U(A, h_A) = A$ is the forgetful functor. Note that we, just as Benton did, are overloading the symbols F and U. Lastly, the functor $i : \mathcal{L}_? \longrightarrow \mathcal{L}^?$ is the injection of the subcategory of free ?-algebras into its parent category.

Lemma 21. If C is a dual linear category, then $C^?$ has finite coproducts.

Proof. We give a proof sketch of this result, because the proof is essentially by duality of Benton's corresponding proof for LNL models (see Lemma 9, [2]). Suppose C is a dual linear category. Then we first need to identify the initial object which is defined by the ?-algebra $(\perp, \mathsf{r}_\perp : ?\perp \longrightarrow \perp)$. The unique map between the initial map and any other ?-algebra $(A, h_A : ?A \longrightarrow A)$ is defined by $\perp \xrightarrow{\mathsf{w}_A} ?A \xrightarrow{h_A} A$. The coproduct of the ?-algebras $(A, h_A : ?A \longrightarrow A)$ and $(B, h_B : ?B \longrightarrow B)$ is $(A \oplus B, \mathsf{r}_{A,B}; (h_A \oplus h_B))$. Injections and the codiagonal map are defined as follows:

- Injections:

$$\iota_1 := A \xrightarrow{\rho_A} A \oplus \perp \xrightarrow{\mathsf{id}_A \oplus \mathsf{w}_B} A \oplus ?B \xrightarrow{\mathsf{id} \oplus h_b} A \oplus B$$
$$\iota_2 := B \xrightarrow{\lambda_A} \perp \oplus B \xrightarrow{\mathsf{w}_A \oplus \mathsf{id}_B} ?A \oplus B \xrightarrow{h_A \oplus \mathsf{id}_B} A \oplus B$$

- Codiagonal map:

$$\bigtriangledown := A \oplus A \xrightarrow{\eta_A \oplus \eta_A} ?A \oplus ?A \xrightarrow{\mathsf{c}_A} ?A \xrightarrow{h_A} A$$

Showing that these respect the appropriate diagrams is straightforward. □

Notice as a direct consequence of the previous result we know the following.

Corollary 22. The Kleisli category, $\mathcal{L}_?$, has finite coproducts.

Thus, both $\mathcal{L}^?$ and $\mathcal{L}_?$ are cocartesian, but we need a cocartesian coclosed category, and in general these are not coclosed, and so we follow Benton's lead and show that there are actually two subcategories of $\mathcal{L}^?$ that are coclosed.

Definition 23. We call an object, A, of a category, $\mathcal{L}$, **subtractable** if for any object B of $\mathcal{L}$, the internal cohom $A \multimapdotinv B$ exists.

We now have the following results:

Lemma 24. In $\mathcal{L}^?$, all the free ?-algebras are subtractable, and the internal cohom is a free ?-algebra.

Proof. The internal cohom is defined as follows:

$$(?A, \delta_A) \multimapdotinv (B, h_B) := (?(A \multimapdotinv B), \delta_{A \multimapdotinv B})$$

We can capitalize on the adjunctions involving F and U from above to lift the internal cohom of $\mathcal{L}$ into $\mathcal{L}^?$:

$$\begin{array}{rcl}
\mathsf{Hom}_{\mathcal{L}^?}((?(A \multimapdotinv B), \delta_{A \multimapdotinv B}), (C, h_C)) & = & \mathsf{Hom}_{\mathcal{L}^?}(\mathsf{F}(A \multimapdotinv B), (C, h_C)) \\
& \cong & \mathsf{Hom}_{\mathcal{L}}(A \multimapdotinv B, \mathsf{U}(C, h_C)) \\
& = & \mathsf{Hom}_{\mathcal{L}}(A \multimapdotinv B, C) \\
& \cong & \mathsf{Hom}_{\mathcal{L}}(A, C \oplus B) \\
& = & \mathsf{Hom}_{\mathcal{L}}(A, \mathsf{U}(C \oplus B, h_{C \oplus B})) \\
& \cong & \mathsf{Hom}_{\mathcal{L}^?}(\mathsf{F}A, (C \oplus B, h_{C \oplus B})) \\
& = & \mathsf{Hom}_{\mathcal{L}^?}((?A, \delta_A), (C \oplus B, h_{C \oplus B}))
\end{array}$$

The previous equation holds for any $h_{C\oplus B}$ making $C \oplus B$ a ?-algebra, in particular, the co-product in $\mathcal{L}^?$ (Lemma 21), and hence, we may instantiate the final line of the previous equation with the following:

$$\mathsf{Hom}_{\mathcal{L}^?}((?\,A, \delta_A), (C, h_c) + (B, \delta_A))$$

Thus, we obtain our result. □

Lemma 25. We have the following cocartesian coclosed categories:

i. The full subcategory, $\mathsf{Sub}(\mathcal{L}^?)$, of $\mathcal{L}^?$ consisting of objects the subtractable ?-algebras is cocartesian coclosed, and contains the Kleisli category.
ii. The full subcategory, $\mathcal{L}^*_?$, of $\mathsf{Sub}(\mathcal{L}^?)$ consisting of finite coproducts of free ?-algebras is cocartesian coclosed.

Let C be either of the previous two categories. Then we must exhibit a adjunction between C and $\mathcal{L}$, but this is easily done.

Lemma 26. The adjunction $\mathcal{L} : \mathsf{F} \vdash \mathsf{U} : C$, with the free functor, F, and the forgetful functor, U, is symmetric comonoidal.

Proof. Showing that F and U are symmetric comonoidal follows similar reasoning to Benton's result, but in the opposite; see Lemma 13 and Lemma 14 of [2]. Lastly, showing that the unit and the counit of the adjunction are comonoidal natural transformations is straightforward, and we leave it to the reader. The reasoning is similar to Benton's, but in the opposite; see Lemma 15 and Lemma 16 of [2]. □

Corollary 27. Any dual linear category gives rise to a dual LNL model.

2.3. **A Mixed Bi-Linear/Non-Linear Model.**

Definition 28. A **mixed bi-linear/non-linear model** consists of the following:

i. a bi-linear category $(\mathcal{L}, \top, \otimes, \multimap, \perp, \oplus, \bullet\!\!-)$,
ii. a cartesian closed category $(\mathcal{I}, 1, \times, \to)$,
iii. a cocartesian coclosed category $(C, 0, +, -)$,
iv. a symmetric monoidal adjunction $\mathcal{I} : F \dashv G$, and
v. a symmetric comonoidal adjunction $\mathcal{L} : H \dashv J : C$.

3. Mixed Linear/Non-Linear Cointuitionistic Logic: Dual LNL Logic

Following Benton's [2] lead we can define a mixed linear/non-linear cointuitionistic logic, called dual LNL logic, based on the categorical model given in the previous section. Dual LNL logic consists of two fragments: an cointuitionistic fragment and a linear cointuitionistic fragment. Each of the fragments are related through a syntactic formalization of the adjoint functors from the dual LNL model. First, we define the syntax of dual LNL logic, and then discuss the inference rules for each fragment.

Definition 29. The syntax for dual LNL logic is defined as follows:

$$\begin{array}{rl}
\text{(Cointuitionistic Formulas)} & R, S, T ::= 0 \mid S + T \mid S - T \mid \mathsf{H}A \\
\text{(Linear Cointuitionistic Formulas)} & A, B, C ::= \perp \mid A \oplus B \mid A \bullet\!\!- B \mid \mathsf{J}\,S \\
\text{(Cointuitionistic Contexts)} & \Psi ::= \cdot \mid R \mid \Psi_1, \Psi_2 \\
\text{(Linear Cointuitionistic Contexts)} & \Gamma, \Delta ::= \cdot \mid A \mid \Gamma_1, \Gamma_2
\end{array}$$

$$
\frac{}{S \vdash_{\mathsf{C}} S}\ \textsc{C\_id}
\qquad
\frac{S \vdash_{\mathsf{C}} T, \Psi_2 \qquad T \vdash_{\mathsf{C}} \Psi_1}{S \vdash_{\mathsf{C}} \Psi_1, \Psi_2}\ \textsc{C\_cut}
\qquad
\frac{S \vdash_{\mathsf{C}} \Psi_1, \Psi_2}{S \vdash_{\mathsf{C}} \Psi_1, T, \Psi_2}\ \textsc{C\_wk}
$$

$$
\frac{S \vdash_{\mathsf{C}} \Psi_1, T, T, \Psi_2}{S \vdash_{\mathsf{C}} \Psi_1, T, \Psi_2}\ \textsc{C\_cr}
\qquad
\frac{R \vdash_{\mathsf{C}} \Psi_1, S, T, \Psi_2}{R \vdash_{\mathsf{C}} \Psi_1, T, S, \Psi_2}\ \textsc{C\_ex}
\qquad
\frac{}{0 \vdash_{\mathsf{C}} \Psi}\ \textsc{C\_f}\mathrm{L}
$$

$$
\frac{S \vdash_{\mathsf{C}} \Psi_1, \Psi_2}{S \vdash_{\mathsf{C}} \Psi_1, 0, \Psi_2}\ \textsc{C\_f}\mathrm{R}
\qquad
\frac{S \vdash_{\mathsf{C}} \Psi_1 \qquad T \vdash_{\mathsf{C}} \Psi_2}{S + T \vdash_{\mathsf{C}} \Psi_1, \Psi_2}\ \textsc{C\_d}\mathrm{L}
\qquad
\frac{R \vdash_{\mathsf{C}} \Psi_1, S, T, \Psi_2}{R \vdash_{\mathsf{C}} \Psi_1, S + T, \Psi_2}\ \textsc{C\_d}\mathrm{R}
$$

$$
\frac{S \vdash_{\mathsf{C}} T, \Psi}{S - T \vdash_{\mathsf{C}} \Psi}\ \textsc{C\_s}\mathrm{L}
\qquad
\frac{R \vdash_{\mathsf{C}} \Psi_1, S, \Psi_2 \qquad T \vdash_{\mathsf{C}} \Psi_3}{R \vdash_{\mathsf{C}} \Psi_1, S - T, \Psi_2, \Psi_3}\ \textsc{C\_s}\mathrm{R}
\qquad
\frac{A \vdash_{\mathsf{L}} \cdot \mid \Psi}{\mathsf{H}A \vdash_{\mathsf{C}} \Psi}\ \textsc{C\_h}\mathrm{L}
$$

Figure 1: Inference Rules for Dual LNL Logic: Cointuitionistic Fragment

$$
\frac{A \vdash_{\mathsf{L}} \Delta \mid \Psi_1, \Psi_2}{A \vdash_{\mathsf{L}} \Delta \mid \Psi_1, S, \Psi_2}\ \textsc{L\_wk}
\qquad
\frac{A \vdash_{\mathsf{L}} \Delta \mid \Psi_1, S, S, \Psi_2}{A \vdash_{\mathsf{L}} \Delta \mid \Psi_1, S, \Psi_2}\ \textsc{L\_ctr}
$$

$$
\frac{A \vdash_{\mathsf{L}} \Delta_1, A, B, \Delta_2 \mid \Psi}{A \vdash_{\mathsf{L}} \Delta_1, B, A, \Delta_2 \mid \Psi}\ \textsc{L\_ex}
\qquad
\frac{A \vdash_{\mathsf{L}} \Delta \mid \Psi_1, S, T, \Psi_2}{A \vdash_{\mathsf{L}} \Delta \mid \Psi_1, T, S, \Psi_2}\ \textsc{L\_Cex}
\qquad
\frac{}{A \vdash_{\mathsf{L}} A \mid \cdot}\ \textsc{L\_id}
$$

$$
\frac{A \vdash_{\mathsf{L}} \Delta_1, B, \Delta_3 \mid \Psi_1 \qquad B \vdash_{\mathsf{L}} \Delta_2 \mid \Psi_2}{A \vdash_{\mathsf{L}} \Delta_1, \Delta_2, \Delta_3 \mid \Psi_1, \Psi_2}\ \textsc{L\_cut}
$$

$$
\frac{A \vdash_{\mathsf{L}} \Delta \mid \Psi_1, S, \Psi_3 \qquad S \vdash_{\mathsf{C}} \Psi_2}{A \vdash_{\mathsf{L}} \Delta \mid \Psi_1, \Psi_2, \Psi_3}\ \textsc{L\_Ccut}
$$

Figure 2: Inference Rules for Dual LNL Logic: Structural Rules, Identity, and Cut Rules

Sequents have the following syntax:

$$
\begin{array}{rl}
\text{(Cointuitionistic Sequents)} & R \vdash_{\mathsf{C}} \Psi \\
\text{(Dual LNL Sequents)} & A \vdash_{\mathsf{L}} \Delta \mid \Psi
\end{array}
$$

The syntax of cointuitionistic formulas are typical. We denote coimplication by $S - T$, but all the other connectives are the usual ones. Linear cointuitionistic formulas are denoted in somewhat of a non-traditional style. We denote par by $A \oplus B$, instead of $A \parr B$. Lastly, we denote linear coimplication by $A \bullet\!\!- B$ to emphasize its duality with linear implication $A \multimap B$. Each syntactic category of formulas contains the respective functor from the dual LNL model, and thus, we should view H as the left adjoint to J.

Sequents for the linear fragment have the form $A \vdash_{\mathsf{L}} \Delta \mid \Psi$. Similarly to the sequents of Benton's LNL logic [2], each context is separated for readability, but should actually be understood as being able to be mixed, that is, the contexts Δ and Ψ could be a single context.

The inference rules for the cointuitionistic fragment can be found in Figure 1.

$$\frac{}{\perp \vdash_{\mathsf{L}} \cdot \mid \cdot}\ \text{L\_FLL} \qquad \frac{A \vdash_{\mathsf{L}} \Delta_1, \Delta_2 \mid \Psi}{A \vdash_{\mathsf{L}} \Delta_1, \perp, \Delta_2 \mid \Psi}\ \text{L\_FLR} \qquad \frac{A \vdash_{\mathsf{L}} \Delta \mid \Psi_1, S, T, \Psi_2}{A \vdash_{\mathsf{L}} \Delta \mid \Psi_1, S + T, \Psi_2}\ \text{L\_DR}$$

$$\frac{A \vdash_{\mathsf{L}} \Delta_1 \mid \Psi_1 \qquad B \vdash_{\mathsf{L}} \Delta_2 \mid \Psi_2}{A \oplus B \vdash_{\mathsf{L}} \Delta_1, \Delta_2 \mid \Psi_1, \Psi_2}\ \text{L\_PL} \qquad \frac{A \vdash_{\mathsf{L}} \Delta_1, B, C, \Delta_2 \mid \Psi}{A \vdash_{\mathsf{L}} \Delta_1, B \oplus C, \Delta_2 \mid \Psi}\ \text{L\_PR}$$

$$\frac{A \vdash_{\mathsf{L}} B, \Delta \mid \Psi}{A \bullet\!\!- B \vdash_{\mathsf{L}} \Delta \mid \Psi}\ \text{L\_SL} \qquad \frac{A \vdash_{\mathsf{L}} \Delta_1, B, \Delta_2 \mid \Psi_1 \qquad C \vdash_{\mathsf{L}} \Delta_3 \mid \Psi_2}{A \vdash_{\mathsf{L}} \Delta_1, B \bullet\!\!- C, \Delta_2, \Delta_3 \mid \Psi_1, \Psi_2}\ \text{L\_SR}$$

$$\frac{A \vdash_{\mathsf{L}} \Delta \mid \Psi_1, S, \Psi_2 \qquad T \vdash_{\mathsf{C}} \Psi_3}{A \vdash_{\mathsf{L}} \Delta \mid \Psi_1, S - T, \Psi_2, \Psi_3}\ \text{L\_CsR} \qquad \frac{S \vdash_{\mathsf{C}} \Psi}{\mathsf{J}\, S \vdash_{\mathsf{L}} \cdot \mid \Psi}\ \text{L\_JL}$$

$$\frac{A \vdash_{\mathsf{L}} \Delta \mid S, \Psi}{A \vdash_{\mathsf{L}} \Delta, \mathsf{J}\, S \mid \Psi}\ \text{L\_JR} \qquad \frac{A \vdash_{\mathsf{L}} \Delta, B \mid \Psi}{A \vdash_{\mathsf{L}} \Delta \mid \mathsf{H}\, B, \Psi}\ \text{L\_HR}$$

Figure 3: Inference Rules for Dual LNL Logic: Cotensor, Coimplication, and Functor Rules

4. Embedding Cointuitionistic Logic in Dual LNL Logic

5. Dual LNL Term Assignment

TODO

6. Related Work

TODO

7. Conclusion

TODO

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Appendix A. Proofs

A.1. **Proof of Lemma 15.** We show that both of the maps:

$$\mathsf{j}^{-1}_{R,S} := \mathsf{J}R \oplus \mathsf{J}S \xrightarrow{\eta} \mathsf{JH}(\mathsf{J}R \oplus \mathsf{J}S) \xrightarrow{\mathsf{Jh}_{A,B}} \mathsf{J}(\mathsf{HJ}R + \mathsf{HJ}S) \xrightarrow{\mathsf{J}(\varepsilon_R + \varepsilon_S)} \mathsf{J}(R+S)$$

$$\mathsf{j}^{-1}_0 := \perp \xrightarrow{\eta} \mathsf{JH}\perp \xrightarrow{\mathsf{Jh}_\perp} \mathsf{J}0$$

are mutual inverses with $\mathsf{j}_{R,S} : \mathsf{J}(R+S) \longrightarrow \mathsf{J}R \oplus \mathsf{J}S$ and $\mathsf{j}_0 : \perp \longrightarrow \mathsf{J}0$ respectively.

Case. The following diagram implies that $\mathsf{j}^{-1}_{R,S} ; \mathsf{j}_{R,S} = \mathsf{id}$:

$$\begin{tikzcd}
 & \mathsf{J}R \oplus \mathsf{J}S \arrow[r, "\eta"] \arrow[dl, equal] \arrow[d, "\eta\oplus\eta"] & \mathsf{JH}(\mathsf{J}R \oplus \mathsf{J}S) \arrow[d, "\mathsf{Jh}"] \\
\mathsf{J}R \oplus \mathsf{J}S & \mathsf{HJ}R \oplus \mathsf{JHJ}S \arrow[l, "\mathsf{J}\varepsilon\oplus\mathsf{J}\varepsilon"] & \mathsf{J}(\mathsf{HJ}R + \mathsf{HJ}S) \arrow[l, "\mathsf{j}"] \arrow[d, "\mathsf{J}(\varepsilon+\varepsilon)"] \\
 & & \mathsf{J}(R+S) \arrow[ull, "\mathsf{j}"]
\end{tikzcd}$$

The two top diagrams both commute because η and ε are the unit and counit of the adjunction respectively, and the bottom diagram commutes by naturality of j.

Case. The following diagram implies that $\mathsf{j}_{R,S} ; \mathsf{j}^{-1}_{R,S} = \mathsf{id}$:

$$\begin{tikzcd}
 & \mathsf{J}(R+S) \arrow[r, "\mathsf{j}"] \arrow[dl, equal] \arrow[d, "\eta"] & \mathsf{J}R \oplus \mathsf{J}S \arrow[d, "\eta"] \\
\mathsf{J}(R+S) & \mathsf{JHJ}(R+S) \arrow[l, "\mathsf{J}\varepsilon"] \arrow[r, "\mathsf{JHj}"] & \mathsf{JH}(\mathsf{J}R \oplus \mathsf{J}S) \arrow[d, "\mathsf{Jh}"] \\
 & & \mathsf{J}(\mathsf{HJ}R + \mathsf{HJ}S) \arrow[ull, "\mathsf{J}(\varepsilon+\varepsilon)"]
\end{tikzcd}$$

The top left and bottom diagrams both commute because η and ε are the unit and counit of the adjunction respectively, and the top right diagram commutes by naturality of η.

Case. The following diagram implies that $\mathsf{j}^{-1}_0 ; \mathsf{j}_0 = \mathsf{id}$:

$$\begin{tikzcd}
\perp \arrow[r, "\eta"] \arrow[d, equal] & \mathsf{JH}\perp \arrow[d, "\mathsf{Jh}_\perp"] \\
\perp & \mathsf{J}0 \arrow[l, "\mathsf{j}_0"]
\end{tikzcd}$$

This diagram holds because η is the unit of the adjunction.

Case. The following diagram implies that $\mathsf{j}_0 ; \mathsf{j}^{-1}_0 = \mathsf{id}$:

$$\begin{tikzcd}
\mathsf{J}0 \arrow[rr, "\mathsf{j}_0"] \arrow[dr, "\eta"] \arrow[dd, equal] & & \perp \arrow[dd, "\eta"] \\
& \mathsf{JHJ}0 \arrow[dl, "\mathsf{J}\varepsilon"'] \arrow[dr, "\mathsf{JHj}_0"] & \\
\mathsf{J}0 & & \mathsf{JH}\perp \arrow[ll, "\mathsf{Jh}_\perp"]
\end{tikzcd}$$

The top-left and bottom diagrams commute because η and ε are the unit and counit of the adjunction respectively, and the top-right digram commutes by naturality of η.

A.2. **Proof of Lemma 17.** Since ? is the composition of two symmetric comonoidal functors we know it is also symmetric comonoidal, and hence, the following diagrams all hold:

$$\begin{tikzcd}
?((A \oplus B) \oplus C) \arrow[r, "\mathsf{r}_{A \oplus B, C}"] \arrow[d, "?\,\alpha_{A,B,C}"] & ?(A \oplus B) \oplus ?\,C \arrow[d, "\mathsf{r}_{A,B} \oplus \mathsf{id}_{?\,C}"] \\
?(A \oplus (B \oplus C)) \arrow[d, "\mathsf{r}_{A, B \oplus C}"] & (?\,A \oplus ?\,B) \oplus ?\,C \arrow[d, "\alpha_{?\,A,?\,B,?\,C}"] \\
?\,A \oplus ?(B \oplus C)) \arrow[r, "\mathsf{id}_{?\,A} \oplus \mathsf{r}_{B,C}"] & ?\,A \oplus (?\,B \oplus ?\,C)
\end{tikzcd}$$

$$\begin{tikzcd}
?(\perp \oplus A) \arrow[r, "\mathsf{r}_{\perp,A}"] \arrow[d, "?\,\lambda_A"] & ?\perp \oplus ?\,A \arrow[d, "\mathsf{r}_\perp \oplus \mathsf{id}_{?\,A}"] \\
?\,A \arrow[r, "\lambda^{-1}{}_{?\,A}"] & \perp \oplus ?\,A
\end{tikzcd}
\qquad
\begin{tikzcd}
?(A \oplus \perp) \arrow[r, "\mathsf{r}_{A,\perp}"] \arrow[d, "?\,\rho_A"] & ?\,A \oplus ?\perp \arrow[d, "\mathsf{id}_{?\,A} \oplus \mathsf{r}_\perp"] \\
?\,A \arrow[r, "\rho^{-1}{}_{?\,A}"] & ?\,A \oplus \perp
\end{tikzcd}$$

$$\begin{tikzcd}
?(A \oplus B) \arrow[r, "\mathsf{r}_{A,B}"] \arrow[d, "?\,\beta_{A,B}"] & ?\,A \oplus ?\,B \arrow[d, "\beta_{?\,A,?\,B}"] \\
?(B \oplus A) \arrow[r, "\mathsf{r}_{B,A}"] & ?\,B \oplus ?\,A
\end{tikzcd}$$

Next we show that $(?, \eta, \mu)$ defines a monad where $\eta_A : A \longrightarrow ?A$ is the unit of the adjunction, and $\mu_A = \mathsf{J}\varepsilon_{\mathsf{H}A} : ?\,?\,A \longrightarrow ?\,A$. It suffices to show that every diagram of Definition 11 holds.

Case.

$$\begin{tikzcd}
?^3 A \arrow[r, "\mu_{?A}"] \arrow[d, "?\mu_A"'] & ?^2 A \arrow[d, "\mu_A"] \\
?^2 A \arrow[r, "\mu_A"'] & ?A
\end{tikzcd}$$

It suffices to show that the following diagram commutes:

$$\begin{tikzcd}
\mathsf{J}(\mathsf{H}(?^2 A)) \arrow[r, "\mathsf{J}\varepsilon_{\mathsf{H}\,?A}"] \arrow[d, "\mathsf{J}(\mathsf{H}\mu_A)"'] & \mathsf{J}(\mathsf{H}\ ?A) \arrow[d, "\mathsf{J}\varepsilon_{\mathsf{H}A}"] \\
\mathsf{J}(\mathsf{H}\ ?A) \arrow[r, "\mathsf{J}\varepsilon_{\mathsf{H}A}"'] & \mathsf{J}(\mathsf{H}A)
\end{tikzcd}$$

But this diagram is equivalent to the following:

$$\begin{tikzcd}
\mathsf{HJHJH}A \arrow[r, "\varepsilon_{\mathsf{HJH}A}"] \arrow[d, "\mathsf{HJ}\varepsilon_{\mathsf{H}A}"'] & \mathsf{HJH}A \arrow[d, "\varepsilon_{\mathsf{H}A}"] \\
\mathsf{HJH}A \arrow[r, "\varepsilon_{\mathsf{H}A}"'] & \mathsf{H}A
\end{tikzcd}$$

The previous diagram commutes by naturality of ε.

Case.

$$\begin{tikzcd}
& ?A & \\
?A \arrow[ur, equal] \arrow[r, "\eta_{?A}"'] & ?^2 A \arrow[u, "\mu_A"] & ?A \arrow[ul, equal] \arrow[l, "?\eta_A"]
\end{tikzcd}$$

It suffices to show that the following diagrams commutes:

$$\begin{tikzcd}
& JHA & \\
JHA \arrow[ur, equal] \arrow[r, "\eta_{JHA}"'] & JHJHA \arrow[u, "J\varepsilon_{HA}"] & JHA \arrow[ul, equal] \arrow[l, "JH\eta_A"]
\end{tikzcd}$$

Both of these diagrams commute because η and ε are the unit and counit of an adjunction.

It remains to be shown that η and μ are both symmetric comonoidal natural transformations, but this easily follows from the fact that we know η is by assumption, and that μ is because it is defined in terms of ε which is a symmetric comonoidal natural transformation. Thus, all of the following diagrams commute:

$$
\begin{tikzcd}
A \oplus B \arrow[rr, "\eta_A \oplus \eta_B"] \arrow[d, "\eta_A"'] & & ?\,A \oplus ?\,B \\
?(A \oplus B) \arrow[urr, "\mathsf{r}_{A,B}"'] & &
\end{tikzcd}
\qquad
\begin{tikzcd}
\perp \arrow[rr, "\eta_\perp"] \arrow[dr, equal] & & ?\perp \arrow[dl, "\mathsf{r}_\perp"] \\
& \perp &
\end{tikzcd}
$$

$$
\begin{tikzcd}
?^2(A \oplus B) \arrow[r, "?\,\mathsf{r}_{A,B}"] \arrow[d, "\mu_{A \oplus B}"'] & ?(?\,A \oplus ?\,B) \arrow[r, "\mathsf{r}_{?A,?B}"] & ?^2\,A \oplus ?^2\,B \arrow[d, "\mu_A \oplus \mu_B"] \\
?(A \oplus B) \arrow[rr, "\mathsf{r}_{A,B}"] & & ?\,A \oplus ?\,B
\end{tikzcd}
\qquad
\begin{tikzcd}
?^2\perp \arrow[r, "?\,\mathsf{r}_\perp"] \arrow[d, "\mu_\perp"'] & ?\perp \arrow[d, "\mathsf{r}_\perp"] \\
?\perp \arrow[r, "\mathsf{r}_\perp"'] & \perp
\end{tikzcd}
$$

A.3. **Proof of Lemma 18.** Suppose (H, h) and (J, j) are two symmetric comonoidal functors, such that, $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$ is a dual LNL model. Again, we know $?\,A = H; J : \mathcal{L} \longrightarrow \mathcal{L}$ is a symmetric comonoidal monad by Lemma 17.

We define the following morphisms:

$$
\begin{aligned}
\mathsf{w}_A &:= \perp \xrightarrow{\mathsf{j}_0^{-1}} \mathsf{J}0 \xrightarrow{\mathsf{J}\diamond_{\mathsf{H}A}} \mathsf{JH}A = ?\,A \\
\mathsf{c}_A &:= ?\,A \oplus ?\,A = \mathsf{JH}A \oplus \mathsf{JH}A \xrightarrow{\mathsf{j}^{-1}_{\mathsf{H}A,\mathsf{H}A}} \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \xrightarrow{\mathsf{J}\,\nabla_{\mathsf{H}A}} \mathsf{JHA} = ?\,A
\end{aligned}
$$

Next we show that both of these are symmetric comonoidal natural transformations, but for which functors? Define $\mathsf{W}(A) = \perp$ and $\mathsf{C}(A) = ?\,A \oplus ?\,A$ on objects of $\mathcal{L}$, and $\mathsf{W}(f : A \longrightarrow B) = \mathsf{id}_\perp$ and $\mathsf{C}(f : A \longrightarrow B) = ?\,f \oplus ?\,f$ on morphisms. So we must show that $\mathsf{w} : \mathsf{W} \longrightarrow\ ?$ and $\mathsf{c} : \mathsf{C} \longrightarrow\ ?$ are symmetric comonoidal natural transformations. We first show that w is and then we show that c is. Throughout the proof we drop subscripts on natural transformations for readability.

Case. To show w is a natural transformation we must show the following diagram commutes for any morphism $f : A \longrightarrow B$:

$$
\begin{tikzcd}
W(A) \arrow[r, "\mathsf{w}_A"] \arrow[d, "W(f)"'] & ?\,A \arrow[d, "?\,f"] \\
W(B) \arrow[r, "\mathsf{w}_B"'] & ?\,B
\end{tikzcd}
$$

This diagram is equivalent to the following:

$$
\begin{tikzcd}
\perp \arrow[r, "\mathsf{w}_A"] \arrow[d, "\mathsf{id}_\perp"'] & ?\,A \arrow[d, "?\,f"] \\
\perp \arrow[r, "\mathsf{w}_B"'] & ?\,B
\end{tikzcd}
$$

It further expands to the following:

$$\begin{tikzcd}
\perp \arrow[r, "\mathsf{j}_0^{-1}"] \arrow[d, "\mathsf{id}_\perp"'] & \mathsf{J}0 \arrow[r, "\mathsf{J}(\diamond_{\mathsf{H}A})"] & \mathsf{JH}A \arrow[d, "\mathsf{JH}f"] \\
\perp \arrow[r, "\mathsf{j}_0^{-1}"'] & \mathsf{J}0 \arrow[r, "\mathsf{J}(\diamond_{\mathsf{H}B})"'] & \mathsf{JH}B
\end{tikzcd}$$

This diagram commutes, because $\mathsf{J}(\diamond_{\mathsf{H}A}); \mathsf{J}f = \mathsf{J}(\diamond_{\mathsf{H}A}; f) = \mathsf{J}(\diamond_{\mathsf{H}B})$, by the uniqueness of the initial map.

Case. The functor W is comonoidal itself. To see this we must exhibit a map

$$\mathsf{s}_\perp := \mathsf{id}_\perp : \mathsf{W}\perp \longrightarrow \perp$$

and a natural transformation

$$\mathsf{s}_{A,B} := \rho_\perp^{-1} : \mathsf{W}(A \oplus B) \longrightarrow \mathsf{W}A \oplus \mathsf{W}B$$

subject to the coherence conditions in Definition 6. Clearly, the second map is a natural transformation, but we leave showing they respect the coherence conditions to the reader. Now we can show that w is indeed symmetric comonoidal.

Case.

$$\begin{tikzcd}
\mathsf{W}(A \oplus B) \arrow[r, "\mathsf{s}_{A,B}"] \arrow[d, "\mathsf{w}_{A\oplus B}"] & \mathsf{W}A \oplus \mathsf{W}B \arrow[d, "\mathsf{w}_A \oplus \mathsf{w}_B"] \\
?(A \oplus B) \arrow[r, "\mathsf{r}_{A,B}"] & ?A \oplus ?B
\end{tikzcd}$$

Expanding the objects of the previous diagram results in the following:

$$\begin{tikzcd}
\perp \arrow[r, "\mathsf{s}_{A,B}"] \arrow[d, "\mathsf{w}_{A\oplus B}"] & \perp \oplus \perp \arrow[d, "\mathsf{w}_A \oplus \mathsf{w}_B"] \\
?(A \oplus B) \arrow[r, "\mathsf{r}_{A,B}"] & ?A \oplus ?B
\end{tikzcd}$$

This diagram commutes, because the following fully expanded diagram commutes:

$$
\begin{tikzcd}
\perp \arrow[rr, "\rho^{-1}"] \arrow[ddd, "j_0^{-1}"'] & \arrow[d, phantom, "(6)"] & \perp \oplus \perp \arrow[dl, "j_0^{-1} \oplus id"'] \arrow[d, "j_0^{-1} \oplus j_0^{-1}"] \arrow[dl, phantom, shift left=6, "(5)"] \\
& J0 \oplus \perp \arrow[r, "id \oplus j_0^{-1}"] \arrow[d, equal] \arrow[dr, phantom, "(4)"] & J0 \oplus J0 \arrow[dl, "id \oplus j_0"] \arrow[dd, equal] \\
& J0 \oplus \perp \arrow[d, phantom, "(3)"] & \\
J0 \arrow[uur, "\rho^{-1}"] \arrow[d, "J\diamond"] \arrow[dr, phantom, "(1)"] & J(0+0) \arrow[l, "J\rho"'] \arrow[r, "j"] \arrow[d, "J(\diamond+\diamond)"] \arrow[dr, phantom, "(2)"] & J0 \oplus J0 \arrow[d, "J\diamond \oplus J\diamond"] \\
JH(A \oplus B) \arrow[r, "Jh"] & J(HA + HB) \arrow[r, "j"] & JHA \oplus JHB
\end{tikzcd}
$$

Diagram 1 commutes because 0 is the initial object, diagram 2 commutes by naturality of j, diagram 3 commutes because J is a symmetric comonoidal functor, diagram 4 commutes because j_0 is an isomorphism (Lemma 15), diagram 5 commutes by functorality of J, and diagram 6 commutes by naturality of ρ.

Case.

$$
\begin{tikzcd}
\perp & & ?\perp \arrow[ll, "r_\perp"'] \\
& W\perp \arrow[ul, "s_\perp"] \arrow[ur, "w_\perp"'] &
\end{tikzcd}
$$

Expanding the objects in the previous diagram results in the following:

$$
\begin{tikzcd}
\perp & & ?\perp \arrow[ll, "r_\perp"'] \\
& \perp \arrow[ul, equal] \arrow[ur, "w_\perp"'] &
\end{tikzcd}
$$

This diagram commutes because the following one does:

$$
\begin{tikzcd}
\perp \arrow[d, equal] & & J0 \arrow[ll, "j_0"'] \\
\perp \arrow[r, "j_0^{-1}"] & J0 \arrow[ur, equal] \arrow[r, "J\diamond"] & JH\perp \arrow[u, "Jh_\perp"']
\end{tikzcd}
$$

The diagram on the left commutes because j_0 is an isomorphism (Lemma 15), and the diagram on the right commutes because 0 is the initial object.

Case. Now we show that $\mathsf{c}_A : ?A \oplus ?A \longrightarrow ?A$ is a natural transformation. This requires the following diagram to commute (for any $f : A \longrightarrow B$):

$$\begin{tikzcd} \mathsf{C}A \arrow[r, "\mathsf{c}_A"] \arrow[d, "\mathsf{C}f"'] & ?A \arrow[d, "?f"] \\ \mathsf{C}B \arrow[r, "\mathsf{c}_B"'] & ?B \end{tikzcd}$$

This expands to the following diagram:

$$\begin{tikzcd} ?A \oplus ?A \arrow[r, "\mathsf{c}_A"] \arrow[d, "?f \oplus ?f"'] & ?A \arrow[d, "?f"] \\ ?B \oplus ?B \arrow[r, "\mathsf{c}_B"'] & ?B \end{tikzcd}$$

This diagram commutes because the following diagram does:

$$\begin{tikzcd} \mathsf{JH}A \oplus \mathsf{JH}A \arrow[r, "\mathsf{j}^{-1}_{\mathsf{H}A,\mathsf{H}A}"] \arrow[d, "\mathsf{JH}f \oplus \mathsf{JH}f"'] & \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \arrow[r, "\mathsf{J}\nabla_{\mathsf{H}A}"] \arrow[d, "\mathsf{J}(\mathsf{H}f + \mathsf{H}f)"] & \mathsf{JH}A \arrow[d, "\mathsf{JH}f"] \\ \mathsf{JH}B \oplus \mathsf{JH}B \arrow[r, "\mathsf{j}^{-1}_{\mathsf{H}B,\mathsf{H}B}"'] & \mathsf{J}(\mathsf{H}B + \mathsf{H}B) \arrow[r, "\mathsf{J}\nabla_{\mathsf{H}B}"'] & \mathsf{JH}B \end{tikzcd}$$

The left square commutes by naturality of j^{-1}, and the right square commutes by naturality of the codiagonal $\nabla_A : A + A \longrightarrow A$.

Case. The functor $\mathsf{C} : \mathcal{L} \longrightarrow \mathcal{L}$ is indeed symmetric comonoidal where the required maps are defined as follows:

$$\mathsf{t}_\perp := ?\perp \oplus ?\perp = \mathsf{JH}\perp \oplus \mathsf{JH}\perp \xrightarrow{\mathsf{j}^{-1}} \mathsf{J}(\mathsf{H}\perp + \mathsf{H}\perp) \xrightarrow{\mathsf{J}\nabla} \mathsf{JH}\perp \xrightarrow{\mathsf{Jh}_\perp} \mathsf{J}0 \xrightarrow{\mathsf{j}_0} \perp$$

$$\mathsf{t}_{A,B} := ?(A \oplus B) \oplus ?(A \oplus B) \xrightarrow{\mathsf{r}_{A,B} \oplus \mathsf{r}_{A,B}} (?A \oplus ?B) \oplus (?A \oplus ?B) \xrightarrow{\mathsf{iso}} (?A \oplus ?A) \oplus (?B \oplus ?B)$$

where iso is a natural isomorphism that can easily be defined using the symmetric monoidal structure of $\mathcal{L}$. Clearly, t is indeed a natural transformation, but we leave checking that the required diagrams in Definition 6 commute to the reader. We can now show that $\mathsf{c}_A : ?A \oplus ?A \longrightarrow ?A$ is symmetric comonoidal. The following diagrams from Definition 8 must commute:

Case.

$$\begin{tikzcd} \mathsf{C}(A \oplus B) \arrow[r, "\mathsf{t}_{A,B}"] \arrow[d, "\mathsf{c}_{A \oplus B}"'] & \mathsf{C}A \oplus \mathsf{C}B \arrow[d, "\mathsf{c}_A \oplus \mathsf{c}_B"] \\ ?(A \oplus B) \arrow[r, "\mathsf{r}_{A,B}"'] & ?A \oplus ?B \end{tikzcd}$$

Expanding the objects in the previous diagram results in the following:

$$\begin{tikzcd}
?(A \oplus B) \oplus ?(A \oplus B) \arrow[r, "\mathsf{t}_{A,B}"] \arrow[d, "\mathsf{c}_{A\oplus B}"'] & (?\,A \oplus ?\,A) \oplus (?\,B \oplus ?\,B) \arrow[d, "\mathsf{c}_A \oplus \mathsf{c}_B"] \\
?(A \oplus B) \arrow[r, "\mathsf{r}_{A,B}"'] & ?\,A \oplus ?\,B
\end{tikzcd}$$

This diagram commutes, because the following fully expanded one does:

$$
\begin{tikzcd}
\mathsf{JH}(A \oplus B) \oplus \mathsf{JH}(A \oplus B) \arrow[r, "\mathsf{Jh} \oplus \mathsf{Jh}"] \arrow[d, "\mathsf{j}^{-1}"'] \arrow[dr, phantom, "(2)"] & \mathsf{J}(\mathsf{H}A + \mathsf{H}B) \oplus \mathsf{J}(\mathsf{H}A + \mathsf{H}B) \arrow[r, "\mathsf{j} \oplus \mathsf{j}"] \arrow[d, "\mathsf{j}^{-1}"'] \arrow[dr, phantom, "(4)"] & (\mathsf{JH}A \oplus \mathsf{JH}B) \oplus (\mathsf{JH}A \oplus \mathsf{JH}B) \arrow[r, "\mathsf{iso}"] & (\mathsf{JH}A \oplus \mathsf{JH}A) \oplus (\mathsf{JH}B \oplus \mathsf{JH}B) \arrow[d, "\mathsf{j}^{-1} \oplus \mathsf{j}^{-1}"] \\
\mathsf{J}(\mathsf{H}(A \oplus B) + \mathsf{H}(A \oplus B)) \arrow[r, "\mathsf{J}(\mathsf{h}+\mathsf{h})"] \arrow[d, "\mathsf{J}\nabla"'] \arrow[dr, phantom, "(1)"] & \mathsf{J}((\mathsf{H}A + \mathsf{H}B) + (\mathsf{H}A + \mathsf{H}B)) \arrow[r, "\mathsf{Jiso}"] \arrow[d, "\mathsf{J}\nabla"'] \arrow[dr, phantom, "(3)"] & \mathsf{J}((\mathsf{H}A + \mathsf{H}A) + (\mathsf{H}B + \mathsf{H}B)) \arrow[r, "\mathsf{j}"] \arrow[ur, "\mathsf{j};(\mathsf{j} \oplus \mathsf{j})"] \arrow[d, "\mathsf{J}(\nabla + \nabla)"'] \arrow[dr, phantom, "(5)"] \arrow[ur, phantom, "(6)", near end] & \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \oplus \mathsf{J}(\mathsf{H}B + \mathsf{H}B) \arrow[d, "\mathsf{J}\nabla \oplus \mathsf{J}\nabla"] \\
\mathsf{JH}(A \oplus B) \arrow[r, "\mathsf{Jh}"] & \mathsf{J}(\mathsf{H}A + \mathsf{H}B) \arrow[r, equal] & \mathsf{J}(\mathsf{H}A + \mathsf{H}B) \arrow[r, "\mathsf{j}"] & \mathsf{JH}A \oplus \mathsf{JH}B
\end{tikzcd}
$$

Diagram 1 commutes by naturality of ∇, diagram 2 commutes by naturality of j^{-1}, diagram 3 commutes by straightforward reasoning on coproducts, diagram 4 commutes by straightforward reasoning on the symmetric monoidal structure of J after expanding the definition of the two isomorphisms – here Jiso is the corresponding isomorphisms on coproducts – diagram 5 commutes by naturality of j, and diagram 6 commutes because j is an isomorphism (Lemma 15).

Case.

$$\begin{tikzcd}
\perp & & ?\perp \arrow[ll, "\mathsf{r}_\perp"'] \\
& \mathsf{C}\perp \arrow[ul, "\mathsf{t}\perp"] \arrow[ur, "\mathsf{c}_\perp"'] &
\end{tikzcd}$$

Expanding the objects of this diagram results in the following:

$$\begin{tikzcd}
\perp & ?\perp \arrow[l, "\mathsf{r}_\perp"'] \\
?\perp \oplus ?\perp \arrow[u, "\mathsf{t}\perp"] \arrow[r, equal] & ?\perp \oplus ?\perp \arrow[u, "\mathsf{c}_\perp"']
\end{tikzcd}$$

Simply unfolding the morphisms in the previous diagram reveals the following:

$$\begin{tikzcd}
\perp \arrow[r, equal] & \perp \\
\mathsf{J}0 \arrow[u, "\mathsf{j}"] & \mathsf{J}0 \arrow[u, "\mathsf{j}"'] \\
\mathsf{JH}\perp \arrow[u, "\mathsf{Jh}_\perp"] & \mathsf{JH}\perp \arrow[u, "\mathsf{Jh}_\perp"'] \\
\mathsf{J}(\mathsf{H}\perp + \mathsf{H}\perp) \arrow[u, "\mathsf{J}\nabla"] & \mathsf{J}(\mathsf{H}\perp + \mathsf{H}\perp) \arrow[u, "\mathsf{J}\nabla"'] \\
\mathsf{JH}\perp \oplus \mathsf{JH}\perp \arrow[u, "\mathsf{j}^{-1}"] \arrow[r, equal] & \mathsf{JH}\perp \oplus \mathsf{JH}\perp \arrow[u, "\mathsf{j}^{-1}"']
\end{tikzcd}$$

Clearly, this diagram commutes.

At this point we have shown that $\mathsf{w}_A : \perp \longrightarrow ?A$ and $\mathsf{c}_A : ?A \oplus ?A \longrightarrow ?A$ are symmetric comonoidal naturality transformations. Now we show that for any $?A$ the triple $(?A, \mathsf{w}_A, \mathsf{c}_A)$ forms a commutative monoid. This means that the following diagrams must commute:

Case.

$$\begin{tikzcd}
(?A \oplus ?A) \oplus ?A \arrow[r, "\alpha_{?A,?A,?A}"] \arrow[d, "\mathsf{c}_A \oplus \mathsf{id}_A"'] & ?A \oplus (?A \oplus ?A) \arrow[r, "\mathsf{id}_{?A} \oplus \mathsf{c}_A"] & ?A \oplus ?A \arrow[d, "\mathsf{c}_A"] \\
?A \oplus ?A \arrow[rr, "\mathsf{c}_A"] & & ?A
\end{tikzcd}$$

The previous diagram commutes, because the following one does (we omit subscripts for readability):

$$\begin{tikzcd}
(\mathsf{JH}A \oplus \mathsf{JH}A) \oplus \mathsf{JH}A \arrow[r, "\alpha"] \arrow[d, "\mathsf{j}^{-1} \oplus \mathsf{id}"'] & \mathsf{JH}A \oplus (\mathsf{JH}A \oplus \mathsf{JH}A) \arrow[r, "\mathsf{id} \oplus \mathsf{j}^{-1}"] \arrow[d, phantom, "(1)"] & \mathsf{JH}A \oplus \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \arrow[r, "\mathsf{id} \oplus \mathsf{J}\bigtriangledown"] \arrow[d, "\mathsf{j}^{-1}"] \arrow[dr, phantom, "(2)"] & \mathsf{JH}A \oplus \mathsf{JH}A \arrow[d, "\mathsf{j}^{-1}"] \\
\mathsf{J}(\mathsf{H}A + \mathsf{H}A) \oplus \mathsf{JH}A \arrow[r, "\mathsf{j}^{-1}"] \arrow[d, "\mathsf{J}\bigtriangledown \oplus \mathsf{id}"'] \arrow[dr, phantom, "(3)"] & \mathsf{J}((\mathsf{H}A + \mathsf{H}A) + \mathsf{H}A) \arrow[r, "\mathsf{J}\alpha"] \arrow[d, "\mathsf{J}(\bigtriangledown + \mathsf{id})"] & \mathsf{J}(\mathsf{H}A + (\mathsf{H}A + \mathsf{H}A)) \arrow[r, "\mathsf{J}(\mathsf{id} + \bigtriangledown)"] \arrow[d, phantom, "(4)"] & \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \arrow[d, "\mathsf{J}\bigtriangledown"] \\
\mathsf{JH}A \oplus \mathsf{JH}A \arrow[r, "\mathsf{j}^{-1}"] & \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \arrow[rr, "\mathsf{J}\bigtriangledown"] & & \mathsf{JH}A
\end{tikzcd}$$

Diagram 1 commutes because J is a symmetric monoidal functor (Corollary 16), diagrams 2 and 3 commute by naturality of j^{-1}, and diagram 4 commutes because $(\mathsf{H}A, \diamond, \bigtriangledown)$ is a commutative monoid in C, but we leave the proof of this to the reader.

Case.

$$\begin{tikzcd}
?A \oplus \perp \arrow[d, "\mathsf{id}_{?A} \oplus \mathsf{w}_A"'] \arrow[dr, "\rho_{?A}"] & \\
?A \oplus ?A \arrow[r, "\mathsf{c}_A"] & ?A
\end{tikzcd}$$

The previous diagram commutes, because the following one does:

$$\begin{tikzcd}
\mathsf{JH}A \oplus \perp \arrow[rr, "\rho"] \arrow[d, "\mathsf{id} \oplus \mathsf{j}_0^{-1}"'] & \arrow[d, phantom, "(1)"] & \mathsf{JH}A \arrow[d, equal] \\
\mathsf{JH}A \oplus \mathsf{J}0 \arrow[r, "\mathsf{j}^{-1}"] \arrow[d, "\mathsf{id} \oplus \mathsf{J}\diamond"'] \arrow[dr, phantom, "(2)"] & \mathsf{J}(\mathsf{H}A + 0) \arrow[r, "\mathsf{J}\rho"] \arrow[d, "\mathsf{J}(\mathsf{id} \oplus \diamond)"] \arrow[dr, phantom, "(3)"] & \mathsf{JH}A \arrow[d, equal] \\
\mathsf{JH}A \oplus \mathsf{JH}A \arrow[r, "\mathsf{j}^{-1}"] & \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \arrow[r, "\mathsf{J}\bigtriangledown"] & \mathsf{JH}A
\end{tikzcd}$$

Diagram 1 commutes because J is a symmetric monoidal functor (Corollary 16), diagram 2 commutes by naturality of j^{-1}, and diagram 3 commutes because $(\mathsf{H}A, \diamond, \bigtriangledown)$ is a commutative monoid in C, but we leave the proof of this to the reader.

Case.

$$\begin{tikzcd}
?A \oplus ?A \arrow[d, "\beta_{?A,?A}"'] \arrow[dr, "\mathsf{c}_A"] & \\
?A \oplus ?A \arrow[r, "\mathsf{c}_A"] & ?A
\end{tikzcd}$$

This diagram commutes, because the following one does:

$$\begin{tikzcd}
\mathsf{JH}A \oplus \mathsf{JH}A \arrow[r, "\mathsf{j}^{-1}"] \arrow[d, "\beta"'] & \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \arrow[r, "\mathsf{J}\,\nabla"] \arrow[d, "\mathsf{J}\beta"] & \mathsf{JH}A \arrow[d, equal] \\
\mathsf{JH}A \oplus \mathsf{JH}A \arrow[r, "\mathsf{j}^{-1}"'] & \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \arrow[r, "\mathsf{J}\,\nabla"'] & \mathsf{JH}A
\end{tikzcd}$$

The left diagram commutes by naturality of j^{-1}, and the right diagram commutes because $(\mathsf{H}A, \diamond, \nabla)$ is a commutative monoid in C, but we leave the proof of this to the reader.

Finally, we must show that $\mathsf{w}_A : \perp \longrightarrow ?A$ and $\mathsf{c}_A : ?A \oplus ?A \longrightarrow ?A$ are $?$-algebra morphisms. The algebras in play here are $(?A, \mu : ??A \longrightarrow ?A)$, $(\perp, \mathsf{r}_\perp : ?\perp \longrightarrow \perp)$, and $(?A \oplus ?A, u_A : ?(?A \oplus ?A) \longrightarrow ?A \oplus ?A)$, where $u_A := ?(?A \oplus ?A) \xrightarrow{\mathsf{r}_{?A,?A}} ?^2A \oplus ?^2A \xrightarrow{\mu_A \oplus \mu_A} ?A \oplus ?A$. It suffices to show that the following diagrams commute:

Case.

$$\begin{tikzcd}
?\perp \arrow[r, "\mathsf{r}_\perp"] \arrow[d, "?\mathsf{w}"'] & \perp \arrow[d, "\mathsf{w}"] \\
??A \arrow[r, "\mu"'] & ?A
\end{tikzcd}$$

This diagram commutes, because the following fully expanded one does:

$$\begin{tikzcd}
\mathsf{JH}\perp \arrow[rr, "\mathsf{Jh}_\perp"] \arrow[dr, "\mathsf{JHj}_0^{-1}"] \arrow[dd, "\mathsf{JHj}_0^{-1}"'] & & \mathsf{J}0 \arrow[rr, "\mathsf{j}_0"] & & \perp \arrow[dd, "\mathsf{j}_0^{-1}"] \\
(3) & \mathsf{JHJ}0 \arrow[r, "\mathsf{JHj}_0"] \arrow[dl, equal] & \mathsf{JH}\perp \arrow[drr, "\mathsf{Jh}_\perp"] & (4) & \\
\mathsf{JHJ}0 \arrow[rrrr, "\mathsf{J}\varepsilon_0"] \arrow[d, "\mathsf{JHJ}\diamond"'] & & (2) & & \mathsf{J}0 \arrow[d, "\mathsf{J}\diamond"] \\
\mathsf{JHJH}A \arrow[rrrr, "\mathsf{J}\varepsilon"] & & (1) & & \mathsf{JH}A
\end{tikzcd}$$

Diagram 1 commutes by naturality of ε, diagram 2 commutes because ε is the counit of the symmetric comonoidal adjunction, diagram 3 clearly commutes, and diagram 4 commutes because j_0 is an isomorphism (Lemma 15).

Case.

$$\begin{tikzcd}
?(?A \oplus ?A) \arrow[r, "u"] \arrow[d, "?\mathsf{c}"'] & ?A \oplus ?A \arrow[d, "\mathsf{c}"] \\
??A \arrow[r, "\mu"] & ?A
\end{tikzcd}$$

This diagram commutes because the following fully expanded one does:

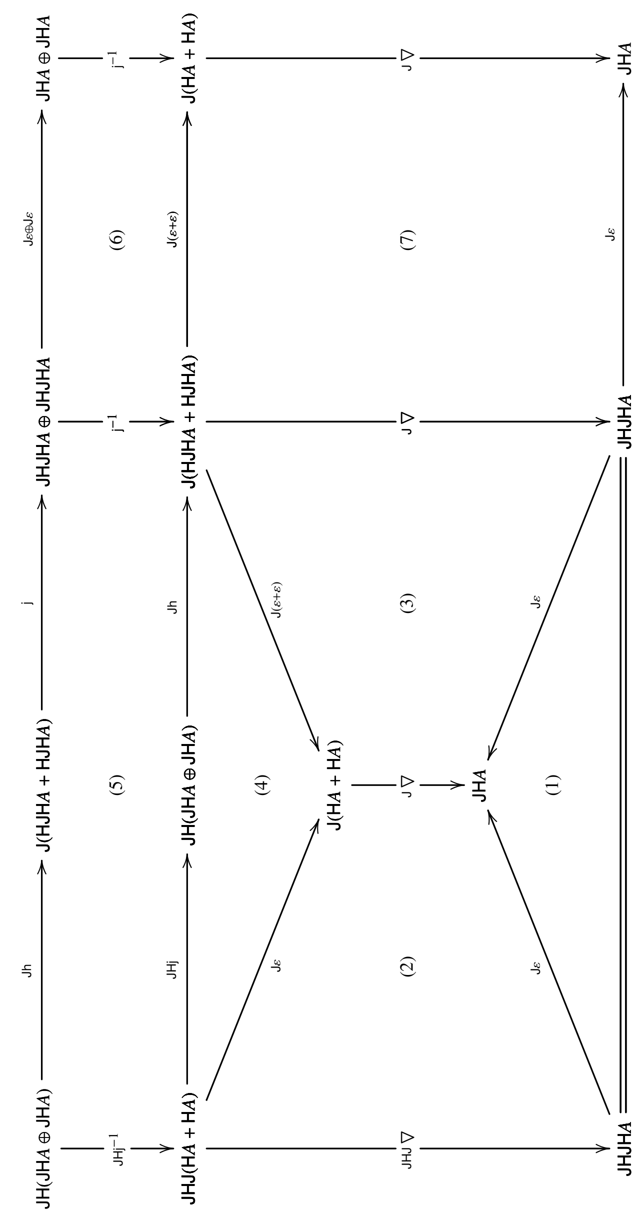

Diagram 1 clearly commutes, diagram 2 commutes by naturality of ε, diagram 3 commutes by naturality of $\bigtriangledown$, diagram 4 commutes because ε is the counit of the symmetric comonoidal adjunction, diagram 5 commutes because j is an isomorphism (Lemma 15), diagram 6 commutes by naturality of j^{-1}, and diagram 7 is the same diagram as 3, but this diagram is redundant for readability.

Appendix B. Proof of Lemma 19

Suppose $\mathcal{L} : \mathsf{H} \dashv \mathsf{J} : C$ is a dual LNL model. Then we know $?A = \mathsf{JH}A$ is a symmetric comonoidal monad by Lemma 17. Bellin [1] remarks that by Maietti, Maneggia de Paiva and Ritter's Proposition 25 [5], it suffices to show that $\mu_A : ??A \longrightarrow ?A$ is a monoid morphism. Thus, the following diagrams must commute:

Case.

$$\begin{tikzcd}
??A \oplus ??A \arrow[r, "\mathsf{c}_{?A}"] \arrow[d, "\mu_A \oplus \mu_A"'] & ??A \arrow[d, "\mu_A"] \\
?A \oplus ?A \arrow[r, "\mathsf{c}_A"] & ?A
\end{tikzcd}$$

This diagram commutes because the following fully expanded one does:

$$\begin{tikzcd}
\mathsf{JHJH}A \oplus \mathsf{JHJH}A \arrow[r, "\mathsf{j}^{-1}"] \arrow[d, "\mathsf{J}\varepsilon \oplus \mathsf{J}\varepsilon"'] & \mathsf{J}(\mathsf{HJH}A + \mathsf{HJH}A) \arrow[r, "\mathsf{J}\bigtriangledown"] \arrow[d, "\mathsf{J}(\varepsilon+\varepsilon)"] & \mathsf{JHJH}A \arrow[d, "\mathsf{J}\varepsilon"] \\
\mathsf{JH}A \oplus \mathsf{JH}A \arrow[r, "\mathsf{j}^{-1}"] & \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \arrow[r, "\mathsf{J}\bigtriangledown"] & \mathsf{JH}A
\end{tikzcd}$$

The left square commutes by naturality of j^{-1} and the right square commutes by naturality of the codiagonal.

Case.

$$\begin{tikzcd}
& \perp \arrow[dl, "\mathsf{w}_{?A}"'] \arrow[dr, "\mathsf{w}_A"] & \\
??A \arrow[rr, "\mu_A"] & & ?A
\end{tikzcd}$$

This diagram commutes because the following fully expanded one does:

$$\begin{tikzcd}
\perp \arrow[r, equal] \arrow[d, "\mathsf{j}_0^{-1}"'] & \perp \arrow[d, "\mathsf{j}_0^{-1}"] \\
\mathsf{J}0 \arrow[r, equal] \arrow[d, "\mathsf{J}\diamond"'] & \mathsf{J}0 \arrow[d, "\mathsf{J}\diamond"] \\
\mathsf{JHJH}A \arrow[r, "\mathsf{J}\varepsilon"] & \mathsf{JH}A
\end{tikzcd}$$

The top square trivially commutes, and the bottom square commutes by uniqueness of the initial map.