

# Separating Linear Modalities

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## Abstract

TODO

## 1 Introduction

TODO [1]

## 2 Categorical Models

### 2.1 Lambek Categories

TODO: Define Lambek Categories

### 2.2 Lambek Categories with Weakening and Contraction

**Definition 1.** A *Lambek category with weakening*,  $(\mathcal{L}, w, \text{weak})$ , is a Lambek category equipped with a monoidal comonad  $(w, \varepsilon, \delta)$ , and a monoidal natural transformation  $\text{weak}_A : wA \longrightarrow I$ . Furthermore,  $\text{weak}$  must be a coalgebra morphism. That is, the following digram must commute:

$$\begin{array}{ccc} wA & \xrightarrow{\text{weak}_A} & I \\ \delta_A \downarrow & & \downarrow q_I \\ w^2A & \xrightarrow{w\text{weak}_A} & wI \end{array}$$

**Definition 2.** A *Lambek category with contraction*,  $(\mathcal{L}, c, \text{contraL}, \text{contraR})$ , is a Lambek category equipped with a monoidal comonad  $(c, \varepsilon, \delta)$ , and two monoidal natural transformations:

$$\begin{aligned} \text{contraL}_{A,B} &: cA \otimes B \longrightarrow (cA \otimes B) \otimes cA \\ \text{contraR}_{A,B} &: B \otimes cA \longrightarrow cA \otimes (B \otimes cA) \end{aligned}$$

Furthermore, the following diagrams must commute:

$$\begin{array}{ccc}
cA \otimes I & \xleftarrow{\rho_{cA}^{-1}} & cA & \xrightarrow{\lambda_{cA}^{-1}} & I \otimes cA \\
\text{contraL}_{A,I} \downarrow & & & & \downarrow \text{contraR}_{A,I} \\
(cA \otimes I) \otimes cA & \xrightarrow{\alpha_{cA,I,cA}} & cA \otimes (I \otimes cA) & & \\
\\
cA \otimes cA & \xrightarrow{id_{cA} \otimes \rho_{cA}^{-1}} & cA \otimes (cA \otimes I) & \xrightarrow{id_{cA} \otimes \text{contraL}_{A,I}} & cA \otimes ((cA \otimes I) \otimes cA) \\
\lambda_{cA}^{-1} \otimes id_{cA} \downarrow & & & & \downarrow id_{cA} \otimes (\rho_{cA} \otimes id_{cA}) \\
(I \otimes cA) \otimes cA & \xrightarrow{\text{contraR}_{A,I} \otimes id_{cA}} & (cA \otimes (I \otimes cA)) \otimes cA & \xrightarrow{(id_{cA} \otimes \lambda_{cA}) \otimes id_{cA}} & (cA \otimes cA) \otimes cA \\
& & & & \uparrow \alpha_{cA,cA,cA}
\end{array}$$

### 2.3 Lambek Categories with Exchange

**Definition 3.** A *Lambek category with exchange*,  $(\mathcal{L}, e, \text{ex})$ , is a Lambek category equipped with a monoidal comonad  $(e, \varepsilon, \delta)$  on  $\mathcal{L}$ , and a monoidal natural transformation  $\text{ex}_{A,B} : e(A \otimes B) \rightarrow eB \otimes eA$ . Furthermore, the following diagrams must commute:

$$\begin{array}{ccc}
e(A \otimes B) & \xrightarrow{\text{ex}_{A,B}} & eB \otimes eA \\
\parallel & & \downarrow q_{B,A} \\
e(A \otimes B) & \xleftarrow{q_{A,B}} eA \otimes eB \xleftarrow{\text{ex}_{B,A}} & e(B \otimes A)
\end{array}$$
  

$$\begin{array}{ccc}
e(A \otimes B) & \xrightarrow{\delta_{A \otimes B}} & e^2(A \otimes B) \\
\text{ex}_{A,B} \downarrow & & \downarrow e\text{ex}_{A,B} \\
eB \otimes eA & \xrightarrow{\delta_B \otimes \delta_A} e^2B \otimes e^2A \xrightarrow{q_{eB,eA}} & e(eB \otimes eA)
\end{array}$$

Note that the second diagram above shows that  $\text{ex}_{A,B}$  is a coalgebra morphism.

**Definition 4.** Let  $(\mathcal{L}, e, \text{ex})$  be a Lambek category with exchange. The *co-Kleisli Category* of  $e$ ,  $\mathcal{L}_e$ , is a category with the same objects as  $\mathcal{L}$ . There is an arrow  $\hat{f} : A \rightarrow B$  in  $\mathcal{L}_e$  if there is an arrow  $f : eA \rightarrow B$  in  $\mathcal{L}$ . The identity arrow  $\hat{id}_A : A \rightarrow A$  is the arrow  $\varepsilon_A : eA \rightarrow A$  in  $\mathcal{L}$ . Given  $\hat{f} : A \rightarrow B$  and  $\hat{g} : B \rightarrow C$  in  $\mathcal{L}_e$ , which are arrows  $f : eA \rightarrow B$  and  $g : eB \rightarrow C$  in  $\mathcal{L}$ , the composition  $\hat{g} \circ \hat{f} : A \rightarrow C$  is defined as  $g \circ ef \circ \delta_A$ .

**Lemma 5** ( $\mathcal{L}_e$  is symmetric). Suppose  $(\mathcal{L}, e, \text{ex})$  is a Lambek category with exchange. Then the co-Kleisli category  $\mathcal{L}_e$  is symmetric monoidal. That is, there is a natural

isomorphism  $\gamma_{A,B} : e(A \otimes B) \longrightarrow B \otimes A$ , and the following diagrams commute:

$$\begin{array}{ccc} e(A \otimes B) & \xrightarrow{\hat{id}_{A \otimes B}} & A \otimes B \\ \delta_{A \otimes B} \downarrow & & \uparrow \gamma_{B,A} \\ e^2(A \otimes B) & \xrightarrow{e\gamma_{A,B}} & e(B \otimes A) \end{array} \quad \begin{array}{ccc} e(I \otimes A) & \xrightarrow{\delta_{I \otimes A}} & e^2(I \otimes A) \\ \hat{\lambda}_A \downarrow & & \downarrow e\gamma_{I,A} \\ A & \xleftarrow{\hat{\rho}_A} & e(A \otimes I) \end{array}$$

, where  $\hat{id}$  is the identity morphism in  $\mathcal{L}_e$ ,  $I$  is the identity object of  $\mathcal{L}_e$ , and  $\hat{\lambda}$  and  $\hat{\rho}$  are the left and right unitors of  $\mathcal{L}_e$ , respectively.

Don't know how to express the two diagrams for monoidal. For example, the morphism  $id_A \otimes \lambda_A : A \otimes (I \otimes B) \rightarrow A \otimes B$  in  $\mathcal{L}$  is  $e(A \otimes (I \otimes B)) \rightarrow A \otimes B$  in  $\mathcal{L}_e$  and can be defined as  $(id_A \otimes \lambda_B) \circ \varepsilon_{A \otimes (I \otimes B)}$ . But I feel like it should use  $\hat{\lambda}$  in the definition.

*Proof.* Let  $I$  be the identity object in  $\mathcal{L}$ . Then the identity object of  $\mathcal{L}_e$  is still  $I$ . The left and right unitors,  $\hat{\lambda}_A : I \otimes A \longrightarrow A$  and  $\hat{\rho}_A : A \otimes I \longrightarrow A$ , in  $\mathcal{L}_e$  are morphisms  $e(I \otimes A) \longrightarrow A$  and  $e(A \otimes I) \longrightarrow A$  in  $\mathcal{L}$ , respectively. Then we define  $\hat{\lambda}$  and  $\hat{\rho}$  as:

$$\begin{aligned} \hat{\lambda}_A &= \varepsilon_A \circ e\lambda_A \\ \hat{\rho}_A &= \varepsilon_A \circ e\rho_A, \end{aligned}$$

where  $\lambda$  and  $\rho$  are the left and right unitors in  $\mathcal{L}$ , respectively. And we define their inverses as:

$$\begin{aligned} \hat{\lambda}_A^{-1} &= \varepsilon_{I \otimes A} \circ e\lambda_A^{-1} \\ \hat{\rho}_A^{-1} &= \varepsilon_{A \otimes I} \circ e\rho_A^{-1} \end{aligned}$$

$\hat{\lambda}$  is a natural isomorphism with inverse  $\hat{\lambda}^{-1}$  because the following diagram chasing commutes:

$$\begin{array}{ccccc} e(I \otimes A) & \xrightarrow{\delta_{I \otimes A}} & e^2(I \otimes A) & \xrightarrow{e^2\lambda_A} & e^2A \\ & \searrow e\lambda_A & \downarrow \delta_A & \nearrow e\lambda_A & \downarrow e\varepsilon_A \\ & & eA & & \\ & \nearrow e\lambda_A^{-1} & \downarrow e\lambda_A^{-1} & \searrow e\lambda_A^{-1} & \\ I \otimes A & \xleftarrow{\varepsilon_{I \otimes A}} & e(I \otimes A) & \xleftarrow{e\lambda_A^{-1}} & eA \end{array}$$

(1) (2) (3) (4) (5)

(1) commutes by the naturality of  $\delta$ . (2), (3) and (4) commute trivially. And (5) commutes because  $e$  is a comonad.

Similarly,  $\hat{\rho}$  is a natural isomorphism with inverse  $\hat{\rho}^{-1}$  by the following diagram

chasing:

$$\begin{array}{ccccc}
e(A \otimes I) & \xrightarrow{\delta_{A \otimes I}} & e^2(A \otimes I) & \xrightarrow{e^2 \rho_A} & e^2 A \\
\downarrow \varepsilon_{A \otimes I} & \searrow e \rho_A & \downarrow e \rho_A^{-1} & \nearrow \delta_A & \downarrow e \varepsilon_A \\
& & eA & & \\
& & \downarrow e \rho_A^{-1} & & \\
A \otimes I & \xleftarrow{\varepsilon_{A \otimes I}} & e(A \otimes I) & \xleftarrow{e \rho_A^{-1}} & eA
\end{array}$$

The associator  $\hat{\alpha}_A : (A \otimes B) \otimes C \longrightarrow A \otimes (B \otimes C)$  in  $\mathcal{L}_e$  is the morphism  $e((A \otimes B) \otimes C) \longrightarrow e(A \otimes (B \otimes C))$  in  $\mathcal{L}$ . We define  $\hat{\alpha}$  as:

$$\hat{\alpha}_{A,B,C} = \varepsilon_{A \otimes (B \otimes C)} \circ e \alpha_{A,B,C},$$

where  $\alpha$  is the associator of  $\mathcal{L}$ . And its inverse is

$$\hat{\alpha}_{A,B,C}^{-1} = \varepsilon_{(A \otimes B) \otimes C} \circ e \alpha_{A,B,C}^{-1}$$

$\hat{\alpha}$  is a natural isomorphism with inverse  $\hat{\alpha}^{-1}$  because the following diagram chasing commutes:

$$\begin{array}{ccccc}
e((A \otimes B) \otimes C) & \xrightarrow{\delta_{(A \otimes B) \otimes C}} & e^2((A \otimes B) \otimes C) & \xrightarrow{e^2 \alpha_{A,B,C}} & e^2(A \otimes (B \otimes C)) \\
\downarrow \varepsilon_{(A \otimes B) \otimes C} & \searrow e \alpha_{A,B,C} & \downarrow e \alpha_{A,B,C}^{-1} & \nearrow \delta_{A \otimes (B \otimes C)} & \downarrow e \varepsilon_{A \otimes (B \otimes C)} \\
& & e(A \otimes (B \otimes C)) & & \\
& & \downarrow e \alpha_{A,B,C}^{-1} & & \\
(A \otimes B) \otimes C & \xleftarrow{\varepsilon_{(A \otimes B) \otimes C}} & e((A \otimes B) \otimes C) & \xleftarrow{e \alpha_{A,B,C}^{-1}} & e(A \otimes (B \otimes C))
\end{array}$$

Therefore,  $\mathcal{L}_e$  is a monoidal category.

Then, we define a natural transformation  $\gamma_{A,B} : e(A \otimes B) \longrightarrow B \otimes A$  as

$$\gamma_{A,B} = (\varepsilon_B \otimes \varepsilon_A) \circ \text{ex}_{A,B}.$$

Clearly,  $\gamma$  is natural because it is the composition of natural transformations. The following diagram shows  $\gamma$  is an isomorphism in  $\mathcal{L}_e$ :

$$\begin{array}{ccc}
e(A \otimes B) & \xrightarrow{\delta_{A \otimes B}} & e^2(A \otimes B) \\
\downarrow \varepsilon_{A \otimes B} & & \downarrow e \gamma_{A,B} \\
A \otimes B & \xleftarrow{\gamma_{B,A}} & e(B \otimes A)
\end{array}$$

The previous diagram commutes because the following one does:

$$\begin{array}{ccccc}
 e(A \otimes B) & \xrightarrow{\delta_{A \otimes B}} & e^2(A \otimes B) & \xrightarrow{e\epsilon_{A,B}} & e(eB \otimes eA) \\
 \downarrow \epsilon_{A \otimes B} & \searrow e\epsilon_{A,B} & \downarrow & \nearrow q_{eB,eA} & \downarrow e(\epsilon_B \otimes \epsilon_A) \\
 & eB \otimes eA & \xrightarrow{\delta_B \otimes \delta_A} & e^2B \otimes e^2A & \\
 & \downarrow & \downarrow e\epsilon_B \otimes e\epsilon_A & \downarrow & \\
 & e(A \otimes B) & \xrightarrow{\delta_B \otimes \delta_A} & eB \otimes eA & \\
 & \downarrow q_{A,B} & \downarrow & \downarrow q_{B,A} & \\
 A \otimes B & \xleftarrow{\epsilon_A \otimes \epsilon_B} & eA \otimes eB & \xleftarrow{e\epsilon_{B,A}} & e(B \otimes A)
 \end{array}$$

(1) (2) (3) (4) (5)

Diagram (1) commutes because  $e$  is monoidal, diagrams (2) and (3) commute by the definition of the Lambek category with exchange, diagram (4) commutes because  $e$  is a comonad, and diagram (5) commutes by the naturality of  $q$ .

Further, the following diagram also commutes

$$\begin{array}{ccc}
 e(I \otimes A) & \xrightarrow{\delta_{I \otimes A}} & e^2(I \otimes A) \\
 \downarrow \hat{\lambda}_A & & \downarrow e\gamma_{I,A} \\
 A & \xleftarrow{\rho_A} & e(A \otimes I)
 \end{array}$$

by the diagram chasing below:

$$\begin{array}{ccccc}
 e(I \otimes A) & \xrightarrow{\delta_{I \otimes A}} & e^2(I \otimes A) & & \\
 \downarrow e\lambda_A & \searrow \epsilon_{I \otimes A} & \downarrow & \nearrow e\gamma_{I,A} & \\
 & A & \xleftarrow{\lambda_A} & I \otimes A & \\
 & \downarrow \epsilon_A & \downarrow & \downarrow \gamma_{A,I} & \\
 eA & \xleftarrow{\epsilon \rho_A} & e(A \otimes I) & & \\
 \downarrow \epsilon_A & & \downarrow e\rho_A & & \\
 A & \xleftarrow{\epsilon_A} & eA & & 
 \end{array}$$

(1) (2) (3) (4)

in which (1) commutes by the naturality of  $\epsilon$ , (3) commutes because  $\gamma$  is a natural isomorphism, and (4) commutes trivially.

In conclusion,  $\mathcal{L}_e$  is symmetric monoidal. □

Need (2)?

## 2.4 Linear Categories

**Definition 6.** A *linear category*,  $(\mathcal{L}, !, \text{weak}, \text{contra})$ , is a symmetric monoidal closed category  $(\mathcal{L}, I, \otimes, \multimap)$  equipped with a symmetric monoidal comonad  $(!, \epsilon, \delta)$  with  $q_{A,B} : !A \otimes !B \rightarrow !(A \otimes B)$  and  $q_I : I \rightarrow !I$ , and two monoidal natural transformations with

components  $\text{weak}_A : !A \longrightarrow I$  and  $\text{contra}_A : !A \longrightarrow !A \otimes !A$ , satisfying the following conditions:

- each  $(!A, \text{weak}_A, \text{contra}_A)$  is a commutative comonoid, i.e. the following diagrams commute and  $\beta \circ \text{contra}_A = \text{contra}_A$  where  $\beta_{B,C} : B \otimes C \longrightarrow C \otimes B$  is the symmetry natural transformation of  $\mathcal{L}$ :

$$\begin{array}{ccccc}
 !A & \xrightarrow{\text{contra}_A} & !A \otimes !A & \xrightarrow{id_{!A} \otimes \text{contra}_A} & !A \otimes (!A \otimes !A) \\
 \text{contra}_A \downarrow & & & & \uparrow \alpha_{!A, !A, !A} \\
 !A \otimes !A & \xrightarrow{\text{contra}_A \otimes id_{!A}} & (!A \otimes !A) \otimes !A & & \\
 & & & & \\
 & & !A & & \\
 & \swarrow \lambda^{-1} & \downarrow \text{contra}_A & \searrow \rho^{-1} & \\
 I \otimes !A & \xleftarrow{\text{weak}_A \otimes id_{!A}} & !A \otimes !A & \xrightarrow{id_{!A} \otimes \text{weak}_A} & !A \otimes I
 \end{array}$$

- $\text{weak}_A$  and  $\text{contra}_A$  are coalgebra morphisms, i.e. the following diagrams commute;

$$\begin{array}{ccc}
 !A & \xrightarrow{\text{weak}_A} & I \\
 \delta_A \downarrow & & \downarrow q_I \\
 !!A & \xrightarrow{! \text{weak}_A} & !I
 \end{array}$$
  

$$\begin{array}{ccccc}
 !A & \xrightarrow{\text{contra}_A} & !A \otimes !A & \xrightarrow{\delta_A \otimes \delta_A} & !!A \otimes !!A \\
 \delta_A \downarrow & & & & \downarrow q_{!A, !A} \\
 !!A & \xrightarrow{! \text{contra}_A} & !(A \otimes A) & & 
 \end{array}$$

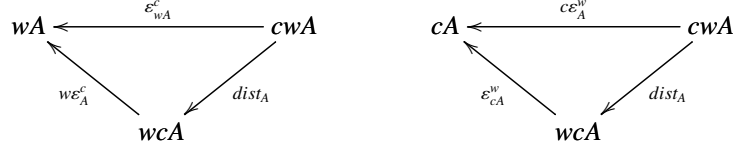
- any coalgebra morphism  $f : (!A, \delta_A) \longrightarrow (!B, \delta_B)$  between free coalgebras preserve the comonoid structure given by  $\text{weak}$  and  $\text{contra}$ , i.e. the following diagrams commute.

$$\begin{array}{ccc}
 !A & \xrightarrow{f} & !B \\
 \text{weak}_A \searrow & & \swarrow \text{weak}_B \\
 & I & 
 \end{array}$$
  

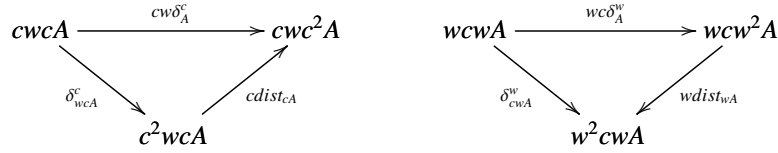
$$\begin{array}{ccc}
 !A & \xrightarrow{\text{contra}_A} & !A \otimes !A \\
 f \downarrow & & \downarrow f \otimes f \\
 !B & \xrightarrow{\text{contra}_B} & !B \otimes !B
 \end{array}$$

**Definition 7.** Given two comonads  $(c, \varepsilon^c, \delta^c)$  and  $(w, \varepsilon^w, \delta^w)$  on a category  $\mathcal{L}$  such that  $(\mathcal{L}, c, \text{contraL}, \text{contraR})$  is a Lambek category with contraction and  $(\mathcal{L}, w, \text{weak})$  is

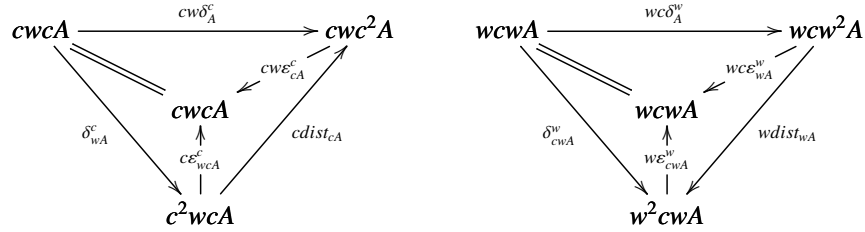
a Lambek category with weakening, we define a **distributive law** of  $c$  over  $w$  to be a natural transformation with components  $\text{dist}_A : cwA \longrightarrow wcA$ , subject to the following coherence diagrams:



**Lemma 8.** Given two comonads  $(c, \varepsilon^c, \delta^c)$  and  $(w, \varepsilon^w, \delta^w)$  on a category  $\mathcal{L}$  such that  $(\mathcal{L}, c, \text{contraL}, \text{contraR})$  is a Lambek category with contraction and  $(\mathcal{L}, w, \text{weak})$  is a Lambek category with weakening, the following two diagrams commute:



*Proof.* The two diagrams above commute because the following ones commute by the distributive law and the comonad laws for  $c$  and  $w$ .



□

**Lemma 9** (Composition of Weakening and Contraction). Suppose  $(\mathcal{L}, I, \otimes, w, \text{weak}^w, c, \text{contraL}, \text{contraR})$  is a Lambek category with weakening and contraction, where  $(w, \varepsilon^w, \delta^w)$  and  $(c, \varepsilon^c, \delta^c)$  are the respective monoidal comonads. Then the composition of  $c$  and  $w$  using the distributive law  $\text{dist}_A : cwA \longrightarrow wcA$  is a monoidal comonad on  $\mathcal{L}$ .

*Proof.* For the complete proof see Appendix B.1. □

**Definition 10.** A **Lambek category with**  $cw$ ,  $(\mathcal{L}, cw, \text{weak}^w, \text{contraL}, \text{contraR}, \text{dist})$ , is a Lambek category with weakening and contraction, and a distributive law. Further-

more, the following coherence diagrams commute:

$$\begin{array}{ccc}
I \otimes cwA & \xrightarrow{\lambda_{I \otimes cwA}^{-1}} & I \otimes (I \otimes cwA) \\
\downarrow \text{contraR}_{wA,I} & & \uparrow \text{weak}_A^w \otimes id_{I \otimes cwA} \\
cwA \otimes (I \otimes cwA) & \xrightarrow{\varepsilon_{wA}^c \otimes id_{I \otimes cwA}} & wA \otimes (I \otimes cwA)
\end{array}$$
  

$$\begin{array}{ccc}
cwA \otimes I & \xrightarrow{\rho_{cwA \otimes I}^{-1}} & (cwA \otimes I) \otimes I \\
\downarrow \text{contraL}_{wA,I} & & \uparrow id_{cwA \otimes I} \otimes \text{weak}_A^w \\
(cwA \otimes I) \otimes cwA & \xrightarrow{id_{cwA \otimes I} \otimes \varepsilon_{wA}^c} & (cwA \otimes I) \otimes wA
\end{array}$$
  

$$\begin{array}{ccc}
cwA & \xrightarrow{f} & cwB \\
\downarrow \varepsilon_{wA}^c & & \downarrow \varepsilon_{wB}^c \\
wA & \xrightarrow{\text{weak}_A^w} & I \xleftarrow{\text{weak}_B^w} wB
\end{array}$$

where  $f : (cwA, \delta_A) \rightarrow (cwB, \delta_B)$  is any coalgebra morphism between free coalgebras.

**Lemma 11.** Let  $(\mathcal{L}, cw, \text{weak}^w, \text{contraL}, \text{contraR})$  be a Lambek category with  $cw$ . Then the following conditions are satisfied:

1. There exist two natural transformations  $\text{weak}_A : cwA \rightarrow I$  and  $\text{contra}_A : cwA \rightarrow cwA \otimes cwA$ .
2. Each  $(cwA, \text{weak}_A, \text{contra}_A)$  is a comonoid.
3.  $\text{weak}_A$  and  $\text{contra}_A$  are coalgebra morphisms.
4. Any coalgebra morphism  $f : (cwA, \delta_A) \rightarrow (cwB, \delta_B)$  between free coalgebras preserves the comonoid structure given by  $\text{weak}$  and  $\text{contra}$ .

*Proof.* We will only prove the first condition by defining  $\text{weak}$  and  $\text{contra}$ . For the complete proof see Appendix B.2. Each of  $\text{weak}$  and  $\text{contra}$  can be given two equivalent definitions.  $\text{weak}_A : cwA \rightarrow I$  is defined as in the diagram below. The left triangle commutes by the definition of  $\text{dist}$  and the right triangle commutes by the definition of  $\text{weak}^w$ .

$$\begin{array}{ccccc}
& & wcA & & \\
& \nearrow \text{dist}_A & \downarrow w\varepsilon_A^c & \searrow \text{weak}_{cA}^w & \\
cwA & \xrightarrow{\varepsilon_{wA}^c} & wA & \xrightarrow{\text{weak}_A^w} & I
\end{array}$$

$\text{contra}_A : cwA \rightarrow cwA \otimes cwA$  is defined as below. The left part of the diagram commutes by the definitions of  $\text{contraL}$  and of  $\text{contraR}$ , and the right part commutes because  $\mathcal{L}$  is monoidal.

$$\begin{array}{ccccc}
cwA & \xrightarrow{\rho_{cwA}^{-1}} & cwA \otimes I & \xrightarrow{\text{contraL}_{wA,I}} & (cwA \otimes I) \otimes cwA \\
\downarrow \lambda_{cwA}^{-1} & & & \swarrow \alpha_{cwA,I,cwA} & \downarrow \rho_{cwA} \otimes id_{cwA} \\
I \otimes cwA & \xrightarrow{\text{contraR}_{wA,I}} & cwA \otimes (I \otimes cwA) & \xrightarrow{id_{cwA} \otimes \lambda_{cwA}^{-1}} & cwA \otimes cwA
\end{array}$$

□



**Definition 12.** Given two comonads  $(cw, \varepsilon^{cw}, \delta^{cw})$  and  $(e, \varepsilon^e, \delta^e)$  on a category  $\mathcal{L}$  such that  $(\mathcal{L}, cw, \text{weak}, \text{contra})$  is a Lambek category with  $cw$  and  $(\mathcal{L}, e, \text{ex})$  is a Lambek category with exchange, we define a **distributive law for exchange** of  $cw$  over  $e$  to be a natural isomorphism with components  $\text{distEx}_A : cweA \longrightarrow ecwA$ , subject to the following coherence diagrams:

$$\begin{array}{ccc} eA & \xleftarrow{\varepsilon_{eA}^{cw}} & cweA \\ & \searrow e\varepsilon_A^{cw} \quad \swarrow \text{distEx}_A & \\ & ecwA & \end{array} \quad \begin{array}{ccc} cwA & \xleftarrow{cw\varepsilon_A^e} & cweA \\ & \searrow \varepsilon_{cwA}^e \quad \swarrow \text{distEx}_A & \\ & ecwA & \end{array}$$

**Lemma 13.** Given two comonads  $(cw, \varepsilon^{cw}, \delta^{cw})$  and  $(e, \varepsilon^e, \delta^e)$  on a category  $\mathcal{L}$  such that  $(\mathcal{L}, cw, \text{weak}, \text{contra})$  is a Lambek category with  $cw$  and  $(\mathcal{L}, e, \text{ex})$  is a Lambek category with exchange, the following two digrams also commute:

$$\begin{array}{ccc} cweA & \xrightarrow{cwe\delta_A^{cw}} & cwe(cw)^2A \\ & \searrow \delta_{cweA}^{cw} \quad \swarrow cw\text{distEx}_{cwA} & \\ & (cw)^2ecwA & \end{array} \quad \begin{array}{ccc} ecweA & \xrightarrow{ecw\delta_A^e} & ecwe^2A \\ & \searrow \delta_{ecweA}^e \quad \swarrow e\text{distEx}_{eA} & \\ & e^2cweA & \end{array}$$

The proof is similar with the proof of Lemma 8 and we will not elaborate it here. Also, notice the difference between  $\text{dist}$  of  $c$  over  $w$  and  $\text{distEx}$  of  $cw$  over  $e$ . While  $\text{dist}$  is a natural transformation,  $\text{distEx}$  is a natural isomorphism.

**Lemma 14.** let  $(cw, \varepsilon^{cw}, \delta^{cw})$  and  $(e, \varepsilon^e, \delta^e)$  be two monoidal comonads on a Lambek category with  $cw$  and exchange  $(\mathcal{L}, I, \otimes, cw, \text{weak}, \text{contra}, e, \text{ex})$ . Then the composition of  $cw$  and  $e$  using the distributive law for exchange  $\text{distEx}_A : cweA \longrightarrow ecwA$  is a monoidal comonad  $(cwe, \varepsilon, \delta)$  on  $\mathcal{L}$ .

*Proof.* Suppose  $(cw, \varepsilon^{cw}, \delta^{cw})$  and  $(e, \varepsilon^e, \delta^e)$  are monoidal comonads, and  $(\mathcal{L}, I, \otimes, cw, \text{weak}, \text{contra}, e, \text{ex})$  is a Lambek category with  $cw$  and exchange. Since by definition  $cw, e : \mathcal{L} \longrightarrow \mathcal{L}$  are monoidal functors, we know that their composition  $cwe : \mathcal{L} \longrightarrow \mathcal{L}$  is a monoidal functor:

$$\begin{aligned} q_{A,B} &: cweA \otimes cweB \longrightarrow cwe(A \otimes B) \\ q_{A,B} &= cwq_{A,B}^e \circ q_{eA,eB}^{cw} \\ q_I &: I \longrightarrow cweI \\ q_I &= cwq_I^e \circ q_I^{cw} \end{aligned}$$

Analogous to the proof of Lemma 9, each of  $\varepsilon$  and  $\delta$  can be given two equivalent definitions:

$$\begin{array}{ccc} cweA & \xrightarrow{\varepsilon_{eA}^{cw}} & eA \\ \downarrow cw\varepsilon_A^e & & \downarrow \varepsilon_A^e \\ cwA & \xrightarrow{\varepsilon_A^{cw}} & A \end{array} \quad \begin{array}{ccccc} cweA & \xrightarrow{cw\delta_A^e} & cwe^2A & \xrightarrow{\delta_{e^2A}^{cw}} & (cw)^2e^2A \\ \downarrow \delta_{eA}^{cw} & & \downarrow \delta_{e^2A}^{cw} & & \downarrow cw\text{dist}_{eA} \\ (cw)^2eA & \xrightarrow{(cw)^2\delta_A^e} & (cw)^2e^2A & \xrightarrow{cw\text{dist}_{eA}} & cweA \end{array}$$

And the comonad laws can be proved similarly, which we will not elaborate for simplicity.  $\square$

**Lemma 15.** *Let  $(cwe, \varepsilon, \delta)$  be a monoidal comonad over a monoidal category  $(\mathcal{L}, I, \otimes)$  such that  $(\mathcal{L}, I, \otimes, cw, \text{weak}, \text{contra}, e, \text{ex})$  is a Lambek category with  $cw$  and exchange. Then the co-Kleisli category of  $\mathcal{L}$ ,  $\mathcal{L}_{cwe}$ , is a linear category.*

*Proof.* The identity object of  $\mathcal{L}_{cwe}$  is still  $I$ .

The left and right unitors,  $\hat{\lambda}_A : I \otimes A \rightarrow A$  and  $\hat{\rho}_A : A \otimes I \rightarrow A$ , in  $\mathcal{L}_{cwe}$  are morphisms  $cwe(I \otimes A) \rightarrow A$  and  $cwe(A \otimes I) \rightarrow A$  in  $\mathcal{L}$ , respectively. Then we define  $\hat{\lambda}$  and  $\hat{\rho}$  as:

$$\begin{aligned}\hat{\lambda}_A &= \varepsilon_A \circ cwe\lambda_A \\ \hat{\rho}_A &= \varepsilon_A \circ cwe\rho_A,\end{aligned}$$

where  $\lambda$  and  $\rho$  are the left and right unitors in  $\mathcal{L}$ , respectively. And we define their inverses as:

$$\begin{aligned}\hat{\lambda}_A^{-1} &= \varepsilon_{I \otimes A} \circ cwe\lambda_A^{-1} \\ \hat{\rho}_A^{-1} &= \varepsilon_{A \otimes I} \circ cwe\rho_A^{-1}\end{aligned}$$

$\hat{\lambda}$  is a natural isomorphism with inverse  $\hat{\lambda}^{-1}$  because the following diagram chasing commutes:

$$\begin{array}{ccccc} cwe(I \otimes A) & \xrightarrow{\delta_{I \otimes A}} & (cwe)^2(I \otimes A) & \xrightarrow{(cwe)^2\lambda_A} & (cwe)^2A \\ & \searrow cwe\lambda_A & \downarrow \delta_A & \nearrow \delta_A & \downarrow cwe\varepsilon_A \\ & (1) & cweA & (5) & \\ \varepsilon_{I \otimes A} \downarrow & & \downarrow cwe\lambda_A^{-1} & & \downarrow cwe\varepsilon_A \\ I \otimes A & \xleftarrow{\varepsilon_{I \otimes A}} & cwe(I \otimes A) & \xleftarrow{cwe\lambda_A^{-1}} & cweA \end{array}$$

(1) commutes by the naturality of  $\delta$ . (2), (3) and (4) commute trivially. And (5) commutes because  $cwe$  is a comonad.

Similarly,  $\hat{\rho}$  is a natural isomorphism with inverse  $\hat{\rho}^{-1}$  by the following diagram chasing:

$$\begin{array}{ccccc} cwe(A \otimes I) & \xrightarrow{\delta_{A \otimes I}} & (cwe)^2(A \otimes I) & \xrightarrow{(cwe)^2\rho_A} & (cwe)^2A \\ & \searrow cwe\rho_A & \downarrow \delta_A & \nearrow \delta_A & \downarrow cwe\varepsilon_A \\ & & cweA & & \\ \varepsilon_{A \otimes I} \downarrow & & \downarrow cwe\rho_A^{-1} & & \downarrow cwe\varepsilon_A \\ A \otimes I & \xleftarrow{\varepsilon_{A \otimes I}} & cwe(A \otimes I) & \xleftarrow{cwe\rho_A^{-1}} & cweA \end{array}$$

changed to  
liner cate-  
gory. Finish  
the proof  
when lemma  
5 is proved.

The associator  $\hat{\alpha}_A : (A \otimes B) \otimes C \longrightarrow A \otimes (B \otimes C)$  in  $\mathcal{L}_{cwe}$  is the morphism  $cwe((A \otimes B) \otimes C) \longrightarrow A \otimes (B \otimes C)$  in  $\mathcal{L}$ . We define  $\hat{\alpha}$  as:

$$\hat{\alpha}_{A,B,C} = \varepsilon_{A \otimes (B \otimes C)} \circ cwe \alpha_{A,B,C},$$

where  $\alpha$  is the associator of  $\mathcal{L}$ . And its inverse is

$$\hat{\alpha}_{A,B,C}^{-1} = \varepsilon_{(A \otimes B) \otimes C} \circ cwe \alpha_{A,B,C}^{-1}$$

$\hat{\alpha}$  is a natural isomorphism with inverse  $\hat{\alpha}^{-1}$  because the following diagram chasing commutes:

$$\begin{array}{ccccc}
cwe((A \otimes B) \otimes C) & \xrightarrow{\delta_{(A \otimes B) \otimes C}} & (cwe)^2((A \otimes B) \otimes C) & \xrightarrow{(cwe)^2 \alpha_{A,B,C}} & (cwe)^2(A \otimes (B \otimes C)) \\
\downarrow \varepsilon_{(A \otimes B) \otimes C} & \searrow cwe \alpha_{A,B,C} & \downarrow cwe \alpha_{A,B,C}^{-1} & \nearrow \delta_{A \otimes (B \otimes C)} & \downarrow cwe \varepsilon_{A \otimes (B \otimes C)} \\
& & cwe(A \otimes (B \otimes C)) & & \\
& & \downarrow cwe \alpha_{A,B,C}^{-1} & & \\
(A \otimes B) \otimes C & \xleftarrow{\varepsilon_{(A \otimes B) \otimes C}} & cwe((A \otimes B) \otimes C) & \xleftarrow{cwe \alpha_{A,B,C}^{-1}} & cwe(A \otimes (B \otimes C))
\end{array}$$

Therefore,  $\mathcal{L}_{cwe}$  is a monoidal category.

The symmetry,  $\hat{\beta}_{A,B} : A \otimes B \longrightarrow B \otimes A$ , in  $\mathcal{L}_{cwe}$  is the morphism  $cwe(A \otimes B) \longrightarrow B \otimes A$  in  $\mathcal{L}$ , which is defined as:

$$\hat{\beta}_{A,B} = \varepsilon_{B \otimes A}^{cw} \circ cw \gamma_{A,B},$$

where  $\varepsilon_A^{cw} : cw A \longrightarrow A$  is a natural transformation associated with the comonad  $cw$ , and  $\gamma$  is the natural isomorphism defined in Lemma ???. Then its inverse is

$$\hat{\beta}_{A,B}^{-1} = \varepsilon_{A \otimes B}^{cw} \circ cw \gamma_{B,A}$$

$\hat{\beta}$  is a natural isomorphism with inverse  $\hat{\beta}^{-1}$  because the following diagram chasing commutes:

$$\begin{array}{ccccc}
A \otimes B & \xleftarrow{\varepsilon_{A \otimes B}^{cw}} & cw(A \otimes B) & \xleftarrow{cwe \varepsilon_{A \otimes B}^e} & cwe(A \otimes B) \\
\uparrow \varepsilon_{A \otimes B}^{cw} & (1) & \downarrow \delta_{A \otimes B}^{cw} & (3) & \downarrow \delta_{e(A \otimes B)}^{cw} \\
cw(A \otimes B) & \xleftarrow{cwe \varepsilon_{A \otimes B}^{cw}} & (cw)^2(A \otimes B) & \xleftarrow{(cw)^2 \varepsilon_{A \otimes B}^e} & (cw)^2 e(A \otimes B) \\
& & \uparrow (cw)^2 \gamma_{B,A} & (5) & \downarrow (cw)^2 \delta_{A \otimes B}^e \\
& & (cw)^2 e(B \otimes A) & \xleftarrow{(cw)^2 e \gamma_{A,B}} & (cw)^2 e^2(A \otimes B) \\
& & \downarrow cwe \varepsilon_{e(B \otimes A)}^{cw} & (7) & \downarrow cwe \gamma_{A,B} \\
& & (cw)^2 e(B \otimes A) & \xleftarrow{cwe \varepsilon_{B \otimes A}^{cw}} & cwe(B \otimes A) \\
& & \downarrow cwe \varepsilon_{B \otimes A}^{cw} & (6) & \\
cwe(B \otimes A) & \xleftarrow{cwe \varepsilon_{B \otimes A}^{cw}} & cwe(B \otimes A) & \xleftarrow{cwe \varepsilon_{B \otimes A}^{cw}} & cwe(B \otimes A)
\end{array}$$

Additional labels in the diagram include: (2)  $\delta_{A \otimes B}^{cw}$ , (4)  $(cw)^2 e(B \otimes A)$ , (8)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (9)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (10)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (11)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (12)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (13)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (14)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (15)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (16)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (17)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (18)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (19)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (20)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (21)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (22)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (23)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (24)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (25)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (26)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (27)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (28)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (29)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (30)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (31)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (32)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (33)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (34)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (35)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (36)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (37)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (38)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (39)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (40)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (41)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (42)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (43)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (44)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (45)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (46)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (47)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (48)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (49)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (50)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (51)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (52)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (53)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (54)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (55)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (56)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (57)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (58)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (59)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (60)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (61)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (62)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (63)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (64)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (65)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (66)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (67)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (68)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (69)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (70)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (71)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (72)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (73)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (74)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (75)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (76)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (77)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (78)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (79)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (80)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (81)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (82)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (83)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (84)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (85)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (86)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (87)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (88)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (89)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (90)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (91)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (92)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (93)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (94)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (95)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (96)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (97)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (98)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (99)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ , (100)  $cw \text{dist} Ex_{e(A \otimes B)}^{-1}$ .

(1), (7) and (9) commute trivially. (2) is the comonad law for  $cw$ . (3) commutes by the naturality of  $\delta^{cw}$ . (4) commutes by the naturality of  $\varepsilon^{cw}$ . (5) commutes because  $\gamma$  is a natural isomorphism (Lemma ??). (6) is the definition of  $distEx$ . (8) is the naturality of  $distEx$ .

In conclusion,  $\mathcal{L}_{cwe}$  is a symmetric monoidal category.  $\square$

### 3 Related Work

TODO

### 4 Conclusion

TODO

### References

- [1] P. N. Benton. A mixed linear and non-linear logic: Proofs, terms and models (preliminary report). Technical Report UCAM-CL-TR-352, University of Cambridge Computer Laboratory, 1994. Accessible online at <http://research.microsoft.com/en-us/um/people/nick/mixed3.ps>.

## A Appendix

### A.1 Symmetric Monoidal Categories

**Definition 16.** A *monoidal category* 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:

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

- Subject to the following coherence diagrams:

$$\begin{array}{ccc}
((A \otimes B) \otimes C) \otimes D & \xrightarrow{\alpha_{A,B,C} \otimes \text{id}_D} & (A \otimes (B \otimes C)) \otimes D \\
\downarrow \alpha_{A \otimes B, C, D} & & \downarrow \alpha_{A, B \otimes C, D} \\
(A \otimes B) \otimes (C \otimes D) & & \\
\downarrow \alpha_{A, B, C \otimes D} & & \\
A \otimes (B \otimes (C \otimes D)) & \xleftarrow{\text{id}_A \otimes \alpha_{B,C,D}} & A \otimes ((B \otimes C) \otimes D)
\end{array}$$
  

$$\begin{array}{ccc}
(A \otimes \top) \otimes B & \xrightarrow{\alpha_{A, \top, B}} & A \otimes (\top \otimes B) \\
\searrow \rho_A \otimes \text{id}_B & & \swarrow \text{id}_A \otimes \lambda_B \\
& A \otimes B &
\end{array}$$

**Definition 17.** 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 isomorphism:

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

- Subject to the following coherence diagrams:

$$\begin{array}{c}
\begin{array}{ccc}
((A \otimes B) \otimes C) \otimes D & \xrightarrow{\alpha_{A,B,C} \otimes \text{id}_D} & (A \otimes (B \otimes C)) \otimes D \\
\downarrow \alpha_{A \otimes B, C, D} & & \downarrow \alpha_{A, B \otimes C, D} \\
(A \otimes B) \otimes (C \otimes D) & & A \otimes ((B \otimes C) \otimes D) \\
\downarrow \alpha_{A, B, C \otimes D} & \xleftarrow{\text{id}_A \otimes \alpha_{B, C, D}} & \\
A \otimes (B \otimes (C \otimes D)) & & 
\end{array} \\
\\
\begin{array}{ccccc}
(A \otimes B) \otimes C & \xrightarrow{\alpha_{A,B,C}} & A \otimes (B \otimes C) & \xrightarrow{\beta_{A, B \otimes C}} & (B \otimes C) \otimes A \\
\downarrow \beta_{A,B} \otimes \text{id}_C & & & & \downarrow \alpha_{B,C,A} \\
(B \otimes A) \otimes C & \xrightarrow{\alpha_{B,A,C}} & B \otimes (A \otimes C) & \xrightarrow{\text{id}_B \otimes \beta_{A,C}} & B \otimes (C \otimes A)
\end{array} \\
\\
\begin{array}{ccc}
(A \otimes \top) \otimes B & \xrightarrow{\alpha_{A,\top,B}} & A \otimes (\top \otimes B) \\
\downarrow \rho_A \otimes \text{id}_B & \searrow \text{id}_A \otimes \lambda_B & \\
A \otimes B & & 
\end{array}
\quad
\begin{array}{ccc}
A \otimes B & & \\
\downarrow \beta_{A,B} & \searrow \text{id}_{A \otimes B} & \\
B \otimes A & \xrightarrow{\beta_{B,A}} & A \otimes B
\end{array} \\
\\
\begin{array}{ccc}
\top \otimes A & \xrightarrow{\beta_{\top,A}} & A \otimes \top \\
\downarrow \lambda_A & \searrow \rho_A & \\
A & & 
\end{array}
\end{array}$$

**Definition 18.** A *monoidal biclosed category* is a monoidal category  $(\mathcal{M}, \top, \otimes)$ , such that, for any object  $B$  of  $\mathcal{M}$ , each of the functors  $-\otimes B : \mathcal{M} \rightarrow \mathcal{M}$  and  $B \otimes - : \mathcal{M} \rightarrow \mathcal{M}$  has a specified right adjoint. Hence, for any object  $A$  and  $C$  of  $\mathcal{M}$ , there are two objects  $C \leftarrow B$  and  $B \rightarrow C$  of  $\mathcal{M}$  and two natural bijections:

$$\begin{aligned}
\text{Hom}_{\mathcal{M}}(A \otimes B, C) &\cong \text{Hom}_{\mathcal{M}}(A, C \leftarrow B) \\
\text{Hom}_{\mathcal{M}}(B \otimes A, C) &\cong \text{Hom}_{\mathcal{M}}(A, B \rightarrow C)
\end{aligned}$$

**Definition 19.** 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  $-\otimes B : \mathcal{M} \rightarrow \mathcal{M}$  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:

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

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

**Definition 20.** Suppose we are given two 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 **monoidal functor** is a functor  $F: \mathcal{M}_1 \rightarrow \mathcal{M}_2$ , a map  $m_{\top_1}: \top_2 \rightarrow F\top_1$  and a natural transformation  $m_{A,B}: FA \otimes_2 FB \rightarrow F(A \otimes_1 B)$  subject to the following coherence conditions:

$$\begin{array}{ccc}
(FA \otimes_2 FB) \otimes_2 FC & \xrightarrow{\alpha_{2FA,FB,FC}} & FA \otimes_2 (FB \otimes_2 FC) \\
\downarrow m_{A,B} \otimes \text{id}_{FC} & & \downarrow \text{id}_{FA} \otimes m_{B,C} \\
F(A \otimes_1 B) \otimes_2 FC & & FA \otimes_2 F(B \otimes_1 C) \\
\downarrow m_{A \otimes_1 B, C} & & \downarrow m_{A, B \otimes_1 C} \\
F((A \otimes_1 B) \otimes_1 C) & \xrightarrow{F\alpha_{1A,B,C}} & F(A \otimes_1 (B \otimes_1 C))
\end{array}$$
  

$$\begin{array}{ccc}
\top_2 \otimes_2 FA & \xrightarrow{\lambda_{2FA}} & FA \\
\downarrow m_{\top_1} \otimes \text{id}_{FA} & & \uparrow F\lambda_{1A} \\
F\top_1 \otimes_2 FA & \xrightarrow{m_{\top_1, A}} & F(\top_1 \otimes_1 A)
\end{array}
\quad
\begin{array}{ccc}
FA \otimes_2 \top_2 & \xrightarrow{\rho_{2FA}} & FA \\
\downarrow \text{id}_{FA} \otimes m_{\top_1} & & \uparrow F\rho_{1A} \\
FA \otimes_2 F\top_1 & \xrightarrow{m_{A, \top_1}} & F(A \otimes_1 \top_1)
\end{array}$$

Need to notice that the composition of monoidal functors is also monoidal, subject to the above coherence conditions.

**Definition 21.** Suppose we are given two symmetric monoidal closed categories  $(\mathcal{M}_1, \top_1, \otimes_1, \alpha_1, \lambda_1, \rho_1, \beta_1)$  and  $(\mathcal{M}_2, \top_2, \otimes_2, \alpha_2, \lambda_2, \rho_2, \beta_2)$ . Then a **symmetric monoidal functor** is a functor  $F: \mathcal{M}_1 \rightarrow \mathcal{M}_2$ , a map  $m_{\top_1}: \top_2 \rightarrow F\top_1$  and a natural transformation  $m_{A,B}: FA \otimes_2 FB \rightarrow F(A \otimes_1 B)$  subject to the following coherence conditions:

$$\begin{array}{ccc}
(FA \otimes_2 FB) \otimes_2 FC & \xrightarrow{\alpha_{2FA,FB,FC}} & FA \otimes_2 (FB \otimes_2 FC) \\
\downarrow m_{A,B} \otimes \text{id}_{FC} & & \downarrow \text{id}_{FA} \otimes m_{B,C} \\
F(A \otimes_1 B) \otimes_2 FC & & FA \otimes_2 F(B \otimes_1 C) \\
\downarrow m_{A \otimes_1 B, C} & & \downarrow m_{A, B \otimes_1 C} \\
F((A \otimes_1 B) \otimes_1 C) & \xrightarrow{F\alpha_{1A,B,C}} & F(A \otimes_1 (B \otimes_1 C))
\end{array}$$
  

$$\begin{array}{ccc}
\top_2 \otimes_2 FA & \xrightarrow{\lambda_{2FA}} & FA \\
\downarrow m_{\top_1} \otimes \text{id}_{FA} & & \uparrow F\lambda_{1A} \\
F\top_1 \otimes_2 FA & \xrightarrow{m_{\top_1, A}} & F(\top_1 \otimes_1 A)
\end{array}
\quad
\begin{array}{ccc}
FA \otimes_2 \top_2 & \xrightarrow{\rho_{2FA}} & FA \\
\downarrow \text{id}_{FA} \otimes m_{\top_1} & & \uparrow F\rho_{1A} \\
FA \otimes_2 F\top_1 & \xrightarrow{m_{A, \top_1}} & F(A \otimes_1 \top_1)
\end{array}$$

$$\begin{array}{ccc}
FA \otimes_2 FB & \xrightarrow{\beta_{2FA,FB}} & FB \otimes_2 FA \\
\downarrow m_{A,B} & & \downarrow m_{B,A} \\
F(A \otimes_1 B) & \xrightarrow{F\beta_{1A,B}} & F(B \otimes_1 A)
\end{array}$$

**Definition 22.** Suppose  $(\mathcal{M}_1, \tau_1, \otimes_1)$  and  $(\mathcal{M}_2, \tau_2, \otimes_2)$  are monoidal categories, and  $(F, m)$  and  $(G, n)$  are monoidal functors between  $\mathcal{M}_1$  and  $\mathcal{M}_2$ . Then a **monoidal natural transformation** is a natural transformation,  $f : F \rightarrow G$ , subject to the following coherence diagrams:

$$\begin{array}{ccc}
FA \otimes_2 FB & \xrightarrow{m_{A,B}} & F(A \otimes_1 B) \\
\downarrow f_A \otimes_2 f_B & & \downarrow f_{A \otimes_1 B} \\
GA \otimes_2 GB & \xrightarrow{n_{A,B}} & G(A \otimes_1 B)
\end{array}
\quad
\begin{array}{ccc}
F\tau_1 & \xrightarrow{f_{\tau_1}} & G\tau_1 \\
\swarrow m_{\tau_1} & & \searrow n_{\tau_1} \\
& \tau_2 &
\end{array}$$

**Definition 23.** Suppose  $(\mathcal{M}_1, \tau_1, \otimes_1)$  and  $(\mathcal{M}_2, \tau_2, \otimes_2)$  are SMCs, and  $(F, m)$  and  $(G, n)$  are symmetric monoidal functors between  $\mathcal{M}_1$  and  $\mathcal{M}_2$ . Then a **symmetric monoidal natural transformation** is a natural transformation,  $f : F \rightarrow G$ , subject to the following coherence diagrams:

$$\begin{array}{ccc}
FA \otimes_2 FB & \xrightarrow{m_{A,B}} & F(A \otimes_1 B) \\
\downarrow f_A \otimes_2 f_B & & \downarrow f_{A \otimes_1 B} \\
GA \otimes_2 GB & \xrightarrow{n_{A,B}} & G(A \otimes_1 B)
\end{array}
\quad
\begin{array}{ccc}
F\tau_1 & \xrightarrow{f_{\tau_1}} & G\tau_1 \\
\swarrow m_{\tau_1} & & \searrow n_{\tau_1} \\
& \tau_2 &
\end{array}$$

**Definition 24.** Suppose  $(\mathcal{M}_1, \tau_1, \otimes_1)$  and  $(\mathcal{M}_2, \tau_2, \otimes_2)$  are monoidal categories, and  $(F, m)$  is a monoidal functor between  $\mathcal{M}_1$  and  $\mathcal{M}_2$  and  $(G, n)$  is a monoidal functor between  $\mathcal{M}_2$  and  $\mathcal{M}_1$ . Then a **monoidal adjunction** is an ordinary adjunction  $\mathcal{M}_1 : F \dashv G : \mathcal{M}_2$  such that the unit,  $\eta_A : A \rightarrow GFA$ , and the counit,  $\varepsilon_A : FGA \rightarrow A$ , are



monoidal natural transformations. Thus, the following diagrams must commute:

$$\begin{array}{ccc}
FGA \otimes_2 FGB & \xrightarrow{m_{GA,GB}} & F(GA \otimes_1 GB) \\
\downarrow \varepsilon_A \otimes_1 \varepsilon_B & & \downarrow Fn_{A,B} \\
A \otimes_2 B & \xleftarrow{\varepsilon_{A \otimes_1 B}} & FGA \otimes_2 FGB
\end{array}
\quad
\begin{array}{ccc}
F\tau_1 & \xrightarrow{Fn_{\tau_2}} & FG\tau_2 \\
\uparrow m_{\tau_1} & & \downarrow \varepsilon_{\tau_1} \\
\tau_2 & \xlongequal{\quad} & \tau_2
\end{array}$$

$$\begin{array}{ccc}
GFA \otimes_1 GFB & \xleftarrow{\eta_A \otimes_1 \eta_B} & A \otimes_1 B \\
\downarrow n_{FA,FB} & & \downarrow \eta_{A \otimes_1 B} \\
G(FA \otimes_2 FB) & \xrightarrow{m_{A,B}} & GF(A \otimes_1 B)
\end{array}
\quad
\begin{array}{ccc}
G\tau_2 & \xrightarrow{Gm_{\tau_1}} & GF\tau_1 \\
\uparrow n_{\tau_2} & & \uparrow \eta_{\tau_1} \\
\tau_1 & \xlongequal{\quad} & \tau_1
\end{array}$$

**Definition 25.** Suppose  $(\mathcal{M}_1, \tau_1, \otimes_1)$  and  $(\mathcal{M}_2, \tau_2, \otimes_2)$  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,  $\eta_A : A \rightarrow GFA$ , and the counit,  $\varepsilon_A : FGA \rightarrow A$ , are symmetric monoidal natural transformations. Thus, the following diagrams must commute:

$$\begin{array}{ccc}
FGA \otimes_2 FGB & \xrightarrow{m_{GA,GB}} & F(GA \otimes_1 GB) \\
\downarrow \varepsilon_A \otimes_1 \varepsilon_B & & \downarrow Fn_{A,B} \\
A \otimes_2 B & \xleftarrow{\varepsilon_{A \otimes_1 B}} & FGA \otimes_2 FGB
\end{array}
\quad
\begin{array}{ccc}
F\tau_1 & \xrightarrow{Fn_{\tau_2}} & FG\tau_2 \\
\uparrow m_{\tau_1} & & \downarrow \varepsilon_{\tau_1} \\
\tau_2 & \xlongequal{\quad} & \tau_2
\end{array}$$

$$\begin{array}{ccc}
GFA \otimes_1 GFB & \xleftarrow{\eta_A \otimes_1 \eta_B} & A \otimes_1 B \\
\downarrow n_{FA,FB} & & \downarrow \eta_{A \otimes_1 B} \\
G(FA \otimes_2 FB) & \xrightarrow{m_{A,B}} & GF(A \otimes_1 B)
\end{array}
\quad
\begin{array}{ccc}
G\tau_2 & \xrightarrow{Gm_{\tau_1}} & GF\tau_1 \\
\uparrow n_{\tau_2} & & \uparrow \eta_{\tau_1} \\
\tau_1 & \xlongequal{\quad} & \tau_1
\end{array}$$

**Definition 26.** A **monoidal comonad** on a monoidal category  $\mathcal{C}$  is a triple  $(T, \varepsilon, \delta)$ , where  $(T, m)$  is a monoidal endofunctor on  $\mathcal{C}$ ,  $\varepsilon_A : TA \rightarrow A$  and  $\delta_A : TA \rightarrow T^2A$  are monoidal natural transformations, which make the following diagrams commute:

$$\begin{array}{ccc}
TA & \xrightarrow{\delta_A} & T^2A \\
\downarrow \delta_A & & \downarrow T\delta_A \\
T^2A & \xrightarrow{\delta_{TA}} & T^3A
\end{array}
\quad
\begin{array}{ccccc}
& & TA & & \\
& \swarrow & \downarrow \delta_A & \searrow & \\
TA & \xleftarrow{\varepsilon_{TA}} & T^2A & \xrightarrow{T\varepsilon_A} & TA
\end{array}$$

The assumption that  $\varepsilon$  and  $\delta$  are monoidal natural transformations amount to the following diagrams commuting:

$$\begin{array}{ccc}
TA \otimes TB & \xrightarrow{m_{A,B}} & T(A \otimes B) \\
& \searrow \varepsilon_A \otimes \varepsilon_B & \downarrow \varepsilon_{A \otimes B} \\
& & A \otimes B
\end{array}
\qquad
\begin{array}{ccc}
T\top & \xleftarrow{m_\top} & \top \\
& \searrow \varepsilon_\top & \downarrow \\
& & \top
\end{array}$$

$$\begin{array}{ccc}
TA \otimes TB & \xrightarrow{m_{A,B}} & T(A \otimes B) \\
\downarrow \delta_A \otimes \delta_B & & \downarrow \delta_{A \otimes B} \\
T^2A \otimes T^2B & \xrightarrow{m_{TA,TB}} T(TA \otimes TB) \xrightarrow{Tm_{A,B}} & T^2(A \otimes B)
\end{array}$$

$$\begin{array}{ccc}
\top & \xrightarrow{m_\top} & T\top \\
\downarrow m_\top & & \downarrow \delta_\top \\
T\top & \xrightarrow{Tm_\top} & T^2\top
\end{array}$$

**Definition 27.** A *symmetric monoidal comonad* on a symmetric monoidal category  $\mathcal{C}$  is a triple  $(T, \varepsilon, \delta)$ , where  $(T, m)$  is a symmetric monoidal endofunctor on  $\mathcal{C}$ ,  $\varepsilon_A : TA \rightarrow A$  and  $\delta_A : TA \rightarrow T^2A$  are symmetric monoidal natural transformations, which make the following diagrams commute:

$$\begin{array}{ccc}
TA & \xrightarrow{\delta_A} & T^2A \\
\downarrow \delta_A & & \downarrow T\delta_A \\
T^2A & \xrightarrow{\delta_{TA}} & T^3A
\end{array}
\qquad
\begin{array}{ccc}
& TA & \\
& \downarrow \delta_A & \\
TA & \xleftarrow{\varepsilon_{TA}} T^2A \xrightarrow{T\varepsilon_A} & TA
\end{array}$$

The assumption that  $\varepsilon$  and  $\delta$  are symmetric monoidal natural transformations amount to the following diagrams commuting:

$$\begin{array}{ccc}
TA \otimes TB & \xrightarrow{m_{A,B}} & T(A \otimes B) \\
& \searrow \varepsilon_A \otimes \varepsilon_B & \downarrow \varepsilon_{A \otimes B} \\
& & A \otimes B
\end{array}
\qquad
\begin{array}{ccc}
T\top & \xleftarrow{m_\top} & \top \\
& \searrow \varepsilon_\top & \downarrow \\
& & \top
\end{array}$$

$$\begin{array}{ccc}
TA \otimes TB & \xrightarrow{m_{A,B}} & T(A \otimes B) \\
\downarrow \delta_A \otimes \delta_B & & \downarrow \delta_{A \otimes B} \\
T^2A \otimes T^2B & \xrightarrow{m_{TA,TB}} T(TA \otimes TB) \xrightarrow{Tm_{A,B}} & T^2(A \otimes B)
\end{array}$$
  

$$\begin{array}{ccc}
\top & \xrightarrow{m_\top} & T\top \\
\downarrow m_\top & & \downarrow \delta_\top \\
T\top & \xrightarrow{Tm_\top} & T^2\top
\end{array}$$

## B Proofs

### B.1 Proof of Composition of Weakening and Contraction (Lemma 9)

Since by definition  $w : \mathcal{L} \longrightarrow \mathcal{L}$  and  $c : \mathcal{L} \longrightarrow \mathcal{L}$  are monoidal functors we know that their composition  $cw : \mathcal{L} \longrightarrow \mathcal{L}$  is a monoidal functor:

$$\begin{aligned}
q_{A,B} &: cwA \otimes cwB \longrightarrow cw(A \otimes B) \\
q_{A,B} &= cq_{A,B}^w \circ q_{wA,wB}^c \\
q_I &: I \longrightarrow cwI \\
q_I &= cq_I^w \circ q_I^c
\end{aligned}$$

We must now define both  $\varepsilon_A : cwA \longrightarrow A$  and  $\delta_A : cwA \longrightarrow cwcwA$ , and then show that they are monoidal natural transformations subject to the comonad laws. Since we are composing two comonads each of  $\varepsilon$  and  $\delta$  can be given two definitions, but they are equivalent:

- $\varepsilon_A : cwA \longrightarrow A$  is defined as in the diagram below, which commutes by the naturality of  $\varepsilon^c$ .

$$\begin{array}{ccc}
cwA & \xrightarrow{\varepsilon_{wA}^c} & wA \\
\downarrow c\varepsilon_A^w & & \downarrow \varepsilon_A^w \\
cA & \xrightarrow{\varepsilon_A^c} & A
\end{array}$$

- $\delta_A : cwA \rightarrow cwcwA$  is defined as in the diagram:

$$\begin{array}{ccccc}
 cwA & \xrightarrow{c\delta_A^w} & cw^2A & \xrightarrow{\delta_{w^2A}^c} & c^2w^2A \\
 \downarrow \delta_{wA}^c & & \downarrow \delta_{w^2A}^c & & \downarrow cdist_{wA} \\
 c^2wA & \xrightarrow{c^2\delta_A^w} & c^2w^2A & \xrightarrow{cdist_{wA}} & cwcwA
 \end{array}$$

The left part of the diagram commutes by the naturality of  $\delta^c$  and the right part commutes trivially.

The remainder of the proof shows that the comonad laws hold.

**Case 1:**

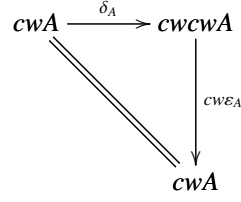
$$\begin{array}{ccc}
 cwA & \xrightarrow{\delta_A} & cwcwA \\
 \downarrow \delta_A & & \downarrow cw\delta_A \\
 cwcwA & \xrightarrow{\delta_{cwcwA}} & cwcwcwA
 \end{array}$$

The previous diagram commutes because the following one does.

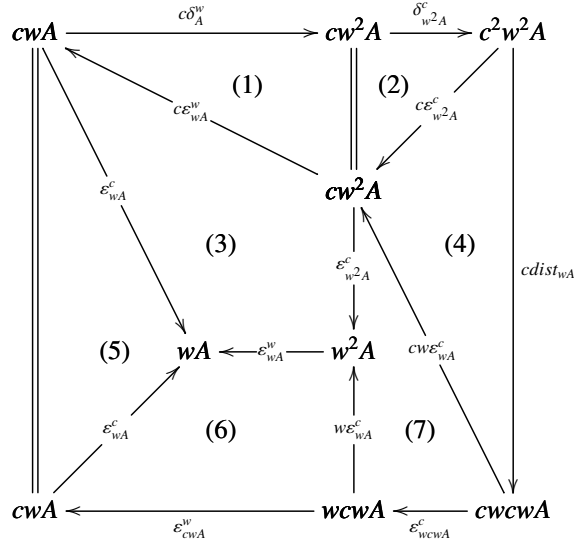
$$\begin{array}{ccccccc}
 cwA & \xrightarrow{\delta_A} & cwcwA & \xrightarrow{cw\delta_A^w} & cwcw^2A & \xrightarrow{cw\delta_{w^2A}^c} & cwc^2w^2A \\
 \downarrow \delta_A & (1) & \downarrow \delta_{cwcwA}^c & (2) & \downarrow \delta_{cwcw^2A}^c & (5) & \downarrow cdist_{cwcw^2A} \\
 cwcwA & & c^2wcwA & \xrightarrow{c^2wc\delta_A^w} & c^2wcw^2A & & \\
 \downarrow c\delta_{cwA}^w & & \downarrow c^2\delta_{cwA}^w & (3) & \downarrow c^2wdist_{wA} & (6) & \downarrow cwcdist_{wA} \\
 cw^2cwA & \xrightarrow{\delta_{w^2cwA}^c} & c^2w^2cwA & \xrightarrow{cdist_{w^2cwA}} & cwcwcwA & & 
 \end{array}$$

(1) commutes by equality and we will not expand  $\delta_A$  for simplicity. (2) and (4) commutes by the naturality of  $\delta^c$ . (3), (5) commutes by the conditions of  $dist$ . (6) commutes by the naturality of  $dist$ .

**Case 2:**

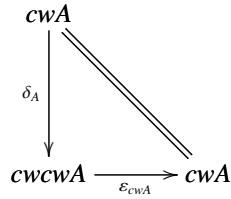


The triangle commutes because of the following diagram chasing.

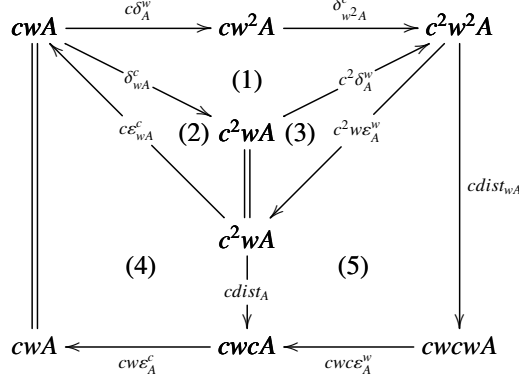


(1) commutes by the comonad law for  $w$  with components  $\delta_A^w$  and  $\varepsilon_{wA}^w$ . (2) commutes by the comonad law for  $c$  with components  $\delta_{w^2A}^c$  and  $\varepsilon_{w^2A}^c$ . (3) and (7) commute by the naturality of  $\varepsilon^c$ . (4) commutes by the condition of  $dist$ . (5) commutes trivially. And (6) commutes by the naturality of  $\varepsilon^w$ .

**Case 3:**



The previous triangle commutes because the following diagram chasing does.



(1) commutes by the naturality of  $\delta^c$ . (2) is the comonad law for  $c$  with components  $\delta_{wA}^c$  and  $\epsilon_{wA}^c$ . (3) is the comonad law for  $w$  with components  $\delta_A^w$  and  $\epsilon_A^w$ . (4) commutes by the condition of  $dist$ . And (5) commute by the naturality of  $dist$ .

## B.2 Proof of Conditions of Lambek category with $cw$ (Lemma 11)

1. As shown in the paper.
2. Each  $(cwA, \text{weak}_A, \text{contra}_A)$  is a comonoid.

**Case 1:**

$$\begin{array}{ccccc}
 cwA & \xrightarrow{\text{contra}_A} & cwA \otimes cwA & \xrightarrow{id_{cwA} \otimes \text{contra}_A} & cwA \otimes (cwA \otimes cwA) \\
 \text{contra}_A \downarrow & & & & \uparrow \alpha_{cwA, cwA, cwA} \\
 cwA \otimes cwA & \xrightarrow{\text{contra}_A \otimes id_{cwA}} & (cwA \otimes cwA) \otimes cwA & & 
 \end{array}$$

The previous diagram commutes by the following diagram chasing.

$$\begin{array}{ccccccc}
 cwA & \xrightarrow{\text{contra}_A} & cwA \otimes cwA & \xrightarrow{id_{cwA} \otimes \rho_{cwA}^{-1}} & cwA \otimes (cwA \otimes I) & & \\
 \text{contra}_A \downarrow & (1) & \swarrow & & \downarrow id_{cwA} \otimes \text{contra}_{cwA, I} & & \\
 cwA \otimes cwA & \xrightarrow{id_{cwA} \otimes \lambda_{cwA}^{-1}} & cwA \otimes (I \otimes cwA) & & cwA \otimes ((cwA \otimes I) \otimes cwA) & & \\
 \rho_{cwA}^{-1} \otimes id_{cwA} \downarrow & & \downarrow id_{cwA} \otimes \text{contra}_{cwA, I} & \nearrow id_{cwA} \otimes \alpha_{cwA, I, cwA} & \downarrow id_{cwA} \otimes (\rho_{cwA} \otimes id_{cwA}) & & \\
 (cwA \otimes I) \otimes cwA & & cwA \otimes (cwA \otimes (I \otimes cwA)) & \xrightarrow{id_{cwA} \otimes (id_{cwA} \otimes \lambda_{cwA})} & cwA \otimes (cwA \otimes cwA) & & \\
 \text{contra}_{cwA, I} \otimes id_{cwA} \downarrow & & & (3) & \uparrow \alpha_{cwA, cwA, cwA} & & \\
 ((cwA \otimes I) \otimes cwA) \otimes cwA & \xrightarrow{(\rho_{cwA} \otimes id_{cwA}) \otimes id_{cwA}} & (cwA \otimes cwA) \otimes cwA & & & & \\
 & (4) & & & & & 
 \end{array}$$

(1) commutes trivially and we would not expand  $\text{contra}$  for simplicity. (2) and (4) commute because  $(\mathcal{L}, c, \text{contraL}, \text{contraR})$  is a Lambek category with contraction. (3) commutes because  $\mathcal{L}$  is monoidal.

**Case 2:**

$$\begin{array}{ccccc}
 & & cwA & & \\
 & \swarrow \lambda^{-1} & \downarrow \text{contra}_A & \searrow \rho^{-1} & \\
 I \otimes cwA & \xleftarrow{\text{weak}_A \otimes id_{cwA}} & cwA \otimes cwA & \xrightarrow{id_{cwA} \otimes \text{weak}_A} & cwA \otimes I
 \end{array}$$

The diagram above commutes by the following diagram chasing.

$$\begin{array}{c}
 \begin{array}{ccccc}
 I \otimes cwA & \xleftarrow{\text{weak}_A^w \otimes id_{cwA}} & & & wA \otimes cwA \\
 \uparrow id_I \otimes \lambda_{cwA} & & (2) & & \uparrow id_{wA} \otimes \lambda_{cwA} \\
 I \otimes (I \otimes cwA) & \xleftarrow{\text{weak}_A^w \otimes id_{I \otimes cwA}} & & & wA \otimes (I \otimes cwA) \\
 \uparrow \lambda_{I \otimes cwA}^{-1} & & (4) & & \uparrow \varepsilon_{wA}^c \otimes id_{I \otimes cwA} \\
 I \otimes cwA & \xrightarrow{\text{contraR}_{wA, I}} & cwA \otimes (I \otimes cwA) & & \\
 \uparrow \lambda_{cwA}^{-1} & & (5) & & \uparrow id_{cwA} \otimes \lambda_{cwA} \\
 cwA & & & & cwA \otimes cwA \\
 \downarrow \rho_{cwA}^{-1} & & (6) & & \downarrow \rho_{cwA} \otimes id_{cwA} \\
 cwA \otimes I & \xrightarrow{\text{contraL}_{wA, I}} & (cwA \otimes I) \otimes cwA & & \\
 \downarrow \rho_{cwA}^{-1} & & (9) & & \downarrow id_{cwA \otimes I} \otimes \varepsilon_{wA}^c \\
 (cwA \otimes I) \otimes I & \xleftarrow{id_{cwA \otimes I} \otimes \text{weak}_A^w} & (cwA \otimes I) \otimes wA & & \\
 \downarrow \rho_{cwA} \otimes id_I & & (7) & & \downarrow \rho_{cwA} \otimes id_{wA} \\
 cwA \otimes I & \xleftarrow{id_{cwA} \otimes \text{weak}_A} & & & cwA \otimes wA
 \end{array}
 \end{array}$$

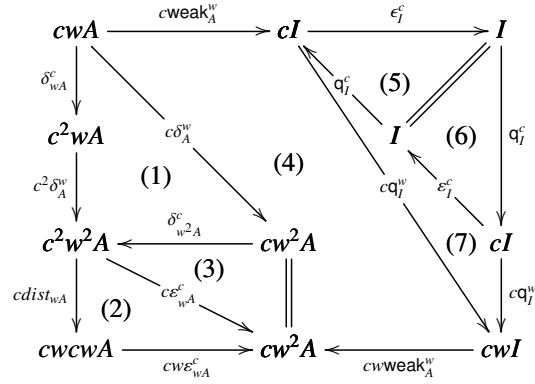
(1), (2) and (3) commute by the functionality of  $\lambda$ . (6), (7) and (8) commute by the functionality of  $\rho$ . (4) and (9) are conditions of the Lambek category with  $cw$ . And (5) is the definition of  $\text{contra}$ .

3.  $\text{weak}$  and  $\text{contra}$  are coalgebra morphisms.

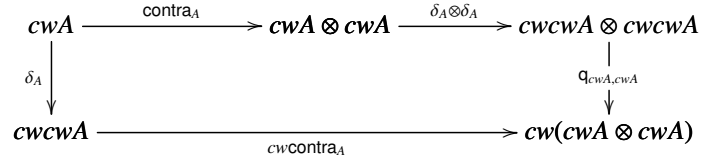
**Case 1:**

$$\begin{array}{ccc}
 cwA & \xrightarrow{\text{weak}_A} & I \\
 \delta_A \downarrow & & \downarrow q_I \\
 cwcwA & \xrightarrow{cw\text{weak}_A} & cwI
 \end{array}$$

The previous diagram commutes by the diagram below. (1) commutes by the naturality of  $\delta^c$ . (2) commutes by the condition of  $dist_{wA}$ . (3), (5) and (6) commute because  $c$  is a monoidal comonad. (4) commutes because  $(\mathcal{L}, w, \text{weak}^w)$  is a Lambek category with weakening. (7) commutes because  $c$  and  $w$  are monoidal comonads.

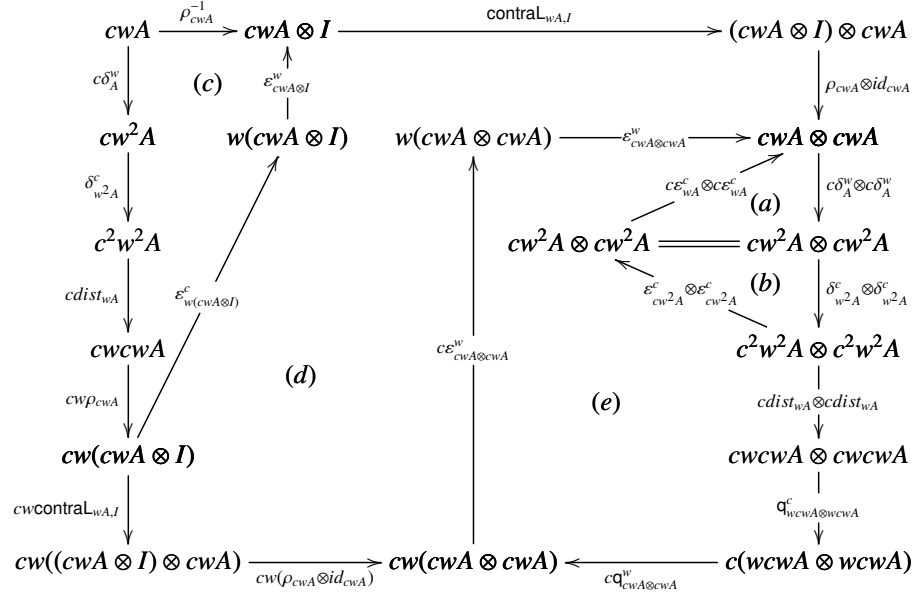


**Case 2:**



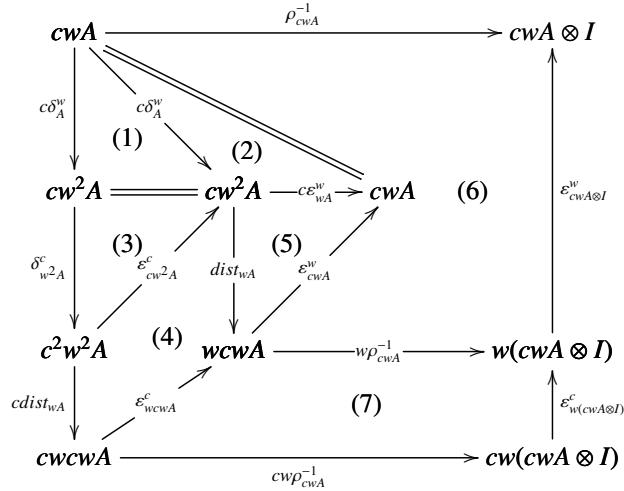
To prove the previous diagram commute, we first expand it, Then we divide it into five parts as shown below, and prove each part commutes.





Part (a) and (b) are comonad laws.

Part (c) commutes by the following diagram chase. (1) is equality. (2) is the comonad law for  $w$ . (3) is the comonad law for  $c$ . (4) commutes by the naturality of  $\varepsilon^c$ . (5) is one of the conditions for  $dist_{wA}$ . (6) commutes by the naturality of  $\varepsilon^w$ . And (7) commutes by the naturality of  $\varepsilon^c$ .



Part (d) commutes by the following diagram chase. The upper two squares both commute by the naturality of  $\varepsilon^w$ , and the lower two squares commute

by the naturality of  $\varepsilon^c$ .

$$\begin{array}{ccccc}
cwA \otimes I & \xrightarrow{\text{contra}_{wA,I}} & (cwA \otimes I) \otimes cwA & \xrightarrow{\rho_{cwA} \otimes id_{cwA}} & cwA \otimes cwA \\
\uparrow \varepsilon_{cwA \otimes I}^w & & \uparrow \varepsilon_{(cwA \otimes I) \otimes cwA}^w & & \uparrow \varepsilon_{cwA \otimes cwA}^w \\
w(cwA \otimes I) & \xrightarrow{w \text{contra}_{wA,I}} & w((cwA \otimes I) \otimes cwA) & \xrightarrow{w(\rho_{cwA} \otimes id_{cwA})} & w(cwA \otimes cwA) \\
\uparrow \varepsilon_{w(cwA \otimes I)}^c & & \uparrow \varepsilon_{w((cwA \otimes I) \otimes cwA)}^c & & \uparrow \varepsilon_{w(cwA \otimes cwA)}^c \\
cw(cwA \otimes I) & \xrightarrow{cw \text{contra}_{wA,I}} & cw((cwA \otimes I) \otimes cwA) & \xrightarrow{cw(\rho_{cwA} \otimes id_{cwA})} & cw(cwA \otimes cwA)
\end{array}$$

Part (e) commutes by the following diagram. (1) commutes by the condition of  $dist_{wA}$ . (2) and (4) commute by the naturality of  $\varepsilon^c$ . (3) and (5) commute because  $w$  and  $c$  are monoidal comonads.

$$\begin{array}{ccccc}
cwA \otimes cwA & \xleftarrow{c\varepsilon_{wA}^w \otimes c\varepsilon_{wA}^w} & cw^2A \otimes cw^2A & \xleftarrow{\varepsilon_{cw^2A}^c \otimes \varepsilon_{cw^2A}^c} & c^2w^2A \otimes c^2w^2A \\
\uparrow \varepsilon_{cwA \otimes cwA}^w & & \downarrow dist_{wA} \otimes dist_{wA} & & \downarrow cdist_{wA} \otimes cdist_{wA} \\
& & (1) \quad w cwA \otimes w cwA & \xleftarrow{\varepsilon_{w cwA}^c \otimes \varepsilon_{w cwA}^c} & c w cwA \otimes c w cwA \\
& & \downarrow q_{cwA, cwA}^w & & \downarrow q_{w cwA, w cwA}^c \\
w(cwA \otimes cwA) & \xleftarrow{\varepsilon_{w(cwA \otimes cwA)}^c} & cw(cwA \otimes cwA) & \xleftarrow{c q_{cwA \otimes cwA}^c} & c(w cwA \otimes w cwA)
\end{array}$$

(2)  $c^2w^2A \otimes c^2w^2A \xrightarrow{cdist_{wA} \otimes cdist_{wA}} c w cwA \otimes c w cwA$

(3)  $w cwA \otimes w cwA \xrightarrow{q_{cwA, cwA}^w} w(cwA \otimes cwA)$

(4)  $w cwA \otimes w cwA \xrightarrow{\varepsilon_{w cwA}^c \otimes \varepsilon_{w cwA}^c} cw(cwA \otimes cwA)$

(5)  $c w cwA \otimes c w cwA \xrightarrow{c q_{cwA \otimes cwA}^c} c(w cwA \otimes w cwA)$

4. Any coalgebra morphism  $f : (cwA, \delta_A) \rightarrow (cwB, \delta_B)$  between free coalgebras preserves the comonoid structure given by weak and contra.

**Case 1:** This coherence diagram is given in the definition of the Lambek category with  $cw$ .

$$\begin{array}{ccc}
cwA & \xrightarrow{f} & cwB \\
& \searrow \text{weak}_A & \swarrow \text{weak}_B \\
& I &
\end{array}$$

**Case 2:**

$$\begin{array}{ccc}
cwA & \xrightarrow{\text{contra}_A} & cwA \otimes cwA \\
f \downarrow & & \downarrow f \otimes f \\
cwB & \xrightarrow{\text{contra}_B} & cwB \otimes cwB
\end{array}$$

The square commutes by the diagram chasing below, which commutes by the naturality of  $\rho$  and  $\text{contra}_L$ .

$$\begin{array}{ccccccc}
cwA & \xrightarrow{\rho_{cwA}^{-1}} & cwA \otimes I & \xrightarrow{\text{contraL}_{wA,I}} & (cwA \otimes I) \otimes cwA & \xrightarrow{\rho_{cwA} \otimes id_{cwA}} & cwA \otimes cwA \\
\downarrow cw f & & \downarrow cw f \otimes id_I & & \downarrow (cw f \otimes id_I) \otimes cw f & & \downarrow cw f \otimes cw f \\
cwB & \xrightarrow{\rho_{cwB}^{-1}} & cwB \otimes I & \xrightarrow{\text{contraL}_{wB,I}} & (cwB \otimes I) \otimes cwB & \xrightarrow{\rho_{cwB} \otimes id_{cwB}} & cwB \otimes cwB
\end{array}$$