Non-Commutative Linear Logic in an Adjoint Model

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— Abstract

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1 Introduction

Linear logic is a well-known resource-sensitive logic. It has been used extensively to model attack trees. This paper concerns a non-commutative variant of linear logic and combines the non-commutative variant with Girard's linear logic []. We will only focus on the multiplicative (i.e. \otimes , \multimap) part of linear logic for simplicity. We construct the non-commutative variant by using a non-commutative tensor product \triangleright instead of the commutative \otimes , and two implications \leftharpoonup and \rightharpoonup for the two directions of \multimap .

We model the non-commutative linear logic categorically using an ajunction between a symmetric monoidal closed category and a Lambek category. Our categorial adjoint model has a similar structure as Benton's adjoint model [], in which the multiplicative part of intuitionistic linear logic (ILL) is modeled using an adjunction between a cartesian closed category and a symmetric monoidal closed category. On the other hand, Moggi [] uses monad models to map intuitionistic logic into ILL. As discussed in [?], Benton's adjoint models only gives rise to commutative monad models and the non-commutative part remained as an open problem. Therefore, by combining our adjoint models with Benton's, we would be able to get non-commutative monad models and thus non-commutative ILL.

The rest of the paper is organized as follows. Section 2 discusses existing approaches on constructing non-commutative linear logic. Section 3 contains the basic definitions in category theory that we will be using in our adjoint model. Familiar readers may skip this section. Section 4 contains the definition and essential properties of our adjoint model. Section 5 discusses the sequent calculus and natural deduction rules for our non-commutative linear logic. We prove that our sequent calculus has the property of cut-elimination and the natural deduction is strongly normalizing. Section 6 talks about the preliminary result after combing our non-commutative model with Benton's commutative model. Section 7 briefly mentions how our model could be used in attack trees and other areas. Section 8 concludes this paper with future work.

2 Related Work

Polakow and Pfenning discuseed Ordered Linear Logic (OLL) [], which combines intuitionistic, commutative linear and non-commutative linear logic, OLL contains sequents of the form $\Gamma, \Delta, \Omega \vdash$

A, where Γ is a multiset of intuitionistic assumptions, Δ is a multiset of commutative linear assumptions, and Ω is a list of non-commutative linear assumptions. OLL contains logical connectives from all three the logics. Therefore, our non-commutative adjoint model is a part of OLL and after combining with Benton's commutative adjoint model, we would get a simplification of OLL.

Greco and Palmigiano [] also presents a variant of the multiplicative fragment of non-commutative ILL. But they focus on proper display calculi while we use sequent calculi.

de Paiva and Eades [] also developed categorical models for the non-commutative ILL by adapting the Dialectica categorical models for linear logic.

3 Category Theory Basics

This section contains the basic definitions in category theory that we will be using in our adjoint model. Our model is based on special kinds of monoidal categories: Lambek categories and symmetric monoidal closed categories and Lambek categories, as defined in Definitions 2 and 3.

- ▶ **Definition 1.** A monoidal category $(\mathcal{M}, \triangleright, I, \alpha, \lambda, \rho)$ is a category \mathcal{M} consists of
- a bifunctor \triangleright : $\mathcal{M} \times \mathcal{M} \to \mathcal{M}$, called the tensor product;
- an object I, called the unit object;
- \blacksquare three natural isomorphisms α , λ , and ρ with components

$$\alpha_{A,B,C}: (A \triangleright B) \triangleright C \to A \triangleright (B \triangleright C)$$

$$\lambda_A: I \triangleright A \to A$$

$$\rho_A: A \triangleright I \to A$$

where α is called associator, λ is left unitor, and ρ is right unitor,

such that the following diagrams commute for any objects A, B, C in \mathcal{M} :

$$((A \triangleright B) \triangleright C) \triangleright D \xrightarrow{\alpha_{A,B,C} \triangleright id_D} (A \triangleright (B \triangleright C)) \triangleright D \xrightarrow{\alpha_{A,B \triangleright C,D}} A \triangleright ((B \triangleright C) \triangleright D)$$

$$\downarrow id_{A} \triangleright \alpha_{B,C,D}$$

$$(A \triangleright B) \triangleright (C \triangleright D) \xrightarrow{\alpha_{A,B,C} \triangleright D} A \triangleright (B \triangleright (C \triangleright D))$$

$$(A \triangleright I) \triangleright B \xrightarrow{\alpha_{A,B,C} \triangleright D} A \triangleright (I \triangleright B)$$

$$\downarrow id_{A} \triangleright \alpha_{B,C,D}$$

$$(A \triangleright I) \triangleright B \xrightarrow{\alpha_{A,I,B}} A \triangleright (I \triangleright B)$$

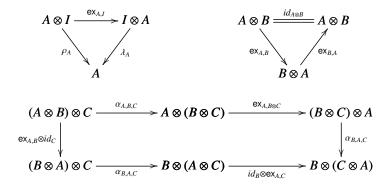
$$\downarrow id_{A} \triangleright \lambda_{B}$$

▶ **Definition 2.** A **Lambek category** (or a **biclosed monoidal category**) is a monoidal category $(\mathcal{M}, \triangleright, I, \alpha, \lambda, \rho)$ equipped with two bifunctors \rightarrow : $\mathcal{M}^{op} \times \mathcal{M} \to \mathcal{M}$ and \leftarrow : $\mathcal{M} \times \mathcal{M}^{op} \to \mathcal{M}$ that are both right adjoint to the tensor product. That is, the following natural bijections hold:

$$\operatorname{\mathsf{Hom}}_{\mathcal{L}}(X \triangleright A, B) \cong \operatorname{\mathsf{Hom}}_{\mathcal{L}}(X, A \rightharpoonup B) \qquad \qquad \operatorname{\mathsf{Hom}}_{\mathcal{L}}(A \triangleright X, B) \cong \operatorname{\mathsf{Hom}}_{\mathcal{L}}(X, B \leftharpoonup A)$$

▶ **Definition 3.** A symmetric monoidal category (SMCC) is a monoidal category $(\mathcal{M}, \otimes, I, \alpha, \lambda, \rho)$ together with a natural transformation with components $ex_{A,B} : A \otimes B \to B \otimes A$, called **exchange**,

such that the following diagrams commute:



We use ▶ for non-symmetric monoidal categories while ⊗ for symmetric ones.

▶ **Definition 4.** A **symmetric monoidal closed category** $(\mathcal{M}, \otimes, I, \alpha, \lambda, \rho)$ is a symmetric monoidal category equipped with a bifunctor \multimap : $\mathcal{M}^{op} \times \mathcal{M} \to \mathcal{M}$ that is right adjoint to the tensor product. That is, the following natural bijection $\mathsf{Hom}_{\mathcal{M}}(X \otimes A, B) \cong \mathsf{Hom}_{\mathcal{M}}(X, A \multimap B)$ holds.

The relation between SMMCs and Lambek categories are demonstrated in Lemma 5 and Corollary 6.

▶ **Lemma 5.** Let A and B be two objects in a Lambek category with the exchange natural transformation. Then $(A \rightarrow B) \cong (B \leftarrow A)$.

Proof. First, notice that for any object C we have

$$Hom[C, A \rightarrow B] \cong Hom[C \otimes A, B]$$
 \mathcal{L} is a Lambek category $\cong Hom[A \otimes C, B]$ By the exchange $ex_{C,A}$ $\cong Hom[C, B \leftarrow A]$ \mathcal{L} is a Lambek category

Thus, $A \rightarrow B \cong B \leftarrow A$ by the Yoneda lemma.

▶ Corollary 6. A Lambek category with exchange is symmetric monoidal closed.

The essential component in our non-commutative adjoint model is a monoidal adjunction, defined in Definitions 7-11.

▶ **Definition 7.** Let $(\mathcal{M}, \triangleright, I, \alpha, \lambda, \rho)$ and $(\mathcal{M}', \triangleright', I', \alpha', \lambda', \rho')$ be monoidal categories. A **monoidal functor** (F, m) from \mathcal{M} to \mathcal{M}' is a functor $F : \mathcal{M} \to \mathcal{M}'$ together with a morphism $\mathsf{m}_I : I' \to F(I)$ and a natural transformation $\mathsf{m}_{A,B} : FA' \triangleright FB' \to F(A \triangleright B)$, such that the following diagrams commute for any objects A, B, and C in \mathcal{M} :

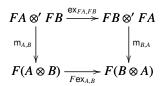
$$(FA \triangleright' FB) \triangleright' FC \xrightarrow{\alpha'_{FA,FB,FC}} FA \triangleright' (FB \triangleright' FC) \xrightarrow{id_{FA}\triangleright' m_{A,B}} FA \triangleright' F(B \triangleright C)$$

$$\downarrow^{m_{A,B}\triangleright' id_{FC}} \downarrow^{m_{A,B}\triangleright} FA \triangleright' FC \xrightarrow{m_{A,B,C}} F(A \triangleright B) \triangleright C) \xrightarrow{F\alpha_{A,B,C}} F(A \triangleright (B \triangleright C))$$

$$\downarrow^{m_{A,B}\triangleright C} \downarrow^{m_{A,B}\triangleright C} \downarrow^{m_{A,$$

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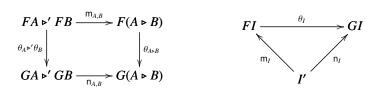
▶ **Definition 8.** Let $(\mathcal{M}, \otimes, I, \alpha, \lambda, \rho)$ and $(\mathcal{M}', \otimes', I', \alpha', \lambda', \rho')$ be symmetric monoidal categories. A **symmetric monoidal functor** $F : \mathcal{M} \to \mathcal{M}'$ is a monoidal functor (F, m) that satisfies the following coherence diagram:



▶ **Definition 9.** An **adjunction** between categories C and \mathcal{D} consists of two functors $F: \mathcal{D} \to C$, called the **left adjoint**, and $G: C \to \mathcal{D}$, called the **right adjoint**, and two natural transformations $\eta: id_{\mathcal{D}} \to GF$, called the **unit**, and $\varepsilon: FG \to id_C$, called the **counit**, such that the following diagrams commute for any object A in C and B in D:



▶ **Definition 10.** Let (F, m) and (G, n) be monoidal functors from a monoidal category $(\mathcal{M}, \otimes, I, \alpha, \lambda, \rho)$ to a monoidal category $(\mathcal{M}', \otimes', I', \alpha', \lambda', \rho')$. A **monoidal natural transformation** from (F, m) to (G, n) is a natural transformation $\theta : (F, m) \to (G, n)$ such that the following diagrams commute for any objects A and B in \mathcal{M} :



▶ **Definition 11.** Let $(\mathcal{M}, \triangleright, I, \alpha, \lambda, \rho)$ and $(\mathcal{M}', \triangleright', I', \alpha', \lambda', \rho')$ be monoidal categories, $F : \mathcal{M} \to \mathcal{M}'$ and $G : \mathcal{M}' \to \mathcal{M}$ be functors. The adjunction $F : \mathcal{M} \to \mathcal{M}' : G$ is a **monoidal adjunction** if F and G are monoidal functors, and the unit η and the counit ε are monoidal natural transformations.

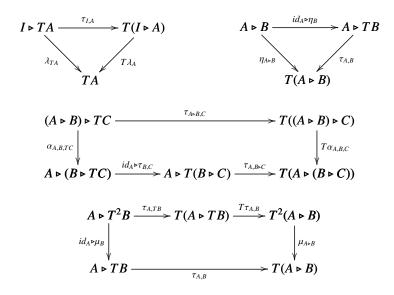
In Moggi's monad model [], the monad is required to be strong, as defined in Definitions 12 and 13.

▶ **Definition 12.** Let C be a category. A **monad** on C consists of an endofunctor $T: C \to C$ together with two natural transformations $\eta: id_C \to T$ and $\mu: T^2 \to T$, where id_C is the identity functor on C, such that the following diagrams commute:



▶ **Definition 13.** Let $(\mathcal{M}, \triangleright, I, \alpha, \lambda, \rho)$ be a monoidal category and (T, η, μ) be a monad on \mathcal{M} . T is a **strong monad** if there is natural transformation τ , called the **tensorial strength**, with components

 $\tau_{A,B}: A \triangleright TB \rightarrow T(A \triangleright B)$ such that the following diagrams commute:



- ▶ **Definition 14.** Let $(\mathcal{M}, \otimes, I, \alpha, \lambda, \rho)$ be a symmetric monoidal category with exchange ex, and (T, η, μ) be a strong monad on \mathcal{M} . Then there is a "**twisted**" **tensorial strength** $\tau'_{A,B}: TA \otimes B \to T(A \otimes B)$ defined as $\tau'_{A,B} = Tex \circ \tau_{B,A} \circ ex$. We can construct a pair of natural transformations Φ , Φ' with components $\Phi_{A,B}, \Phi'_{A,B}: TA \otimes TB \to T(A \otimes B)$ defined as $\Phi_{A,B} = \mu_{A\otimes B} \circ T\tau'_{A,B} \circ \tau_{TA,B}$ and $\Phi'_{A,B} = \mu_{A\otimes B} \circ T\tau_{A,B} \circ \tau'_{A,TB}$. If $\Phi = \Phi'$, then the monad T is **commutative**.
- ▶ **Definition 15.** Let \mathcal{L} be a category. A **comonad** on \mathcal{L} consists of an endofunctor $S: \mathcal{L} \to \mathcal{L}$ together with two natural transformations $\varepsilon: S \to id_{\mathcal{L}}$ and $\delta: S^2 \to S$ such that the following diagrams commute:

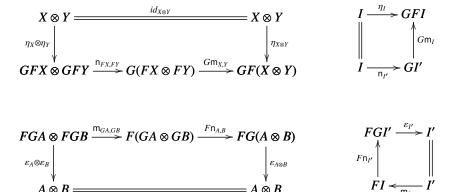
4 Lambek Adjoint Model

Our adjoint model, Lambek Adjoint Model (LAM), has a similar structure as Benton's LNL model []. Benton's LNL model consists of a symmetric monoidal adjunction $F: C \dashv \mathcal{L}: G$ between a cartesian closed category C and a symmetric monoidal closed category \mathcal{L} . LAM consists of a monoidal adjunction between a symmetric monoidal closed category and a Lambek category.

- ▶ **Definition 16.** A **Lambek Adjoint Model** (LAM) $(C, \mathcal{L}, F, G, \eta, \varepsilon)$ consists of
- \blacksquare a symmetric monoidal closed category $(C, \otimes, I, \alpha, \lambda, \rho)$;
- a Lambek category $(\mathcal{L}, \triangleright, I', \alpha', \lambda', \rho')$;
- a monoidal adjunction $F: C \dashv \mathcal{L}: G$ with unit $\eta_X: X \to GFX$ and counit $\varepsilon: FG \to id_{\mathcal{L}}$, where $(F: C \to \mathcal{L}, m)$ and $(G: \mathcal{L} \to C, n)$ are monoidal functors.

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Thus, in LAM, the following four diagrams commute because η and ε are monoidal natural transformations:



And the following two triangles commute because of the adjunction:



Following the tradition, we use letters X, Y, Z for objects in C and A, B, C for objects in \mathcal{L} . The rest of this section proves essential properties of a LAM.

4.1 An Isomorphism

Let $(C, \mathcal{L}, F, G, \eta, \varepsilon)$ be a LAM, where (F, m) and (G, n) are monoidal functors. Similarly as in Benton's LNL model, $m_{X,Y}$ are components of a natural isomorphism and m_I is an isomorphism. This is essential for deriving certain rules of our non-commutative linear logic, such as tensor elimination in natural deduction.

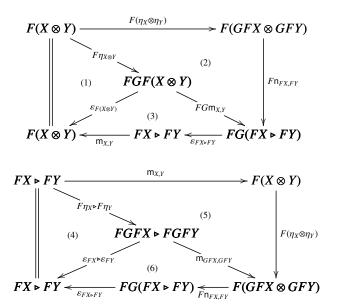
We define the inverses of $\mathsf{m}_{X,Y}: FX \triangleright FY \to F(X \otimes Y)$ and $\mathsf{m}_I: I' \to FI$ as:

$$\mathsf{p}_{X,Y}: F(X \otimes Y) \xrightarrow{F(\eta_X \otimes \eta_Y)} F(GFX \otimes GFY) \xrightarrow{F\mathsf{n}_{FX,FY}} FG(FX \triangleright FY) \xrightarrow{\varepsilon_{FX \triangleright FX}} FX \triangleright FY$$
$$\mathsf{p}_I: FI \xrightarrow{F\mathsf{n}_{I'}} FGI' \xrightarrow{\varepsilon_{I'}} I'$$

▶ **Theorem 17.** $m_{X,Y}$ are components of a natural isomorphism and their inverses are $p_{X,Y}$.

Proof. We need to show that $\mathsf{m}_{X,Y} \circ \mathsf{p}_{X,Y} = id_{F(X \otimes Y)}$ and $\mathsf{p}_{X,Y} \circ \mathsf{m}_{X,Y} = id_{FX \triangleright FX}$. The two equations hold because the following diagrams commute: (1)-adjunction; (2)- η is a monoidal natural transformation; (3)-naturality of ε ; (4)-adjunction; (5)-naturality of m ; (6)- ε is a monoidal natural

transformation.



▶ **Theorem 18.** m_I is an isomorphism and its inverse is p_I .

Proof. This is equivalent to equations $\mathsf{m}_I \circ \mathsf{p}_I = id_{FI}$ and $\mathsf{p}_I \circ \mathsf{m}_I = id_{I'}$, equivalent to the following diagrams, which commute because ε is a monoidal natural transformation.



4.2 Monad on C

We first show that the monad on *C* in LAM is strong but non-commutative. In Benton's LNL model, the monad on the cartesian closed category is commutative.

▶ **Lemma 19.** The monad on the symmetric monoidal closed category C in LAM is monoidal.

Proof. Let $(C, \mathcal{L}, F, G, \eta, \varepsilon)$ be a LAM. We define the monad $(T, \eta : id_C \to T, \mu : T^2 \to T)$ on C as

$$T = GF$$
 $\eta_X : X \to GFX$ $\mu_X = G\varepsilon_{FX} : GFGFX \to GFX$

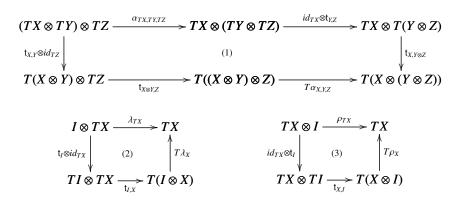
Since (F, m) and (G, n) are monoidal functors, we have

$$\mathsf{t}_{X,Y} = G\mathsf{m}_{X,Y} \circ \mathsf{n}_{FX,FY} : TX \otimes TY \to T(X \otimes Y) \qquad \qquad \mathsf{t}_I = G\mathsf{m}_I \circ \mathsf{n}_{I'} : I \to TI$$

The monad *T* being monoidal means:

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1. T is a monoidal functor, i.e. the following diagrams commute:



We write GF instead of T in the proof for clarity.

By replacing $t_{X,Y}$ with its definition, diagram (1) above commutes by the following commutative diagram, in which the two hexagons commute because G and F are monoidal functors, and the two quadrilaterals commute by the naturality of n.

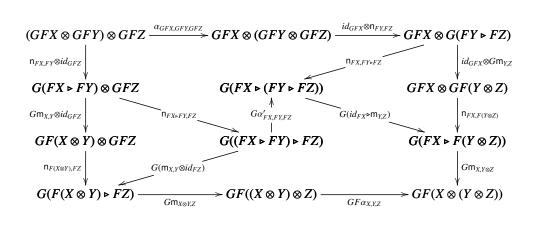


Diagram (2) commutes by the following commutative diagrams, in which the top quadrilateral commutes because G is monoidal, the right quadrilateral commutes because F is monoidal, and the left square commutes by the naturality of n.

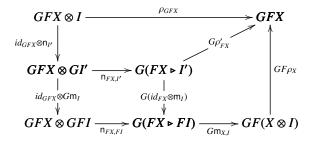
$$I \otimes GFX \xrightarrow{\lambda_{GFX}} GFX$$

$$GI' \otimes GFX \xrightarrow{\mathsf{n}_{I'} \otimes id_{GFX}} G(I' \triangleright FX)$$

$$Gm_{I} \otimes id_{GFX} G(m_{I} \triangleright id_{FX})$$

$$GFI \otimes GFX \xrightarrow{\mathsf{n}_{FI,FX}} G(FI \triangleright FX) \xrightarrow{Gm_{I,X}} GF(I \otimes X)$$

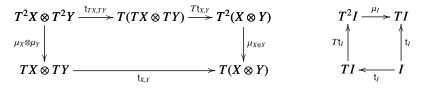
Similarly, diagram (3) commutes as follows:



2. η is a monoidal natural transformation. In fact, since η is the unit of the monoidal adjunction, η is monoidal by definition and thus the following two diagrams commute.



3. μ is a monoidal natural transformation. It is obvious that since $\mu = G\varepsilon_{FA}$ and ε is monoidal, so is μ . Thus the following diagrams commute.



However, the monad is not symmetric because the following diagram does not commute, for the Lambek category $\mathcal L$ is not symmetric.

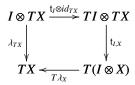
$$GFX \otimes GFY \xrightarrow{\exp_{GFX,GFY}} GFY \otimes GFX \xrightarrow{\mathsf{n}_{FY,FX}} G(FY \triangleright FX)$$

$$\downarrow \mathsf{n}_{FX,FY} \qquad \qquad \qquad \downarrow \mathsf{G}\mathsf{m}_{Y,X}$$

$$G(FX \triangleright FY) \xrightarrow{G\mathsf{m}_{X,Y}} GF(X \otimes Y) \xrightarrow{GF\mathsf{ex}_{X,Y}} GF(Y \otimes X)$$

▶ **Lemma 20.** The monad on the symmetric monoidal closed category in LAM is strong.

Proof. Let $(C, \mathcal{L}, F, G, \eta, \varepsilon)$ be a LAM, where $(C, \otimes, I, \alpha, \lambda, \rho)$ is symmetric monoidal closed, $(\mathcal{L}, \triangleright, I', \alpha', \lambda', \rho')$ is Lambek. In Lemma 19, we have proved that the monad $(T = GF, \eta, \mu)$ is monoidal with the natural transformation $\mathsf{t}_{X,Y} : TX \otimes TY \to T(X \otimes Y)$ and the morphism $\mathsf{t}_I : I \to TI$. We define the tensorial strength $\tau_{X,Y} : X \otimes TY \to T(X \otimes Y)$ as $\tau_{X,Y} = \mathsf{t}_{X,Y} \circ (\eta_X \otimes id_{TY})$. Since η is a monoidal natural transformation, we have $\eta_I = G\mathsf{m}_I \circ \mathsf{n}_{I'}$. Therefore $\eta_I = \mathsf{t}_I$. Thus the following diagram commutes because T is monoidal, where the composition $\mathsf{t}_{I,X} \circ (\mathsf{t}_I \otimes id_{TX})$ is the definition of $\tau_{I,X}$. So the first triangle in Defition 13 commutes.



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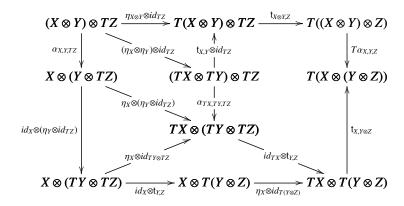
Similarly, by using the definition of τ , the second triangle in the definition is equivalent to the following diagram, which commutes because η is a monoidal natural transformation:

$$X \otimes Y \xrightarrow{id_X \otimes \eta_Y} X \otimes TY$$

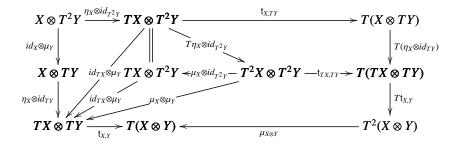
$$\downarrow \eta_{X \otimes Y} \qquad \qquad \downarrow \eta_{X} \otimes id_{TY}$$

$$T(X \otimes Y) \xrightarrow{f_{Y,Y}} TX \otimes TY$$

The first pentagon in the definition commutes by the following commutative diagrams, because η and α are natural transformations and T is monoidal:



The last diagram in the definition commtues by the following commutative diagram, because T is a monad, t is a natural transformation, and μ is a monoidal natural transformation:



The following lemma is adopted from [].

- ▶ **Lemma 21.** Let \mathcal{M} be a symmetric monoidal category and T be a strong monad on \mathcal{M} . Then T is commutative iff it is symmetric.
- ▶ **Theorem 22.** *The monad on the SMCC in LAM is strong but non-commutative.*

Proof. The proof is obvious. Based on Lemma 20 and Lemma 21, the monad is non-commutative.

4.3 Comonad on \mathcal{L}

▶ Lemma 23. The comonad on the Lambek category in a LAM is monoidal.

4

Proof. We define the comonad $(S, \varepsilon : S \to id_{\mathcal{L}}, \delta : S \to S^2)$ on the Lambek category \mathcal{L} as:

$$S = FG$$
 $\varepsilon_A : SA \to A$ $\delta_A = F\eta_{GA} : SA \to S^2A$

Thus, we have natural transformation s and morphism s_I defined as:

$$\mathsf{s}_{A,B} = F\mathsf{n}_{A,B} \circ \mathsf{m}_{GA,GB} : SA \triangleright SB \to SA \triangleright SB \qquad \qquad \mathsf{s}_I = F\mathsf{n}_{I'} \circ \mathsf{m}_I : I' \to SI'$$

The comonad S being monoidal means

1. S is a monoidal functor, i.e. the following diagrams commute:

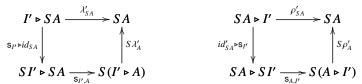
$$(SA \triangleright SB) \triangleright SC \xrightarrow{\alpha'_{SA,SB,SC}} \Rightarrow SA \triangleright (SB \triangleright SC) \xrightarrow{id_{SA} \triangleright S_{B,C}} \Rightarrow SA \triangleright S(B \triangleright C)$$

$$\downarrow S_{A,B} \triangleright id_{SC} \downarrow \qquad \qquad \downarrow S_{A,B} \triangleright C$$

$$S(A \triangleright B) \triangleright SC \xrightarrow{S_{A} \triangleright B,C} \Rightarrow S((A \triangleright B) \triangleright C) \xrightarrow{S\alpha'_{A,B,C}} \Rightarrow S(A \triangleright (B \triangleright C))$$

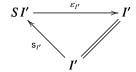
$$I' \triangleright SA \xrightarrow{\mathcal{X}_{SA}} SA$$

$$\downarrow SI' \triangleright SA \xrightarrow{SU} S(I' \triangleright A)$$



2. ε is a monoidal natural transformation:

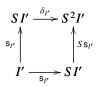




3. δ is a monoidal natural transformation:

$$SA \triangleright SA \xrightarrow{S_{A,B}} S(A \triangleright B) \qquad SI' \xrightarrow{\delta_{I'}} S^2I'$$

$$\downarrow \delta_{A} \triangleright \delta_B \downarrow \qquad \qquad \downarrow \delta_{A} \triangleright B \qquad \qquad \downarrow \delta_$$



The proof for the commutativity of the diagrams are similar as the proof in Lemma 19. We do not include the proof here for simplicity.

We then show that the co-Eilenberg-Moore category of the comonad S is symmetric monoidal closed.

- ▶ **Definition 24.** Let (S, ε, δ) be a comonad on a category \mathcal{L} . Then the **co-Eilenberg-Moore category** \mathcal{L}^S of the comonad has
- \blacksquare as objects the S-coalgebras $(A, h_A : A \to SA)$, where A is an object in \mathcal{L} , s.t. the following diagrams commute:





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as morphisms the coalgebra morphisms, i.e. morphisms $f:(A,h_A)\to (B,h_B)$ between coalgebras s.t. the diagram commutes:

$$\begin{array}{ccc}
A & \xrightarrow{f} & B \\
\downarrow h_A & & \downarrow h_B \\
SA & \xrightarrow{Sf} & SB
\end{array}$$

▶ **Lemma 25.** Given a LAM $(C, \mathcal{L}, F, G, \eta, \varepsilon)$ and the comonad S on \mathcal{L} , the co-Eilenberg-Moore category \mathcal{L}^S has an exchange natural transformation $ex_{A,B}^S : A \triangleright B \rightarrow B \triangleright A$.

Proof. We define the exchange $\exp_{A,B}^S: A \triangleright B \to B \triangleright A$ as

$$A \triangleright B \xrightarrow{h_A \triangleright h_B} FGA \triangleright FGB \xrightarrow{\mathsf{m}_{GA,GB}} F(GA \otimes GB) \xrightarrow{F \in \mathsf{x}_{GA,GB}} F(GB \otimes GA) \xrightarrow{F \cap B_A} FG(B \triangleright A) \xrightarrow{\varepsilon_{B\triangleright A}} B \triangleright A$$

in which (F, m) and (G, n) are monoidal functors, and ex is the exchange for C. Then ex^S is a natural transformation because the following diagrams commute for morphisms $f: A \to A'$ and $g: B \to B'$:

▶ **Lemma 26.** The following diagrams commute in the co-Eilenberg-Moore category \mathcal{L}^S :

$$F((GA \otimes GB) \otimes GC) \xrightarrow{F(\mathsf{n}_{A,B} \otimes id_{GC})} F(G(A \triangleright B) \otimes GC) \xrightarrow{F(\mathsf{ex}_{A,B} \otimes id_{GC})} FG((A \triangleright B) \triangleright C)$$

$$\downarrow c_{(A\triangleright B)\triangleright C}$$

$$\downarrow c_{(A\triangleright B)\triangleright C}$$

$$\downarrow F(G(B \triangleright A) \otimes GC) \qquad \qquad \qquad \downarrow c_{(A\triangleright B)\triangleright C}$$

$$\downarrow F(\mathsf{n}_{B,A} \otimes id_{GC}) \qquad \qquad \qquad \downarrow c_{(A\triangleright B)\triangleright C}$$

$$\downarrow F(\mathsf{n}_{B,A} \otimes id_{GC}) \qquad \qquad \qquad \downarrow c_{(A\triangleright B)\triangleright C}$$

$$\downarrow F(\mathsf{n}_{B,A} \otimes id_{GC}) \qquad \qquad \qquad \downarrow c_{(A\triangleright A)\triangleright C}$$

$$\downarrow F(\mathsf{n}_{B,A} \otimes id_{GC}) \qquad \qquad \qquad \downarrow c_{(A\triangleright A)\triangleright C}$$

$$\downarrow F(\mathsf{n}_{B,A} \otimes id_{GC}) \qquad \qquad \qquad \downarrow c_{(A\triangleright A)\triangleright C}$$

$$\downarrow F(\mathsf{n}_{B,A} \otimes id_{GC}) \qquad \qquad \downarrow c_{(A\triangleright A)\triangleright C}$$

$$\downarrow F(\mathsf{n}_{B,A} \otimes id_{GC}) \qquad \qquad \downarrow c_{(A\triangleright A)\triangleright C}$$

$$\downarrow F(\mathsf{n}_{B,A} \otimes id_{GC}) \qquad \qquad \downarrow c_{(A\triangleright A)\triangleright C}$$

$$\downarrow F(\mathsf{n}_{B,A} \otimes id_{GC}) \qquad \qquad \downarrow c_{(A\triangleright A)\triangleright C}$$

$$\downarrow F(\mathsf{n}_{B,A} \otimes id_{GC}) \qquad \qquad \downarrow c_{(A\triangleright A)\triangleright C}$$

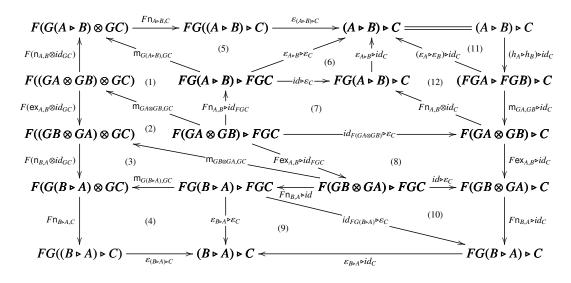
$$\downarrow F(\mathsf{n}_{B,A} \otimes id_{GC}) \qquad \qquad \downarrow c_{(A\triangleright A)\triangleright C}$$

$$F(GB \otimes (GC \otimes GA)) \xrightarrow{F(id_{GB} \otimes \mathsf{n}_{CA})} F(GB \otimes G(C \triangleright A)) \xrightarrow{F\mathsf{n}_{B,C \triangleright A}} FG(B \triangleright (C \triangleright A))$$

$$\downarrow^{\mathcal{E}_{B \triangleright (C \triangleright A)}} \downarrow^{\mathcal{E}_{B \triangleright (A \triangleright C)}} \downarrow^{\mathcal{E}_{B \triangleright (A \triangleright C)}} \downarrow^{\mathcal{E}_{B \triangleright (A \triangleright C)}} \rightarrow B \triangleright (A \triangleright C)$$

Proof. We only write the proof for the first diagram. The proof for the second one is similar. (1), (2), (3)–naturality of m; (4)–F is monoidal; (5), (12)– ε is monoidal; (6), (7), (8), (9), (10)–obvious;

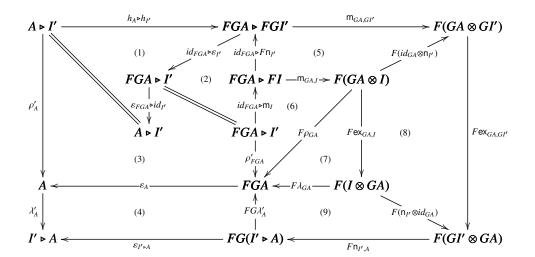
(11)-coalgebra.



▶ **Theorem 27.** The co-Eilenberg-Moore category \mathcal{L}^S of S is symmetric monoidal closed.

Proof. Let $(\mathcal{L}, \triangleright, l', \alpha', \lambda', \rho')$ be the Lambek category in a SMCC-Lambek model and S be the comonad on \mathcal{L} . Since \mathcal{L} is a Lambek category, it is obvious that \mathcal{L} is also Lambek. By Corollary 6, we only need to prove the exchange defined in Lemma 25 satisfies the three commutative diagrams in Definition 3.

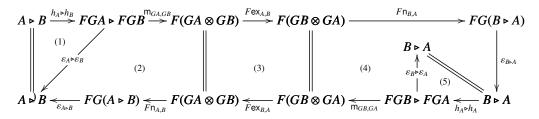
The first triangle in Definition 3 commutes as follows: (1)–coalgebra; (2)– ε is monoidal; (3)–naturality of ρ ; (4)–naturality of ε ; (5)–naturality of m; (6)–F is monoidal; (7)–C is symmetric; (8)–naturality of ex; (9)–G is monoidal.



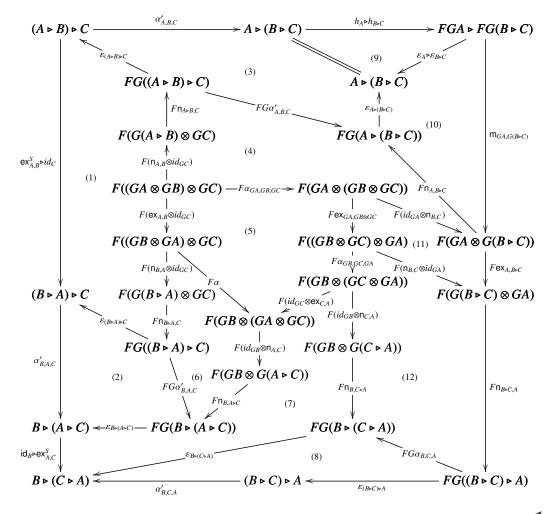
The second triangle in the proof commutes as follows: (1) and (5)-coalgebra; (2) and (4)- ε is

 \triangleleft

monoidal; (3)–C is symmetric.



The third diagram commutes as follows: (1) and (7)–Lemma 26; (2)–naturality of α' ; (3) and (8)–naturality of ε ; (4), (6) and (12)–G is a monoidal functor; (5)–C is symmetrical monoidal closed; (9)–coalgebra; (10)– ε is a monoidal natural transformation; (11)–naturality of ex.



5 Non-Commutative Linear Logic

In a LAM, the SMCC C models the commutative linear logic and the Lambeck category \mathcal{L} models the non-commutative variant. In Section 5.1, we will present the term assignment for sequent calculus of both sides and prove the cut elimination theorem. In Section 5.2, we present the term assignment for natural deduction of both sides and prove the logic is strongly normalizing.

A sequent in the commutative side is of the form $\Psi, \Phi \vdash_C t : X$. The types must be X, Y, Z, etc., which are objects in the SMCC C. Tye typing contexts are multisets. Suppose Ψ is the set $x_1 : X_1, x_2 : X_2, ..., x_m : X_m$ and Φ is the set $y_1 : Y_1, y_2 : Y_2, ..., y_n : Y_n$, then the categorical interpretation of the sequent is the morphism $(X_1 \otimes X_2 \otimes ... \otimes X_m) \otimes (Y_1 \otimes Y_2 \otimes ... \otimes Y_n) \to X$.

A sequent in the non-commutative side is of the form $\Gamma, \Delta \vdash_{\mathcal{L}} s : A$. The types must be A, B, C, etc., which are objects in the Lambek category \mathcal{L} . Tye typing contexts are lists instead of multisets. The typing contexts are mixed in the sense that they could include contexts from the commutative side. When a commutative context $\Psi = \{x_1 : X_1, ..., x_m : X_m\}$ is included, it is interpreted as the object $F(X_1 \otimes ... \otimes X_m)$. Therefore, the interpretation of the sequent $\Psi, \Gamma \vdash_{\mathcal{L}} s : A$, where Ψ is defined as above and Γ is the list $y_1 : A_1, ..., y_n : A_n$, is the morphism $F(X_1 \otimes ... \otimes X_m) \triangleright (A_1 \triangleright ... \triangleright A_n) \to A$.

For the commutative side, since the contexts are multisets, the following exchange rule is implicit in both sequent calculus and natural deduction:

$$\frac{\Phi, x: X, y: Y, \Psi \vdash_C t: Z}{\Phi, z: Y, w: X, \Psi \vdash_C \operatorname{ex} w, z \operatorname{with} x, y \operatorname{in} t: Z} \quad \mathsf{T}_{\operatorname{BETA}}$$

5.1 Sequent Calculus

The term assignment for sequent calculus of the commutative part of the model, i.e. the SMCC of the adjunction, is defined in Figure 1. And the term assignme for the non-commutative part, i.e. the Lambek category of the adjunction, is defined in Figure 2. We do not have the structural rules except for exchange because the calculus is for linear logic.

$$\frac{\Psi \vdash_{C} t : X}{x : X \vdash_{C} x : X} \quad T_{_AX} \qquad \frac{\Psi \vdash_{C} t : X}{x : \mathsf{UnitT}, \Psi \vdash_{C} \mathsf{let} x : \mathsf{UnitT} \mathsf{be} \mathsf{trivT} \mathsf{in} t : X} \quad T_{_\mathsf{UNITL}} \qquad \frac{}{} \vdash_{C} \mathsf{trivT} : \mathsf{UnitT}} \quad T_{_\mathsf{UNITR}}$$

$$\frac{\Phi, x : X, y : Y, \Psi \vdash_{C} t : Z}{\Phi, z : X \otimes Y, \Psi \vdash_{C} \mathsf{let} z : X \otimes Y \mathsf{be} x \otimes y \mathsf{in} t : Z} \quad T_{_\mathsf{TENL}} \qquad \frac{\Phi \vdash_{C} t_{1} : X \quad \Psi \vdash_{C} t_{2} : Y}{\Phi, \Psi \vdash_{C} t_{1} \otimes t_{2} : X \otimes Y} \quad T_{_\mathsf{TENR}}$$

$$\frac{\Phi \vdash_{C} t_{1} : X \quad \Psi_{1}, x : Y, \Psi_{2} \vdash_{C} t_{2} : Z}{\Psi_{1}, y : X \multimap Y, \Phi, \Psi_{2} \vdash_{C} [\mathsf{app} y t_{1}/x] t_{2} : Z} \quad T_{_\mathsf{IMPL}} \qquad \frac{\Phi, x : X \vdash_{C} t : Y}{\Phi \vdash_{C} \lambda x : X : X : X \multimap Y} \quad T_{_\mathsf{IMPR}}$$

$$\frac{\Phi \vdash_{L} s : A}{\Phi \vdash_{C} \mathsf{Gs} : \mathsf{GA}} \quad T_{_\mathsf{GR}} \qquad \frac{\Phi \vdash_{C} t_{1} : X \quad \Psi_{1}, x : X, \Psi_{2} \vdash_{C} t_{2} : Y}{\Psi_{1}, \Phi, \Psi_{2} \vdash_{C} [t_{1}/x] t_{2} : Y} \quad T_{_\mathsf{CUT}}$$

Figure 1 Sequent Calculus: Commutative Part

Next, we prove cut elimination for the sequent calculus. We define the **degree** |X| (**or** |A|) **of a commutative** (**or non-commutative**) **formula** to be the number of logical connectives |X| plus 1. For instance, $|X \otimes Y| = |X| + |Y| + 1$. And the **degree of a cut rule** is the degree of the cut formula. The following key cases demonstrate how we can replace a cut with at most two cuts with lower degree. The **degree** $|\Pi|$ **of a proof** Π is the maximum of the degrees of all cut fules in the proof and $|\Pi| = 0$ if Π is cut-free. Finally, the **height** $h(\Pi)$ **of a proof** Π is the length of the longest path in the proof tree and the height of an axiom is 0.

We consider the following 11 key cases in proving cut elimination, each of which is a (R, L) pair for the same connective.

is transformed to

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$$\frac{\Delta \vdash_{\mathcal{L}} s : A}{x : \mathsf{A} \vdash_{\mathcal{L}} x : A} \quad S_{\mathsf{A}} x \qquad \frac{\Delta \vdash_{\mathcal{L}} t \mathsf{rivS} : \mathsf{UnitS}}{\mathsf{E}} \quad S_{\mathsf{LNITL2}} \qquad \frac{\Delta \vdash_{\mathcal{L}} s : A}{x : \mathsf{UnitT}, \Delta \vdash_{\mathcal{L}} \mathsf{let} x : \mathsf{UnitT} \mathsf{be} \mathsf{trivT} \mathsf{in} s : A} \quad S_{\mathsf{LNITL2}} \qquad \frac{\Delta \vdash_{\mathcal{L}} s : A}{x : \mathsf{UnitS}, \Delta \vdash_{\mathcal{L}} \mathsf{let} x : \mathsf{UnitS} \mathsf{be} \mathsf{trivS} \mathsf{in} s : A} \quad S_{\mathsf{LNITL2}} \qquad \frac{\Gamma, x : X, y : Y, \Delta \vdash_{\mathcal{L}} s : A}{\Gamma, z : Y, w : X, \Delta \vdash_{\mathcal{L}} \mathsf{ex} w, z \mathsf{with} x, y \mathsf{in} s : A} \quad S_{\mathsf{BETA}} \qquad \frac{\Gamma, x : X, y : Y, \Delta \vdash_{\mathcal{L}} s : A}{\Gamma, z : Y, \omega \vdash_{\mathcal{L}} \mathsf{cx} x \otimes Y \mathsf{be} x \otimes y \mathsf{in} s : A} \quad S_{\mathsf{LENL1}} \qquad \frac{\Gamma, x : A, y : B, \Delta \vdash_{\mathcal{L}} s : C}{\Gamma, z : A \triangleright_{\mathcal{L}} \mathsf{be} \mathsf{Lz} : X \otimes Y \mathsf{be} x \otimes y \mathsf{in} s : A} \quad S_{\mathsf{LENL2}} \qquad \frac{\Gamma \vdash_{\mathcal{L}} s_1 : A}{\Gamma, \Delta \vdash_{\mathcal{L}} s_1 : A} \quad \Delta \vdash_{\mathcal{L}} s_2 : B} \quad S_{\mathsf{LENR}} \qquad \frac{\Phi \vdash_{\mathcal{C}} t : X}{\Gamma, x : Y, \Delta \vdash_{\mathcal{L}} s : A} \quad S_{\mathsf{LMPL}} \qquad S_{\mathsf{LENL2}} \qquad S_{\mathsf{LENL2}} \qquad S_{\mathsf{LMPL}} \qquad \frac{\Gamma \vdash_{\mathcal{L}} s_1 : A}{\Lambda, x : B \vdash_{\mathcal{L}} s_2 : A \triangleright_{\mathcal{B}}} \quad S_{\mathsf{LENL2}} \qquad S_{\mathsf{LMPL}} \qquad \frac{\Gamma \vdash_{\mathcal{L}} s_1 : A}{\Gamma, y : A \to_{\mathcal{L}} s : B} \quad S_{\mathsf{LMPL}} \qquad S_{\mathsf{$$

Figure 2 Sequent Calculus: Non-Commutative Part

 \blacksquare (T_IMPR, T_IMPL)

 $\begin{array}{c} \Psi_{\vdash_C t:X} \\ & = (T_unitR, S_unitL1): \\ & \frac{A \vdash_L s:A}{x \cdot UnitT \cup unitT} \underbrace{vnrR} \underbrace{x \cdot UnitT \cup unitT$

 $\frac{ \frac{\Phi_1, x: X \vdash_C t_1 : Y}{\Phi_1 \vdash_C \lambda x: X \vdash_I : X \to Y} \max_{\Psi_1, \Phi_1, \Phi_2, \Psi_2 \vdash_C (2 : X)} \frac{\Phi_2 \vdash_C t_2 : X}{\Psi_1, y: Y \to_{\Psi_2} \vdash_C (2 : X)} \frac{\Psi_1, y: Y, \Psi_2 \vdash_C t_3 : Z}{\Psi_1, z: X \to Y, \Phi_2, \Psi_2 \vdash_C (2 : X)} \min_{t \to t_1} \sum_{cut} cut$

is transformed to

$$\frac{\frac{\Phi_{1},x:X\vdash_{C}t_{1}:Y}{\Phi_{1},\Phi_{2}\vdash_{C}[t_{2}/x]t_{1}:Y}}{\Psi_{1},\Phi_{1},\Phi_{2},\Phi_{2}:Y}\underbrace{\text{cut}}_{\Psi_{1},\Phi_{1},\Phi_{2},Y}\underbrace{\Psi_{1},x:Y}_{\Psi_{1},\Phi_{1},\Phi_{2}:Z} \text{cut}}_{\text{cut}}$$

 \blacksquare (S_unitR, S_unitL2):

$$\frac{\frac{\Delta \vdash_{\mathcal{L}} s : A}{\text{$\Sigma \vdash_{\mathcal{L}}$ trivS : UnitS}} \frac{\text{UNITR}}{\sum_{s \vdash_{\mathcal{L}} \text{ [trivS / x] (let $x : UnitS be trivS in $s : A$}} \frac{\Delta \vdash_{\mathcal{L}} s : A}{\text{UNITL2}}}{\frac{\Delta \vdash_{\mathcal{L}} [\text{trivS / x] (let $x : UnitS be trivS in $s : A$}}{\text{UNITL2}}} \frac{\text{UNITL2}}{\text{UNITL3}}$$

is transformed to

$$\Delta \vdash_{\mathcal{L}} s : A$$

 \blacksquare (S_TENR, S_TENL2):

$$\frac{\Gamma_1 \vdash_{\mathcal{L}} s_1 : A \qquad \Gamma_2 \vdash_{\mathcal{L}} s_2 : B}{\Gamma_1, \Gamma_2 \vdash_{\mathcal{L}} s_1 \vdash s_2 : A \vdash B} \xrightarrow{\text{TENL}} \frac{\Delta_1, x : A, y : B, \Delta_2 \vdash_{\mathcal{L}} s_3 : C}{\Delta_1, z : A \vdash B, \Delta_2 \vdash_{\mathcal{L}} \text{let}z : A \vdash B \text{be}x \vdash_{\mathcal{Y}} \text{in}s : C} \xrightarrow{\text{TENL}1} \frac{1}{2} \frac{1}{$$

is transformed to

 \blacksquare (S_IMPRR, S_IMPRL):

$$\frac{\frac{\Gamma, x: A \vdash_{\underline{\mathcal{L}}} s_1 : B}{\Gamma \vdash_{\underline{\mathcal{L}}} \lambda_{\mathit{F}} x: A \cdot s_1 : A \rightarrow B} \text{ imprR}}{\Delta_2, z: A \rightarrow B, \Delta_1 \vdash_{\underline{\mathcal{L}}} s_2 : A} \frac{\Delta_2, y: B \vdash_{\underline{\mathcal{L}}} s_3 : C}{\Delta_2, z: A \rightarrow B, \Delta_1 \vdash_{\underline{\mathcal{L}}} [\mathsf{app}_{\mathit{F}} zs_2/y] s_3 : C}}{\Delta_2, \Gamma, \Delta_1 \vdash_{\underline{\mathcal{L}}} [(\lambda_{\mathit{F}} x: As_1)/z] [\mathsf{app}_{\mathit{F}} zs_2/y] s_3 : C}} \text{ imprL}}$$

is transformed to

$$\frac{\frac{\Gamma,x:A \vdash_{\underline{L}} s_1:B - \Delta_1 \vdash_{\underline{L}} s_2:A}{\Gamma,\Delta_1 \vdash_{\underline{L}} [s_2/x] s_1:B} \text{ cut2}}{\Delta_2,\Gamma,\Delta_1 \vdash_{\underline{L}} [([s_2/x] s_1)/y] s_3:C} \xrightarrow{\Delta_2,y:B \vdash_{\underline{L}} s_3:C} \text{ cut2}}$$

 \blacksquare (S_IMPLR, S_IMPLL):

$$\frac{\sum\limits_{\Gamma \vdash \underline{\mathcal{L}}} \lambda_I x : A.s_1 : B}{\sum\limits_{\Gamma \vdash \underline{\mathcal{L}}} \lambda_I x : A.s_1 : B - A} \text{ interpolation} \qquad \frac{\Delta_1 \vdash \underline{\mathcal{L}} s_2 : A}{\sum\limits_{\Gamma \vdash \underline{\mathcal{L}}} \sum\limits_{\Gamma \vdash \underline{\mathcal{L}}} \left(\sum\limits_{\Gamma \vdash \underline{\mathcal{L}}} \sum\limits_{\Gamma \vdash \underline{\mathcal{L}}} \left(\sum\limits_{\Gamma \vdash \underline{\mathcal{L}}} \sum\limits_{\Gamma \vdash \underline{\mathcal{L}}} \left(\sum\limits_{\Gamma \vdash \underline{\mathcal{L}}} \sum\limits_{\Gamma \vdash \underline{\mathcal{L}}} \sum\limits_{\Gamma \vdash \underline{\mathcal{L}}} \left(\sum\limits_{\Gamma \vdash \underline{\mathcal{L}}} \sum\limits_{\Gamma$$

is transformed to

$$\frac{x:A,\Gamma\vdash_{\underline{\mathcal{L}}}s_1:B \qquad \Delta_1\vdash_{\underline{\mathcal{L}}}s_2:A}{\Delta_1,\Gamma\vdash_{\underline{\mathcal{L}}}[s_2/x]s_1:B} \text{ cut2} \\ \qquad \frac{\lambda_1,\Gamma\vdash_{\underline{\mathcal{L}}}[s_2/x]s_1:B}{\Delta_1,\Gamma,\Delta_2\vdash_{\underline{\mathcal{L}}}[([s_2/x]s_1)/y]s_3:C} \text{ cut2}$$

= (S_FR, S_FL):

$$\frac{\frac{\Phi \vdash_{C} t : X}{\Phi \vdash_{L} F : FX} \vdash_{FR} FR}{\Gamma, \Phi, \Phi \vdash_{L} [Ft/y] (\text{let} y : FX \land \Phi \vdash_{L} Ex \land s : A)} \vdash_{L} FL}{\Gamma, \Phi, \Phi, \Phi \vdash_{L} [Ft/y] (\text{let} y : FX \land \Phi \vdash_{L} x \text{in} s) : A)} \vdash_{L} Cur2}$$

is transformed to

$$\frac{\Phi \vdash_{C} t : X \qquad \Gamma, x : A, \Delta \vdash_{\mathcal{L}} s : A}{\Gamma, \Phi, \Delta \vdash_{\mathcal{L}} [t/x]s : A} \text{ cutl}$$

= (T_GR, S_GL):

$$\frac{\frac{\Phi \vdash_{\mathcal{L}} s_1 : A}{\Phi \vdash_{\mathcal{L}} \mathsf{G} s_1 : \mathsf{G} A} \; \mathsf{GR} \quad \frac{\Gamma, x : A, \Delta \vdash_{\mathcal{L}} s_2 : B}{\Gamma, y : \mathsf{G} A, \Delta \vdash_{\mathcal{L}} \mathsf{let} y : \mathsf{G} A \, \mathsf{be} \, \mathsf{G} x \mathsf{in} \, s_2 : B} \; \mathsf{GL}}{\Gamma, \Phi, \Delta \vdash_{\mathcal{L}} [\mathsf{G} s_1/y] (\mathsf{let} y : \mathsf{G} A \, \mathsf{be} \, \mathsf{G} x \mathsf{in} \, s_2) : B} \; \mathsf{curl}}$$

is transformed to

$$\frac{\Phi \vdash_{\mathrel{\pounds}} s_1 : A \qquad \Gamma, x : A, \Delta \vdash_{\mathrel{\pounds}} s_2 : B}{\Gamma, \Phi, \Delta \vdash_{\mathrel{\pounds}} [s_1/x] s_2 : B} \text{ cut}$$

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Based on the key cases, given a formula (either commutative or non-commutative) L and proofs Π , Π' , of sequents $M \vdash N$ and $M' \vdash N'$ respectively with degrees less than |L|, there is a proof of $M, N \vdash M', N'$ with degree less than |L|, s.t. all currences of formula L is removed. This can be proved by induction on $h(\Pi) + h(\Pi')$. Therefore, we have the result that given a proof of a sequent with degree d > 0, there is a proof of the same sequent. As a result, we have the cut elimination theorem.

▶ **Theorem 28** (Cut Elimination). *Let* Π *be a proof of a sequent* $\Phi \vdash_C t : X$ *or a sequent* $\Gamma \vdash_{\mathcal{L}} s : A$ *s.t.* $|\Pi| > 0$. *Then there is a cut-free proof of the same sequent.*

5.2 Natural Deduction

The term assignment for natural deduction of the commutative part of the model, i.e. the SMCC of the adjunction, is defined in Figure 3. And the term assignme for the non-commutative part, i.e. the Lambek category of the adjunction, is defined in Figure 4.

$$\frac{d \vdash_{C} t_{1} : \text{UnitT} \quad \forall \vdash_{C} t_{2} : Y}{\Phi, \Psi \vdash_{C} t_{1} : \text{UnitT} \quad \forall \vdash_{C} t_{2} : Y} \quad \text{T_UNITE}$$

$$\frac{d \vdash_{C} t_{1} : X \quad \Psi \vdash_{C} t_{2} : Y}{\Phi, \Psi \vdash_{C} t_{1} : X \otimes Y} \quad \text{T_UNITE}$$

$$\frac{d \vdash_{C} t_{1} : X \otimes Y \quad \Psi_{1}, x : X, y : Y, \Psi_{2} \vdash_{C} t_{2} : Z}{\Psi_{1}, \Phi, \Psi_{2} \vdash_{C} \text{let} t_{1} : X \otimes Y \text{be } x \otimes y \text{ in } t_{2} : Z} \quad \text{T_TENE}$$

$$\frac{d \vdash_{C} t_{1} : X \otimes Y \quad \Psi_{1}, x : X, y : Y, \Psi_{2} \vdash_{C} t_{2} : Z}{\Psi_{1}, \Phi, \Psi_{2} \vdash_{C} \text{let} t_{1} : X \otimes Y \text{be } x \otimes y \text{ in } t_{2} : Z} \quad \text{T_TENE}$$

$$\frac{d \vdash_{C} t_{1} : X \multimap Y \quad \Psi \vdash_{C} t_{2} : X}{\Phi, \Psi \vdash_{C} \text{app } t_{1} t_{2} : Y} \quad \text{T_IMPE} \quad \frac{d \vdash_{L} s : A}{\Phi \vdash_{C} \text{Gs} : \text{GA}} \quad \text{T_GI}$$

$$\frac{\Gamma, x : X, y : Y, \Delta \vdash_{L} s : A}{\Gamma, z : Y, w : X, \Delta \vdash_{L} \text{exw}, z \text{with } x, y \text{ in } s : A} \quad \text{S_BETA}$$

Figure 3 Natural Deduction: Commutative Part

$$\frac{A \vdash_{\mathcal{L}} x : A \vdash_{\mathcal{L}} x : A}{A \vdash_{\mathcal{L}} x : A} \quad S_{_DD} \qquad \frac{A \vdash_{\mathcal{L}} trivS : UnitS}{A} \quad S_{_UNITEI} \qquad \frac{A \vdash_{\mathcal{L}} t : UnitT}{A} \quad \Gamma \vdash_{\mathcal{L}} s : A}{A \vdash_{\mathcal{L}} t : UnitT} \quad \Gamma \vdash_{\mathcal{L}} s : A} \quad S_{_UNITEI}$$

$$\frac{A \vdash_{\mathcal{L}} t : UnitT}{A} \quad \Gamma \vdash_{\mathcal{L}} s : A}{A \vdash_{\mathcal{L}} t : UnitT} \quad \Gamma \vdash_{\mathcal{L}} s : A} \quad S_{_UNITEI} \qquad \frac{A \vdash_{\mathcal{L}} t : UnitS}{A \vdash_{\mathcal{L}} t : UnitS} \quad \Delta \vdash_{\mathcal{L}} s_2 : A}{A \vdash_{\mathcal{L}} t : UnitS} \quad \Delta \vdash_{\mathcal{L}} s_2 : A} \quad S_{_UNITE2}$$

$$\frac{A \vdash_{\mathcal{L}} t : A \land_{\mathcal{L}} s_2 : B}{A \vdash_{\mathcal{L}} t : A \vdash_{\mathcal{L}} s_2 : A \vdash_{\mathcal{B}}} \quad S_{_TENI} \qquad \frac{A \vdash_{\mathcal{L}} t : X \otimes Y \quad \Gamma_1, x : X, y : Y, \Gamma_2 \vdash_{\mathcal{L}} t : A}{A \vdash_{\mathcal{L}} t : X \otimes Y be x \otimes y in s : A} \quad S_{_TENEI}$$

$$\frac{A \vdash_{\mathcal{L}} t : A \vdash_{\mathcal{L}} s_1 : A \vdash_{\mathcal{B}} \Delta_1, x : A, y : B, \Delta_2 \vdash_{\mathcal{L}} s_2 : C}{A \vdash_{\mathcal{L}} t : A \vdash_{\mathcal{L}} t$$

Figure 4 Natural Deduction: Non-Commutative Part

We could derive exchange comonadically as follows:

$$\frac{y_0: \mathsf{GB} \vdash_{\mathsf{C}} y_0: \mathsf{GB}}{y_0: \mathsf{GB} \vdash_{\mathsf{C}} y_0: \mathsf{FGB}} \vdash_{\mathsf{D}} \mathsf{Er} \frac{y_0: \mathsf{GB} \vdash_{\mathsf{C}} \mathsf{FG} \mathsf{GG}}{x_0: \mathsf{GA} \vdash_{\mathsf{C}} \mathsf{FG} \mathsf{G}} \vdash_{\mathsf{F}} \mathsf{Er} \frac{\mathsf{BE}}{x_0: \mathsf{GA} \vdash_{\mathsf{C}} \mathsf{FG} \mathsf{G}} \vdash_{\mathsf{F}} \mathsf{Er} \frac{\mathsf{BE}}{x_0: \mathsf{GA} \vdash_{\mathsf{C}} \mathsf{FG} \mathsf{G}} \vdash_{\mathsf{F}} \mathsf{Er} \frac{\mathsf{BE}}{x_0: \mathsf{GA} \vdash_{\mathsf{C}} \mathsf{FG} \mathsf{G}} \vdash_{\mathsf{F}} \mathsf{Er} + \mathsf{FG} + \mathsf{FG} \mathsf{Er} + \mathsf{FG} \mathsf{Er} + \mathsf{FG} \mathsf{Er} + \mathsf{FG} \mathsf{Er} + \mathsf{FG} + \mathsf{FG} \mathsf{Er} + \mathsf{FG} \mathsf{Er} + \mathsf{FG} + \mathsf{$$

We also have the three cut rules derivable in the natural deduction: (NOTE: Don't know how to prove the third one S_cut2.)

$$\frac{\Phi \vdash_{C} t_{1} : X \quad \Psi_{1}, x : X, \Psi_{2} \vdash_{C} t_{2} : Y}{\Psi_{1}, \Phi, \Psi_{2} \vdash_{C} [t_{1}/x]t_{2} : Y} \quad T_{_\text{CUT}} \qquad \frac{\Phi \vdash_{C} t : X \quad \Gamma_{1}, x : X, \Gamma_{2} \vdash_{\mathcal{L}} s : A}{\Gamma_{1}, \Phi, \Gamma_{1} \vdash_{\mathcal{L}} [t/x]s : A} \quad S_{_\text{CUT}} \qquad \frac{\Gamma \vdash_{\mathcal{L}} s_{1} : A \quad \Delta_{1}, x : A, \Delta_{2} \vdash_{\mathcal{L}} s_{2} : B}{\Delta_{1}, \Gamma, \Delta_{2} \vdash_{\mathcal{L}} [s_{1}/x]s_{2} : B} \quad S_{_\text{CUT}} \qquad S_{_\text{CUT}} \qquad$$

5.2.1 One Step β -Reduction

 \blacksquare (T_IMPI, T_IMPE):

We define the normalization procedure by considering the following pairs of introduction and elimination rules:

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$$\frac{\frac{\Phi,x:X \vdash_{C} t_{1}:Y}{\Phi \vdash_{C} \lambda x:X.t_{1}:X \multimap Y} \text{ mpI}}{\Phi,\Psi \vdash_{C} \text{ app}\left(\lambda x:X.t_{1}\right) t_{2}:Y} \text{ mpE}}{\Phi,\Psi \vdash_{C} \text{ app}\left(\lambda x:X.t_{1}\right) t_{2}:Y}$$

normalizes to

$$\frac{\Phi,x:X\vdash_C t_1:Y\qquad \Psi\vdash_C t_2:X}{\Phi,\Psi\vdash_C [t_2/x]t_1:Y}\text{ cut}$$

 \blacksquare (S_unitI, S_unitE2):

normalizes to

$$\Delta \vdash_{\mathcal{L}} s : A$$

■ (S_TENI, S_TENE2):

$$\frac{\frac{\Gamma_1 \vdash_{\mathcal{L}} s_1 : A - \Gamma_2 \vdash_{\mathcal{L}} s_2 : B}{\Gamma_1, \Gamma_2 \vdash_{\mathcal{L}} s_1 \triangleright s_2 : A \triangleright B}}{\Delta_1, \Gamma_1, \Gamma_2, \Delta_2 \vdash_{\mathcal{L}} \operatorname{let} s_1 \triangleright s_2 : A \triangleright B \operatorname{be} x \triangleright y \operatorname{in} s_3 : C}} \times \Delta_1 + \sum_{i=1}^{n} \frac{\Gamma_i \vdash_{\mathcal{L}} s_1 \vdash_{\mathcal{L}} s_2 : A \triangleright B}{\Gamma_i \vdash_{\mathcal{L}} s_2 \vdash_{\mathcal{L}} \operatorname{be} s_1 \triangleright s_2 : A \triangleright B \operatorname{be} x \triangleright y \operatorname{in} s_3 : C}}{\Delta_1 \vdash_{\mathcal{L}} c_1 \vdash_{\mathcal{L}} c_2 \vdash_{\mathcal{L}} \operatorname{be} s_1 \triangleright s_2 : A \triangleright B \operatorname{be} x \triangleright y \operatorname{in} s_3 : C}} \times \Delta_1 + \Delta_1 + \Delta_2 \vdash_{\mathcal{L}} c_2 \vdash_{\mathcal{L}} c_3 \vdash_{$$

normalizes to

$$\frac{\Gamma_1 \vdash_{\underline{\mathcal{L}}} s_1 : A \qquad \frac{\Gamma_2 \vdash_{\underline{\mathcal{L}}} s_2 : B \qquad \Delta_1, x : X, y : Y, \Delta_2 \vdash_{\underline{\mathcal{L}}} s_3 : C}{\Delta_1, x : X, \Gamma_2, \Delta_2 \vdash_{\underline{\mathcal{L}}} [s_2/y] s_3 : C} \text{ cut2}}{\Delta_1, \Gamma_1, \Gamma_2, \Delta_2 \vdash_{\underline{\mathcal{L}}} [s_1/x] [s_2/y] s_3 : C} \text{ cut2}}$$

 \blacksquare (S_IMPRI, S_IMPRE):

$$\frac{\frac{\Gamma, x: A \vdash_{\pounds} s_1: B}{\Gamma \vdash_{\pounds} \lambda_{\digamma} x: A.s_1: A \rightarrow B} \text{ impril}}{\Gamma, \Delta \vdash_{\pounds} \mathsf{app}_{\digamma} (\lambda_{\digamma} x: A.s_1) s_2: B} \text{ unitE2}$$

normalizes to

$$\frac{\Gamma, x : A \vdash_{\mathrel{\mathcal{L}}} s_1 : B \qquad \Delta \vdash_{\mathrel{\mathcal{L}}} s_2 : A}{\Gamma, \Delta \vdash_{\mathrel{\mathcal{L}}} [s_2/x] s_1 : B} \text{ cut2}$$

 \blacksquare (S_IMPLI, S_IMPLE):

$$\frac{\frac{x:A,\Gamma \vdash_{\underline{\mathcal{L}}} s_1:B}{\Gamma \vdash_{\underline{\mathcal{L}}} \lambda_l x:As_1:B \leftarrow A}}{\Delta,\Gamma \vdash_{\underline{\mathcal{L}}} \operatorname{app}_l (\lambda_l x:As_1)s_2:B} \xrightarrow{\Delta \vdash_{\underline{\mathcal{L}}} s_2:A} \operatorname{unitE2}$$

normalizes to

$$\frac{x:A,\Gamma \vdash_{\mathrel{\mathcal{L}}} s_1:B \qquad \Delta \vdash_{\mathrel{\mathcal{L}}} s_2:A}{\Delta,\Gamma \vdash_{\mathrel{\mathcal{L}}} [s_2/x]s_1:B} \text{ cut} 2$$

= (S_FI, S_FE):

$$\frac{\frac{\Phi \vdash_{\mathcal{L}} y : X}{\Phi \vdash_{\mathcal{L}} \mathsf{F} y : \mathsf{F} X} \ \mathsf{FI}}{\Delta_1, \Phi, \Delta_2 \vdash_{\mathcal{L}} \mathsf{let} \mathsf{F} x : \mathsf{F} X \mathsf{be} \, \mathsf{F} y \, \mathsf{in} \, s : A} \ \mathsf{FE}$$

normalizes to

$$\frac{\Phi \vdash_{C} y : X \qquad \Delta_{1}, x : X, \Delta_{2} \vdash_{\mathcal{L}} s : A}{\Delta_{1}, \Phi, \Delta_{2} \vdash_{\mathcal{L}} [y/x]s : A} \text{ cutl}$$

■ (T_GI, S_GE):

$$\frac{\frac{\Phi \vdash_{\mathcal{L}} s : A}{\Phi \vdash_{\mathcal{C}} \mathsf{G}s : \mathsf{G}A} \; \mathsf{GI}}{\Phi \vdash_{\mathcal{L}} \mathsf{derelict} \mathsf{G}s : A} \; \mathsf{GE}$$

normalizes to

$$\Phi \vdash_{\mathcal{L}} s : A$$

▶ **Theorem 29** (Normalization). *For a cut-free deduction* Π , *there is a deduction which is in normal form.*

Proof. By induction on the structure of Π .

5.2.2 Commuting Conversions

- \blacksquare Commutation of UnitT_E:
 - \blacksquare (T_unite, T_unite):

$$\frac{\Phi_1 \vdash_C r_1 : \mathsf{UnitT}}{\Phi_2, \Phi_1 \vdash_C \mathsf{let}_2 : \mathsf{UnitT}} \underbrace{\Phi_2 \vdash_C r_2 : \mathsf{UnitT}}_{\mathsf{UnitT}} \underbrace{\mathsf{unitTE}}_{\mathsf{UnitT}} \underbrace{\mathsf{unitTE}}_{\mathsf{Q}_2, \Phi_1, \Phi_3 \vdash_C \mathsf{let}(\mathsf{let}_2 : \mathsf{UnitT}) \mathsf{betrivTin}_{1}) : \mathsf{UnitT}}_{\mathsf{UnitT}} \underbrace{\mathsf{unitTE}}_{\mathsf{UnitT}} \underbrace{\Phi_3 \vdash_C r_3 : X}_{\mathsf{unitTE}} \underbrace{\mathsf{unitTE}}_{\mathsf{UnitT}}$$

commutes to

$$\frac{\Phi_1 +_C r_1 : \mathsf{UnitT}}{\Phi_1 + \Phi_3 +_C \mathsf{let} r_1 : \mathsf{UnitT}} = \frac{\Phi_3 +_C r_3 : X}{\mathsf{trivT}} \quad \underset{\mathsf{UnitT}}{\mathsf{unitE}} = \frac{\Phi_2 +_C r_2 : \mathsf{UnitT}}{\Phi_2 +_C r_2 : \mathsf{UnitT}} \quad \underset{\mathsf{UnitE}}{\mathsf{unitE}}$$

■ (T_UNITE, T_TENE) need multiple exchanges at the end:

$$\frac{\Phi_1 \vdash_C t_1 : X \otimes Y \qquad \Phi_2 \vdash_C t_2 : \mathsf{UnitT}}{\Phi_2, \Phi_1 \vdash_C \mathsf{let} t_2 : \mathsf{UnitT} \mathsf{betrivTin} t_1 : X \otimes Y \qquad \mathsf{UNITE}}{\Psi_1, \Phi_2, \Phi_1, \Psi_2 \vdash_C \mathsf{let} (\mathsf{let} t_2 : \mathsf{UnitT} \mathsf{betrivTin} t_1) : X \otimes Y \mathsf{be} x \otimes y \mathsf{in} t_3 : Z} \qquad \mathsf{TENE}$$

commutes to

$$\frac{\Phi_1 \vdash_C t_1 : X \otimes Y \qquad \Psi_1, x : X, y : Y, \Psi_2 \vdash_C t_3 : Z}{\Psi_1, \Phi_1, \Psi_2 \vdash_C \mathsf{let} t_1 : X \otimes Y \mathsf{be} \, x \otimes y \mathsf{in} \, t_3 : Z} \xrightarrow{\mathsf{TENE}} \frac{\Phi_2 \vdash_C t_2 : \mathsf{UnitT}}{\Phi_2, \Psi_1, \Phi_1, \Psi_2 \vdash_C \mathsf{let} t_2 : \mathsf{UnitT} \mathsf{be} \, \mathsf{trivT} \, \mathsf{in} \, (\mathsf{let} \, t_1 : X \otimes Y \mathsf{be} \, x \otimes y \mathsf{in} \, t_3) : Z} \xrightarrow{\mathsf{UNITE}} \mathsf{UNITE}$$

- (T_UNITE, T_IMPE):

$$\frac{\Phi_1 \vdash_C t_1 : X \multimap Y \qquad \Phi_2 \vdash_C t_2 : \mathsf{UnitT}}{\Phi_2, \Phi_1 \vdash_C \mathsf{let} t_2 : \mathsf{UnitT} \mathsf{be} \mathsf{trivT} \mathsf{in} t_1 : X \multimap Y} \quad \mathsf{^{TENE}} \quad \Phi_3 \vdash_C t_3 : X}{\Phi_2, \Phi_1, \Phi_3 \vdash_C \mathsf{app} (\mathsf{let} t_2 : \mathsf{UnitT} \mathsf{be} \mathsf{trivT} \mathsf{in} t_1) t_3 : Y} \quad \mathsf{unitE}$$

commutes to

$$\frac{\frac{\Phi_1 \vdash_C t_1 : X \multimap Y \qquad \Phi_3 \vdash_C t_3 : X}{\Phi_1, \Phi_3 \vdash_C \operatorname{app} t_1 t_3 : Y} \text{ unitE}}{\Phi_2, \Phi_1, \Phi_3 \vdash_C \operatorname{let} t_2 : \operatorname{UnitT} \operatorname{betrivT in (app} t_1 t_3) : Y} \text{ TENE}}$$

- Commutation of \otimes_E :
 - \blacksquare (T_TENE, T_UNITE):

$$\frac{\Phi_1, x: X, y: Y, \Phi_2 \vdash_C t_1: \mathsf{UnitT} \qquad \Psi_1 \vdash_C t_2: X \otimes Y}{\Phi_1, \Psi_1, \Phi_2 \vdash_C \mathsf{let} t_2: X \otimes Y \mathsf{be} \, x \otimes \mathsf{yin} t_1: \mathsf{UnitT}} \xrightarrow{\mathsf{TENE}} \qquad \Psi_2 \vdash_C t_3: Z}{\Phi_1, \Psi_1, \Phi_2, \Psi_2 \vdash_C \mathsf{let} (\mathsf{let} t_2: X \otimes Y \mathsf{be} \, x \otimes \mathsf{yin} t_1): \mathsf{UnitT} \mathsf{be} \, \mathsf{trivTin} \, t_3: Z} \xrightarrow{\mathsf{UNITE}}$$

commutes to

$$\frac{\Phi_1,x:X,y:Y,\Phi_2 \vdash_C t_1: \mathsf{UnitT} \quad \Psi_2 \vdash_C t_3:Z}{\Phi_1,x:X,y:Y,\Phi_2,\Psi_2 \vdash_C \mathsf{let} t_1: \mathsf{UnitT} \mathsf{be trivT} \mathsf{in} t_3:Z} \underbrace{\mathsf{UNITE}}_{\mathsf{TENE}} \quad \Psi_1 \vdash_C t_2:X \otimes Y \\ \Phi_1,\Psi_1,\Phi_2,\Psi_2 \vdash_C \mathsf{let} t_2:X \otimes Y \mathsf{be} x \otimes y \mathsf{in} (\mathsf{let} t_1: \mathsf{UnitT} \mathsf{be trivT} \mathsf{in} t_3):Z} \\ \mathsf{TENE}$$

= (T_TENE, T_TENE):

$$\frac{\frac{\Phi_{1},x:X_{2},y:Y_{2},\Phi_{2}\vdash_{C}t_{1}:X_{1}\otimes Y_{1}}{\Phi_{1},\Psi,\Phi_{2}\vdash_{C}\operatorname{let}t_{2}:X_{2}\otimes Y_{2}\operatorname{be}x\otimes y\operatorname{in}t_{1}:X_{1}\otimes Y_{1}}}{\Psi_{1},\Phi_{1},\Psi,\Phi_{2},\Psi_{2}\vdash_{C}\operatorname{let}(\operatorname{let}t_{2}:X_{2}\otimes Y_{2}\operatorname{be}x\otimes y\operatorname{in}t_{1}):X_{1}\otimes Y_{1}}} \underset{\mathsf{TENE}}{\mathsf{TENE}} \Psi_{1},w:X_{1},z:Y_{1},\Psi_{2}\vdash_{C}t_{3}:Z} \underset{\mathsf{TENE}}{\mathsf{TENE}}$$

commutes to

$$\frac{\frac{\Phi_{1},x:X_{2},y:Y_{2},\Phi_{2} \vdash_{C} t_{1}:X_{1} \otimes Y_{1}}{\Psi_{1},\Phi_{1},x:X_{2},y:Y_{2},\Phi_{2},\Psi_{2} \vdash_{C} \operatorname{let} t_{1}:X_{1} \otimes Y_{1} \operatorname{be} w \otimes z \operatorname{in} t_{3}:Z}}{\Psi_{1},\Phi_{1},\psi,\Phi_{2},\Psi_{2} \vdash_{C} \operatorname{let} t_{2}:X_{2} \otimes Y_{2} \operatorname{be} x \otimes y \operatorname{in} (\operatorname{let} t_{1}:X_{1} \otimes Y_{1} \operatorname{be} w \otimes z \operatorname{in} t_{3}:Z}} \underset{\text{TENE}}{\text{TENE}} \Psi \vdash_{C} t_{2}:X_{2} \otimes Y_{2} \underset{\text{TENE}}{\text{TENE}}$$

 \blacksquare (T_TENE, T_IMPE):

$$\frac{\frac{\Phi_1,x:X_2,y:Y_2,\Phi_2 \vdash_C t_1:X_1 \multimap Y_1 \qquad \Psi_1 \vdash_C t_2:X_2 \otimes Y_2}{\Phi_1,\Psi_1,\Phi_2 \vdash_C \text{let} t_2:X_2 \otimes Y_2 \text{be} x \otimes y \text{in} t_1:X_1 \multimap Y_1} \text{ }_{\text{MMPE}} \qquad \frac{\Psi_2 \vdash_C t_3:X_1}{\Phi_1,\Psi_1,\Phi_2,\Psi_2 \vdash_C \text{app} (\text{let} t_2:X_2 \otimes Y_2 \text{be} x \otimes y \text{in} t_1)t_3:Y_1} \text{ }_{\text{TENE}}$$

commutes to

$$\frac{\frac{\Phi_{1},x:X_{2},y:Y_{2},\Phi_{2} \vdash_{C}t_{1}:X_{1} \multimap Y_{1} \qquad \Psi_{2} \vdash_{C}t_{3}:X_{1}}{\Phi_{1},x:X_{2},y:Y_{2},\Phi_{2},\Psi_{2} \vdash_{C}\operatorname{app}t_{1}t_{3}:Y_{1}} \xrightarrow{\operatorname{TENE}} \frac{\Psi_{1} \vdash_{C}t_{2}:X_{2} \otimes Y_{2}}{\Phi_{1},\Psi_{1},\Phi_{2},\Psi_{2} \vdash_{C}\operatorname{let}t_{2}:X_{2} \otimes Y_{2}\operatorname{be}x \otimes y\operatorname{in}(\operatorname{app}t_{1}t_{3}):Y_{1}} \xrightarrow{\operatorname{MPE}} \frac{\Phi_{1} \vdash_{C}t_{2}:X_{2} \otimes Y_{2}}{\operatorname{ImpE}}$$

- Commutation of \multimap_E :
 - (T_IMPE, T_UNITE):

$$\frac{\frac{\Phi_1 \vdash_C t_1 : \mathsf{UnitT}}{\Phi_2, \Phi_1 \vdash_C \mathsf{app} t_2 t_1 : \mathsf{UnitT} - \mathsf{UnitT}}{\Phi_2, \Phi_1 \vdash_C \mathsf{app} t_2 t_1 : \mathsf{UnitT}} \underset{\mathsf{MaPE}}{\mathsf{namE}} \quad \frac{\Phi_3 \vdash_C t_3 : \mathsf{UnitT}}{\Phi_3 \vdash_C \mathsf{InitT}} \xrightarrow{\mathsf{TENE}}$$

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commutes to

$$\frac{\Phi_1 \vdash_C \iota_1 : \mathsf{UnitT} \quad \Phi_3 \vdash_C \iota_3 : \mathsf{UnitT}}{\Phi_1, \Phi_3 \vdash_C \mathsf{I} : \mathsf{UnitT} \mathsf{DetrivT} \mathsf{in} \iota_3 : \mathsf{UnitT}} \\ \frac{\Phi_2, \Phi_1, \Phi_3 \vdash_C \mathsf{Int} \iota_1 : \mathsf{UnitT} \mathsf{DetrivT} \mathsf{in} \iota_3 : \mathsf{UnitT}}{\Phi_2, \Phi_1, \Phi_3 \vdash_C \mathsf{app} \iota_2 (\mathsf{Iet} \iota_1 : \mathsf{UnitT} \mathsf{DetrivT} \mathsf{in} \iota_3) : \mathsf{UnitT}} \\ \mathsf{ImpE}$$

- \blacksquare (T_IMPE, T_TENE): ?
- (T IMPE, T IMPE): ?
- Commutation of \triangleright_E :
 - \blacksquare (S_unitE2, S_unitE2):

$$\frac{\Gamma_1 \vdash_{\mathcal{L}} s_1 : \text{UnitS}}{\Gamma_2, \Gamma_1 \vdash_{\mathcal{L}} \text{let} s_2 : \text{UnitS}} \frac{\Gamma_2 \vdash_{\mathcal{L}} s_2 : \text{UnitS}}{\text{UnitT}} \xrightarrow{\text{UnitTE}} \frac{\text{UnitT}}{\Gamma_3 \vdash_{\mathcal{L}} \text{let} s_2 : \text{UnitS}} \frac{1}{\text{UnitT}} \frac{s_3 \vdash_{\mathcal{L}} s_3 : A}{\text{UnitT}}$$

commutes to

$$\frac{\Gamma_1 \vdash_{\mathcal{L}} s_1 : \mathsf{UnitS}}{\Gamma_1, \Gamma_3 \vdash_{\mathcal{L}} \mathsf{let} s_1 : \mathsf{UnitS}} \underbrace{\Gamma_3 \vdash_{\mathcal{L}} s_3 : A}_{\mathsf{UNITE}} \underbrace{\mathsf{UnitS}}_{\mathsf{C}_2, \Gamma_1, \Gamma_3 \vdash_{\mathcal{L}} \mathsf{let} s_2 : \mathsf{UnitS}} \underbrace{\mathsf{DetrivS} \mathsf{in} s_3 : A}_{\mathsf{UNITE}} \underbrace{\Gamma_2 \vdash_{\mathcal{L}} s_2 : \mathsf{UnitS}}_{\mathsf{C}_2, \Gamma_1, \Gamma_3 \vdash_{\mathcal{L}} \mathsf{let} s_2 : \mathsf{UnitS}} \underbrace{\mathsf{UnitS}}_{\mathsf{UNITE}} \underbrace{\mathsf{UnitS}}_{\mathsf{UNITE}}$$

■ (S_UNITE2, S_TENE2): Does NOT commute

$$\frac{\Gamma_1 \vdash_{\mathcal{L}} s_1 : A \triangleright B \qquad \Gamma_2 \vdash_{\mathcal{L}} s_2 : \mathsf{UnitS}}{\Gamma_2, \Gamma_1 \vdash_{\mathcal{L}} \mathsf{let} s_2 : \mathsf{UnitS} \, \mathsf{be} \, \mathsf{trivS} \, \mathsf{in} \, s_1 : A \triangleright B} \quad \mathsf{unitE} \qquad \qquad \Delta_1, x : A, y : B, \Delta_2 \vdash_{\mathcal{L}} s_3 : C} \\ \Delta_1, \Gamma_2, \Gamma_1, \Delta_2 \vdash_{\mathcal{L}} \mathsf{let} \, (\mathsf{let} s_2 : \mathsf{UnitS} \, \mathsf{be} \, \mathsf{trivS} \, \mathsf{in} \, s_1) : A \triangleright B \, \mathsf{be} \, x \triangleright y \, \mathsf{in} \, s_3 : C} \quad \mathsf{TENE2}$$

commutes to

$$\frac{\Gamma_1 \vdash_{\mathcal{L}} s_1 : A \triangleright B \qquad \Delta_1, x : A, y : B, \Delta_2 \vdash_{\mathcal{L}} s_3 : C}{\Delta_1, \Gamma_1, \Delta_2 \vdash_{\mathcal{L}} \mathsf{let} s_1 : A \triangleright B \, \mathsf{be} x \triangleright y \mathsf{in} s_3 : C} \qquad \text{TENE2} \\ \frac{\Gamma_2, \Delta_1, \Gamma_1, \Delta_2 \vdash_{\mathcal{L}} \mathsf{let} s_2 : \mathsf{JonitS}}{\Gamma_2, \Delta_1, \Gamma_1, \Delta_2 \vdash_{\mathcal{L}} \mathsf{let} s_2 : \mathsf{UnitS} \, \mathsf{be} \, \mathsf{trivS} \, \mathsf{in} \, (\mathsf{let} s_1 : A \triangleright B \, \mathsf{be} \, x \triangleright y \mathsf{in} s_3) : C} \quad \mathsf{unitE}$$

= (S_unitE2, S_imprE):

$$\frac{ \frac{\Gamma_1 \vdash_{\mathcal{L}} s_1 : A \rightarrow B \qquad \Gamma_2 \vdash_{\mathcal{L}} s_2 : \text{UnitS}}{\Gamma_2, \Gamma_1 \vdash_{\mathcal{L}} \text{let} s_2 : \text{UnitS be trivS in} s_1 : A \rightarrow B} \text{ unitE}}{\Gamma_2, \Gamma_1, \Gamma_3 \vdash_{\mathcal{L}} \text{app}_r (\text{let} s_2 : \text{UnitS be trivS in} s_1) s_3 : B}} \text{ Impre}$$

commutes to

$$\frac{\Gamma_1 \vdash_{\mathcal{L}} s_1 : A \rightarrow B \qquad \Gamma_3 \vdash_{\mathcal{L}} s_3 : A}{\Gamma_1, \Gamma_3 \vdash_{\mathcal{L}} \mathsf{app}_r s_1 s_3 : B} \qquad \mathsf{MERE} \\ \hline \Gamma_2, \Gamma_1, \Gamma_3 \vdash_{\mathcal{L}} \mathsf{let} s_2 : \mathsf{UnitS be trivS in (app_r s_1 s_3) : } B \qquad \mathsf{unitE}$$

■ (S_UNITE2, S_IMPLE): Does NOT commute.

$$\frac{\Gamma_1 \vdash_{\mathcal{L}} s_1 : B \vdash_A \qquad \Gamma_2 \vdash_{\mathcal{L}} s_2 : \mathsf{UnitS}}{\Gamma_2 . \Gamma_1 \vdash_{\mathcal{L}} \mathsf{let} s_2 : \mathsf{UnitS} \, \mathsf{betrivS} \, \mathsf{in} s_1 : B \vdash_A} \, \mathsf{unitE} \qquad \Gamma_3 \vdash_{\mathcal{L}} s_3 : A} \\ \Gamma_3 . \Gamma_2 . \Gamma_1 \vdash_{\mathcal{L}} \mathsf{pap}_I \, (\mathsf{let} s_2 : \mathsf{UnitS} \, \mathsf{betrivS} \, \mathsf{in} s_1) \, s_3 : B} \quad \mathsf{impRE}$$

commutes to

$$\frac{\Gamma_1 \vdash_{\mathcal{L}} s_1 : B \leftarrow A \qquad \Gamma_3 \vdash_{\mathcal{L}} s_3 : A}{\Gamma_3, \Gamma_1 \vdash_{\mathcal{L}} \mathsf{app}_I s_1 s_3 : B} \qquad \text{\tiny mBPRE} \qquad \Gamma_2 \vdash_{\mathcal{L}} s_2 : \mathsf{UnitS} \\ \hline \Gamma_2, \Gamma_3, \Gamma_1 \vdash_{\mathcal{L}} \mathsf{let} s_2 : \mathsf{UnitS} \, \mathsf{be trivS} \, \mathsf{in} \, (\mathsf{app}_I s_1 s_3) : B} \qquad \mathsf{unitE}$$

 \blacksquare (S_TENE2, S_UNITE2):

$$\frac{\Gamma_1, x: A, y: B, \Gamma_2 \vdash_{\mathcal{L}} s_1 : \text{UnitS} \qquad \Delta_1 \vdash_{\mathcal{L}} s_2 : A \triangleright B}{\Gamma_1, \Delta_1, \Gamma_2 \vdash_{\mathcal{L}} \text{let} s_2 : A \triangleright B \text{ be } x \triangleright y \text{in } s_1 : \text{UnitS}} \qquad \frac{\Delta_2 \vdash_{\mathcal{L}} s_3 : C}{\Gamma_1, \Delta_1, \Gamma_2, \Delta_2 \vdash_{\mathcal{L}} \text{let} (\text{let} s_2 : A \triangleright B \text{ be } x \triangleright y \text{in } s_1) : \text{UnitS be trivS in } s_3 : C} \text{ UNITE2}$$

commutes to

$$\frac{\Gamma_1.x:A.y:B,\Gamma_2 \vdash_{\mathcal{L}} s_1: \text{UnitS} \qquad \Delta_2 \vdash_{\mathcal{L}} s_3:C}{\Gamma_1.x:A.y:B,\Gamma_2.\Delta_2 \vdash_{\mathcal{L}} \text{let} s_1: \text{UnitS} \text{ be trivS in} s_3:C} \qquad \qquad \Delta_1 \vdash_{\mathcal{L}} s_2:A \models B}{\Gamma_1.\Delta_1.\Gamma_2.\Delta_2 \vdash_{\mathcal{L}} \text{let} s_2:A \models B \text{ be } x \vdash_{\mathcal{Y}} \text{in} (\text{let} s_1: \text{UnitS be trivS in} s_3):C} \qquad \qquad \Delta_1 \vdash_{\mathcal{L}} s_2:A \models B} \text{ TENE2}$$

 \blacksquare (S_TENE2, S_TENE2):

$$\frac{\frac{\Gamma_{1}.x:A_{2}.y:B_{2}.\Gamma_{2}\vdash_{\mathcal{L}}s_{1}:A_{1}\triangleright B_{1} \qquad \Gamma\vdash_{\mathcal{L}}s_{2}:A_{2}\triangleright B_{2}}{\Gamma_{1}.\Gamma_{1}.\Gamma_{2}\vdash_{\mathcal{L}}\operatorname{let}s_{2}:A_{2}\triangleright B_{2}\operatorname{be}x\triangleright\operatorname{yin}s_{1}:A_{1}\triangleright B_{1}} \qquad \text{TENE2}}{\Delta_{1}.\Gamma_{1}.\Gamma_{1}.\Gamma_{1}.\Gamma_{2}.\Delta_{2}\vdash_{\mathcal{L}}\operatorname{let}(\operatorname{let}s_{2}:A_{2}\triangleright B_{2}\operatorname{be}x\triangleright\operatorname{yin}s_{1}):A_{1}\triangleright B_{1}\operatorname{be}w\triangleright\operatorname{zin}s_{3}:C}} \qquad \text{TENE2}$$

commutes to

$$\frac{\Gamma_1,x:A_2,y:B_2,\Gamma_2 \vdash_{\mathcal{L}} s_1:A_1 \vdash_B 1}{\Delta_1,\Gamma_1,x:A_2,y:B_2,\Gamma_2,\Delta_2 \vdash_{\mathcal{L}} \operatorname{let} s_1:A_1 \vdash_B 1} \underbrace{\Delta_1,w:A_1,z:B_1,\Delta_2 \vdash_{\mathcal{L}} s_3:C}_{\text{TENE2}} \underbrace{\Gamma \vdash_{\mathcal{L}} s_2:A_2 \vdash_B 2}_{\text{TENE2}} \underbrace{\Gamma \vdash_{\mathcal{L}} s_2:A_2 \vdash_B 2}_{\text{TENE2}}$$

= (S_TENE2, S_IMPRE):

$$\frac{\Gamma_{1}.x:A_{2}.y:B_{2}.\Gamma_{2}\vdash_{\mathcal{L}}s_{1}:A_{1}\rightarrow B_{1}\qquad \Delta_{1}\vdash_{\mathcal{L}}s_{2}:A_{2}\triangleright B_{2}}{\Gamma_{1}.\Delta_{1}.\Gamma_{2}\vdash_{\mathcal{L}}\text{let}s_{2}:A_{2}\triangleright B_{2}\text{be}x + yins_{1}:A_{1}\rightarrow B_{1}} \xrightarrow{\text{TENE2}} \frac{\Delta_{2}\vdash_{\mathcal{L}}s_{3}:A_{1}}{\Gamma_{1}.\Delta_{1}.\Gamma_{2}.\Delta_{2}\vdash_{\mathcal{L}}\text{appr}(\text{let}s_{2}:A_{2}\triangleright B_{2}\text{be}x + yins_{1})s_{3}:B_{1}} \xrightarrow{\text{TENE2}} \frac{\Delta_{2}\vdash_{\mathcal{L}}s_{3}:A_{1}}{\Gamma_{1}.\Delta_{1}.\Gamma_{2}.\Delta_{2}\vdash_{\mathcal{L}}\text{appr}(\text{let}s_{2}:A_{2}\triangleright B_{2}\text{be}x + yins_{1})s_{3}:B_{1}} \xrightarrow{\text{TENE2}}$$

commutes to

$$\frac{\frac{\Gamma_1,x:A_2,y:B_2,\Gamma_2 \vdash_{\mathcal{L}} s_1:A_1 \rightarrow B_1}{\Gamma_1,x:A_2,y:B_2,\Gamma_2,\Delta_2 \vdash_{\mathcal{L}} \mathsf{app}_r s_1 s_3:B_1}}{\frac{\Delta_1 \vdash_{\mathcal{L}} s_2:A_2 \vdash_{\mathcal{L}} \mathsf{app}_r s_1 s_3:B_1}{\Gamma_1,\Delta_1,\Gamma_2,\Delta_2 \vdash_{\mathcal{L}} \mathsf{let} s_2:A_2 \vdash_{\mathcal{B}} \mathsf{be} \, \mathsf{x} \vdash_{\mathcal{Y}} \mathsf{in}(\mathsf{app}_r s_1 s_3):B_1}} \xrightarrow{\mathsf{Mapp} E} \frac{\Delta_1 \vdash_{\mathcal{L}} s_2:A_2 \vdash_{\mathcal{B}} \mathsf{be} \, \mathsf{x} \vdash_{\mathcal{L}} \mathsf{$$

 \blacksquare (S_TENE2, S_IMPLE):

$$\frac{\Gamma_1, x: A_2, y: B_2, \Gamma_2 \vdash_{\mathcal{L}} s_1 : B_1 \vdash_{A_1} \quad \Delta_1 \vdash_{\mathcal{L}} s_2 : A_2 \triangleright_{B_2}}{\Gamma_1, \Delta_1, \Gamma_2 \vdash_{\mathcal{L}} \operatorname{let} s_2 : A_2 \triangleright_{B_2} \operatorname{bex} \triangleright yins_1 : B_1 \vdash_{A_1} \quad \text{TENE2}} \frac{\Delta_2 \vdash_{\mathcal{L}} s_3 : A_1}{\Delta_2, \Gamma_1, \Delta_1, \Gamma_2 \vdash_{\mathcal{L}} \operatorname{app}_{\ell} (\operatorname{let} s_2 : A_2 \triangleright_{B_2} \operatorname{bex} \triangleright yins_1) s_3 : B_1} \operatorname{markE}$$

commutes to

$$\frac{\frac{\Gamma_1.x:A_2.y:B_2.\Gamma_2 + \underline{\ell}.s_1:B_1 \leftarrow A_1}{\Delta_2.\Gamma_1.x:A_2.y:B_2.\Gamma_2 + \underline{\ell}.\operatorname{app}/s_1.s_3:B_1}{\Delta_2.\Gamma_1.\lambda:A_1.\Gamma_2 + \underline{\ell}.\operatorname{let} s_2:A_2 \triangleright B_2 \operatorname{be}.x \triangleright \operatorname{yin}(\operatorname{app}/s_1.s_3):B_1}}{\operatorname{La}_1.\Gamma_2 + \underline{\ell}.\operatorname{let} s_2:A_2 \triangleright B_2 \operatorname{be}.x \triangleright \operatorname{yin}(\operatorname{app}/s_1.s_3):B_1}} \text{ TENE2}$$

- \blacksquare Commutation of F_E :
 - (S_FE, S_UNITE2):

commutes to

$$\frac{\Gamma_{1}.x: X, \Gamma_{2} \vdash_{\mathcal{L}} s_{1} : \text{UnitS} \quad \Delta_{2} \vdash_{\mathcal{L}} s_{2} : A}{\Gamma_{1}.x: X, \Gamma_{2} \cdot \Delta_{2} \vdash_{\mathcal{L}} \text{let} s_{1} : \text{UnitS De trivS in } s_{2} : A} \xrightarrow{\text{unitE2}} \Delta_{1} \vdash_{\mathcal{L}} y : \mathsf{FX}}{\Gamma_{1}.\Delta_{1}.\Gamma_{2}.\Delta_{2} \vdash_{\mathcal{L}} \text{let} \mathsf{Fx} : \mathsf{FX} \text{ bey in (let} s_{1} : \text{UnitS De trivS in } s_{2}) : A} \text{ FE}$$

 \blacksquare (S_FE, S_TENE2):

$$\frac{\Gamma_{1},x:X,\Gamma_{2} \vdash_{\mathcal{L}} s_{1}:A \triangleright B \qquad \Delta \vdash_{\mathcal{L}} y: \mathsf{FX}}{\Gamma_{1},\Delta,\Gamma_{2} \vdash_{\mathcal{L}} \mathsf{let} \mathsf{Fx}: \mathsf{FX} \mathsf{beyin} s_{1}:A \triangleright B} \quad \mathsf{FE} \qquad \Delta_{1},x:A,y:B,\Delta_{2} \vdash_{\mathcal{L}} s_{2}:C}{\Delta_{1},\Gamma_{1},\Delta,\Gamma_{2},\Delta_{2} \vdash_{\mathcal{L}} \mathsf{let} \left(\mathsf{let} \mathsf{Fx}: \mathsf{FX} \mathsf{beyin} s_{1}\right):A \triangleright B \, \mathsf{be} \, x \triangleright y \mathsf{in} \, s_{2}:C} \quad \mathsf{TENE2}$$

commutes to

$$\frac{\Gamma_{1}.x:X,\Gamma_{2} \vdash_{\mathcal{L}} s_{1}:A \triangleright B \qquad \Delta_{1}.x:A,y:B,\Delta_{2} \vdash_{\mathcal{L}} s_{2}:C}{\Delta_{1},\Gamma_{1}.x:X,\Gamma_{2}.\Delta_{2} \vdash_{\mathcal{L}} \operatorname{lets}_{1}:A \triangleright B \operatorname{be} x \triangleright \operatorname{yins}_{2}:C} \xrightarrow{\operatorname{TENE2}} \frac{\Delta \vdash_{\mathcal{L}} y:\mathsf{FX}}{\Delta_{1},\Gamma_{1},\Delta,\Gamma_{2}.\Delta_{2} \vdash_{\mathcal{L}} \operatorname{letEx}:\mathsf{FX} \operatorname{be} \operatorname{yin} (\operatorname{lets}_{1}:A \triangleright B \operatorname{be} x \triangleright \operatorname{yins}_{2}):C} \xrightarrow{\mathsf{FE}} \mathsf{FE}$$

- (S_FE, S_IMPRE):

$$\frac{\Gamma_{1}.x: X, \Gamma_{2} \vdash_{\mathcal{L}} s_{1}: A \rightarrow B \qquad \Delta_{1} \vdash_{\mathcal{L}} y: \mathsf{FX}}{\Gamma_{1}.\Delta_{1}.\Gamma_{2} \vdash_{\mathcal{L}} \mathsf{let} Fx: \mathsf{FX} \mathsf{be} \mathsf{yin} s_{1}: A \rightarrow B} \underset{\Gamma_{1}.\Delta_{1},\Gamma_{2} \mathrel{\vdash_{\mathcal{L}}} \mathsf{let} Fx: \mathsf{FX} \mathsf{be} \mathsf{yin} s_{1}: A \rightarrow B}{\Gamma_{1}.\Delta_{1},\Gamma_{2}.\Delta_{2} \vdash_{\mathcal{L}} \mathsf{app}_{r}} (\mathsf{let} Fx: \mathsf{FX} \mathsf{be} \mathsf{yin} s_{1}) s_{2}: B} \underset{\mathsf{IMPRE}}{} \mathsf{IMPRE}$$

commutes to

$$\frac{\Gamma_{1}.x:X,\Gamma_{2} \vdash_{\mathcal{L}} s_{1}:A \rightarrow B \qquad \Delta_{2} \vdash_{\mathcal{L}} s_{2}:A}{\Gamma_{1}.x:X,\Gamma_{2}.\Delta_{2} \vdash_{\mathcal{L}} \operatorname{app}_{r} s_{1} s_{2}:B} \quad \operatorname{mark}}{\Gamma_{1}.\Delta_{1},\Gamma_{2}.\Delta_{2} \vdash_{\mathcal{L}} \operatorname{let} Fx: FX \operatorname{beyin}(\operatorname{app}_{r} s_{1} s_{2}):B} \quad \Gamma_{1}.\Delta_{1}.\Gamma_{2}.\Delta_{2} \vdash_{\mathcal{L}} \operatorname{let} Fx: FX \operatorname{beyin}(\operatorname{app}_{r} s_{1} s_{2}):B}$$

= (S_FE, S_IMPLE):

$$\frac{\frac{\Gamma_{1}.x:X,\Gamma_{2}\vdash_{\mathcal{L}}s_{1}:A\leftarrow B}{\Gamma_{1}.\Delta_{1}.\Gamma_{2}\vdash_{\mathcal{L}}\operatorname{let}Fx:\mathsf{FX}\operatorname{be}\operatorname{yin}s_{1}:A\leftarrow B}}_{\Delta_{2},\Gamma_{1}.\Delta_{1},\Gamma_{2}\vdash_{\mathcal{L}}\operatorname{dep}_{\mathcal{L}}(\operatorname{let}Fx:\mathsf{FX}\operatorname{be}\operatorname{yin}s_{1})s_{2}:B}}_{\operatorname{IMPLE}}\operatorname{FE}$$

commutes to

$$\frac{\frac{\Gamma_{1}.x:X,\Gamma_{2}\vdash_{\mathcal{L}}s_{1}:A\leftarrow B}{\Delta_{2},\Gamma_{1}.x:X,\Gamma_{2}\vdash_{\mathcal{L}}\mathsf{app}_{I}s_{1}s_{2}:B}}{\Delta_{2},\Gamma_{1}.\lambda_{1},\Gamma_{2}\vdash_{\mathcal{L}}\mathsf{let}\,\mathsf{fx}:\mathsf{FX}\,\mathsf{be}\,\mathsf{yin}\,(\mathsf{app}_{I}s_{1}s_{2}):B}}\frac{\Delta_{1}\vdash_{\mathcal{L}}y:\mathsf{FX}}{\mathsf{FE}}_{\mathsf{FE}}$$

5.3 Mappings Between Sequent Calculus and Natural Deduction

Function $S: ND \to SE$ maps a proof in the natural deduction to a proof of the same sequent in the sequent calculus. The function is defined as follows:

- The axioms map to axioms.
- Introduction rules map to right rules.
- Elimination rules map to combinations of left rules with cuts:

$$\frac{\Phi \vdash_C t_1 : \mathsf{UnitT} \quad \Psi \vdash_C t_2 : Y}{\Phi, \Psi \vdash_C \mathsf{let} t_1 : \mathsf{UnitT} \mathsf{be} \, \mathsf{trivTin} \, t_2 : Y} \quad \mathsf{T}_{_\mathsf{UNITE}}$$

maps to

$$\frac{\Phi \vdash_C t_1 : \mathsf{UnitT}}{\Phi, \Psi \vdash_C [t_1 : \mathsf{VnitT}, \Psi \vdash_C \mathsf{letz} : \mathsf{UnitT} \mathsf{be} \mathsf{trivT} \mathsf{in} \ t_2 : Y} \cdot \frac{\mathsf{unitL}}{\Phi, \Psi \vdash_C [t_1 / x] (\mathsf{letx} : \mathsf{UnitT} \mathsf{be} \mathsf{trivT} \mathsf{in} \ t_2) : Y} \cdot \frac{\mathsf{unitL}}{\mathsf{unitT}} \mathsf{cut}$$

 T_{TENE}

$$\frac{ - \Phi \vdash_{C} t_{1} : X \otimes Y - \Psi_{1}, x : X, y : Y, \Psi_{2} \vdash_{C} t_{2} : Z}{ \Psi_{1}, \Phi, \Psi_{2} \vdash_{C} \text{let} t_{1} : X \otimes Y \text{be} \, x \otimes y \text{in} \, t_{2} : Z} - \text{T_tenE}$$

maps to

$$\frac{\Phi \vdash_{C} t_{1}: X \otimes Y \qquad \frac{\Psi_{1}, x: X, y: Y, \Psi_{2} \vdash_{C} t_{2}: Z}{\Psi_{1}, z: X \otimes Y, \Psi_{2} \vdash_{C} \text{let} z: X \otimes Y \text{be} x \otimes y \text{in} t_{2}: Z}}{\Psi_{1}, \Phi, \Psi_{2} \vdash_{C} \text{lf}_{1}/z] (\text{let} z: X \otimes Y \text{be} x \otimes y \text{in} t_{2}): Z}} \text{ until.}$$

 $T_{IMP}E$:

$$\frac{ \Phi \vdash_{C} t_{1} : X \multimap Y \quad \Psi \vdash_{C} t_{2} : X }{ \Phi, \Psi \vdash_{C} \mathsf{app} \, t_{1} \, t_{2} : Y } \quad \mathsf{T}_{\underline{}\mathsf{IMPE}}$$

maps to

$$\frac{\Phi \vdash_{C} t_{1}: X \multimap Y}{\Phi, \Psi \vdash_{C} [t_{1}/y] [appyt_{2}/x]x: Y} \underbrace{ \text{unitL}}_{\Phi, \Psi \vdash_{C} [t_{1}/y] [appyt_{2}/x]x: Y} \underbrace{ \text{unitL}}_{\text{cut}}$$

= S_unitE1:

$$\frac{\Phi \vdash_{C} t : \mathsf{UnitT} \quad \Gamma \vdash_{\underline{\mathcal{L}}} s : A}{\Phi, \Gamma \vdash_{\underline{\mathcal{L}}} \mathsf{let} t : \mathsf{UnitT} \mathsf{be} \, \mathsf{trivTin} \, s : A} \quad \mathsf{S_unitE1}$$

maps to

$$\frac{\Phi \vdash_{C} t : \mathsf{UnitT} \qquad \frac{\Gamma \vdash_{L} s : A}{x : \mathsf{UnitT}, \Gamma \vdash_{L} \mathsf{let} x : \mathsf{UnitT} \mathsf{be} \, \mathsf{trivT} \mathsf{in} \, s : A} \, \overset{\mathsf{UnrtL1}}{\Phi, \Psi \vdash_{L} [t/x] (\mathsf{let} x : \mathsf{UnitT} \mathsf{be} \, \mathsf{trivT} \mathsf{in} \, s) : A}} \, \overset{\mathsf{UnrtL1}}{\mathsf{curt}}$$

= S_unitE2:

$$\frac{\Gamma \vdash_{\mathrel{\mathcal{L}}} s_1 : \mathsf{UnitS} \quad \Delta \vdash_{\mathrel{\mathcal{L}}} s_2 : A}{\Gamma, \Delta \vdash_{\mathrel{\mathcal{L}}} \mathsf{let} s_1 : \mathsf{UnitS} \, \mathsf{be} \, \mathsf{trivS} \, \mathsf{in} \, s_2 : A} \quad \mathsf{S}_\mathsf{unitE2}$$

maps to

$$\frac{\Gamma \vdash_{\underline{L}} s_1 : \text{UnitS}}{\Gamma, \Delta \vdash_{\underline{L}} [s_1/s] (\text{let} x : \text{UnitS}) \Delta \vdash_{\underline{L}} [s_1/s] (\text{let} x : \text{UnitS}) \text{ be trivS} \text{ in } s_2 : A} \xrightarrow{\text{UNITL } 2} \text{CUT2}$$

S_TENE1:

$$\frac{ \Phi \vdash_{C} t : X \otimes Y \quad \Gamma_{1}, x : X, y : Y, \Gamma_{2} \vdash_{\mathcal{L}} s : A}{\Gamma_{1}, \Phi, \Gamma_{2} \vdash_{\mathcal{L}} \text{let} t : X \otimes Y \text{be} \, x \otimes y \, \text{in} \, s : A} \quad \text{S_tenE1}$$

maps to

$$\frac{\Phi \vdash_{C} t: X \otimes Y \qquad \frac{\Gamma_{1}, x: X, y: Y, \Gamma_{2} \vdash_{\mathcal{L}} s: A}{\Gamma_{1}, z: X \otimes Y, \Gamma_{2} \vdash_{\mathcal{L}} \text{let} z: X \otimes Y \text{be } x \otimes y \text{in } s: A}}{\Gamma_{1}, \Phi, \Gamma_{2} \vdash_{\mathcal{L}} [t/z] (\text{let} z: X \otimes Y \text{be } x \otimes y \text{in } s): A}} \xrightarrow{\text{tribL} 1} \text{cutl}$$

 $= S_{TENE2}$:

$$\frac{ \Gamma \vdash_{\mathrel{\mathcal{L}}} s_1 : A \triangleright B \quad \Delta_1, x : A, y : B, \Delta_2 \vdash_{\mathrel{\mathcal{L}}} s_2 : C}{\Delta_1, \Gamma, \Delta_2 \vdash_{\mathrel{\mathcal{L}}} \operatorname{let} s_1 : A \triangleright B \operatorname{be} x \triangleright y \operatorname{in} s_2 : C} \quad \mathbf{S}_{\underline{\mathsf{TENE2}}}$$

maps to

$$\frac{\Gamma \vdash_{\mathcal{L}} s_1 : A \triangleright B \qquad \frac{\Delta_1, x : A, y : B, \Delta_2 \vdash_{\mathcal{L}} s_2 : C}{\Delta_1, z : A \triangleright B, \Delta_2 \vdash_{\mathcal{L}} \operatorname{let} z : A \triangleright B \operatorname{be} x \triangleright y \operatorname{in} s_2 : C}}{\Delta_1, \Gamma, \Delta_2 \vdash_{\mathcal{L}} \left[s_1/z | (\operatorname{det} z : A \triangleright B \operatorname{be} x \triangleright y \operatorname{in} s_2) : C} \right]} \operatorname{cur2}$$

$$\begin{array}{c} = S_IMPRE: (NOT SURE) \\ & \frac{\Gamma \vdash_{\mathcal{L}} s_1 : A \rightarrow B \quad \Delta \vdash_{\mathcal{L}} s_2 : A}{\Gamma, \Delta \vdash_{\mathcal{L}} app_r s_1 s_2 : B} \quad S_IMPRE \\ \\ maps to \\ & \frac{\Gamma \vdash_{\mathcal{L}} s_1 : A \rightarrow B \quad \Delta \vdash_{\mathcal{L}} s_2 : A \quad x : B \vdash_{\mathcal{L}} x : B}{y : A \rightarrow B, \Delta \vdash_{\mathcal{L}} [app_r y s_2 / x] x : B} \quad IMPRL} \\ & \frac{\Gamma \vdash_{\mathcal{L}} s_1 : A \rightarrow B \quad \frac{\Delta \vdash_{\mathcal{L}} s_2 : A \quad x : B \vdash_{\mathcal{L}} x : B}{y : A \rightarrow B, \Delta \vdash_{\mathcal{L}} [app_r y s_2 / x] x : B} \quad CUT^2 \\ \\ = S_IMPLE: (NOT SURE) \\ & \frac{\Gamma \vdash_{\mathcal{L}} s_1 : B \leftarrow A \quad \Delta \vdash_{\mathcal{L}} s_2 : A \quad x : B \vdash_{\mathcal{L}} x : B}{\Delta, \Gamma \vdash_{\mathcal{L}} app_r s_1 s_2 : B} \quad S_IMPLE} \\ \\ maps to \\ & \frac{\Gamma \vdash_{\mathcal{L}} s_1 : B \leftarrow A \quad \Delta \vdash_{\mathcal{L}} s_2 : A \quad x : B \vdash_{\mathcal{L}} x : B}{\Delta, \Gamma \vdash_{\mathcal{L}} [app_r y s_2 / x] x : B} \quad IMPLL} \\ \\ = S_FE: \\ & \frac{\Gamma \vdash_{\mathcal{L}} y : FX \quad \Delta_1, x : X, \Delta_2 \vdash_{\mathcal{L}} s : A}{\Delta, \Gamma \vdash_{\mathcal{L}} [app_r y s_2 / x] x : B} \quad CUT^2 \\ \\ = S_GE: \\ & \frac{\Gamma \vdash_{\mathcal{L}} y : FX \quad \Delta_1, x : X, \Delta_2 \vdash_{\mathcal{L}} s : A}{\Delta_1, C, \Delta_2 \vdash_{\mathcal{L}} [app_r y s_2 / x] x : B} \quad CUT^2 \\ \\ = S_GE: \\ & \frac{\Delta_1, C, \Delta_2 \vdash_{\mathcal{L}} [app_r y s_2 / x] x : B}{\Delta_1, C, \Delta_2 \vdash_{\mathcal{L}} [app_r y s_2 / x] x : B} \quad CUT^2 \\ \\ = S_GE: \\ & \frac{\Gamma \vdash_{\mathcal{L}} y : FX \quad \Delta_1, x : X, \Delta_2 \vdash_{\mathcal{L}} s : A}{\Delta_1, C, \Delta_2 \vdash_{\mathcal{L}} [app_r y s_2 / x] x : B} \quad CUT^2 \\ \\ = S_GE: \\ & \frac{\Delta_1, C, \Delta_2 \vdash_{\mathcal{L}} [app_r y s_2 / x] x : B}{\Delta, C \vdash_{\mathcal{L}} [app_r y s_2 / x] x : B} \quad CUT^2 \\ \\ = S_GE: \\ & \frac{\Gamma \vdash_{\mathcal{L}} y : FX \quad \Delta_1, x : X, \Delta_2 \vdash_{\mathcal{L}} s : A}{\Delta_1, C, \Delta_2 \vdash_{\mathcal{L}} [app_r y s_2 / x] x : B} \quad CUT^2 \\ \\ = S_GE: \\ & \frac{\Delta_1, c : X, \Delta_2 \vdash_{\mathcal{L}} s : A}{\Delta_1, c : X, \Delta_2 \vdash_{\mathcal{L}} s : A} \quad CUT^2 \\ \\ = S_GE: \\ & \frac{\Delta_1, C, C, C, C}{\Delta_1, C, C} \vdash_{\mathcal{L}} [app_r y s_2 / x] x : B} \quad CUT^2 \\ \\ = S_GE: \\ & \frac{\Delta_1, c : X, \Delta_2 \vdash_{\mathcal{L}} s : A}{\Delta_1, c : X, \Delta_2 \vdash_{\mathcal{L}} s : A} \quad CUT^2 \\ \\ = S_GE: \\ & \frac{\Delta_1, c : X, \Delta_2 \vdash_{\mathcal{L}} s : A}{\Delta_1, c : X, \Delta_2 \vdash_{\mathcal{L}} s : A} \quad CUT^2 \\ \\ = S_GE: \\ & \frac{\Delta_1, c : X, \Delta_2 \vdash_{\mathcal{L}} s : A}{\Delta_1, c : X, \Delta_2 \vdash_{\mathcal{L}} s : A} \quad CUT^2 \\ \\ = S_GE: \\ & \frac{\Delta_1, c : X, \Delta_2 \vdash_{\mathcal{L}} s : A}{\Delta_1, c : X, \Delta_2 \vdash_{\mathcal{L}} s : A} \quad CUT^2 \\ \\ = C_GE: \\ & \frac{\Delta_1, c : X, \Delta_2, c : A}{\Delta_1, c : X, \Delta_2, c : A} \quad CUT^2 \\ \\ = C_GE: \\ & \frac{\Delta_1, c : X, \Delta_2, c : A}$$

Function $N: SE \to ND$ maps a proof in the sequent calculus to a proof of the same sequent in the natural deduction. The function is defined as follows:

- Axioms map to axioms.
- Instances of cut rules map to the admissible substitution rules.
- Right rules map to introductions.
- Left rules map to eliminations modulo some structural fiddling.
 - = T_unitL:

$$\frac{\Psi \vdash_{C} t : X}{x : \mathsf{UnitT}, \Psi \vdash_{C} \mathsf{let} x : \mathsf{UnitT} \mathsf{be} \mathsf{trivT} \mathsf{in} \, t : X} \quad \mathsf{T}_{_\mathsf{UNITL}}$$

maps to

$$\frac{x: \mathsf{UnitT} \vdash_{C} x: \mathsf{UnitT} \qquad \Psi \vdash_{C} t: X}{x: \mathsf{UnitT}, \Psi \vdash_{C} \mathsf{let} x: \mathsf{UnitT} \mathsf{be} \, \mathsf{trivT} \, \mathsf{in} \, t: X} \text{ }_{\mathsf{UNITE}}$$

 T_{TENL}

$$\frac{\Phi, x: X, y: Y, \Psi \vdash_{C} t: Z}{\Phi, z: X \otimes Y, \Psi \vdash_{C} \text{let} z: X \otimes Y \text{be} \, x \otimes y \text{in} \, t: Z} \quad \text{$\mathbf{T}_{\sf TENL}$}$$

maps to

$$\frac{z: X \otimes Y \vdash_{C} z: X \otimes Y \quad \quad \Phi, x: X, y: Y, \Psi \vdash_{C} t: Z}{\Phi, z: X \otimes Y, \Psi \vdash_{C} \mathsf{let}z: X \otimes Y \mathsf{be} \, x \otimes y \mathsf{in} \, t: Z} \; \mathsf{\tiny TENE}$$

 $T_{IMP}L$:

$$\frac{\Phi \vdash_C t_1 : X - \Psi_1, x : Y, \Psi_2 \vdash_C t_2 : Z}{\Psi_1, y : X \multimap Y, \Phi, \Psi_2 \vdash_C [\mathsf{app}\,y\,t_1/x]t_2 : Z} \quad \mathsf{T_mpL}$$

maps to

$$\frac{z: X \rightarrow Y \vdash_{\mathbf{C}} z: X \rightarrow Y \quad \Phi \vdash_{\mathbf{C}} t_1: X}{z: X \rightarrow Y, \Phi \vdash_{\mathbf{C}} \mathsf{app} z t_1: Y} \quad \mathsf{IMPE} \quad \underbrace{\Psi_1, x: Y, \Psi_2 \vdash_{\mathbf{C}} t_2: Z}_{\Psi_1, z: X \rightarrow Y, \Phi, \Psi_2 \vdash_{\mathbf{C}} [\mathsf{app} z t_2 / x] t_2: Z}_{\mathsf{curl}} \quad \mathsf{curl}$$

= S_unitL1:

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$$\frac{\Delta \cdot \xi_{-1} \cdot \lambda}{z \cdot \text{Unit} \cdot \lambda_{-2} \cdot \text{Unit}} = \sum_{\text{Similar}} S_{-1} \text{SortL}$$
maps to
$$\frac{z \cdot \text{Unit} \cdot \lambda_{-2} \cdot \text{Unit}}{z \cdot \text{Unit} \cdot \lambda_{-2} \cdot \text{Unit}} = \frac{\lambda_{-2} \cdot z \cdot \lambda}{\lambda_{-2} \cdot \text{Unit}} \text{ confidential in } z \cdot \lambda \text{ confide$$

- 6 Combining with Benton's Adjoint Model
- 7 Applications
- 8 Conclusion

TODO

A Appendix