Categorical model of noncommutative linear logic with subexponentials

Definition 1. *A subexponential signature is an ordered quintuple:*
$\Sigma = \langle I, \preceq, W, C, E \rangle$,

where $I = \{s_1, \ldots, s_n\}$, $\langle I, \preceq \rangle$ is a preorder. W, C, E are subsets of I and $W \cup C \subseteq E$.

Definition 2. *Noncommutative linear logic with subexponentials ($SMALC_\Sigma$), where Σ is a subexponential signature.*

$$\frac{}{A \Rightarrow A}\ ax$$

$$\frac{\Gamma \Rightarrow A \qquad \Delta, B, \Theta \Rightarrow C}{\Delta, \Gamma, A\backslash B, \Theta \Rightarrow C}\ \backslash\to \qquad\qquad \frac{A, \Pi \Rightarrow B}{\Pi \Rightarrow A\backslash B}\ \to\backslash$$

$$\frac{\Gamma \Rightarrow A \qquad \Delta, B, \Theta \Rightarrow C}{\Delta, B/A, \Gamma, \Theta \Rightarrow C}\ /\to \qquad\qquad \frac{\Pi, A \Rightarrow B}{\Pi \Rightarrow B/A}\ \to/$$

$$\frac{\Gamma, A, B, \Delta \Rightarrow C}{\Gamma, A \bullet B, \Delta \Rightarrow C}\ \bullet\to \qquad\qquad \frac{\Gamma \Rightarrow A \qquad \Delta \Rightarrow B}{\Gamma, \Delta \Rightarrow A \bullet B}\ \to\bullet$$

$$\frac{\Gamma, A_i, \Delta \Rightarrow B}{\Gamma, A_1 \& A_2, \Delta \Rightarrow B}\ \&, i = 1,2 \to \qquad\qquad \frac{\Gamma \Rightarrow A \qquad \Gamma \Rightarrow B}{\Gamma \Rightarrow A \& B}\ \to\&$$

$$\frac{\Gamma, A, \Delta \Rightarrow C \qquad \Gamma, B, \Delta \Rightarrow C}{\Gamma, A \vee B, \Delta \Rightarrow C}\ \vee\to \qquad\qquad \frac{\Gamma \Rightarrow A_i}{\Gamma \Rightarrow A_1 \vee A_2}\ \to\vee, i = 1,2$$

$$\frac{\Gamma, \Delta \Rightarrow A}{\Gamma, \mathbf{1}, \Delta \Rightarrow A}\ \mathbf{1}\to \qquad\qquad \frac{}{\Rightarrow \mathbf{1}}\ \to\mathbf{1}$$

$$\frac{\Gamma, A, \Delta \Rightarrow C}{\Gamma, !^s A, \Delta \Rightarrow C}\ !\to \qquad\qquad \frac{!^{s_1} A_1, \ldots, !^{s_n} A_n \Rightarrow A}{!^{s_1} A_1, \ldots, !^{s_n} A_n \Rightarrow !^s A}\ \to!, \forall j, s_j \succeq s$$

$$\frac{\Gamma, \Delta \Rightarrow B}{\Gamma, !^s A, \Delta \Rightarrow B}\ \mathbf{weak}_!, s \in C$$

$$\frac{\Gamma, !^s A, \Delta, !^s A, \Theta \Rightarrow B}{\Gamma, !^s A, \Delta, \Theta \Rightarrow B}\ \mathbf{ncontr}_1, s \in C$$

$$\frac{\Gamma, !^s A, \Delta, !^s A, \Theta \Rightarrow B}{\Gamma, \Delta, !^s A, \Theta \Rightarrow B}\ \mathbf{ncontr}_2, s \in C$$

$$\frac{\Gamma, \Delta, !^s A, \Theta \Rightarrow B}{\Gamma, !^s A, \Delta, \Theta \Rightarrow A}\ \mathbf{ex}_1, s \in E$$

$$\frac{\Gamma, !^s A, \Delta, \Theta \Rightarrow B}{\Gamma, \Delta, !^s A, \Theta \Rightarrow A}\ \mathbf{ex}_1, s \in E$$

Lemma 1. *Let $A \Leftrightarrow B$, then $C[p_i := A] \Leftrightarrow C[p_i := B]$*

Proof. By induction on C. □

Definition 3. *Monoidal comonad*

A monoidal comonad on some monoidal category $\mathcal{C}$ is a triple $\langle \mathcal{F}, \epsilon, \delta \rangle$, where $\mathcal{F}$ is a monoidal endofunctor and $\epsilon : \mathcal{F} \Rightarrow Id_{\mathcal{C}}$ (counit) and $\epsilon : \mathcal{F} \Rightarrow \mathcal{F}^2$ (comultiplication), such that the following diagrams commute:

$$\begin{tikzcd}
\mathcal{F}A \otimes \mathcal{F}B \arrow[r, "\phi_{A,B}"] \arrow[d, "\delta_A \otimes \delta_B"'] & \mathcal{F}(A \otimes B) \arrow[dr, "\delta_{A \otimes B}"] & \\
 & & \mathcal{F}\mathcal{F}(A \otimes B) \\
\mathcal{F}\mathcal{F}A \otimes \mathcal{F}\mathcal{F}B \arrow[r, "\phi_{\mathcal{F}A,\mathcal{F}B}"'] & \mathcal{F}(\mathcal{F}A \otimes \mathcal{F}B) \arrow[ur, "\mathcal{F}(\phi_{A,B})"'] &
\end{tikzcd}
\qquad
\begin{tikzcd}
\mathcal{F}A \otimes \mathcal{F}B \arrow[rr, "\phi_{A,B}"] \arrow[dr, "\epsilon_A \otimes \epsilon_B"'] & & \mathcal{F}(A \otimes B) \arrow[dl, "\epsilon_{A \otimes B}"] \\
 & A \otimes B &
\end{tikzcd}$$

$$\begin{tikzcd}
\mathbb{1} \arrow[r, "\phi"] \arrow[d, "\phi"'] & \mathcal{F}\mathbb{1} \arrow[d, "\delta_{\mathbb{1}}"] \\
\mathcal{F}\mathbb{1} \arrow[r, "\mathcal{F}(\phi)"'] & \mathcal{F}\mathcal{F}\mathbb{1}
\end{tikzcd}$$

$$\begin{tikzcd}
\mathbb{1} \arrow[rr, "id_{\mathbb{1}}"] \arrow[dr, "\phi"'] & & \mathbb{1} \\
 & \mathcal{F}\mathbb{1} \arrow[ur, "\epsilon_{\mathbb{1}}"'] &
\end{tikzcd}$$

Definition 4. *Biclosed monoidal category*

Let $\mathcal{C}$ be a monoidal category. Biclosed monoidal category is a monoidal category with the following additional data:

1. *Bifunctors $\_\_ \multimapinv \_\_, \_\_ \multimap \_\_ : \mathcal{C}^{op} \times \mathcal{C} \to \mathcal{C}$;*
2. *Natural isomophism $\mathbf{curry}_{A,B,C} : Hom(A \otimes B, C) \cong (B, A \multimap C)$;*
3. *Natural isomophism $\mathbf{curry}'_{A,B,C} : Hom(A \otimes B, C) \cong (A, C \multimap B)$;*
4. *For each $A, B \in Ob_{\mathcal{C}}$, there are exist arrows $ev_{A,B} : A \otimes (A \Rightarrow B) \to B$ and $ev'_{A,B} : (B \Leftarrow A) \otimes A \to B$, such that for all $f : A \otimes C \to B$:*
   (a) $\Lambda_l \circ (id_A \otimes \mathbf{curry}(f)) = f$;
   (b) $\Lambda_r \circ (\mathbf{curry}'(f) \otimes id_A) = f$

Definition 5. *Let F be endofunctor and $A \in Ob\mathcal{C}$, then a coalgebra of F is a tuple $\langle A, \theta \rangle$, where $\theta : A \to FA$.*

Given coalgebras $\langle A, \theta \rangle$ and $\langle A, \psi \rangle$, a homomorphism is a morphism $f : A \to B$, s.t. the diagram below commutes:

$$\begin{tikzcd} A \arrow[r, "\theta"] \arrow[d, "f"'] & FA \arrow[d, "Ff"] \\ B \arrow[r, "\psi"'] & FB \end{tikzcd}$$

that is, $Ff \circ \theta = \psi \circ f$

Definition 6. *Subexponential model structure*

Let $\Sigma = \langle I, \preceq, W, C, E \rangle$ be a subexponential signature and $\mathcal{C}$ be a biclosed monoidal category, then a subexponential model structure is $\langle \mathcal{C}, \{\mathcal{F}_s\}_{s \in I} \rangle$ with the following additional data:

- *for all $s \in I$, $\mathcal{F}_s$ is a monoidal comonad;*
- *if $s \in W$, then for all $A \in Ob(\mathcal{C})$, there exists a morphism $w_{A s} : F_s A \to \mathbb{1}$;*
- *if $s \in C$, then for all $A \in Ob(\mathcal{C})$, there exists morphisms $w_{A l} : F_s A \otimes A \otimes F_s A \to F_s A \otimes B$ and $w_{A r} : F_s A \otimes A \otimes F_s A \to B \otimes F_s A$;*
- *if $s \in E$, then for all $A \in Ob(\mathcal{C})$, there is an isomorpism, $e_A : F_s A \otimes B \cong B \otimes F_s A$;*
- *if $s_1 \in W$, $s_2 \in I$ and $s_1 \preceq s_2$, then there is a morphism $w_{A s_2} : F_{s_2} A \to \mathbb{1}$ for all $A \in Ob(\mathcal{C})$ and ditto for E and C;*
- *Let $\bigotimes_{s \in J, i=0}^{n} F_s A$, where $J \subset I$, and $s^{'} \in I$, s.t. $s \geq s^{'}$ for all $s \in I'$; Then there exists morphism a morphism $\theta_{\bigotimes_{s \in J, i=1}^{n} F_{s\,j} A_i} : \bigotimes_{s \in J, i=0}^{n} F_s A \to F_{s'}(\bigotimes_{s \in J, i=0}^{n} F_s A)$, such that $\langle \bigotimes_{s \in J, i=1}^{n} F_{s\,j} A_i, \theta_{\bigotimes_{s \in J, i=1}^{n} F_{s\,j} A_i} \rangle$ is a coalgebra on F_s.*

Definition 7. *Let $\langle \mathcal{C}, \{\mathcal{F}_s\}_{s \in I} \rangle$ be a subexponential model structure for subexponential signature $\Sigma = \langle I, \preceq, W, C, E \rangle$. Let $v : Tp \to Ob(\mathcal{C})$ be a valuation map. Then the interpretation function $[\![.]\!]$ is defined as follows:*

(1) $[\![\mathbf{1}]\!] = \mathbb{1}$
(2) $[\![A \backslash B]\!] = [\![A]\!] \multimap [\![B]\!]$
(3) $[\![A / B]\!] = [\![A]\!] \multimapinv [\![B]\!]$
(4) $[\![A \bullet B]\!] = [\![A]\!] \otimes [\![B]\!]$
(5) $[\![!_s A]\!] = F_s [\![A]\!]$

Theorem 1. *The following statements are equivalent:*

- $SMLC_{\Sigma} + (cut) \vdash \Gamma \Rightarrow A$
- $SMLC_{\Sigma} \vdash \Gamma \Rightarrow A$
- $\exists f, f : [\![\Gamma]\!] \to [\![A]\!]$

  Proof.
  (1) $\Rightarrow$ (2): cut elimination.

- (2) $\Rightarrow$ (3): Soundness:

$$\frac{}{id_A : A \to A}$$

$$\frac{f : \Gamma \to A \qquad g : \Delta \otimes B \otimes \Theta \to C}{g \circ (id_\Delta \otimes (ev_{A,B_l} \circ (f \otimes id_{A \multimap B})) \otimes id_\Theta) : \Delta \otimes (\Gamma \otimes A \multimap B) \otimes \Theta \to C}$$

$$\frac{f : A \otimes \Pi \to B}{\Lambda_l(f) : \Pi \to A \multimap B}$$

$$\frac{f : \Gamma \to A \qquad g : \Delta \otimes B \otimes \Theta \to C}{g \circ (id_\Delta \otimes (ev_{A,B_l} \circ (id_{B \circ\!- A} \otimes f)) \otimes id_\Theta) : \Delta \otimes (B \circ\!- A \otimes \Gamma) \otimes \Theta \to C}$$

$$\frac{f : \Pi \otimes A \to B}{\Lambda_r(f) : \Pi \to B \circ\!- A}$$

$$\frac{f : \Gamma \otimes A \otimes B \otimes \Delta \to C}{f \circ (\alpha_{\Gamma,A,B} \otimes id_\Delta) : \Gamma \otimes (A \otimes B) \otimes \Delta \to C}$$

$$\frac{f : \Gamma \to A \qquad g : \Delta \to B}{f \otimes g : \Gamma \otimes \Delta \to A \otimes B}$$

$$\frac{f : \Gamma \otimes A_i \otimes \Delta \to B}{f \circ (id_\Gamma \otimes \pi_i id_\Delta) : \Gamma \otimes (A_1 \times A_2) \otimes \Delta \to B}$$

$$\frac{f : \Gamma \to A \qquad g : \Gamma \to B}{\langle f, g \rangle : \Gamma \to A \times B}$$

$$\frac{f : \Gamma \otimes A \otimes \Delta \to C \qquad g : \Gamma \otimes B \otimes \Delta \to C}{id_\Gamma \otimes [f, g] \otimes id_\Delta : \Gamma \otimes (A + B) \otimes \Delta \to C}$$

$$\frac{}{id_{\mathbb{1}} : \mathbb{1} \to \mathbb{1}}$$

$$\frac{f : \Gamma \otimes \Delta \to A}{f \circ (\rho_\Gamma \otimes id_\Delta) : (\Gamma \otimes \mathbb{1}) \otimes \Delta \to A}$$

$$\frac{f : \Gamma \otimes A \otimes \Delta \to B}{f \circ (id_\Gamma \otimes \delta_s^A \otimes id_\Delta) : \Gamma \otimes F_s A \otimes \Delta \to B}$$

$$\frac{\dfrac{f : F_{s_1} A_1 \otimes \cdots \otimes F_{s_n} A_n \to B}{F_s(f) : F_s(F_{s_1} A_1 \otimes \cdots \otimes F_{s_n} A_n) \to F_s B}}{F_s(f) \circ \theta_{\bigotimes_{s \in J, i=1}^{n} F_{sj} A_i} : F_{s_1} A_1 \otimes \cdots \otimes F_{s_n} A_n \to F_s B}$$

$$\frac{\dfrac{f : \Gamma \otimes \Delta \to A}{f \circ (\rho_\Gamma \otimes id_\Delta) : (\Gamma \otimes \mathbb{1}) \otimes \Delta \to A}}{f \circ (\rho_\Gamma \otimes id_\Delta) \circ (id_\Gamma \otimes w_{As}) \otimes id_\Delta : (\Gamma \otimes F_s A) \otimes \Delta \to A}$$

$$\frac{f : \Gamma \otimes (F_s A \otimes B \otimes F_s A) \otimes \Delta \to C}{f \circ (id_\Gamma \otimes {c_{A_s}}^l \otimes id_\Delta) : \Gamma \otimes (F_s A \otimes B) \otimes \Delta \to C}$$

$$\frac{f : \Gamma \otimes (F_s A \otimes B \otimes F_s A) \otimes \Delta \to C}{(id_\Gamma \otimes {c_{A_s}}^r \otimes id_\Delta) \circ f : \Gamma \otimes (B \otimes F_s A) \otimes \Delta \to C}$$

$$\frac{f : \Gamma \otimes (\Delta \otimes F_s A) \otimes \Theta \to B}{(id_\Gamma \otimes (id_\Delta \otimes e_{A_s}) \otimes id_\Theta) \circ f : \Gamma \otimes (F_s A \otimes \Delta) \otimes \Theta \to B}$$

$$\frac{f : \Gamma \otimes (F_s A \otimes \Delta) \otimes \Theta \to B}{(id_\Gamma \otimes (id_\Delta \otimes {e_{A_s}}^{-1}) \otimes id_\Theta) \circ f : \Gamma \otimes (\Delta \otimes F_s A) \otimes \Theta \to B}$$

- Completeness:

  Definition 8.

$\square$

1 Concrete model

Definition 9. *Quantale A quantale is a triple $\langle A, \bigvee, \cdot \rangle$, such that $\langle A, \bigvee \rangle$ is a complete lattice and $\langle A, \cdot \rangle$ is a semigroup. A quanlate is called unital, if $\langle A, \cdot \rangle$ is a monoid.*

It is easy to see, that any (unital) quantale is a residual (monoid) semigroup. We define divisions as follows:

1. $a \backslash b = \bigvee \{c \mid a \cdot c \leqslant b\}$
2. $b/a = \bigvee \{c \mid c \cdot a \leqslant b\}$

Definition 10. *Let $\langle A, \bigvee, \cdot \rangle$ be a quantale. The center of a quantale is the set $Z(Q) = \{a \in Q \mid \forall b \in Q, a \cdot b = b \cdot a\}$*

Definition 11. *An open modality on quantale Q is a map $I : Q \to Q$, such that*

1. $I(x) \leqslant x$;
2. $I(x) = I(I(x))$;
3. $x \leqslant y \Rightarrow I(x) \leqslant I(y)$;
4. $I(x) \cdot I(y) = I(I(x) \cdot I(y))$.

Lemma 2.
Let $\langle A, \bigvee, \cdot \rangle$ be a quantale and $I : Q \to Q$ is an open modality on Q, then $I(x) \cdot I(y) \leqslant I(x \cdot y)$.

Proof.
$I(x) \cdot I(y) \leqslant x \cdot y$, then $I(I(x) \cdot I(y)) \leqslant I(x \cdot y)$, but $I(x) \cdot I(y) \leqslant I(I(x) \cdot I(y))$. Thus, $I(x) \cdot I(y) \leqslant I(x \cdot y)$. $\square$

Definition 12. *An open modality is called central, if $\forall a, b \in Q, I(a) \cdot b = b \cdot I(a)$.*

Definition 13. *An open modality is called weak idempotent, if* $\forall a, b \in Q, I(a) \cdot b \leqslant I(a) \cdot b \cdot I(a)$ *and* $b \cdot I(a) \leqslant I(a) \cdot b \cdot I(a)$.

Definition 14. *An open modality is called unital, if* $\forall a \in Q, I(a) \leqslant e$.

Lemma 3. *Let* I *be an interior on some unital quantale* $\langle Q, \bigvee, \cdot, e \rangle$*. Then, if* I *is unital and weak idempotent, then* I *is central.*

Proof.

$b \cdot I(a) \leqslant$
Right weak idempotence
$I(a) \cdot b \cdot I(a) \leqslant$
Unitality
$I(a) \cdot b \cdot I(e) \leqslant$
Identity
$I(a) \cdot b \leqslant$
Left weak idempotence
$I(a) \cdot b \cdot I(a) \leqslant$
Unitality
$e \cdot b \cdot I(a) \leqslant$
Identity
$b \cdot I(a)$

Hence, $b \cdot I(a) = I(a) \cdot b$

□

Proposition 1.

Let Q *be a quantale and* $S \subseteq Q$ *a subquantale, then* $I : Q \to Q$*, such that* $I(a) = \bigvee\{s \in S \mid x \leqslant a\}$*, is an open modality.*

Proof. See □

Proposition 2.

Let Q *be a quantale and* $S_1, S_2 \subseteq Q$*, such that* $S_1 \subseteq S_2$.
Then $I_1(a) \leqslant I_2(a)$.

Proof.

Let $a \in Q$, so $\{s \in S_1 \mid s \leqslant a\} \subseteq \{s \in S_2 \mid s \leqslant a\}$, so $\bigvee\{s \in S_1 \mid s \leqslant a\} \subseteq \bigvee\{s \in S_2 \mid s \leqslant a\}$. Thus, $I_1(a) \leqslant I_2(a)$. □

Proposition 3.

Let Q *be a quantale and* $S \subseteq Q$ *a subquantale, then the following operations are open modalities:*

1. $I_z(a) = \bigvee\{s \in S \mid s \leqslant a, s \in Z(Q)\}$;
2. $I_{\mathbb{1}}(a) = \bigvee\{s \in S \mid s \leqslant a, s \leqslant \mathbb{1}\}$;
3. $I_{idem}(a) = \bigvee\{s \in S \mid s \leqslant a, \forall b \in Q, b \cdot s \vee s \cdot b \leqslant s \cdot b \cdot s\}$;
4. $I_{z,\mathbb{1}}, I_{z,idem}, I_{\mathbb{1},idem}, I_{z,\mathbb{1},idem}$.

Proof. Immediatly. □

Proposition 4.

1. $\forall a \in Q, I_{\mathbb{1},idem}(a) \leqslant I_z(a)$.

2. $\forall a \in Q, I_{z,\mathbb{1},idem} = I_{\mathbb{1},idem}(a)$

Proof. Follows from Lemma 3. □

Proposition 5.

1. $I_z(a) \vee I_{\mathbb{1}}(a) \vee I_{idem}(a) \leqslant I(a)$

2. $I_{z,\mathbb{1},idem} \leqslant I_{z,\mathbb{1}}(a) \wedge I_{z,idem}(a)$

Proposition 6.
$I_2(I_1(a)) = I_1(I_2(a))$, *for* $I_2(a) \leqslant I_1(a)$.

Proof.

1. $I_2(I_1(a)) \leqslant I_1(I_2(a))$
   $I_2(I_1(a)) \leqslant I_2(a) = I_2(I_2(a)) \leqslant I_1(I_2(a))$

2. $I_1(I_2(a)) \leqslant I_2(I_1(a))$
   (1) $I_2(a) \leqslant a$
   Monotonicity
   (2) $I_1(I_2(a)) \leqslant I_1(a)$
   Monotonicity
   (3) $I_2(I_1(I_2(a))) \leqslant I_2(I_1(a))$
   The previous part
   (4) $I_2(I_1(a)) \leqslant I_1(I_2(a))$
   Monotonicity
   (5) $I_2(I_2(I_1(a))) \leqslant I_2(I_1(I_2(a)))$
   Idempotence
   (6) $I_1(a) \leqslant I_2(I_1(I_2(a)))$
   (1), (6), transitivity
   (7) $I_1(I_2(a)) \leqslant I_2(I_1(I_2(a)))$
   (1), (6), transitivity
   (8) $I_2(I_1(I_2(a))) \leqslant I_2(I_1(a))$
   (1), monotonicity twice
   (9) $I_1(I_2(a)) \leqslant I_2(I_1(a))$
   (7), (8), transitivity

□

Lemma 4. $\forall a \in Q, I_1(a) \leqslant I_2(I_1(a))$, *if* $I_2(a) \leqslant I_1(a)$.

Proof. $I_1(a) \leqslant$ □

Lemma 5. $I_1(a_1) \cdot I_2(a_2) \leqslant I^{'}(I_1(a_1) \cdot I_2(a_2))$, *where* $I^{'} \leqslant I_i, i = 1, 2$.

Proof. $I_1(a_1) \cdot I_2(a_2) \leqslant a_1 \cdot a_2$, so $I^{'}(I_1(a_1) \cdot I_2(a_2)) \leqslant I^{'}(a_1 \cdot a_2) \leqslant$ □

Proof. $I^{'}(I_1(a_1) \cdot I_2(a_2)) \leqslant$ □

Lemma 6.

$I_1, \ldots, I_n$ are open modalities, thus: $I_1(a_1) \cdot I_2(a_2) \cdot \cdots I_n(a_n) \leqslant a$, then $I_1(a_1) \cdot \ldots I_n(a_n) \leqslant I^{'}(a)$, where $I^{'} \leqslant I_i$ for all i.

Proof. $\square$

Theorem 2. $\Gamma \rightarrow A \Rightarrow \Gamma \models A$