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 directly contributes to the solution of this open problem by giving a new categorical model based on adjunctions for cointuitionistic logic, and then proposing a new categorical model for BINT.

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 [6] showed that combining these two categories into the same category results in it degenerating to a poset, i.e. there is at most one morphism between any two objects; we review this result in Section 2.2. However, this degeneration does not occur when both logics are linear.

We propose that IL and coIL need to be separated, and then mixed in a controlled 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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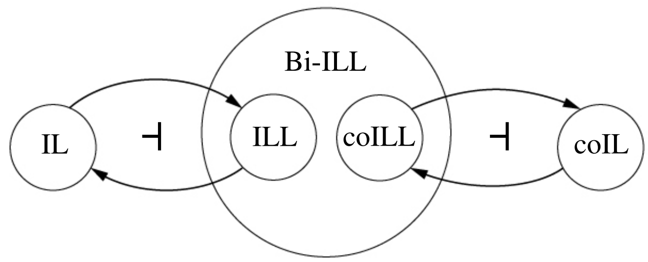

The adjoint between IL and ILL is known as a Linear/Non-linear model (LNL model) of ILL, and is due to Benton [2]. However, the dual to LNL models which would amount to the adjoint between coILL and coIL has yet to appear in the literature.

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 11), 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 7. 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 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. The main contribution of this paper is the definition and study of the dual to Benton's LNL models as models of cointuitionistic logic.

Taking the dual of the previous model results in what we call dual LNL models. They consist of a cocartesian coclosed category, $(C, 0, +, -)$ where $- : C \times C \longrightarrow C$ is left adjoint to the coproduct, a symmetric monoidal coclosed category (Definition 4), $(\mathcal{L}', \perp, \oplus, \bullet\!-)$, where $\bullet\!- : \mathcal{L}' \times \mathcal{L}' \longrightarrow \mathcal{L}'$ is left adjoint to cotensor (sometimes called parr), and a symmetric comonoidal adjunction (Definition 12) $\mathcal{L}' : \mathsf{H} \dashv \mathsf{J} : C$, where H and J are symmetric comonoidal functors. Dual to the above, this implies that there are natural transformations $\mathsf{m}_{X,Y} : \mathsf{J}(X + Y) \longrightarrow \mathsf{J}X \oplus \mathsf{J}Y$ and $\mathsf{n}_{A,B} : \mathsf{H}(A \oplus B) \longrightarrow \mathsf{H}A + \mathsf{H}B$, and maps $\mathsf{m}_0 : \mathsf{J}0 \longrightarrow \perp$ and $\mathsf{n}_{\perp} : \mathsf{H} \perp \longrightarrow 0$ subject to several coherence conditions; see Definition 8. In fact, one can define Girard's exponential why-not by $?A = \mathsf{J}\mathsf{H}A$, and hence, is the monad induced by the adjunction.

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 2.3.2), and that from a dual linear category we may obtain a dual LNL model (Section 2.3.3). 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 2.4), but we leave its analysis and corresponding logic to a future paper.

Benton [2] showed that, syntactically, LNL models have a corresponding logic by first defining intuitionistic logic, whose sequent is denoted, $\Theta \vdash_C X$, and then intuitionistic linear logic, $\Theta; \Gamma \vdash_{\mathcal{L}} A$, but the key insight was that Θ contains non-linear assumptions while Γ contains linear assumptions, but one should view their separation as merely cosmetic; all assumptions can consistently be mixed within a single context. The two logics are then connected by syntactic versions of the functors F and G which allow formulas to move between both fragments.

Following Benton's lead the design of dual LNL logic is similar. We have a non-linear cointuitionistic fragment, $T \vdash_C \Psi$, and a linear cointuitionistic fragment, $A \vdash_C \Delta; \Psi$, where Δ contains linear conclusions and Ψ contains non-linear conclusions, but again the separation of contexts is only cosmetic. The non-linear fragment has the following structural rules:

$$\frac{S \vdash_{\mathsf{C}} \Psi}{S \vdash_{\mathsf{C}} T, \Psi}\ \mathrm{C\_weak} \qquad\qquad \frac{S \vdash_{\mathsf{C}} T, T, \Psi}{S \vdash_{\mathsf{C}} T, \Psi}\ \mathrm{C\_contr}$$

Then we connect these two fragments together using the following rules for the functors H and J:

$$\frac{A \vdash_{\mathsf{L}} \cdot; \Psi}{\mathsf{H}A \vdash_{\mathsf{C}} \Psi}\ \mathsf{H}_L \qquad \frac{A \vdash_{\mathsf{L}} \Delta, B; \Psi}{A \vdash_{\mathsf{L}} \Delta; \mathsf{H}B, \Psi}\ \mathsf{H}_R \qquad \frac{T \vdash_{\mathsf{C}} \Psi}{\mathsf{J}T \vdash_{\mathsf{L}} \cdot; \Psi}\ \mathsf{J}_L \qquad \frac{A \vdash_{\mathsf{L}} \Delta; T, \Psi}{A \vdash_{\mathsf{L}} \Delta, \mathsf{J}T; \Psi}\ \mathsf{J}_R$$

These allow for linear and non-linear formulas to move from one fragment to the other. We will give a sequent calculus and natural deduction formalization (Section 3.1 and Section 3.2) as well as a term assignment (Section 3.3). The latter is particularly interesting, because of the fact that cointuitionistic logic has multiple conclusions, but only a single hypothesis.

2. The Adjoint Model

****short section intro*****

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 known definition of symmetric comonoidal 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 notation $(\mathcal{M}, \perp, \oplus)$ 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 $\mathcal{M}$.

We combine a symmetric monoidal closed category with a symmetric monoidal coclosed category in a single category. First, we define the notion of a distributive category due to Cockett and Seely [5].

Definition 5. We call a symmetric monoidal category, $(\mathcal{M}, \top, \otimes, \perp, \oplus)$ equipped with the structure of a cotensor $(\mathcal{M}, \perp, \oplus)$, a **distributive category** if there are natural transformations:

$$\begin{array}{l} \delta^L_{A,B,C} : A \otimes (B \oplus C) \longrightarrow (A \otimes B) \oplus C \\ \delta^R_{A,B,C} : (B \oplus C) \otimes A \longrightarrow B \oplus (C \otimes A) \end{array}$$

subject to several coherence diagrams. Due to the large number of coherence diagrams we do not list them here, but they all can be found in Cockett and Seely's paper [5].

Requiring that the tensor and cotensor products have the corresponding right and left adjoints results in the following definition.

Definition 6. A **bilinear category** is a distributive category $(\mathcal{M}, \top, \otimes, \perp, \oplus)$ such that $(\mathcal{M}, \top, \otimes)$ is closed, and $(\mathcal{M}, \perp, \oplus)$ is coclosed. We will denote bi-linear categories by $(\mathcal{M}, \top, \otimes, \multimap, \perp, \oplus, \bullet\!\!-)$.

Originally, Lambek defined bilinear categories to be similar to the previous definition, but the tensor and cotensor were non-commutative [4], however, the bilinear categories given here are. We retain the name in homage to his original work. As we will see below bilinear categories form the core of a categorical model for bi-intuitionism.

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 7. Suppose we are given two symmetric monoidal 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 8. Suppose we are given two symmetric monoidal 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:

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

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

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

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 9. 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 10. Suppose $(\mathcal{M}_1, \bot_1, \oplus_1)$ and $(\mathcal{M}_2, \bot_2, \oplus_2)$ 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:

$$\begin{tikzcd}
F(A \oplus_1 B) \arrow[r, "m_{A,B}"] \arrow[d, "f_{A \oplus_1 B}"'] & FA \oplus_2 FB \arrow[d, "f_A \oplus_2 f_B"] \\
G(A \oplus_1 B) \arrow[r, "n_{A,B}"'] & GA \oplus_2 GB
\end{tikzcd}
\qquad
\begin{tikzcd}
\bot_2 & & G\,\bot_1 \arrow[ll, "n_{\bot_1}"'] \\
& F\,\bot_1 \arrow[ul, "m_{\bot_1}"] \arrow[ur, "f_{\bot_1}"'] &
\end{tikzcd}$$

Definition 11. 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 12. 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 comonad on the left, and a symmetric comonoidal monad on the right.

Definition 13. 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:

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

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

Finally, the dual concept of a symmetric comonoidal comonad.

Definition 14. 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. **Cartesian Closed and Cocartesian Coclosed Categories.** The notion of a cartesian closed category is well-known, but for completeness we define them here. However, their dual is lesser known, especially in computer science, and so we given their full definition. We also review some know results concerning cocartesian coclosed categories and categories that are both cartesian closed and cocartesian coclosed.

Definition 15. A **cartesian category** is a category, $(C, 1, \times)$, with an object, 1, and a bi-functor, $\times : C \times C \longrightarrow C$, such that for any object A there is exactly one morphism $\diamond : A \to 1$, and for any morphisms $f : C \longrightarrow A$ and $g : C \longrightarrow B$ there is a morphism $\langle f, g\rangle : C \to A \times B$ subject to the following diagram:

$$\begin{tikzcd}
 & C \arrow[dl, "f"'] \arrow[d, "\langle f,g\rangle"] \arrow[dr, "g"] & \\
A & A \times B \arrow[l, "\pi_1"] \arrow[r, "\pi_2"'] & B
\end{tikzcd}$$

A cartesian category models conjunction by the product functor, $\times : C \times C \longrightarrow C$, and the unit of conjunction by the terminal object. As we mention above modeling implication requires closer, and since it is well-known that any cartesian category is also a symmetric monoidal category the definition of closer for a cartesian category is the same as the definition of closer for a symmetric monoidal category (Definition 2). We denote the internal hom for cartesian closed categories by $A \to B$.

The dual of a cartesian category is a cocartesian category. They are a model of intuitionistic logic with disjunction and its unit.

Definition 16. A **cocartesian category** is a category, $(C, 0, +)$, with an object, 0, and a bi-functor, $+ : C \times C \longrightarrow C$, such that for any object A there is exactly one morphism $\Box : 0 \to A$, and for any morphisms $f : A \longrightarrow C$ and $g : B \longrightarrow C$ there is a morphism $[f, g] : A + B \longrightarrow C$ subject to the following diagram:

$$\begin{tikzcd}
 & C & \\
A \arrow[ur, "f"] \arrow[r, "\iota_1"'] & A + B \arrow[u, "{[f,g]}"] & B \arrow[ul, "g"'] \arrow[l, "\iota_2"]
\end{tikzcd}$$

Cocloser, just like closer for cartesian categories, is defined in the same way that cocloser is defined for symmetric monoidal categories, because cocartesian categories are also symmetric monoidal categories. Thus, a cocartesian category is coclosed if there is a specified left-adjoint, which we denote $S - T$, to the coproduct.

There are many examples of cocartesian coclosed categories. Basically, any interesting cartesian category has an interesting dual, and hence, induces an interesting cocartesian coclosed category. The opposite of the category of sets and functions between them is isomorphic to the category of complete atomic boolean algebras, and both of which, are examples of cocartesian coclosed categories. As we mentioned above bi-linear categories [4] are models of bi-linear logic where the left adjoint to the cotensor models coimplication. Similarly, cocartesian coclosed categories model cointuitionistic logic with disjunction and intuitionistic coimplication [6, 1].

Put more examples in here.

We might now ask if a category can be both cartesian closed and cocartesian coclosed just as bi-linear categories, but this turns out to be where the matter meets antimatter in such away that the category degenerates to a preorder. That is, every homspace contains at most one morphism. We recall this proof here, which is due to Crolard [6]. We need a couple basic facts about cartesian closed categories with initial objects.

Lemma 17. In any cartesian category C, if 0 is an initial object in C and $\mathsf{Hom}_C(A, 0)$ is non-empty, then $A \cong A \times 0$.

Proof. This follows easily from the universal mapping property for products. $\Box$

Lemma 18. In any cartesian closed category C, if 0 is an initial object in C, then so is $0 \times A$ for any object A of C.

Proof. We know that the universal morphism for the initial object is unique, and hence, the homspace $\mathsf{Hom}_C(0, A \Rightarrow B)$ for any object B of C contains exactly one morphism. Then using the right adjoint to the product functor we know that $\mathsf{Hom}_C(0, A \Rightarrow B) \cong \mathsf{Hom}_C(0 \times A, B)$, and hence, there is only one arrow between $0 \times A$ and B. □

The following lemma is due to Joyal [**?**], and is key to the next theorem.

Lemma 19 (Joyal's)**.** In any cartesian closed category C, if 0 is an initial object in C and $\mathsf{Hom}_C(A, 0)$ is non-empty, then A is an initial object in C.

Proof. Suppose C is a cartesian closed category, such that, 0 is an initial object in C, and A is an arbitrary object in C. Furthermore, suppose $\mathsf{Hom}_C(A, 0)$ is non-empty. By the first basic lemma above we know that $A \cong A \times 0$, and by the second $A \times 0$ is initial, thus A is initial. □

Finally, the following theorem shows that any category that is both cartesian closed and cocartesian coclosed is a preorder.

Theorem 20 ((co)Cartesian (co)Closed Categories are Preorders (Crolard[6]))**.** If C is both cartesian closed and cocartesian coclosed, then for any two objects A and B of C, $\mathsf{Hom}_C(A, B)$ has at most one element.

Proof. Suppose C is both cartesian closed and cocartesian coclosed, and A and B are objects of C. Then by using the basic fact that the initial object is the unit to the coproduct, and the coproducts left adjoint we know the following:

$$\mathsf{Hom}_C(A, B) \cong \mathsf{Hom}_C(A, 0 + B) \cong \mathsf{Hom}_C(B - A, 0)$$

Therefore, by Joyal's theorem above $\mathsf{Hom}_C(A, B)$ has at most one element. □

Notice that the previous result hinges on the fact that there are initial and terminal objects, and thus, this result does not hold for bi-linear categories, because the units to the tensor and cotensor are not initial nor terminal.

The repercussions of this result are that if we do not want to work with preorders, but do want to work with all of the structure, then we must separate the two worlds. Thus, this result can be seen as the motivation for the current work. We enforce the separation using linear logic, but through the power of linear logic this separation is not far.

2.3. **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 21. 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 $?A = \mathsf{JH}A$. 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 22. 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.

2.3.1. *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 23 (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 24. 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 7, to the diagrams defining a symmetric comonoidal functor, Definition 8, using the fact that j^{-1} is an isomorphism. □

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

Lemma 25 (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 8 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 $\eta_A : A \longrightarrow \mathsf{JH}A$ and $\varepsilon_R : \mathsf{HJ}R \longrightarrow R$ which correspond to the unit and counit of the adjunction respectfully. Define $\mu_A := \mathsf{J}\varepsilon_{\mathsf{H}A} : \mathsf{JHJH}A \longrightarrow \mathsf{JH}A$. 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. □

The monad from the previous result must be equipped with the additional structure to model the right weakening and contraction structural rules.

Lemma 26 (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 25.

We define the following morphisms:

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

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

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

Lemma 27 (?-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 $?A = \mathsf{JH}A$ is a symmetric comonoidal monad by Lemma 25. Bellin [1] remarks that by Maietti, Maneggia de Paiva and Ritter's Proposition 25 [7], it suffices to show that $\mu_A : ??A \longrightarrow ?A$ is a monoid morphism. For the details see the complete proof in Appendix A.4. □

Finally, we may now conclude the following corollary.

Corollary 28. Every dual LNL model is a dual linear category.

2.3.3. *Dual Linear Category implies Dual LNL Model.* This section shows essentially the inverse to the result from the previous section. That is, that from any dual linear category we may construct a dual LNL model. By exploiting the duality between LNL models and dual LNL models this result follows straightforwardly from Benton's result. The proof of this result must first find a symmetric monoid coclosed category, a cocartesian coclosed category, and finally, a symmetric comonoidal adjunction between them. Take the symmetric monoid coclosed category to be an arbitrary dual linear category $\mathcal{L}$. Then we may define the following categories.

- 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 $(?A, \mu_A : ??A \longrightarrow ?A)$.

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.

We are now going to show that both $\mathcal{L}^?$ and $\mathcal{L}_?$ are induce two cocartesian coclosed categories. Then we could take either of those when constructing a dual LNL model from a dual linear category. First, we show $C^?$ is cocartesian.

Lemma 29. If $\mathcal{L}$ is a dual linear category, then $\mathcal{L}^?$ 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 $\mathcal{L}$ 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 30. 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 31. We call an object, A, of a category, $\mathcal{L}$, **subtractable** if for any object B of $\mathcal{L}$, the internal cohom $[[A * -B]]$ exists.

We now have the following results:

Lemma 32. 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:

$$(?\,A, \delta_A)[[*-]](B, h_B) := (?([[A * -B]]), \delta_{[[A*-B]]})$$

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

$$\begin{array}{lll}
\mathsf{Hom}_{\mathcal{L}^?}((?([[A * -B]]), \delta_{[[A*-B]]}), (C, h_C)) & = & \mathsf{Hom}_{\mathcal{L}^?}(\mathsf{F}([[A * -B]]), (C, h_C)) \\
 & \cong & \mathsf{Hom}_{\mathcal{L}}([[A * -B]], \mathsf{U}(C, h_C)) \\
 & = & \mathsf{Hom}_{\mathcal{L}}([[A * -B]], C) \\
 & \cong & \mathsf{Hom}_{\mathcal{L}}([[A]], [[C(+)B]]) \\
 & = & \mathsf{Hom}_{\mathcal{L}}([[A]], \mathsf{U}([[C(+)B]], h_{[[C(+)B]]})) \\
 & \cong & \mathsf{Hom}_{\mathcal{L}^?}(\mathsf{F}[[A]], ([[C(+)B]], h_{[[C(+)B]]})) \\
 & = & \mathsf{Hom}_{\mathcal{L}^?}((?\,A, \delta_A), ([[C(+)B]], h_{[[C(+)B]]}))
\end{array}$$

The previous equation holds for any $h_{[[C(+)B]]}$ making $[[C(+)B]]$ a ?-algebra, in particular, the coproduct in $\mathcal{L}^?$ (Lemma 29), 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 33. 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 34. 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 35. Any dual linear category gives rise to a dual LNL model.

2.4. **A Mixed Bilinear/Non-Linear Model.** The main goal of our research program is to give a non-trivial categorical model of bi-intuitionistic logic. In this section we give a introduction of the model we have in mind, but leave the details and the study of the logical and programmatic sides to future work.

The naive approach would be to try and define a LNL-style model of bi-intuitionistic logic as an adjunction between a bilinear category and a bi-cartesian bi-closed category, but this results in a few problems. First, should the adjunction be monoidal or comonoidal? Furthermore, we know bi-cartesian bi-closed categories are trivial (Theorem 20), and hence, this model is not very interesting nor incorrect. We must separate the two worlds using two dual adjunctions, and hence, we arrive at the following definition.

Definition 36. A **mixed bilinear/non-linear model** consists of the following:

i. a bilinear category $(\mathcal{L}, \top, \otimes, \multimap, \perp, \oplus, \bullet\!\!-)$,
ii. a cartesian closed category $(\mathcal{I}, 1, \times, \rightarrow)$,
iii. a cocartesian coclosed category $(\mathcal{C}, 0, +, -)$,
iv. a LNL model $\mathcal{I} : F \dashv G : \mathcal{L}$, and
v. a dual LNL model $\mathcal{L} : H \dashv J : \mathcal{C}$.

Since $\mathcal{L}$ is a bilinear category then it is also a linear category, and a dual linear category. Thus, the LNL model intuitively corresponds to an adjunction between $\mathcal{I}$ and the linear subcategory of $\mathcal{L}$, and the dual LNL model corresponds to an adjunction between the dual linear subcategory of $\mathcal{L}$ and $\mathcal{C}$. In addition, both intuitionistic logic and cointuitionistic logic can be embedded into $\mathcal{L}$ via the linear modalities of-course, $!A$, and why-not, $?A$, using the well-known Girard embeddings. This implies that we have a very controlled way of mixing $\mathcal{I}$ and $\mathcal{C}$ within $\mathcal{L}$, and hence, linear logic is the key.

3. Dual LNL Logic

We now turn to developing the syntactic side of dual LNL models called dual LNL logic (DLNL). First, we give a sequent calculus formalization which we will simply refer to as DLNL logic, then a natural deduction formalization called DND logic, and finally a term assignment to the natural deduction version. Each of these systems will consistently use the same syntax and naming conventions for formulas, types, and contexts given by the following definition.

Definition 37. The the syntax for formulas, types, and contexts are given as follows:

$$\begin{array}{rl}
\text{(non-linear formulas/types)} & R, S, T ::= 0 \mid S + T \mid S - T \mid \mathsf{H} A \\
\text{(linear formulas/types)} & A, B, C ::= \perp \mid A \oplus B \mid A \bullet\!\!- B \mid \mathsf{J} S \\
\text{(non-linear contexts)} & \Psi, \Theta ::= \cdot \mid T \mid \Psi, \Theta \\
\text{(linear contexts)} & \Gamma, \Delta ::= \cdot \mid A \mid \Gamma, \Delta
\end{array}$$

The term assignment will index contexts by terms, but we will maintain the same naming convention throughout.

$$\frac{}{S \vdash_{\mathsf{C}} S}\,\text{C\_id} \qquad \frac{S \vdash_{\mathsf{C}} \Psi}{S \vdash_{\mathsf{C}} T, \Psi}\,\text{C\_weak} \qquad \frac{S \vdash_{\mathsf{C}} T, T, \Psi}{S \vdash_{\mathsf{C}} T, \Psi}\,\text{C\_contr} \qquad \frac{R \vdash_{\mathsf{C}} \Psi_1, S, T, \Psi_2}{R \vdash_{\mathsf{C}} \Psi_1, T, S, \Psi_2}\,\text{C\_ex}$$

$$\frac{}{0 \vdash_{\mathsf{C}} \Psi}\,\text{C\_0} \qquad \frac{T_1 \vdash_{\mathsf{C}} \Psi_1 \quad T_2 \vdash_{\mathsf{C}} \Psi_2}{T_1 + T_2 \vdash_{\mathsf{C}} \Psi_1, \Psi_2}\,\text{C\_}{+}_L \qquad \frac{R \vdash_{\mathsf{C}} \Psi, T_1}{R \vdash_{\mathsf{C}} \Psi, T_1 + T_2}\,\text{C\_}{+}_{R_1}$$

$$\frac{R \vdash_{\mathsf{C}} \Psi, T_2}{R \vdash_{\mathsf{C}} \Psi, T_1 + T_2}\,\text{C\_}{+}_{R_2} \qquad \frac{T_1 \vdash_{\mathsf{C}} T_2, \Psi}{T_1 - T_2 \vdash_{\mathsf{C}} \Psi}\,\text{C\_}{-}_L \qquad \frac{S \vdash_{\mathsf{C}} \Psi_1, T_1 \quad T_2 \vdash_{\mathsf{C}} \Psi_2}{S \vdash_{\mathsf{C}} \Psi_1, \Psi_2, T_1 - T_2}\,\text{C\_}{-}_R$$

$$\frac{S \vdash_{\mathsf{C}} \Psi_1, T \quad T \vdash_{\mathsf{C}} \Psi_2}{S \vdash_{\mathsf{C}} \Psi_1, \Psi_2}\,\text{C\_cut} \qquad \frac{A \vdash_{\mathsf{L}} \cdot; \Psi}{\mathsf{H} A \vdash_{\mathsf{C}} \Psi}\,\mathsf{H}_L$$

Figure 1: Non-linear fragment of the DLNL logic

$$\frac{}{A \vdash_{\mathsf{L}} A; \cdot}\,\text{LL\_id} \qquad \frac{A \vdash_{\mathsf{L}} \Delta; \Psi}{A \vdash_{\mathsf{L}} \Delta; T, \Psi}\,\text{LC\_weak} \qquad \frac{A \vdash_{\mathsf{L}} \Delta; T, T, \Psi}{A \vdash_{\mathsf{L}} \Delta; T, \Psi}\,\text{LC\_contr}$$

$$\frac{A \vdash_{\mathsf{L}} \Delta_1, A, B, \Delta_2; \Psi}{A \vdash_{\mathsf{L}} \Delta_1, B, A, \Delta_2; \Psi}\,\text{LL\_ex} \qquad \frac{A \vdash_{\mathsf{L}} \Delta; \Psi_1, S, T, \Psi_2}{A \vdash_{\mathsf{L}} \Delta; \Psi_1, T, S, \Psi_2}\,\text{LC\_ex}$$

$$\frac{A \vdash_{\mathsf{L}} \Delta_1, B; \Psi_1 \quad B \vdash_{\mathsf{L}} \Delta_2; \Psi_2}{A \vdash_{\mathsf{L}} \Delta_1, \Delta_2; \Psi_1, \Psi_2}\,\text{LL\_cut} \qquad \frac{A \vdash_{\mathsf{L}} \Delta; \Psi_1, T \quad T \vdash_{\mathsf{C}} \Psi_2}{A \vdash_{\mathsf{L}} \Delta; \Psi_1, \Psi_2}\,\text{LC\_cut}$$

$$\frac{}{\perp \vdash_{\mathsf{L}} \cdot; \cdot}\,\text{LL\_}{\perp}_L \qquad \frac{A \vdash_{\mathsf{L}} \Delta; \Psi}{A \vdash_{\mathsf{L}} \perp, \Delta; \Psi}\,\text{LL\_}{\perp}_R \qquad \frac{A \vdash_{\mathsf{L}} \Delta; \Psi, T_1}{A \vdash_{\mathsf{L}} \Delta; \Psi, T_1 + T_2}\,\text{LC\_}{+}_{R_1}$$

$$\frac{A \vdash_{\mathsf{L}} \Delta; \Psi, T_2}{A \vdash_{\mathsf{L}} \Delta; \Psi, T_1 + T_2}\,\text{LC\_}{+}_{R_2} \qquad \frac{B_1 \vdash_{\mathsf{L}} \Delta_1; \Psi_1 \quad B_2 \vdash_{\mathsf{L}} \Delta_2; \Psi_2}{B_1 \oplus B_2 \vdash_{\mathsf{L}} \Delta_1, \Delta_2; \Psi_1, \Psi_2}\,\text{LL\_}{\oplus}_L$$

$$\frac{A \vdash_{\mathsf{L}} \Delta, B, C; \Psi}{A \vdash_{\mathsf{L}} \Delta, B \oplus C; \Psi}\,\text{LL\_}{\oplus}_R \qquad \frac{B_1 \vdash_{\mathsf{L}} B_2, \Delta; \Psi}{B_1 \bullet\!\!- B_2 \vdash_{\mathsf{L}} \Delta; \Psi}\,\text{LL\_}{\bullet\!\!-}_L$$

$$\frac{A \vdash_{\mathsf{L}} B_1, \Delta_1; \Psi_1 \quad B_2 \vdash_{\mathsf{L}} \Delta_2; \Psi_2}{A \vdash_{\mathsf{L}} B \bullet\!\!- C, \Delta_1, \Delta_2; \Psi_1, \Psi_2}\,\text{LL\_}{\bullet\!\!-}_R \qquad \frac{A \vdash_{\mathsf{L}} \Delta; \Psi_1, T_1 \quad T_2 \vdash_{\mathsf{C}} \Psi_2}{A \vdash_{\mathsf{L}} \Delta; \Psi_1, \Psi_2, T_1 - T_2}\,\text{LL\_}{-}_R$$

$$\frac{T \vdash_{\mathsf{C}} \Psi}{\mathsf{J} T \vdash_{\mathsf{L}} \cdot; \Psi}\,\mathsf{J}_L \qquad \frac{A \vdash_{\mathsf{L}} \Delta; T, \Psi}{A \vdash_{\mathsf{L}} \Delta, \mathsf{J} T; \Psi}\,\mathsf{J}_R \qquad \frac{A \vdash_{\mathsf{L}} \Delta, B; \Psi}{A \vdash_{\mathsf{L}} \Delta; \mathsf{H} B, \Psi}\,\mathsf{H}_R$$

Figure 2: Linear fragment of the DLNL logic

3.1. **The Sequent Calculus for Dual LNL Logic.** In this section we take the dual of Benton's [2] sequent calculus for LNL logic to obtain the sequent calculus for dual LNL logic. The inference rules for the non-linear fragment can be found in Figure 1 and the linear fragment in Figure 2. The remainder of this section is devoted to proving cut-elimination. However, the proof is simply a dualization of Benton's [2] proof of cut-elimination for LNL logic.

Just as Benton we use n-ary cuts:

$$\frac{S \vdash_{\mathsf{C}} \Psi, S^n \quad S \vdash_{\mathsf{C}} \Psi'}{S \vdash_{\mathsf{C}} \Psi, \Psi'}\ \mathrm{C\_cut}_n \qquad \frac{A \vdash_{\mathsf{L}} \Delta; \Psi, S^n \quad S \vdash_{\mathsf{C}} \Psi'}{A \vdash_{\mathsf{L}} \Delta; \Psi, \Psi'}\ \mathrm{LC\_cut}_n$$

where $S^n = S, \ldots, S$ n-times. We call DLNL$^+$ the system DLNL with n-cuts replacing ordinary 1-cuts. Such cuts are admissible in DLNL and cut-elimination for DLNL$^+$ implies cut-elimination for DLNL.

We begin with the a few standard definitions. The *rank* of a formula, denoted by $|A|$ or $|S|$, is the number of the logical symbols in the given formula. The *cut-rank* of a derivation Π, denoted by $c(\Pi)$, is the maximum of the ranks of the cut formulas in Π plus one; if Π is cut-free its cut rank is 0. Finally, the *depth* of a derivation Π, denoted by $d(\Pi)$, is the length of the longest path in Π. The following three results establishes cut elimination.

Lemma 38 (Cut Reduction)**.** The following defines the cut reduction procedure:

(1) If Π_1 is a derivation of $T \vdash_{\mathsf{C}} \Psi, S^n$ and Π_2 is a derivation of $S \vdash_{\mathsf{C}} \Psi'$ with $c(\Pi_1), c(\Pi_2) \leq |S|$, then there exists a derivation Π of $T \vdash_{\mathsf{C}} \Psi, \Psi'$ with $c(\Pi) \leq |S|$;
(2) If Π_1 is a derivation of $T \vdash_{\mathsf{L}} \Delta; \Psi, S^n$ and Π_2 is a derivation of $S \vdash_{\mathsf{C}} \Psi'$ with $c(\Pi_1), c(\Pi_2) \leq |S|$, then there exists a derivation Π of $T \vdash_{\mathsf{L}} \Delta; \Psi, \Psi'$ with $c(\Pi) \leq |S|$;
(3) If Π_1 is a derivation of $B \vdash_{\mathsf{L}} \Delta; \Psi, A^n$ and Π_2 is a derivation of $A \vdash_{\mathsf{L}} \Delta', \Psi'$ with $c(\Pi_1), c(\Pi_2) \leq |S|$, then there exists a derivation Π of $B \vdash_{\mathsf{C}} \Delta, \Delta', \Psi, \Psi'$ with $c(\Pi) \leq |A|$.

Proof. By induction on $d(\Pi_1) + d(\Pi_2)$. We give one case where the last inferences of Π_1 and Π_2 are logical inferences; please see Appendix A.5 for the complete proof.

$\bullet\!\!-$ right / $\bullet\!\!-$ left. We have

$$\Pi_1 = \cfrac{\cfrac{\begin{matrix}\pi_1\\ A \vdash_{\mathsf{L}} \Delta_1; \Psi_1, B_1\end{matrix} \qquad \begin{matrix}\pi_2\\ B_2 \vdash_{\mathsf{L}} \Delta_2; \Psi_2\end{matrix}}{A \vdash_{\mathsf{L}} B_1 \bullet\!\!- B_2, \Delta_1, \Delta_2; \Psi_1, \Psi_2}\ \mathrm{LL\_}\bullet\!\!-_R \qquad \Pi_2 = \cfrac{\begin{matrix}\pi_3\\ B_1 \vdash_{\mathsf{L}} B_2, \Delta; \Psi\end{matrix}}{B_1 \bullet\!\!- B_2 \vdash_{\mathsf{L}} \Delta; \Psi}\ \mathrm{LL\_}\bullet\!\!-_L}{A \vdash_{\mathsf{L}} \Delta_1, \Delta_2, \Delta; \Psi_1, \Psi_2, \Psi}\ \mathrm{LL\_cut}$$

reduces to Π

$$\cfrac{\cfrac{\begin{matrix}\pi_1\\ A \vdash_{\mathsf{L}} \Delta_1, B_1; \Psi_1\end{matrix} \qquad \begin{matrix}\pi_3\\ B_1 \vdash_{\mathsf{L}} B_2, \Delta; \Psi\end{matrix}}{A \vdash_{\mathsf{L}} \Delta_1, \Delta, B_2; \Psi_1, \Psi}\ \mathrm{LL\_cut} \qquad \begin{matrix}\pi_2\\ B_2 \vdash_{\mathsf{L}} \Delta_2; \Psi_2\end{matrix}}{A \vdash_{\mathsf{L}} \Delta_1, \Delta_2, \Delta; \Psi_1, \Psi_2, \Psi}\ \mathrm{LL\_cut}$$

The resulting derivation Π has cut rank $c(\Pi) = max(|B_1| + 1, c(\pi_1), c(\pi_2), |B_2| + 1, c(\pi_3)) \leq |B_1 \bullet\!\!- B_2|$. $\square$

Lemma 39 (Decrease in Cut-Rank)**.** Let Π be a DLNL$^+$ proof of a sequent $S \vdash_{\mathsf{C}} \Psi$ or $A \vdash_{\mathsf{L}} \Delta; \Psi$ with $c(\Pi) > 0$. Then there exists a proof Π' of the same sequent with $c(\Pi') < c(\Pi)$.

Proof. By induction on $d(\Pi)$. If the last inference is not a cut, then we apply the induction hypothesis. If the last inference is a cut on a formula A, but A is not of maximal rank among the cut formulas, so that $c(\Pi) > |A| + 1$, then we apply the induction hypothesis. Finally, if the last inference is a cut on A and $c(\Pi) = |A| + 1$ we have the following situation:

$$\frac{}{S \vdash_{\mathsf{C}} S}\text{NC\_id} \qquad \frac{S \vdash_{\mathsf{C}} 0, \Psi \quad S_1 \vdash_{\mathsf{C}} \Psi_1, \dots, S_n \vdash_{\mathsf{C}} \Psi_n}{S \vdash_{\mathsf{C}} \Psi, \Psi_1, \dots, \Psi_n}\text{NC\_}0_E \qquad \frac{S \vdash_{\mathsf{C}} \Psi, T_1}{S \vdash_{\mathsf{C}} \Psi, T_1 + T_2}\text{NC\_}+_{I_1}$$

$$\frac{S \vdash_{\mathsf{C}} \Psi, T_2}{S \vdash_{\mathsf{C}} \Psi, T_1 + T_2}\text{NC\_}+_{I_2} \qquad \frac{S \vdash_{\mathsf{C}} \Psi_1, T_1 + T_2 \quad T_1 \vdash_{\mathsf{C}} \Psi_2 \quad T_2 \vdash_{\mathsf{C}} \Psi_2}{S \vdash_{\mathsf{C}} \Psi_1, \Psi_2}\text{NC\_}+_E$$

$$\frac{S \vdash_{\mathsf{C}} \Psi_1, T_1 \quad T_2 \vdash_{\mathsf{C}} \Psi_2}{S \vdash_{\mathsf{C}} \Psi_1, \Psi_2, T_1 - T_2}\text{NC\_}-_I \qquad \frac{S \vdash_{\mathsf{C}} \Psi_1, T_1 - T_2 \quad T_1 \vdash_{\mathsf{C}} T_2, \Psi_2}{S \vdash_{\mathsf{C}} \Psi_1, \Psi_2}\text{NC\_}-_E$$

$$\frac{S \vdash_{\mathsf{C}} \Psi_1, \mathsf{H}A \quad A \vdash_{\mathsf{L}} \cdot; \Psi_2}{S \vdash_{\mathsf{C}} \Psi_1, \Psi_2}\text{NC\_}\mathsf{H}_E$$

Figure 3: Non-linear fragment of DND logic

$$\Pi = \frac{\begin{matrix}\Pi_1 \\ B \vdash_{\mathsf{L}} \Delta, A; \Psi\end{matrix} \qquad \begin{matrix}\Pi_2 \\ A \vdash_{\mathsf{L}} \Delta'; \Psi'\end{matrix}}{B \vdash_{\mathsf{L}} \Delta, \Delta'; \Psi, \Psi'}\text{LL\_cut}$$

Now since $c(\Pi_1), c(\Pi_2) \leq |A| + 1$ then by applying the induction hypothesis to the premises of the previous derivation we can construct derivations Π'_1 and Π'_2 with $c(\Pi'_1) \leq |A|$ and $c(\Pi'_2) \leq |A|$. Then by cut reduction we can construct a derivation Π' proving $B \vdash_{\mathsf{L}} \Delta, \Delta'; \Psi, \Psi'$ with $c(\Pi') \leq |A|$ as required. □

Theorem 40 (Cut Elimination)**.** Let Π be a proof of a sequent $S \vdash_{\mathsf{C}} \Psi$ or $A \vdash_{\mathsf{L}} \Delta; \Psi$ such that $c(\Pi) > 0$. There is an algorithm which yields a cut free proof of the same sequent.

Proof. By induction on $c(\Pi)$ using the previous lemma. □

Remark 41. In DLNL logic contexts are treated multiplicatively. Some cases of the previous proof would be best treated with additive contexts, for instance non-linear disjunction elimination to match the categorical interpretation of disjunction as coproduct. Of course additive contexts can be simulated using weakening and contraction.

3.2. **Sequent-style Natural Deduction.** The inference rules for the non-linear and linear fragments of the sequent-style natural deduction formalization of DLNL (DND) can be found in Figure 3 and Figure 4 respectively. Some of the inference rules are formulated *additively* instead of multiplicatively as we explained in the previous section; see Remark 41.

We now give a correspondence between DND and DLNL logic. First, we have several admissible rules.

$$\frac{}{A \vdash_{\mathsf{L}} A;\cdot}\text{NLL\_id} \qquad \frac{A \vdash_{\mathsf{L}} \Delta;\Psi}{A \vdash_{\mathsf{L}} \Delta,\perp;\Psi}\text{NLL\_}\perp_I \qquad \frac{A \vdash_{\mathsf{L}} \perp,\Delta;\cdot}{A \vdash_{\mathsf{L}} \Delta;\cdot}\text{NLL\_}\perp_E$$

$$\frac{A \vdash_{\mathsf{L}} \Delta, B_1, B_2;\Psi}{A \vdash_{\mathsf{L}} \Delta, B_1 \oplus B_2;\Psi}\text{NLL\_}\oplus_I \qquad \frac{A \vdash_{\mathsf{L}} \Delta, B_1 \oplus B_2;\Psi \quad B_1 \vdash_{\mathsf{L}} \Delta_1;\Psi_1 \quad B_2 \vdash_{\mathsf{L}} \Delta_2;\Psi_2}{A \vdash_{\mathsf{L}} \Delta,\Delta_1,\Delta_2;\Psi,\Psi_1,\Psi_2}\text{NLL\_}\oplus_E$$

$$\frac{A \vdash_{\mathsf{L}} \Delta_1, B_1;\Psi_1 \quad B_2 \vdash_{\mathsf{L}} \Delta_2;\Psi_2}{A \vdash_{\mathsf{L}} B_1 \bullet\!\!- B_2,\Delta_1,\Delta_2;\Psi_1,\Psi_2}\text{NLL\_}\bullet\!\!-_I$$

$$\frac{A \vdash_{\mathsf{L}} \Delta_1, B_1 \bullet\!\!- B_2;\Psi_1 \quad B_1 \vdash_{\mathsf{L}} B_1,\Delta_2;\Psi_2}{A \vdash_{\mathsf{L}} \Delta_1,\Delta_2;\Psi_1,\Psi_2}\text{NLL\_}\bullet\!\!-_E \qquad \frac{A \vdash_{\mathsf{L}} \Delta;T,\Psi}{A \vdash_{\mathsf{L}} \Delta,\mathsf{J}\,T;\Psi}\text{NLL\_}\mathsf{J}_I$$

$$\frac{A \vdash_{\mathsf{L}} \Delta,\mathsf{J}\,T;\Psi_1 \quad T \vdash_{\mathsf{C}} \Psi_2}{A \vdash_{\mathsf{L}} \Delta;\Psi_1,\Psi_2}\text{NLL\_}\mathsf{J}_E \qquad \frac{A \vdash_{\mathsf{L}} \Delta,B;\Psi}{A \vdash_{\mathsf{L}} \Delta;\mathsf{H}\,B,\Psi}\text{NLL\_}\mathsf{H}_I$$

$$\frac{A \vdash_{\mathsf{L}} \Delta;\Psi_1,\mathsf{H}A \quad A \vdash_{\mathsf{L}} \cdot;\Psi_2}{A \vdash_{\mathsf{L}} \Delta;\Psi_1,\Psi_2}\text{NLL\_}\mathsf{H}_E$$

Figure 4: Linear fragment of DND logic

Lemma 42 (Admissible Rules in DND)**.** The following rules are admissible in DND:

$$\frac{S \vdash_{\mathsf{C}} \Psi}{S \vdash_{\mathsf{C}} T,\Psi}\text{NC\_weak} \qquad \frac{S \vdash_{\mathsf{C}} T,T,\Psi}{S \vdash_{\mathsf{C}} T,\Psi}\text{NC\_contr} \qquad \frac{S \vdash_{\mathsf{C}} \Psi_1,T \quad T \vdash_{\mathsf{C}} \Psi_2}{S \vdash_{\mathsf{C}} \Psi_1,\Psi_2}\text{NC\_cut}$$

$$\frac{A \vdash_{\mathsf{L}} \Delta;\Psi}{A \vdash_{\mathsf{L}} \Delta;T,\Psi}\text{NLC\_weak} \qquad \frac{A \vdash_{\mathsf{L}} \Delta;T,T,\Psi}{A \vdash_{\mathsf{L}} \Delta;T,\Psi}\text{NLC\_contr}$$

$$\frac{A \vdash_{\mathsf{L}} \Delta;\Psi_1,T \quad T \vdash_{\mathsf{C}} \Psi_2}{A \vdash_{\mathsf{L}} \Delta;\Psi_1,\Psi_2}\text{NLC\_cut} \qquad \frac{A \vdash_{\mathsf{L}} \Delta_1,B;\Psi_1 \quad B \vdash_{\mathsf{L}} \Delta_2;\Psi_2}{A \vdash_{\mathsf{L}} \Delta_1,\Delta_2;\Psi_1,\Psi_2}\text{NLL\_cut}$$

Using these admissible rules we can construct a proof preserving translation between DND and DLNL logic.

Lemma 43 (Translations between DND and DLNL logic)**.** There are functions $\mathcal{S} : DND \to DLNL$ and $\mathcal{N} : DLNL \to DND$ from natural deduction to sequent calculus derivations.

Notice that the right rules of the sequent calculus and the introductions of natural deduction have the same form. Elimination rules are derivable from left rules with *cut* and left rules are derivable using the admissible cut rule in DND. For instance, the NC_0_E rule

$$\frac{S \vdash_{\mathsf{C}} 0,\Psi \quad S_1 \vdash_{\mathsf{C}} \Psi_1,\ \ldots, S_n \vdash_{\mathsf{C}} \Psi_n}{S \vdash_{\mathsf{C}} \Psi,\Psi_1,\ \ldots,\Psi_n}\text{NC\_}0_E$$

is derivable in the sequent calculus as follows:

$$\dfrac{\dfrac{\dfrac{\dfrac{S \vdash_{\mathsf{C}} 0,\Psi \qquad 0 \vdash S_1,\dots S_n}{S \vdash_{\mathsf{C}} \Psi, S_1,\dots S_n}\,\text{C\_cut} \qquad S_1 \vdash_{\mathsf{C}} \Psi_1}{S \vdash_{\mathsf{C}} \Psi,\Psi_1,S_2,\dots,S_n}\,\text{C\_cut} \qquad \vdots}{S \vdash_{\mathsf{C}} \Psi,\Psi_1,\dots\Psi_{n-1},S_n} \qquad S_n \vdash \Psi_n}{S \vdash_{\mathsf{C}} \Psi,\Psi_1,\dots\Psi_{n-1},\Psi_n}\,\text{C\_cut}$$

3.3. **Term Assignment.** We now turn to giving a term assignment to DND logic called TND. The most interesting aspect of this system is that there are multiple conclusions, but only a single hypothesis. [TND is greatly influenced by Crolard's [6] term assignment for subtractive logic which is based on Parigot's [8] $\lambda\mu$-calculus. Crolard shows that the theory of coroutines can be modeled by co-intuitionistic logic, and it is this result we pull inspiration from. In fact, this result shows that the reduction of a term in the context may impact other terms in the context.] TND takes off from Crolard' s paper *A formulae-as-types interpretation of subtractive logic* JLC 2004, where he gives a term assignment to bi-intuitionisitc logic within a variant of Parigot's [8] classical $\lambda\mu$-calculus and interprets the term assigned to subtraction rules in terms of coroutines. He then restricts the calculus to provide a constructive version of it (*safe coroutines*). The second author has then used a variant of Crolard's calculus as a term assignment to co-intuitionistic logic and to linear co-intuitionistic logic [1] without using the $\lambda\mu$-calculus. In this formulation, the reduction of a term in context may impact other terms in the context.

The syntax of TND terms is defined by the following definition.

Definition 44. The syntax for TND terms and typing judgments are given by the following grammar:

$$\begin{array}{lll}
\text{(non-linear terms)} \quad s,t & ::= & x \mid \mathsf{connect}_w\ \mathsf{to}\ t \mid t_1 \cdot t_2 \mid \mathsf{false}\ t \mid x(t) \mid \mathsf{mkc}(t,x) \mid \mathsf{inl}\ t \mid \mathsf{inr}\ t \mid \\
 & & \mathsf{case}\ t\ \mathsf{of}\ x.t_1, y.t_2 \mid \mathsf{H}\ e \mid \mathsf{let}\ \mathsf{J}\ x = e\ \mathsf{in}\ t \mid \mathsf{postp}\,(x \mapsto t_1, t_2) \mid \\
 & & \mathsf{let}\ \mathsf{H}\ x = t_1\ \mathsf{in}\ t_2
\end{array}$$

$$\begin{array}{lll}
\text{(linear terms)} \quad e,u & ::= & x \mid \mathsf{connect}_\perp\ \mathsf{to}\ e \mid \mathsf{postp}_\perp\ e \mid \mathsf{postp}\,(x \mapsto e_1, e_2) \mid \mathsf{mkc}(e,x) \mid x(e) \mid \\
 & & e_1 \oplus e_2 \mid \mathsf{casel}\ e \mid \mathsf{caser}\ e \mid \mathsf{J}\ t
\end{array}$$

$$\text{(non-linear judgment)} \quad x : R \vdash_{\mathsf{C}} \Psi$$

$$\text{(linear judgment)} \quad x : A \vdash_{\mathsf{L}} \Delta;\Psi$$

Contexts, Δ and Ψ, are the straightforward extension where each type is annotated with a term from the respective fragment.

To aid the reader in understanding the variable structure, which variable annotations are bound, deployed throughout the TND term syntax we give the definitions of the free variable functions in the following definition.

$$\frac{}{x : S \vdash_{\mathsf{C}} x : S}\text{TC\_id} \qquad \frac{x : S \vdash_{\mathsf{C}} t : 0, \Psi \quad x_1 : S_1 \vdash_{\mathsf{C}} \Psi_1, \ldots, x_n : S_n \vdash_{\mathsf{C}} \Psi_n}{x : S \vdash_{\mathsf{C}} \Psi, [\mathsf{false}\, t/x_1]\Psi_1, \ldots, [\mathsf{false}\, t/x_n]\Psi_n}\text{TC\_}0_E$$

$$\frac{x : S \vdash_{\mathsf{C}} \Psi, t : T_1}{x : S \vdash_{\mathsf{C}} \Psi, \mathsf{inl}\, t : T_1 + T_2}\text{TC\_}+_{I_1} \qquad \frac{x : S \vdash_{\mathsf{C}} \Psi, t : T_2}{x : S \vdash_{\mathsf{C}} \Psi, \mathsf{inr}\, t : T_1 + T_2}\text{TC\_}+_{I_2}$$

$$\frac{x : S \vdash_{\mathsf{C}} \Psi_1, t : T_1 + T_2 \quad y : T_1 \vdash_{\mathsf{C}} \Psi_2 \quad z : T_2 \vdash_{\mathsf{C}} \Psi_3 \quad |\Psi_2| = |\Psi_3|}{x : S \vdash_{\mathsf{C}} \Psi_1, \mathsf{case}\, t\, \mathsf{of}\, y.\Psi_2, z.\Psi_3}\text{TC\_}+_E$$

$$\frac{x : S \vdash_{\mathsf{C}} \Psi_1, t : T_1 \quad y : T_2 \vdash_{\mathsf{C}} \Psi_2}{x : S \vdash_{\mathsf{C}} \Psi_1, \mathsf{mkc}(t, y) : T_1 - T_2, [y(t)/y]\Psi_2}\text{TC\_}-_I$$

$$\frac{x : S \vdash_{\mathsf{C}} \Psi_1, s : T_1 - T_2 \quad y : T_1 \vdash_{\mathsf{C}} t : T_2, \Psi_2}{x : S \vdash_{\mathsf{C}} \Psi_1, \mathsf{postp}\,(y \mapsto t, s), [y(s)/y]\Psi_2}\text{TC\_}-_E$$

$$\frac{x : S \vdash_{\mathsf{C}} \Psi_1, t : \mathsf{H}A \quad y : A \vdash_{\mathsf{L}} \cdot; \Psi_2 \quad |\Psi_1| = |\Psi_2|}{x : S \vdash_{\mathsf{C}} \Psi_1 \cdot (\mathsf{let}\, \mathsf{H}\, y = t\, \mathsf{in}\, \Psi_2)}\text{TC\_H}_E$$

Figure 5: Non-linear fragment of the term assignment for TND

Definition 45. The free variable functions, $FV(t)$ and $FV(e)$, for linear and non-linear terms t and e are defined by mutual recursion as follows:

linear terms:

$FV(x) = \{x\}$
$FV(\mathsf{connect}_\perp\, \mathsf{to}\, e) = FV(e)$
$FV(x(e)) = FV(e)$
$FV(\mathsf{mkc}(e, y)) = FV(e)$
$FV(e_1 \oplus e_2) = FV(e_1) \cup FV(e_2)$
$FV(\mathsf{casel}\, e) = FV(e)$
$FV(\mathsf{caser}\, e) = FV(e)$
$FV(\mathsf{J}\, t) = FV(t)$

non-linear terms:

$FV(x) = \{x\}$
$FV(\mathsf{connect}_w\, \mathsf{to}\, t) = FV(t)$
$FV(t_1 \cdot t_2) = FV(t_1) \cup FV(t_2)$
$FV(\mathsf{false}\, t) = FV(t)$
$FV(x(t)) = FV(t)$
$FV(\mathsf{mkc}(t, y)) = FV(t)$
$FV(\mathsf{inl}\, t) = FV(\mathsf{inr}\, t) = FV(t)$
$FV(\mathsf{case}\, t_1\, \mathsf{of}\, x.t_2, y.t_3) =$
$\quad FV(t_1) \cup FV(t_2) \setminus \{x\} \cup FV(t_3) \setminus \{y\}$
$FV(\mathsf{let}\, \mathsf{J}\, y = e\, \mathsf{in}\, t) = FV(e) \cup FV(t) \setminus \{y\}$
$FV(\mathsf{let}\, \mathsf{H}\, y = t_1\, \mathsf{in}\, t_2) = FV(t_1) \cup FV(t_2) \setminus \{y\}$
$FV(\mathsf{H}\, e) = FV(e)$

The free variables of a p-term are defined s follows:

$$\begin{array}{rcl} FV(\mathtt{postp}_\perp\ e) & = & FV(e) \\ FV(\mathtt{postp}(x \mapsto e_1, e_2)) & = & FV(e_1) \setminus \{x\} \cup FV(e_2) \end{array}$$

and similarly for terms $\mathtt{postp}(x \mapsto t_1, t_2)$.

Terms are then typed by annotating the previous term structure over DND derivations, and this is accomplished by annotating the DND inference rules. The typing rules for the non-linear fragment of TND can be found in Figure 5, and the typing rules for the linear fragment of TND can be found in Figure 6.

$$\frac{}{x : A \vdash_{\mathsf{L}} x : A; \cdot}\ \mathrm{TLL\_id} \qquad \frac{x : A \vdash_{\mathsf{L}} \Delta; \Psi \quad e : B \in \Delta}{x : A \vdash_{\mathsf{L}} \Delta, \mathsf{connect}_{\perp}\ \mathsf{to}\ e : \perp; \Psi}\ \mathrm{TLL\_}\perp_I$$

$$\frac{x : A \vdash_{\mathsf{L}} e : \perp, \Delta; \cdot}{x : A \vdash_{\mathsf{L}} \mathsf{postp}_{\perp}\ e, \Delta; \cdot}\ \mathrm{TLL\_}\perp_E \qquad \frac{x : A \vdash_{\mathsf{L}} \Delta, e_1 : B_1, e_2 : B_2; \Psi}{x : A \vdash_{\mathsf{L}} \Delta, e_1 \oplus e_2 : B_1 \oplus B_2; \Psi}\ \mathrm{TLL\_}\oplus_I$$

$$\frac{x : A \vdash_{\mathsf{L}} \Delta, e : B_1 \oplus B_2; \Psi \quad y : B_1 \vdash_{\mathsf{L}} \Delta_1; \Psi_1 \quad z : B_2 \vdash_{\mathsf{L}} \Delta_2; \Psi_2}{x : A \vdash_{\mathsf{L}} \Delta, [\mathsf{casel}\,(e)/y]\Delta_1, [\mathsf{caser}\,(e)/z]\Delta_2; \Psi, [\mathsf{casel}\,(e)/y]\Psi_1, [\mathsf{caser}\,(e)/z]\Psi_2}\ \mathrm{TLL\_}\oplus_E$$

$$\frac{x : A \vdash_{\mathsf{L}} \Delta_1, e : B_1; \Psi_1 \quad y : B_2 \vdash_{\mathsf{L}} \Delta_2; \Psi_2}{x : A \vdash_{\mathsf{L}} \mathsf{mkc}(e, y) : B_1 \bullet\!\!- B_2, \Delta_1, [y(e)/y]\Delta_2; \Psi_1, [y(e)/y]\Psi_2}\ \mathrm{TLL\_}\bullet\!\!-_I$$

$$\frac{x : A \vdash_{\mathsf{L}} \Delta_1, e_1 : B_1 \bullet\!\!- B_2; \Psi_1 \quad y : B_1 \vdash_{\mathsf{L}} e_2 : B_1, \Delta_2; \Psi_2}{x : A \vdash_{\mathsf{L}} \Delta_1, \mathsf{postp}\,(y \mapsto e_2, e_1), \Delta_2; \Psi_1, \Psi_2}\ \mathrm{TLL\_}\bullet\!\!-_E$$

$$\frac{x : A \vdash_{\mathsf{L}} \Delta; t : T, \Psi}{x : A \vdash_{\mathsf{L}} \Delta, \mathsf{J}\,t : \mathsf{J}\,T; \Psi}\ \mathrm{TLL\_J}_I \qquad \frac{x : A \vdash_{\mathsf{L}} \Delta, e : \mathsf{J}\,T; \Psi_1 \quad y : T \vdash_{\mathsf{C}} \Psi_2}{x : A \vdash_{\mathsf{L}} \Delta; \Psi_1, \mathsf{let}\,\mathsf{J}\,y = e\ \mathsf{in}\,\Psi_2}\ \mathrm{TLL\_J}_E$$

$$\frac{x : A \vdash_{\mathsf{L}} \Delta, e : B; \Psi}{x : A \vdash_{\mathsf{L}} \Delta; \mathsf{H}\,e : \mathsf{H}\,B, \Psi}\ \mathrm{TLL\_H}_I \qquad \frac{x : A \vdash_{\mathsf{L}} \Delta; \Psi_1, t : \mathsf{H}A \quad y : A \vdash_{\mathsf{L}} \cdot; \Psi_2}{x : A \vdash_{\mathsf{L}} \Delta; \Psi_1, \mathsf{let}\,\mathsf{H}\,y = t\,\mathsf{in}\,\Psi_2}\ \mathrm{TLL\_H}_E$$

Figure 6: Linear fragment of the term assignment for TND

Remark 46. Let us call terms of the form $\mathsf{postp}\,(x \mapsto t_1, t_2)$, $\mathsf{postp}\,(x \mapsto e_1, e_2)$, and $\mathsf{postp}_{\perp}\,e$ *p-terms*. Let us say that a term t is *p-normal* if t does not contain any p-term as a proper subterm. We denote this class of *p-normal* terms by r. When the calculus is typed, linear p-terms can be typed with $\perp$, non-linear p terms can be typed with 0. In presence of the $\perp$ rule and of the TC_0_E rule it is possible to replace a non-p-normal p-term removed by a β-reduction with a $\perp$ or TC_0_E rule. However, this creates an anomaly in the proof theory since the newly introduced unit rule is unnecessary and could be eliminated in the case of p-normal terms. Hence, we choose to leave the typing of p terms implicit in the syntax and enforce the requirement of p-normality.

The typing rules depend on the extension of let and case expressions to typing contexts. We use the following notation for *parallel composition* of typing contexts:

$$\Delta = e_1 : A_1 \,\|\, \cdots \,\|\, e_n : A_n$$

This operation should be regarded as associative, commutative and having the empty context as its identity. The extension of let expressions to contexts is given as follows:

$$\begin{aligned} \mathtt{let}\ p\ = t\ \mathtt{in} \cdot \quad &= \quad \cdot \\ \mathtt{let}\ p\ = t_1\ \mathtt{in}\,(t_2 : A) \quad &= \quad \mathtt{let}\ p\ = t_1\,\mathsf{in}\,t_2 : A \\ \mathtt{let}\ p\ = t\ \mathtt{in}\,(\Psi_1 \,\|\, \Psi_2) \quad &= \quad (\mathtt{let}\ p\ = t\ \mathtt{in}\,\Psi_1) \,\|\, (\mathtt{let}\ p\ = t\ \mathtt{in}\,\Psi_2) \end{aligned}$$

where $p = \mathsf{H}\,y$ or $p = \mathsf{J}\,y$. Case expressions are handled similarly.

Similarly to DND logic we have the following admissible rules.

Lemma 47 (Admissible Typing Rules)**.** The term assignment for the admissible rules of the calculus is as follows:

$$\frac{x : S \vdash_{\mathsf{C}} \Psi \quad s : T' \in \Psi}{x : S \vdash_{\mathsf{C}} \mathsf{connect}_w\,\mathsf{to}\, s : T, \Psi}\text{TC\_weak} \qquad \frac{x : S \vdash_{\mathsf{C}} t_1 : T, t_2 : T, \Psi}{x : S \vdash_{\mathsf{C}} (t_1 \cdot t_2) : T, \Psi}\text{TC\_contr}$$

$$\frac{x : S \vdash_{\mathsf{C}} \Psi_1, t : T \quad y : T \vdash_{\mathsf{C}} \Psi_2}{x : S \vdash_{\mathsf{C}} \Psi_1, [t/y]\Psi_2}\text{TC\_cut} \qquad \frac{x : A \vdash_{\mathsf{L}} \Delta; \Psi \quad r : T' \in \Psi \text{ or } r : B \in \Delta}{x : A \vdash_{\mathsf{L}} \Delta; \mathsf{connect}_w\,\mathsf{to}\, r : T, \Psi}\text{TLC\_weak}$$

$$\frac{x : A \vdash_{\mathsf{L}} \Delta; t_1 : T, t_2 : T, \Psi}{x : A \vdash_{\mathsf{L}} \Delta; t_1 \cdot t_2 : T, \Psi}\text{TLC\_contr} \qquad \frac{x : A \vdash_{\mathsf{L}} \Delta; \Psi_1, t : T \quad y : T \vdash_{\mathsf{C}} \Psi_2}{x : A \vdash_{\mathsf{L}} \Delta; \Psi_1, [t/y]\Psi_2}\text{NLC\_cut}$$

$$\frac{x : A \vdash_{\mathsf{L}} \Delta_1, e : B; \Psi_1 \quad y : B \vdash_{\mathsf{L}} \Delta_2; \Psi_2}{x : A \vdash_{\mathsf{L}} \Delta_1, [e/y]\Delta_2; \Psi_1, [e/y]\Psi_2}\text{TLL\_cut}$$

We generalize the admissible rule of contraction on the non-linear side to contexts. Let m_1 and m_2 be multisets of terms, then we denote by $m_1 \cdot m_2$ the sum of multisets; if multisets are represented as lists, then the sum is representable as the appending of the lists. We denote singleton multisets, $\{t\}$, by the term that inhabits it, e.g. t. We extend this to contexts, $\Psi_1 \cdot \Psi_2$, recursively as follows:

$$\begin{array}{rcl}
(\cdot) \cdot (\cdot) & = & (\cdot) \\
(t_1 : S) \cdot (t_2 : S) & = & t_1 \cdot t_2 : S \\
(\Psi_1 \,\|\, \Psi_3) \cdot (\Psi_2 \,\|\, \Psi_4) & = & (\Psi_1 \cdot \Psi_2) \,\|\, (\Psi_3 \cdot \Psi_4)
\end{array}$$

where $|\Psi_1| = |\Psi_3|$ and $|\Psi_2| = |\Psi_4|$.

At this point we are now ready to turn to computing in TND by specifying the reduction relation. This definition is perhaps the most interesting aspect of the theory, because reducing one term may affect others.

β-**Reduction in TND.** As we discussed above cointuitionistic logic corresponds to the theory of coroutines that manipulate local context. Thus, reducing one term in a typing context could affect other terms in the context. This implies that the definition of the reduction relation for TND must account for more than a single term. We accomplish this by defining the reduction relation of terms in context, $x : S \vdash_{\mathsf{C}} \Psi_1, t : T, \Psi_2$ and $x : A \vdash_{\mathsf{L}} \Delta_1, e : B, \Delta_2; \Psi$, so that the manipulation of the context is made explicit.

The reduction rules for the linear and non-linear fragments can be found in Figure 7 and Figure 8 respectively. We denote a reduction rule by $x : S \vdash_{\mathsf{C}} \Psi_1 \rightsquigarrow x : S \vdash_{\mathsf{C}} \Psi_2$ and $x : A \vdash_{\mathsf{L}} \Delta_1; \Psi_1 \rightsquigarrow x : A \vdash_{\mathsf{L}} \Delta_2; \Psi_2$. In the interest of readability we do not show full derivations, but it should be noted that it is assumed that every term mentioned in a reduction rule is typable with the expected type given where it occurs in the judgment. Furthermore, the reduction relation depends on a few standard definitions.

Capture-avoiding substitution, denoted by $[t_1/x]t_2$, $[e/x]t$, $[t/x]e$, and $[e_1/x]e_2$, is defined in the usual way. We extend capture-avoiding substitution to multisets in the following way:

- $[t_1 \cdot \ldots \cdot t_n/z]s = [t_1/z]s \cdot \ldots \cdot [t_n/z]s$
- $[t_1 \cdot \ldots \cdot t_n/z]p = [t_1/z]p \,\|\, \ldots \,\|\, [t_n/z]p$, where p is a p-term

The extension of the other flavors of substitution to multisets are similar. Standard extension of substitution to contexts was also necessary.

3.4. **Categorical interpretation of rules.** Given a *signature* Sg, consisting of a collection of types σ_i, where $\sigma_i = A$ or S, and a collection of *sorted function symbols* $f_j : \sigma_1, \ldots, \sigma_n \to \tau$ and given

Bottom:

$$x : A \vdash_{\mathsf{L}} \mathsf{postp}_{\perp}\,(\mathsf{connect}_{\perp}\ \mathsf{to}\ e), \Delta; \Psi \quad\rightsquigarrow\quad x : A \vdash_{\mathsf{L}} \Delta; \Psi$$

H:

$$x : B \vdash_{\mathsf{L}} \Delta; \Psi_1 \cdot (\mathsf{let}\,\mathsf{H}\,y = \mathsf{H}\,e\ \mathsf{in}\ \Psi_2) \quad\rightsquigarrow\quad x : B \vdash_{\mathsf{L}} \Delta; \Psi_1 \cdot [e/y]\Psi_2$$

J:

$$x : A \vdash_{\mathsf{L}} \Delta; \Psi_1 \cdot \mathsf{let}\,\mathsf{J}\,y = \mathsf{J}\,t\ \mathsf{in}\ \Psi_2 \quad\rightsquigarrow\quad x : A \vdash_{\mathsf{L}} \Delta; \Psi_1 \cdot [t/y]\Psi_2$$

Linear Subtraction:

$$\Psi_2' = [y(e_1)/y]\Psi_2, [z(\mathsf{mkc}(e_1, y))/z]\Psi_3$$

$$\Psi_2'' = [[e_1/z]e_2/y]\Psi_2, [e_1/z]\Psi_3$$

$$x : B \vdash_{\mathsf{L}} \Delta_1, \mathsf{postp}\,(z \mapsto e_2, \mathsf{mkc}(e_1, y)), [y(e_1)/y]\Delta_2, [z(\mathsf{mkc}(e_1, y))/z]\Delta_3; \Psi_1, \Psi_2' \quad\rightsquigarrow\quad x : B \vdash_{\mathsf{L}} \Delta_1, [[e_1/z]e_2/y]\Delta_2, [e_1/z]\Delta_3; \Psi_1, \Psi_2''$$

Par:

$$\Psi' = [\mathsf{casel}\,(e_1 \oplus e_2)/y]\Psi_1, [\mathsf{caser}\,(e_1 \oplus e_2)/z]\Psi_2$$

$$\Psi'' = [e_1/y]\Psi_1, [e_2/x]\Psi_2$$

$$x : A \vdash_{\mathsf{L}} \Delta, [\mathsf{casel}\,(e_1 \oplus e_2)/y]\Delta_1, [\mathsf{caser}\,(e_1 \oplus e_2)/z]\Delta_2; \Psi, \Psi' \quad\rightsquigarrow\quad x : A \vdash_{\mathsf{L}} \Delta, [e_1/y]\Delta_1, [e_2/x]\Delta_2; \Psi, \Psi''$$

Figure 7: Reductions for Linear Terms

Subtraction:

$$x : S \vdash_{\mathsf{C}} \Psi_1, \mathsf{postp}\,(z \mapsto t_2, \mathsf{mkc}(t_1, y)), [y(t_1)/y]\Psi_2, [\mathsf{mkc}(t_1, y)/z]\Psi_3 \quad\rightsquigarrow\quad x : S \vdash_{\mathsf{C}} \Psi_1, [[t_1/z]t_2/y]\Psi_2, [t_1/x]\Psi_3$$

Coproduct Left:

$$x : S \vdash_{\mathsf{C}} \Psi_1, \mathsf{case}\,(\mathsf{inl}\,t_1)\ \mathsf{of}\ y.\Psi_2, z.\Psi_3 \quad\rightsquigarrow\quad x : S \vdash_{\mathsf{C}} \Psi_1, [t_1/y]\Psi_2$$

Coproduct Right:

$$x : S \vdash_{\mathsf{C}} \Psi_1, \mathsf{case}\,(\mathsf{inr}\,t_1)\ \mathsf{of}\ y.\Psi_2, z.\Psi_3 \quad\rightsquigarrow\quad x : S \vdash_{\mathsf{C}} \Psi_1, [t_1/z]\Psi_3$$

H:

$$x : \mathsf{H}\,B \vdash_{\mathsf{C}} (\mathsf{let}\,\mathsf{H}\,x = y\ \mathsf{in}\ \Psi_1) \cdot \mathsf{let}\,\mathsf{H}\,z = (\mathsf{let}\,\mathsf{H}\,x = y\ \mathsf{in}\ \mathsf{H}\,e)\ \mathsf{in}\ \Psi_2 \quad\rightsquigarrow\quad x : \mathsf{H}\,B \vdash_{\mathsf{C}} (\mathsf{let}\,\mathsf{H}\,x = y\ \mathsf{in}\ \Psi_1) \cdot (\mathsf{let}\,\mathsf{H}\,x = y\ \mathsf{in}\ [e/z]\Psi_2)$$

Figure 8: Reductions for Non-linear Terms

a Symmetric Monoidal Category (SMC) $(\mathbb{C}, \bullet, 1, \alpha, \lambda, \rho, \gamma)$, a *structure* $\mathcal{M}$ for Sg is an assignment of an object $[\![\sigma]\!]$ of $\mathcal{L}$ for each type σ and of a morphism $[\![f]\!] : [\![\sigma_1]\!] \bullet \ldots \bullet [\![\sigma_n]\!] \to [\![\tau]\!]$ for each function $f : \sigma_1, \ldots, \sigma_n \to \tau$ of Sg.[1]

The types of terms in context $\Delta = [e_1 : A_1, \ldots, e_n : A_n]$ or $\Delta = [t_1 : T_1, \ldots, t_n : T_n]$ are interpreted as $[\![\sigma_1, \sigma_2, \ldots, \sigma_n]\!] = (\ldots([\![\sigma_1]\!] \bullet [\![\sigma_2]\!]) \ldots) \bullet [\![\sigma_n]\!]$; left associativity is also intended for concatenations of type sequences Γ, Δ. Thus we need the "book-keeping" functions $\mathtt{Split}(\Gamma, \Delta) : [\![\Gamma, \Delta]\!] \to [\![\Gamma]\!] \bullet [\![\Delta]\!]$ and $\mathtt{Join}(\Gamma, \Delta) : [\![\Gamma]\!] \bullet [\![\Delta]\!] \to [\![\Gamma, \Delta]\!]$ inductively defined using the associativity laws α and their inverse α^{-1} (cfr Bierman 1994, Bellin 2015).

The semantics of terms in context is then specified by induction on terms:

$$[\![x : A \vdash_{\mathsf{L}} x : A]\!] =_{df} id_{[\![\sigma]\!]}$$

$$[\![x : A \vdash_{\mathsf{L}} f(e_1, \ldots, e_n) : B]\!] =_{df} [\![x : A \vdash e_1 : A_1]\!] \bullet \ldots \bullet [\![x : \sigma \triangleright e_n : A_n]\!]; [\![f]\!]$$

and similarly with non-linear types. Next one proves by induction on the type derivation that substitution in the term calculus corresponds to composition in the category ([?], Lemma 13).

In a Linear Non-Linear Co-intuitionistic logic sequent, mixed sequents $x : A \vdash_{\mathsf{L}} \Delta; \Psi, t : T$ non-linear terms are interpreted through the functor $J : \mathcal{C} \to \mathcal{L}$. Here we use the same symbol for the functor J in the structure and the name of the functor in the syntax of the langage. Thus we have

$$[\![x : A \vdash_{\mathsf{L}} \Delta; \Psi, t : T]\!] \quad = \quad [\![x : A \vdash_{\mathsf{L}} \Delta, J\Psi, Jt : J(T)]\!]$$

Let $\mathcal{M}$ be a structure for a signature Sg in a SMC $\mathcal{L}$. Given an equation in context for Sg

$$x : A \vdash_{\mathsf{L}} \overline{e} : \Gamma, e_1 = e_2 : B; \Psi$$

we say that the structure *satisfies* the equation if it assigns the same morphisms to $x : A \vdash_{\mathsf{L}} \overline{e} : \Gamma, e_1 : B; \Psi$. and to $A \vdash \overline{e} : \Gamma, e_2 : B; \Psi$. Similarly, $\mathcal{M}$ satisfies $x : S \vdash_{\mathsf{L}} \overline{t} : \Psi, t_1 = t_2$ if it assigns the same morphism to $x : S \vdash_{\mathsf{L}} \overline{t} : \Psi, t_1 : T$ and to $x : S \vdash_{\mathsf{L}} \overline{t} : \Psi, t_2 : Y$. Then given an algebraic theory $Th = (Sg, Ax)$, a structure $\mathcal{M}$ for Sg is a *model* for Th if it satisfies all the axioms in Ax.

We now go through some cases of the rules in the sequent-style Natural Deduction calculus to specify their categorical interpretation so as to satify the equations in context and to prove consistency of the LNL co-intuitionistic logic in the model thus defined.

3.4.1. *Linear disjunction Par.* 3.4.1.1. *Par introduction.* The introduction rule for Par is of the form

$$\frac{x : A \vdash_{\mathsf{L}} \Delta_1, e_1 : B, e_2 : C; \Psi}{x : A \vdash_{\mathsf{L}} \Delta_1, e_1 \oplus e_2 : B \oplus C, \Psi} \oplus \mathrm{I}$$

This suggests an operation on Hom-sets of the form

$$\Phi_{A,\Delta J\Psi} : \mathcal{L}(A, \Delta \bullet A \bullet B \bullet J\Psi) \to \mathcal{L}(A, \Delta \bullet B \oplus C \bullet J\Psi)$$

natural in Δ, A and $J\Psi$. Given

$$e : A \to \Delta \bullet B \bullet C \bullet J\Psi,$$

and $d : A' \to A$ $h : \Delta \to \Delta'$ and $p : J\Psi \to J\Psi'$, naturality yields

$$\Phi_{A',\Delta'}(d; e; h \bullet id_B \bullet id_{\mathsf{C}} \bullet p) = d; \Phi_{A,\Delta}(e); h \bullet id_{B \oplus C} \bullet p$$

[1] In this subsection only we use the symbol $\bullet$ and 1 for the monoidal binary operation and its unit in the categorical structure, distinguished from the $\oplus$ and $\perp$ symbols in the formal language. We shall show that the interpretation of $\oplus$ is isomorphic to the operation $\bullet$, so we shall be able to identify them (and similarly for $\perp$ and 1).

In particular, letting
$$e = id_\Delta \bullet id_B \bullet id_{\mathsf{C}}, \quad d : A \to \Delta \bullet B \bullet C,$$
$h = id_\Delta$ and $p = id_{J\Psi}$ we have
$$\Phi_{A,\Delta}(d) = d; \Phi_\Delta(id_\Delta \bullet id_B \bullet id_{\mathsf{C}})$$
By functoriality of $\bullet$ we have $id_B \bullet id_C = id_{B\bullet C}$. Hence, writing $\bigoplus$ for $\Phi_\Delta(id_\Delta \bullet id_{B\bullet C})$ we have $\Phi_{A,\Delta}(d) = d; \bigoplus$. We define
$$[\![x : A \vdash_{\mathsf{L}} : \Delta, e_1 \oplus e_2 : B \oplus C]\!] =_{df} [\![x : A \vdash_{\mathsf{L}} \Delta, e_1 : B, e_2 : C,]\!]; \bigoplus .$$

3.4.1.2. *Par elimination.* The Par elimination rule has the form
$$\frac{z : A \vdash_{\mathsf{L}} e : B \oplus C, \Delta_1; \Psi_1 \qquad x : B \vdash_{\mathsf{L}} \Delta_2; \Psi_2 \qquad y : C \vdash_{\mathsf{L}} \Delta_3; \Psi_3}{z : A \vdash_{\mathsf{L}} \Delta_1, [\mathtt{casel} z/x]\Delta_2, [\mathtt{caser} z/y]\Delta_3; \Psi_1 \cdot \Psi_2 \cdot \Psi_3} \oplus \mathrm{E}$$
This suggests an operation on Hom-sets of the form
$$\Psi_{A,\Delta,J\Psi} : \mathcal{L}(A, B \oplus C \bullet \Delta_1 \bullet J\Psi_1) \times \mathcal{L}(B, \Delta_2 \bullet J\Psi_2) \times \mathcal{L}(C, \Delta_3 \bullet J\Psi_3) \to \mathcal{L}(A, \Delta \bullet J\Psi)$$
natural in $A, \Delta, J\Psi$ where we write $\Delta = \Delta_1, \Delta_2, \Delta_3$, $J\Psi = J\Psi_1, J\Psi_2, J\Psi_3$. Given morphisms
$$g : A \to \Delta_1 \bullet J\Psi_1 \bullet B \wp C, \quad e : B \to \Delta_2 \bullet J\Psi_2 \quad \text{and } f : C \to \Delta_3 \bullet J\Psi_3$$
and also $a : A' \to A$, $d_1 : \Delta_1 \to \Delta_1'$, $d_2 : \Delta_2 \to \Delta_2'$ and $d_3 : \Delta_3 \to \Delta_3'$, $p_1 : J\Psi_1 \to J\Psi_1'$, $p_2 : J\Psi_2 \to J\Psi_2'$ and $p_3 : J\Psi_3 \to J\Psi_3'$ naturality yields
$$\begin{aligned}\Psi_{A',\Delta',\Gamma',J\Psi'}((a; g; d_1 \bullet id_{B\oplus C}), (e; d_2 \bullet p_2), \quad (f; d_3 \bullet p_3)) = \\ a; \Psi_{A,\Delta,J\Psi}(g, e, f); \quad d_1 \bullet d_2 \bullet d_3 \bullet p_1 \bullet p_2 \bullet p_3; \mathtt{Join}(\Delta', J\Psi').\end{aligned}$$
In particular, set
$$e = id_B, \quad f = id_{\mathsf{C}}$$
and also $a = id_A$, $d_i = id_{\Delta_i}$, $p_i = id_{J\Psi_i}$ we get
$$\Psi_{A,\Delta J\Psi}(g, e, f) = \Psi_{A,\Delta,J\Psi}(g, id_B, id_{\mathsf{C}}); id_\Delta \bullet c \bullet d; \mathtt{Join}(\Delta, J\Psi)$$
where the operation $\mathtt{Join}$ establishes left associativity. Writing $(g)^*$ for $\Psi_{D,\Delta}(g, id_B, id_{\mathsf{C}})$ we define
$$\begin{aligned}&[\![z : A \vdash_{\mathsf{L}} \Delta_1, [\mathtt{casel}\ e/x]\Delta_2, [\mathtt{caser}\ e/y]\Delta_3; \Psi_2, \Psi_3]\!] =_{df} \\ &[\![z : A \vdash_{\mathsf{L}} \Delta_1, e, B \oplus C; \Psi_1]\!]^*; id_{\Delta_1} \bullet [\![x : B \vdash_{\mathsf{L}} \Delta_2; \Psi_2]\!] \bullet [\![y : C \vdash_{\mathsf{L}} \Delta_3; \Psi_3]\!]; \mathtt{Join}(\Delta, J\Psi).\end{aligned}$$

3.4.1.3. *Equations in context.* We have equations in context of the form

$\oplus - \beta$ rules:
$$\frac{\begin{array}{ll} \multicolumn{2}{l}{e \equiv \mathtt{casel}(e_1 \oplus e_2) \quad e' \equiv \mathtt{caser}(e_1 \oplus e_2)} \\ |\Delta_1| = |\Delta_1'|\ |\Psi_1| = |\Psi_1'| & x : A_1 \vdash_{\mathsf{L}} \Delta_2; J\Psi_2 = \Delta_2'; J\Psi_2' \\ |\Delta_2| = |\Delta_2'|\ |\Psi_2| = |\Psi_2'| & y : A_2 \vdash_{\mathsf{L}} \Delta_3; J\Psi_3 = \Delta_3'; J\Psi_3' \\ |\Delta_3| = |\Delta_3'|\ |\Psi_3| = |\Psi_3'| & z : B \vdash_{\mathsf{L}} e_1 : A_1, e_2 : A_2, \Delta_1; J\Psi_1 = e_1' : A_1, e_2' : A_2, \Delta_1'; J\Psi_1' \end{array}}{\begin{array}{l} z : B \vdash_{\mathsf{L}} \Delta_1, [e/x]\Delta_2, [e'/x]\Delta_3; \Psi_1, [e/x]\Psi_2, [e'/x]\Psi_3 = \\ \quad = \Delta_1', [e_1'/x]\Delta_2, [e_2'/x]\Delta_3; \Psi_1, [e_1'/x]\Psi_2', [e_2'/x]\Psi_3' \end{array}} \tag{3.1}$$
Let
$$q : B \to A_1 \bullet A_2 \bullet \Delta_1 \bullet J\Psi, \qquad m : A_1 \to \Delta_2 \bullet J\Psi_2 \quad \text{and} \quad n : A_2 \to \Delta_3 \bullet J\Psi_3.$$
Then to satisfy the above equations in context we need that the following diagram commutes:

$$\begin{tikzcd}
B \arrow[r, "q"] & \Delta_1 \bullet J\Psi_1 \bullet (A_1 \bullet A_2) \arrow[rr, "id_{\Delta_1} \bullet m \bullet n"] \arrow[d, "\oplus"'] & & \Delta_1 \bullet J\Psi_1 \bullet \Delta_2 \bullet J\Psi_2 \bullet \Delta_3 \bullet J\Psi_3 \\
& \Delta_1 \bullet J\Psi_1 \bullet A \oplus B \arrow[rr, "*"'] & & \Delta_1 \bullet J\Psi_1 \bullet A \bullet B \arrow[u, "id_{\Delta_1} \bullet m \bullet n"']
\end{tikzcd}$$

We make the assumption that the above decomposition is unique. Moreover, supposing Δ_1 to be empty and $m = id_A$, $n = id_B$, $q = id_A \bullet id_B = id_{A \bullet B}$ we obtain $(id_A \bullet id_B; \bigoplus)^* = id_A \bullet id_B$ and similarly $(id_{A \oplus B})^*; \bigoplus = id_{A \oplus B}$; hence we may conclude that there is a natural isomorphism

$$\frac{D \to \Gamma \bullet A \bullet B}{\overline{D \to \Gamma \bullet A \oplus B}}$$

so we can identify $\bullet$ and $\oplus$. Finally we see that the following η equation in context is also satisfied:

$$\boxed{\begin{array}{c} \oplus - \eta \text{ rule} \\ \dfrac{|\Delta| = |\Delta'| \quad |\Psi| = |\Psi'| \quad z : B \vdash_{\mathsf{L}} \Delta; \Psi = \Delta'; \Psi'}{z : B \vdash_{\mathsf{L}} (\mathtt{casel}\ \mathtt{e} \oplus \mathtt{caser}\ e) : A_1 \oplus A_2, \Delta; \Psi = e : A_1 \oplus A_2, \Delta'; \Psi'} \end{array}} \tag{3.2}$$

3.4.2. *Linear subtraction.* 3.4.2.1. *Subtraction introduction.* The introduction rule for subtraction has the form

$$\frac{x : A \vdash_{\mathsf{L}} \Delta_1, e : B; \Psi_1 \qquad y : C \vdash_{\mathsf{L}} \Delta_2; \Psi_2 \quad |\Psi_1| = |\Psi_2|}{x : A \vdash_{\mathsf{L}} \Delta_1, \mathtt{mkc}(e, y) : B \bullet\!\!- C, [y(e)/y]\Delta_2; \Psi_1 \cdot [y(e)/y]\Psi_2}\ LsubI$$

This suggests a natural transformation with components

$$\Phi_{A,\Delta,J\Psi} : \mathcal{L}(A, \Delta_1 \bullet B \bullet J\Psi_1) \times \mathcal{L}(C, \Delta_2 \bullet J\Psi_2) \to \mathcal{L}(A, \Delta_1 \bullet (B \bullet\!\!- C) \bullet \Delta_2 \bullet J\Psi_1 \bullet J\Psi_2)$$

natural in $A, \Delta_1, \Delta_2, J\Psi_1, J\Psi_2$. Taking morphisms

$$e : A \to \Delta_1 \bullet B \bullet J\Psi_1, \quad f : C \to \Delta_2 \bullet J\Psi_2$$

and also $a : A' \to A$, $d_1 : \Delta_1 \to \Delta'_1$, $d_2 : \Delta_2 \to \Delta'_2$, $p_1 : J\Psi_1 \to J\Psi'_1$, $p_2 : J\Psi_2 \to J\Psi'_2$, by naturality we have

$$\begin{array}{l} \Phi_{A',\Delta'_1,\Delta'_2,J\Psi'_1 J\Psi'_2}((a; e; d_1 \bullet id_B \bullet p_1), (f; d_2; p_2)) = \\ \quad = a; \Phi_{A,\Delta,J\Psi}(e, f); d_1 \bullet d_2 \bullet id_{B \bullet\!-C}; \mathtt{Join}(\Delta'_1, \Delta'_2, B \bullet\!\!- C, J\Psi'_1, J\Psi'_2) \end{array}$$

In particular, taking $a = id_A$, $d_1 = id_{\Delta_1}$, $p_1 = id_{J\Psi_1}$, $p_2 = id_{J\Psi_2}$ but $d_2 : C \to \Delta_2 \cdot J\Psi_2$ and $f = id_{\mathsf{C}}$ we have:

$$\begin{array}{r} \Phi_{A,\Delta_1,\Delta_2,J\Psi_1,J\Psi_2}(e, d_2) = \Phi_{A,\Delta_1}(e, id_{\mathsf{C}}); id_{\Delta_1} \bullet d_2 \bullet id_{A \bullet\!-B} \bullet id_{J\Psi_1} \bullet id J\Psi_2; \\ \mathtt{Join}(\Delta_1, \Delta_2, A \bullet\!\!- B, J\Psi_1, J\Psi_2) \end{array}$$

Writing $\mathbf{MKC}^C_{A,\Delta_1,J\Psi_1}(e)$ for $\Phi_{A,\Delta_1 J\Psi_1}(e, id_{\mathsf{C}})$, $\Phi_{A,\Delta,J\Psi}(e, d_2)$ can be expressed as the composition

$$\mathbf{MKC}^C_{A,\Delta_1,J\Psi_1}(e); id_{\Delta_1} \bullet d_2 \bullet id_{B \bullet\!-C}$$

where $\mathbf{MKC}^C_{A,\Delta_1,J\Psi_1}$ is a natural transformation with components

$$\mathcal{L}(A, \Delta_1 \bullet B \bullet J\Psi) \times \mathcal{L}(C, C) \to \mathcal{L}(A, \Delta_1 \bullet C \bullet C \bullet\!\!- C)$$

so we make the definition

$$\begin{array}{r} [\![x : A \vdash_{\mathsf{L}} \Delta_1, \mathtt{mkc}(e, y) :\ B \bullet\!\!- C, [y(e)/y + \Delta_2; \Psi_1 \cdot [y(e)/y]\Psi_2]\!] =_{df} \\ \mathbf{MKC}^C_{A,\Delta_1,J\Psi_1}[\![x : A \vdash_{\mathsf{L}} \Delta_1, e_1 : B]\!]; id_\Delta \bullet [\![y : C \vdash_{\mathsf{L}} \Delta_2; \Psi_2]\!] \bullet id_{B \bullet\!-C}; \\ \mathtt{Join}(\Delta_1, \Delta_2, B \bullet\!\!- C, J\Psi_1, J\Psi_2) \end{array}$$

Notice that $\mathbf{MKC}^C_{A,\Delta_1,J\Psi_1}$ corresponds to the one-premise form of the subtraction introduction rule

$$\frac{x : A \vdash_{\mathsf{L}} \Delta_1, e : B; \Psi_1}{x : A \vdash_{\mathsf{L}} \Delta_1, \mathtt{mkc}(e, y) : B \multimapdotinv C, y(e) : C; \Psi_1}\ LsubI$$

which is equivalent in terms of provability to the more general form considered here (cfr Crolard 2004).

3.4.2.2. *Subtraction elimination.* The subtraction elimination rule has the form

$$\frac{x : A \vdash_{\mathsf{L}} \Delta_1, e_1 : B \multimapdotinv C; \Psi_1 \qquad y : B \vdash_{\mathsf{L}} e_2 : C, \Delta_2; \Psi_2 \quad |\Psi_1| = |\Psi_2|}{x : A \vdash_{\mathsf{L}} \mathtt{postp}(y \mapsto e_2, e_1), \Delta_1, [y(e_1)/y]\Delta_2; \Psi_1, [y(e_1)/y]\Psi_2}\ \setminus \mathrm{E}$$

This suggests a natural transformation with components

$$\Psi_{A,\Delta_1,\Delta_2,J\Psi_1,J\Psi_2} : \mathcal{L}(A, \Delta_1 \bullet (B \multimapdotinv C) \bullet J\Psi_1) \times \mathcal{L}(B, C \bullet \Delta_2 \bullet J\Psi_2) \to \mathcal{L}(A, \Delta_1 \bullet \Delta_2 \bullet J\Psi_1 \bullet J\Psi_2)$$

natural in $A, \Delta_1, \Delta_2, J\Psi_1, J\Psi_2$. Here $\mathtt{postp}(y \mapsto e_2, e_1)$ is given type 1 and an application of left identity λ_{1,Δ_2} is assumed implicitly.

Given

$$e : A \to \Delta_1 \bullet (B \multimapdotinv C) \bullet J\Psi_1, \qquad f : B \to C \bullet \Delta_2 \bullet J\Psi_2$$

and also $a : A' \to A$, $d_1 : \Delta_1 \to \Delta_1'$, $d_2 : \Delta_2 \to \Delta_2'$, $p_1 : J\Psi_1 \to J\Psi_1'$ $p_2 : J\Psi_2 \to J\Psi_2'$ naturality yields

$$\begin{array}{l}\Psi_{A',\Delta_1',\Delta_2',J\Psi_1',J\Psi_2'}((a; e; d_1 \bullet id_{B \multimapdotinv C} \bullet p_1), (f; id_{\mathsf{C}} \bullet d_2 \bullet p_2)) = \\ a; \Psi_{A,\Delta_1,\Delta_2,J\Psi_1}(e, f); \lambda_{1,\Delta_1} \bullet d_1 \bullet d_2 \bullet p_1 \bullet p_2; \mathtt{Join}(\Delta_1', \Delta_2', J\Psi_1, J\Psi_2)\end{array}$$

In particular, taking $a : A \to \Delta_1 \bullet (B \multimapdotinv C)$, $e = id_{\Delta_1 \bullet (B \multimapdotinv C)}$, $d_1 = id_{\Delta_1}$, $d_2 : id_{\Delta_2}$, $p_1 = id_{J\Psi_1}$, $p_2 = idJ\Psi_2$ we obtain

$$\Psi_{A,\Delta_1,\Delta_2}(a, f) = a; \Psi_{A,\Delta_1,\Delta_2}(id_{\Delta_1 \bullet (C \multimapdotinv D) \bullet id_{J\Psi_1}}, f); \mathtt{Join}(\Delta_1, \Delta_2, J\Psi_1, J\Psi_2)$$

Writing $\mathbf{POSTP}(f)$ for $\Psi_{A,\Delta_1,\Delta_2,J\Psi_1,J\Psi_2}(id_{\Delta_1 \bullet (B \multimapdotinv C) \bullet J\Psi_1}, f)$ we define

$$\begin{array}{l}[\![x : A \vdash_{\mathsf{L}} \Delta_1, \mathtt{postp}(y \mapsto e_2, e_1), [y(e_1)/y]\Delta_2; \Psi_1, [y(e_1)/y], \Psi_2]\!] =_{df} \\ \quad [\![x : A \vdash_{\mathsf{L}} \Delta_1, e_1 : B \multimapdotinv C]\!]; id_{\Delta_1} \bullet \mathbf{POSTP}[\![y : B \vdash_{\mathsf{L}} e_2 : C, \Delta_2; \Psi_2]\!]; \mathtt{Join}(\Delta_1, \Delta_2, J\Psi_1, J\Psi_2)\end{array}$$

3.4.2.3. *Equations in context.* We have equations in context of the form

$$\boxed{\begin{array}{c}\multimapdotinv - \beta \text{ rules:} \\ e_p \equiv \mathtt{postp}(z \mapsto e_2, \mathtt{mkc}(e_1, y)) \quad e_z \equiv z(\mathtt{mkc}(e_1, y)) \\ |\Delta_1| = |\Delta_1'|\ |\Psi_1| = |\Psi_1'| \qquad x : B \vdash_{\mathsf{L}} e_1 : A_1, \Delta_1; \Psi_1 = e_1' : A_1, \Delta_1'; \Psi_1' \\ |\Delta_2| = |\Delta_2'|\ |\Psi_2| = |\Psi_2'| \qquad y : A_2 \vdash_{\mathsf{L}} \Delta_2; \Psi_2 = \Delta_2'; \Psi_2' \\ z : A_1 \vdash_{\mathsf{L}} e_2 : A_2, \Delta_3; \Psi_3 = e_2' : A_2, \Delta_3'; \Psi_3' \\ \hline x : B \vdash_{\mathsf{L}} \Delta_1.e_p, [y(e_1)/y]\Delta_2, [e_z/z]\Delta_3; \Psi_1, [y(e_1))y]\Psi_2, [e_z/z]\Psi_3 = \\ = \Delta_1', [[e_1'/z]e_2'/y]\Delta_2, [e_1'/z]\Delta_3'; \Psi_1', [[e_1'/z]e_2'/y]\Psi_2', [e_1'/z]\Psi_3'\end{array}} \tag{3.3}$$

We repeat the derivations of the redex and of the reductum.

Redex:

$$\frac{\dfrac{x : B \vdash_{\mathsf{L}} e_1 : A_1, \Delta_1; \Psi_1 \qquad y : A_2 \vdash_{\mathsf{L}} \Delta_2; \Psi_2}{x : B \vdash_{\mathsf{L}} \mathtt{mkc}(e_1, y) : A_1 \multimapdotinv A_2, \Delta_1, [y(e_1)/y]\Delta_2; \Psi_1, [y(e_1)/y]\Psi_2} \qquad z : A_1 \vdash_{\mathsf{L}} e_2 : A_2, \Delta_3; \Psi_3}{\begin{array}{l}x : B \vdash_{\mathsf{L}} \Delta_1, \overbrace{\mathtt{postp}(z \mapsto e_2, \mathtt{mkc}(e_1, y))}^{e_p}, [y(e_1)/y]\Delta_2, [\overbrace{z(\mathtt{mkc}(e_1, y))}^{e_z}/z]\Delta_3; \\ \qquad \Psi_1, [y(e_1)/y]\Psi_2, [z(\mathtt{mkc}(e_1, y)/z)] : \Psi_3\end{array}}$$

Reductum:

$$\dfrac{\dfrac{x : B \vdash_{\mathsf{L}} e'_1 : A_1, \Delta'_1 ; \Psi'_1 \qquad z : A_1 \vdash_{\mathsf{L}} e'_2 : A_2, \Delta'_3 ; \Psi'_3}{x : B \vdash_{\mathsf{L}} \Delta'_1, [e'_1/z]\Delta'_3, [e'_1/z]e'_2 : A_2 ; \Psi'_1, [e'_1/z]\Psi'_3} \qquad y : A_2 \vdash_{\mathsf{L}} \Delta_2 ; \Psi_2}{x : B \vdash_{\mathsf{L}} \Delta'_1, [[e'_1/z]e'_2/y]\Delta'_2,\ [e'_1/z]\Delta'_3 ; \Psi'_1, [[e'_1/z]e'_2]\Psi'_2,\ [e'_1/z]\Psi'_3}$$

Given morphisms $n : B \to \Delta_1 \bullet A_1$ and $m : A_1 \to \Delta_3 \bullet A_2$, for these equations to be satisfied we need the following diagram to commute (omitting non-linear terms):

$$\begin{tikzcd}
B \arrow[r, "n"] \arrow[d, "\mathbf{MKC}^{A_2}(n)"'] & \Delta_1 \bullet A_1 \arrow[d, "id_{\Delta_1} \bullet m"] \\
\Delta_1 \bullet (A_1 \multimap\!\bullet\ A_2) \bullet A_2 \arrow[r, "\mathbf{POSTP}(m) \bullet id_{A_2}"'] & \Delta_1 \bullet \Delta_3 \bullet A_2
\end{tikzcd}$$

in particular, taking $n = id_{A_1}$ we have

$$\begin{tikzcd}
A_1 \arrow[r, "m"] \arrow[d, "\mathbf{MKC}^{A}_{2}(id_{A_1})"'] & \Delta_3 \bullet A_2 \\
(A_1 \multimap\!\bullet\ A_2) \bullet A_2 \arrow[ur, "\mathbf{POSTP}(m) \bullet id_{A_2}"'] &
\end{tikzcd}$$

Assuming the above decomposition to be unique, we can show that the η equation in context is also satisfied:

$$\boxed{\dfrac{|\Delta| = |\Delta'| \quad |\Psi| = |\Psi'| \quad z ; B \vdash_{\mathsf{L}} \Delta, \Psi = \Delta', \Psi'}{z : B \vdash_{\mathsf{L}} \mathtt{postp}(x \mapsto y, e), \mathtt{mkc}(x(e), y) : A_1 \multimap\!\bullet\ A_2, \Delta, \Psi = e : A_1 \multimap\!\bullet\ A_2, \Delta' ; \Psi'}} \tag{3.4}$$

and conclude that there is a natural isomorphism between the maps

$$\dfrac{A \to \Delta \bullet B}{\overline{A \setminus B \to \Delta}}$$

i.e., that $\setminus$ is the left adjoint to the bifunctor $\bullet$.

3.4.3. *Unit rules.* The introduction and elimination rules for the unit $\perp$ are

$\perp$ *introduction*

$$\dfrac{x : A \vdash_{\mathsf{L}} \Delta ; \Psi \quad r : B \in Delta, \text{ or } r : S \in \Psi}{x : A \vdash_{\mathsf{L}} \Delta, \mathtt{connect}_{\perp}\ \mathtt{to}(r) : \perp ; \Psi}$$

$\perp$ *elimination*

$$\dfrac{x : A \vdash_{\mathsf{L}} e : \perp, \Delta ; \Psi}{x : A \vdash_{\mathsf{L}} \mathtt{postp}_{\perp}(e), \Delta ; \Psi}$$

Both the introduction and the elimination rules can be interpreted by a map $a : A \to 1$, if we give the term $\mathtt{postp}_{\perp}(e)$ the type $\perp$. However, it is a syntactic requirement that in the case of an elimination the type $\perp$ cannot be a subtype of another type.

The introduction rule requires a natural transformation with components

$$\Phi_{A,\Delta,J\Psi} : \mathcal{L}(A, \Delta, J\Psi) \to \mathcal{L}(A, \Delta \bullet \perp \bullet J\Psi)$$

natural in A, Δ, $J\Psi$. Given morphisms $e : A \to \Delta \bullet J\Psi$, $d : A' \to A$, $c : \Delta \to \Delta'$ and $p : J\Psi \to J\Psi'$, naturality yields

$$\Phi_{A',\Delta',J\Psi}(d; e; c \bullet id_{J\Psi}) = d; \Phi_{A,\Delta}(e); c \bullet id_{J\Psi}.$$

Letting $d : A \to \Delta, J\Psi$ and $e = id_{\Delta \bullet J\Psi}$, $c = id_{\Delta \bullet \perp}$ we have

$$\Phi_{A,\Delta,J\Psi}(d) = d; \mathbf{Bot}_{\Delta,J\Psi}$$

where we write $\mathbf{Bot}_{\Delta,J\Psi}$ for $\Phi_{\Delta,J\Psi}(id_{\Delta}, id_{J\Psi})$. We define

$$[\![x : A \vdash_{\mathsf{L}} \Delta \mathtt{connect\ to}(x) : \perp ; J\Psi]\!] =_{df} [\![x : A \vdash_{\mathsf{L}} \Delta, J\Psi]\!]; \mathbf{Bot}_{\Delta,J\Psi}.$$

3.4.3.2. *Equations in context.*

The equation in context

$$\boxed{\begin{array}{c}\perp-\beta\ \textbf{rule}\\ \dfrac{x:A\vdash_{\mathsf{L}}\Delta;\Psi=\Delta';\Psi'}{x:A\vdash_{\mathsf{L}}\Delta,\mathtt{postp}_{\perp}(\mathtt{connect}_{\perp}\ \mathtt{to}(x));\Psi=\Delta';\Psi'}\end{array}} \tag{3.5}$$

requires that for any $m : D \to \Gamma$ the following diagram commutes:

$$\begin{tikzcd} D \arrow[r, "m;\mathbf{Bot}"] \arrow[dr, "m"'] & \Gamma \bullet \perp \arrow[d, "id_\Gamma \bullet \langle\rangle;\lambda_A"] \\ & \Gamma. \end{tikzcd}$$

Assuming that this decomposition is unique and taking $m = id_A$ we have that $\mathbf{Bot}_A; id_A \bullet \langle\rangle; \lambda_A = id_A$. Arguing as before, we see that there is a natural isomorphism

$$\frac{D \to \Gamma \bullet 1}{\overline{D \to \Gamma \bullet \perp}}$$

(so we identify $\perp$ and 1) and that the following equation in context is satisfied:

$$\boxed{\begin{array}{c}\perp-\eta\ \textbf{rule:}\\ \dfrac{z:B\vdash_{\mathsf{L}}\Delta;\Psi=\Delta';\Psi'}{z:B\vdash_{\mathsf{L}}\mathtt{connect}_{\perp}\ \mathtt{to}(x):\perp,\mathtt{postp}_{\perp}(e)\Delta;\Psi=\perp e:\perp,\Delta';\Psi'}\end{array}} \tag{3.6}$$

3.4.4. *Functors.* Recall that a model of Linear-Non Linear co-intuitionistic logic consists of a symmetric comonoidal adjunction $\mathcal{L} : H \dashv J : C$ where $\mathcal{L} = (\mathcal{L}, \perp, \oplus, \multimap)$ is a symmetric monoidal coclosed category and $C = (C, 0, +, -)$ is a cocartesian coclosed category.

We use the same symbols for the functors $J : C \to \mathcal{L}$ and $\mathcal{H} : \mathcal{L} \to C$ in the models and for the operators that represent them in the language.

3.4.4.1 *rules for $J : C \to \mathcal{L}$.*

$$\boxed{\begin{array}{c}J\ \textit{introduction}\\ \dfrac{x:A\vdash_{\mathsf{L}},\Delta;t:T,\Psi}{x:A\vdash_{\mathsf{L}}\Delta,Jt:JT;\Psi}\end{array}} \tag{3.7}$$

If $\Delta = \overline{R} : \Delta$ and $\Psi = \overline{S} : \Psi$, then the categorical interpetation of the rule is an application of α^{-1}:

$$\frac{A \xrightarrow{\overline{R}\bullet Jt\bullet J\overline{S}} \Delta \bullet JT \bullet J\Psi}{A \xrightarrow{(\overline{R}\bullet Jt)\bullet J\overline{S}} (\Delta \bullet JT) \bullet J\Psi}$$

$$\boxed{\begin{array}{c}J\ \textit{elimination}\\ \dfrac{x:A\vdash_{\mathsf{L}}\Delta,e:JT;\Psi_1\qquad y:T\vdash_{\mathsf{C}}\Psi_2\ \text{where}\ |\Psi_1|=|\Psi_2|}{x:A\vdash_{\mathsf{L}}\Delta;\Psi_1\cdot\mathtt{let}\ Jy=e\ \mathtt{in}\ \Psi_2}\end{array}} \tag{3.8}$$

If $\Delta = \overline{R} : \Delta$, $\Psi_1 = \overline{R'} : \Psi_1$, $\Psi_2 = \overline{S} : \Psi_2$, then the categorical interpretation of the rule is given by an operation of the form

$$\mathcal{L}(A, \Delta \bullet JT \bullet J\Psi_1) \times C(T, \Psi_2) \to \mathcal{L}(A, \Delta \bullet J\Psi_1 \bullet J\Psi_2)$$

given by the following compositions

$$\frac{A \xrightarrow{\overline{R} \bullet e \bullet J\overline{R}'} \Delta \bullet JT \bullet J\Psi_1 \qquad \dfrac{T \xrightarrow{\overline{S}} \Psi_2 \quad \text{in } C}{JT \xrightarrow{J\overline{S}} J\Psi_2 \quad \text{in } \mathcal{L}}}{A \xrightarrow{\overline{R} \bullet e \bullet J(\overline{R}')} \Delta \bullet J(T) \bullet J(\Psi_1) \xrightarrow{id_\Delta \bullet J(\overline{S}) \bullet id_{J(\Psi_1)}} \Delta \bullet J(\Psi_1) \bullet J(\Psi_2) \xrightarrow{id_\Delta \bullet j^{-1}_{\Psi_1 \Psi_2}} \Delta \bullet J(\Psi_1 + \Psi_2)}$$

$$\text{since } |\Psi_1| = |\Psi_2|, \qquad \xrightarrow{id_\Delta \bullet \nabla_{\Psi_1}} \Delta \bullet J(\Psi_1)$$

3.4.4.2 *rules for* $H : \mathcal{L} \to C$.

$$\boxed{\begin{array}{c} H\ intro \\ \dfrac{x : A \vdash_{\mathsf{L}} \overline{R} : \Delta, e : B; \Psi}{x : A \vdash_{\mathsf{L}} \overline{R} : \Delta; He : HB, \Psi} \end{array}} \tag{3.9}$$

Let $\Delta = \overline{R} : \Delta$ and $\Psi = \overline{S} : \Psi$: then

$$\frac{A \xrightarrow{\overline{R} \wp e \wp J(\overline{S})} \Delta \bullet B \bullet J(\Psi)}{A \xrightarrow{\overline{R} \wp JH(e) \bullet J(\overline{S})} \Delta \bullet JH(B) \bullet J(\Psi)} \text{ using } \eta_B : B \to JHB$$

$$\boxed{\begin{array}{c} H\ elim_1 \\ \dfrac{x : B \vdash_{\mathsf{L}} \Delta; t : HA, \Psi_1 \qquad y : A \vdash_{\mathsf{L}} ; \Psi_2 \quad \text{where } |\Psi_1| = |\Psi_2|}{x : B \vdash_{\mathsf{L}} \Delta; \Psi_1 \cdot (\mathtt{let}\ Hy = t\ \mathtt{in}\ \Psi_2)} \end{array}} \tag{3.10}$$

$$\boxed{\begin{array}{c} H\ elim_2 \\ \dfrac{x : S \vdash_{\mathsf{C}} t : HA, \Psi_1 \qquad y : A \vdash_{\mathsf{L}} ; \Psi_2 \quad \text{where } |\Psi_1| = |\Psi_2|}{x : S \vdash_{\mathsf{C}} \Psi_1 \cdot (\mathtt{let}\ Hy = t\ \mathtt{in}\ \Psi_2)} \end{array}} \tag{3.11}$$

The categorical interpretation of H elim$_2$ is as follows: Let $\Psi_1 = \overline{R} : \Psi_1$ and $\Psi_2 = \overline{S} : \Psi_2$. Then we have the following compositions:

$$\frac{S \xrightarrow{t + \overline{R}} H(A) + \Psi \qquad \dfrac{A \xrightarrow{J(\overline{S})} J(\Psi) \quad \text{in } \mathcal{L}}{HA \xrightarrow{HJ(\overline{S})} HJ(\Psi) \xrightarrow{\epsilon_\Psi} \Psi \quad \text{in } C}}{S \xrightarrow{t + \overline{R}} H(A) + \Psi \xrightarrow{HJ(\overline{S}) + id_\Psi} \Psi + \Psi \xrightarrow{\nabla_\Psi} \Psi}$$

4. Related Work

TODO The most comprehensive treatment of ILL is in Gavin Bierman's thesis [3]. There one finds the Proof Theory (Chapter 2), i..e, the sequent calculus with cut-eliminaton, natural deduction and axiomatic versions of ILL. Then (Chapter 3) a term assignment to the natural deduction and to the sequent calculus versions are presented with β-reductions and commutative conversions, and strong normalization and confluence are proved for the resulting calculus. A painstaking analysis of the rules of the labelled calculus allows us to construct a categorical model of ILL, in particular of the exponential part, which is a main contribution of Bierman and of the Cambridge school of the 1990s with respect to previous models by Seely and Lafont.

Benton's work [2] on LNL logic, which we read in a TeX report, is much less systematc and detailed than Bierman's, but presents effectively the categorical model of LNL (Chapter 2) shows how to obtain a LNL model from a Linear Category and viceversa. Then versions of the sequent calculus for LNL are considered and cut-elimination is proved for one calculus. Then Natural Deduction is given with term assignment and the categorical interpretaiton of a fragment of the natural deduction system. β reductions and commuting conversions are then presented. Undoubtedly N.Benton's TeX report provides an agile tool which we followed very closed in our investigation.

5. Conclusion

TODO

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Appendix A. Proofs

A.1. **Proof of Lemma 23.** 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 $\mathsf{j}^{-1}_{R,S} ; \mathsf{j}_{R,S} = \mathsf{id}$:

$$\begin{tikzcd}
& JR \oplus JS \arrow[r, "\eta"] \arrow[dl, equal] \arrow[d, "\eta\oplus\eta"] & JH(JR \oplus JS) \arrow[d, "Jh"] \\
JR \oplus JS & JHJR \oplus JHJS \arrow[l, "J\varepsilon\oplus J\varepsilon"'] & J(HJR + HJS) \arrow[l, "j"'] \arrow[d, "J(\varepsilon+\varepsilon)"] \\
& & J(R+S) \arrow[ull, "j"]
\end{tikzcd}$$

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 $j_{R,S} ; j^{-1}_{R,S} = id$:

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

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 $j_0^{-1}; j_0 = id$:

$$\begin{tikzcd}
\perp \arrow[r, "\eta"] \arrow[d, equal] & JH\perp \arrow[d, "Jh_\perp"] \\
\perp & J0 \arrow[l, "j_0"']
\end{tikzcd}$$

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

Case. The following diagram implies that $j_0; j_0^{-1} = id$:

$$\begin{tikzcd}
J0 \arrow[rr, "j_0"] \arrow[dr, "\eta"] \arrow[dd, equal] & & \perp \arrow[dd, "\eta"] \\
& JHJ0 \arrow[dl, "J\varepsilon"'] \arrow[dr, "JHj_0"] & \\
J0 & & JH\perp \arrow[ll, "Jh_\perp"']
\end{tikzcd}$$

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 25.** 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 13 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:

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

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

A.3. **Proof of Lemma 26.** 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 25.

We define the following morphisms:

$$\mathsf{w}_A := \perp \xrightarrow{\mathsf{j}_0^{-1}} \mathsf{J}0 \xrightarrow{\mathsf{J}\diamond_{\mathsf{H}A}} \mathsf{JH}A = ?A$$

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

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 8. 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:

$$
\begin{tikzcd}
\perp \arrow[rr, "\rho^{-1}"] \arrow[ddd, "\mathsf{j}_0^{-1}"'] \arrow[dr, phantom, "(6)"] & & \perp \oplus \perp \arrow[dl, "\mathsf{j}_0^{-1} \oplus \mathsf{id}"'] \arrow[d, "\mathsf{j}_0^{-1} \oplus \mathsf{j}_0^{-1}"] \\
& \mathsf{J}0 \oplus \perp \arrow[r, "\mathsf{id} \oplus \mathsf{j}_0^{-1}"] \arrow[d, equal] \arrow[ur, phantom, "(5)"] \arrow[dr, phantom, "(4)"] & \mathsf{J}0 \oplus \mathsf{J}0 \arrow[dl, "\mathsf{id} \oplus \mathsf{j}_0"] \arrow[dd, equal] \\
& \mathsf{J}0 \oplus \perp \arrow[d, phantom, "(3)"] & \\
\mathsf{J}0 \arrow[uur, "\rho^{-1}"] \arrow[d, "\mathsf{J}\diamond"'] \arrow[dr, phantom, "(1)"] & \mathsf{J}(0+0) \arrow[l, "\mathsf{J}\rho"'] \arrow[r, "\mathsf{j}"] \arrow[d, "\mathsf{J}(\diamond + \diamond)"] \arrow[dr, phantom, "(2)"] & \mathsf{J}0 \oplus \mathsf{J}0 \arrow[d, "\mathsf{J}\diamond \oplus \mathsf{J}\diamond"] \\
\mathsf{JH}(A \oplus B) \arrow[r, "\mathsf{Jh}"] & \mathsf{J}(\mathsf{H}A + \mathsf{H}B) \arrow[r, "\mathsf{j}"] & \mathsf{JH}A \oplus \mathsf{JH}B
\end{tikzcd}
$$

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 23), diagram 5 commutes by functorality of J, and diagram 6 commutes by naturality of ρ.

Case.

$$\begin{tikzcd}
\bot & & ?\,\bot \arrow[ll, "\mathsf{r}_\bot"'] \\
& \mathsf{W}\,\bot \arrow[ul, "\mathsf{s}_\bot"] \arrow[ur, "\mathsf{w}_\bot"'] &
\end{tikzcd}$$

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

$$\begin{tikzcd}
\bot & & ?\,\bot \arrow[ll, "\mathsf{r}_\bot"'] \\
& \bot \arrow[ul, equal] \arrow[ur, "\mathsf{w}_\bot"'] &
\end{tikzcd}$$

This diagram commutes because the following one does:

$$\begin{tikzcd}
\bot & & \mathsf{J}0 \arrow[ll, "\mathsf{j}_0"'] \\
\bot \arrow[u, equal] \arrow[r, "\mathsf{j}_0^{-1}"] & \mathsf{J}0 \arrow[ur, equal] \arrow[r, "\mathsf{J}\diamond"] & \mathsf{JH}\,\bot \arrow[u, "\mathsf{Jh}_\bot"']
\end{tikzcd}$$

The diagram on the left commutes because j_0 is an isomorphism (Lemma 23), 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:

$$\mathsf{t}_\perp := ?\perp \oplus ?\perp = \mathsf{JH}\perp \oplus \mathsf{JH}\perp \xrightarrow{\mathsf{j}^{-1}} \mathsf{J}(\mathsf{H}\perp + \mathsf{H}\perp) \xrightarrow{\mathsf{J}\nabla} \mathsf{JH}\perp \xrightarrow{\mathsf{Jh}_\perp} \mathsf{J0} \xrightarrow{\mathsf{j}_0} \perp$$

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

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 8 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 10 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:

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

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 23).

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 24), 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 24), 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:

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

The left diagram commutes by naturality of j^{-1}, and the right diagram commutes because $(\mathsf{H}A, \diamond, \bigtriangledown)$ 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:

$$\begin{tikzcd}
\mathsf{JH}\perp \arrow[rr, "\mathsf{Jh}_\perp"] \arrow[dd, "\mathsf{JHj}_0^{-1}"'] \arrow[drr, "\mathsf{JHj}_0^{-1}"] & & \mathsf{J0} \arrow[rr, "\mathsf{j}_0"] \arrow[drr, phantom, "(4)"] & & \perp \arrow[dd, "\mathsf{j}_0^{-1}"] \\
 & & \mathsf{JHJ0} \arrow[r, "\mathsf{JHj}_0"] \arrow[dr, phantom, "(2)"] & \mathsf{JH}\perp \arrow[dr, "\mathsf{Jh}_\perp"] & \\
\mathsf{JHJ0} \arrow[urr, equal] \arrow[rrrr, "\mathsf{J}\varepsilon_0"] \arrow[d, "\mathsf{JHJ}\diamond"'] \arrow[ur, phantom, "(3)"] \arrow[drrrr, phantom, "(1)"] & & & & \mathsf{J0} \arrow[d, "\mathsf{J}\diamond"] \\
\mathsf{JHJH}A \arrow[rrrr, "\mathsf{J}\varepsilon"] & & & & \mathsf{JH}A
\end{tikzcd}$$

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 23).

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:

$$\begin{tikzcd}
\mathsf{JH}(\mathsf{JH}A \oplus \mathsf{JH}A) \arrow[r, "\mathsf{Jh}"] \arrow[d, "\mathsf{JHj}^{-1}"] \arrow[dr, phantom, "(5)"] & \mathsf{J}(\mathsf{HJH}A + \mathsf{HJH}A) \arrow[r, "\mathsf{j}"] & \mathsf{JHJH}A \oplus \mathsf{JHJH}A \arrow[r, "\mathsf{J}\varepsilon \oplus \mathsf{J}\varepsilon"] \arrow[d, "\mathsf{j}^{-1}"] \arrow[dr, phantom, "(6)"] & \mathsf{JH}A \oplus \mathsf{JH}A \arrow[d, "\mathsf{j}^{-1}"] \\
\mathsf{JHJ}(\mathsf{H}A + \mathsf{H}A) \arrow[r, "\mathsf{JHj}"] \arrow[dr, "\mathsf{J}\varepsilon"] \arrow[ddd, "\mathsf{JHJ}\nabla"] & \mathsf{JH}(\mathsf{JH}A \oplus \mathsf{JH}A) \arrow[r, "\mathsf{Jh}"] \arrow[d, phantom, "(4)"] & \mathsf{J}(\mathsf{HJH}A + \mathsf{HJH}A) \arrow[r, "\mathsf{J}(\varepsilon+\varepsilon)"] \arrow[dl, "\mathsf{J}(\varepsilon+\varepsilon)"] \arrow[ddd, "\mathsf{J}\nabla"] \arrow[dr, phantom, "(7)"] & \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \arrow[ddd, "\mathsf{J}\nabla"] \\
 & \mathsf{J}(\mathsf{H}A + \mathsf{H}A) \arrow[d, "\mathsf{J}\nabla"] \arrow[r, phantom, "(3)"] & & \\
 & \mathsf{JH}A \arrow[d, phantom, "(1)"] & & \\
\mathsf{JHJH}A \arrow[ur, "\mathsf{J}\varepsilon"] \arrow[rr, equal] \arrow[r, phantom, "(2)"] & & \mathsf{JHJH}A \arrow[ul, "\mathsf{J}\varepsilon"] \arrow[r, "\mathsf{J}\varepsilon"] & \mathsf{JH}A
\end{tikzcd}$$

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 23), diagram 6 commutes by naturality of j^{-1}, and diagram 7 is the same diagram as 3, but this diagram is redundant for readability.

A.4. **Proof of Lemma 27.** 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 25. Bellin [1] remarks that by Maietti, Maneggia de Paiva and Ritter's Proposition 25 [7], 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.

A.5. **Proof of Cut Reduction (Lemma 38).** By induction on $d(\Pi_1) + d(\Pi_2)$. We consider only the case where the last inferences of Π_1 and Π_2 are logical inferences. The other cases are handled mainly by permutation of inferences and use of the inductive hypothesis; we refer to Benton's text for them. Throughout the proof we will add an asterisk to the name of an inference rule to indicate that the rule may be applied zero or more times.

J right / J left. We have

$$\Pi_1 = \dfrac{\overset{\pi_1}{A \vdash_{\mathsf{L}} \Delta, JT^n; T, \Psi}}{A \vdash_{\mathsf{L}} \Delta, JT^{n+1}; \Psi}\,\mathsf{J}_R \qquad \Pi_2 = \dfrac{\overset{\pi_2}{T \vdash_{\mathsf{C}} \Psi'}}{JT \vdash_{\mathsf{L}}; \Delta, JT^{n+1}, \Psi'}\,\mathsf{J}_L$$

By the inductive hypothesis appled to Π_2 and π_1 there exists a proof Π' of $A \vdash_{\mathsf{L}} \Delta; T, \Psi, \Psi'$ with $c(\Pi') \leq |JT| = |T| + 1$. Then the following derivation

$$\Pi_1 = \cfrac{\cfrac{\overset{\Pi'}{A \vdash_{\mathsf{L}} \Delta; T, \Psi, \Psi'} \qquad \overset{\pi_2}{T \vdash_{\mathsf{C}} \Psi'}}{A \vdash_{\mathsf{L}} \Delta, \Psi, \Psi', \Psi'}\,\text{LC\_cut}}{A \vdash_{\mathsf{L}} \Delta, \Psi, \Psi'}\,\text{C\_contr}^*$$

has cut rank $max(|T| + 1, c(\Pi'), c(\pi_2)) = |T| + 1 = |JT|$.

H right / H left. We have

$$\Pi_1 = \dfrac{\overset{\pi_1}{B \vdash_{\mathsf{L}} \Delta, A; HA^n; \Psi}}{B \vdash_{\mathsf{L}} \Delta; HA^{n+1}, \Psi}\,\mathsf{H}_R \qquad \Pi_2 = \dfrac{\overset{\pi_2}{A \vdash_{\mathsf{L}}; \Psi'}}{HA \vdash_{\mathsf{C}}; \Psi'}\,\mathsf{H}_L$$

By the inductive hypothesis applied to Π_2 and π_1 there exists a proof Π' of $B \vdash_{\mathsf{L}} \Delta; A, \Psi, \Psi'$ with $c(\Pi') \leq |HA| = |A| + 1$. Then the following derivation

$$\Pi_1 = \cfrac{\cfrac{\overset{\Pi'}{B \vdash_{\mathsf{L}} \Delta; A, \Psi, \Psi'} \qquad \overset{\pi_2}{A \vdash_{\mathsf{L}}; \Psi'}}{B \vdash_{\mathsf{L}} \Delta, \Psi, \Psi', \Psi'}\,\text{LL\_cut}}{B \vdash_{\mathsf{L}} \Delta, \Psi, \Psi'}\,\text{C\_contr}^*$$

has cut rank $max(|A| + 1, c(\Pi'), c(\pi_2)) = |A| + 1 = |HA|$.

+ right$_1$ / + left. We have

$$\Pi_1 = \dfrac{\overset{\pi_1}{S \vdash_{\mathsf{C}} T_1, (T_1 + T_2)^n, \Psi}}{S \vdash_{\mathsf{C}} (T_1 + T_2)^{n+1}, \Psi}\,\text{C\_+}_{R_1} \qquad \Pi_2 = \dfrac{\overset{\pi_2}{T_1 \vdash_{\mathsf{C}} \Psi_1} \qquad \overset{\pi_3}{T_2 \vdash_{\mathsf{C}} \Psi_2}}{T_1 + T_2 \vdash_{\mathsf{C}}; \Psi_1, \Psi_2}\,\text{C\_+}_L$$

If $n = 0$, then the reduction is as follows:

$$\cfrac{\Pi_1 = \dfrac{\overset{\pi_1}{S \vdash_{\mathsf{C}} T_1, \Psi}}{S \vdash_{\mathsf{C}} T_1 + T_2, \Psi}\,\text{C\_+}_{R_1} \qquad \Pi_2 = \dfrac{\overset{\pi_2}{T_1 \vdash_{\mathsf{C}} \Psi_1} \qquad \overset{\pi_3}{T_2 \vdash_{\mathsf{C}} \Psi_2}}{T_1 + T_2 \vdash_{\mathsf{C}} \Psi_1, \Psi_2}\,\text{C\_+}_L}{S \vdash_{\mathsf{C}} \Psi, \Psi_1, \Psi_2}\,\text{C\_cut}$$

reduces to

$$\Pi\ \cfrac{\cfrac{\overset{\pi_1}{S \vdash_{\mathsf{C}} T_1, \Psi} \qquad \overset{\pi_2}{T_1 \vdash_{\mathsf{C}} \Psi_1}}{S \vdash_{\mathsf{C}} \Psi, \Psi_1}\,\text{C\_cut}}{S \vdash_{\mathsf{C}} \Psi, \Psi_1, \Psi_2}\,\text{C\_weak}^*$$

Here $c(\Pi) = max(|T_1 + 1|, c(\pi_1), c(\pi_2)) \leq |T_1 + T_2|$.

If $n > 0$, then by the inductive hypothesis applied to Π_2 and π_1 there exists a proof Π' of $S \vdash_{\mathsf{C}} T_1, \Psi, \Psi_1, \Psi_2$ with $c(\Pi') \leq |T_1 + T_2| = |T_1| + |T_2| + 1$. Then the following derivation

$$\Pi = \dfrac{\dfrac{\overset{\Pi'}{S \vdash_{\mathsf{C}} T_1, \Psi, \Psi_1, \Psi_2} \qquad \overset{\pi_2}{T_1 \vdash_{\mathsf{C}} \Psi_1}}{S \vdash_{\mathsf{C}} \Psi, \Psi_1, \Psi_1, \Psi_2}\,\text{C\_cut}}{S \vdash_{\mathsf{C}} \Psi, \Psi_1, \Psi_2}\,\text{C\_contr}^*$$

has cut rank $max(|T_1| + 1, c(\Pi'), c(\pi_2)) \leq |T_1 + T_2|$.

$\bullet\!-$ right / $\bullet\!-$ left. We have

$$\dfrac{\Pi_1 = \dfrac{\overset{\pi_1}{A \vdash_{\mathsf{L}} \Delta_1; \Psi_1, B_1} \qquad \overset{\pi_2}{B_2 \vdash_{\mathsf{L}} \Delta_2; \Psi_2}}{A \vdash_{\mathsf{L}} B_1 \bullet\!- B_2, \Delta_1, \Delta_2; \Psi_1, \Psi_2}\,\text{LL\_}{\bullet\!-}_R \qquad \Pi_2 = \dfrac{\overset{\pi_3}{B_1 \vdash_{\mathsf{L}} B_2, \Delta; \Psi}}{B_1 \bullet\!- B_2 \vdash_{\mathsf{L}} \Delta; \Psi}\,\text{LL\_}{\bullet\!-}_L}{A \vdash_{\mathsf{L}} \Delta_1, \Delta_2, \Delta; \Psi_1, \Psi_2, \Psi}\,\text{LL\_cut}$$

reduces to Π

$$\dfrac{\dfrac{\overset{\pi_1}{A \vdash_{\mathsf{L}} \Delta_1, B_1; \Psi_1} \qquad \overset{\pi_3}{B_1 \vdash_{\mathsf{L}} B_2, \Delta; \Psi}}{A \vdash_{\mathsf{L}} \Delta_1, \Delta, B_2; \Psi_1, \Psi}\,\text{LL\_cut} \qquad \overset{\pi_2}{B_2 \vdash_{\mathsf{L}} \Delta_2; \Psi_2}}{A \vdash_{\mathsf{L}} \Delta_1, \Delta_2, \Delta; \Psi_1, \Psi_2, \Psi}\,\text{LL\_cut}$$

The resulting derivation Π has cut rank $c(\Pi) = max(|B_1| + 1, c(\pi_1), c(\pi_2), |B_2| + 1, c(\pi_3)) \leq |B_1 \bullet\!- B_2|$.