Cut-elimination of the term assignment formulation of FILL

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In [2] Martin Hyland and Veleria de Paiva give a term formalization of Full Intuitionistic Linear Logic (FILL), but later Bierman was able to give a counterexample to cut-elimination [1]. As Bierman explains the problem was that the left rule for par introduced a fresh variable into to many terms on the right-side of the conclusion. This resulted in a counterexample where this fresh variable became bound in one term, but is left free in another. This resulted from first doing a commuting conversion on cut, and then λ-binding the fresh variable. Thus, cut-elmination failed. In the conclusion of Bierman's paper he gives an alternate left-par rule which he attributes to Bellin, and states that this alternate rule should fix the problem with cut-elimination [1]. In this note we adopt Bellin's rule, and then show cut-elimination in Section 3.

1 Full Intuitionistic Linear Logic (FILL)

In this section we give a brief description of Full Intuitionistic Linear Logic (FILL) in the style found in [2]. However, we use a slightly different presentation that we feel provides a more elegant description of the logic. We first give the syntax of formulas, patterns, terms, and contexts. Following the syntax we define several meta-functions that will be used when defining the inference rules of the logic.

Definition 1. *The syntax for FILL is as follows:*

$$
\begin{array}{rl}
\textit{(Formulas)} & A, B, C, D, E ::= I \mid \perp \mid A \multimap B \mid A \otimes B \mid A \parr B \\
\textit{(Patterns)} & p ::= * \mid - \mid x \mid p_1 \otimes p_2 \mid p_1 \parr p_2 \\
\textit{(Terms)} & t, e ::= x \mid * \mid \circ \mid t_1 \otimes t_2 \mid t_1 \parr t_2 \mid \lambda x.t \mid \mathsf{let}\, t\, \mathsf{be}\, p\, \mathsf{in}\, e \mid t_1\; t_2 \\
\textit{(Left Contexts)} & \Gamma ::= \cdot \mid x : A \mid \Gamma_1, \Gamma_2 \\
\textit{(Right Contexts)} & \Delta ::= \cdot \mid t : A \mid \Delta_1, \Delta_2
\end{array}
$$

At this point we introduce some basic syntax and definitions to facilitate readability, and presentation of the inference rules. First, we will often write $\Delta_1 \mid \Delta_2$ as syntactic sugar for Δ_1, Δ_2. The former syntax should be read as "Δ_1 or Δ_2." This will help readability of the sequent we will introduce below. We denote the usual capture-avoiding substitution by $[t/x]t'$.

Definition 2. *We extend the capture-avoiding substitution function to right contexts as follows:*

$$
\begin{array}{l}
[t/x]\cdot = \cdot \\
[t/x](t' : A) = ([t/x]t') : A \\
[t/x](\Delta_1 \mid \Delta_2) = ([t/x]\Delta_1) \mid ([t/x]\Delta_2)
\end{array}
$$

The previous extension will make conducting substitutions across a sequence of terms in an inference rule easier. Similarly, we find it convenient to be able to do this style of extension for the let-binding as well.

Definition 3. *We extend let-binding terms to right contexts as follows:*

$$
\begin{array}{l}
\mathsf{let}\, t\, \mathsf{be}\, p\, \mathsf{in} \cdot = \cdot \\
\mathsf{let}\, t\, \mathsf{be}\, p\, \mathsf{in}\, (t' : A) = (\mathsf{let}\, t\, \mathsf{be}\, p\, \mathsf{in}\, t') : A \\
\mathsf{let}\, t\, \mathsf{be}\, p\, \mathsf{in}\, (\Delta_1 \mid \Delta_2) = (\mathsf{let}\, t\, \mathsf{be}\, p\, \mathsf{in}\, \Delta_1) \mid (\mathsf{let}\, t\, \mathsf{be}\, p\, \mathsf{in}\, \Delta_2)
\end{array}
$$

We denote the usual function that computes the set of free variables in a term by $\mathsf{FV}(t)$.

Definition 4. *We extend the free-variable function on terms to right contexts as follows:*

$$\begin{array}{l} \mathsf{FV}(\cdot) = \emptyset \\ \mathsf{FV}(t : A) = \mathsf{FV}(t) \\ \mathsf{FV}(\Delta_1 \mid \Delta_2) = \mathsf{FV}(\Delta_1) \cup \mathsf{FV}(\Delta_2) \end{array}$$

Finally, we arrive at the inference rules of FILL.

Definition 5. *The inference rules for derivability in FILL are as follows:*

$$\frac{}{x : A \vdash x : A}\ \textsc{Ax} \qquad \frac{\Gamma \vdash t : A \mid \Delta \quad y : A, \Gamma' \vdash \Delta'}{\Gamma, \Gamma' \vdash \Delta \mid [t/y]\Delta'}\ \textsc{Cut} \qquad \frac{\Gamma \vdash \Delta}{\Gamma, x : I \vdash \mathsf{let}\, x\, \mathsf{be} * \mathsf{in}\, \Delta}\ \textsc{Il}$$

$$\frac{}{\cdot \vdash * : I}\ \textsc{Ir} \qquad \frac{\Gamma, x : A, y : B \vdash \Delta}{\Gamma, z : A \otimes B \vdash \mathsf{let}\, z\, \mathsf{be}\, x \otimes y\, \mathsf{in}\, \Delta}\ \textsc{Tl} \qquad \frac{\Gamma \vdash e : A \mid \Delta \quad \Gamma' \vdash f : B \mid \Delta'}{\Gamma, \Gamma' \vdash e \otimes f : A \otimes B \mid \Delta \mid \Delta'}\ \textsc{Tr}$$

$$\frac{}{x : \perp \vdash \cdot}\ \textsc{Pl} \qquad \frac{\Gamma \vdash \Delta}{\Gamma \vdash \circ : \perp \mid \Delta}\ \textsc{Pr} \qquad \frac{\Gamma, x : A \vdash \Delta \quad \Gamma', y : B \vdash \Delta'}{\Gamma, \Gamma', z : A \parr B \vdash \text{let-pat}\, z\, (x \parr -)\, \Delta \mid \text{let-pat}\, z\, (- \parr y)\, \Delta'}\ \textsc{Parl}$$

$$\frac{\Gamma \vdash \Delta \mid e : A \mid f : B \mid \Delta'}{\Gamma \vdash \Delta \mid e \parr f : A \parr B \mid \Delta'}\ \textsc{Parr} \qquad \frac{\Gamma \vdash e : A \mid \Delta \quad \Gamma', x : B \vdash \Delta'}{\Gamma, y : A \multimap B, \Gamma' \vdash \Delta \mid [y\, e/x]\Delta'}\ \textsc{Impl}$$

$$\frac{\Gamma, x : A \vdash e : B \mid \Delta \quad x \notin \mathsf{FV}(\Delta)}{\Gamma \vdash \lambda x.e : A \multimap B \mid \Delta}\ \textsc{Impr} \qquad \frac{\Gamma, x : A, y : B \vdash \Delta}{\Gamma, y : B, x : A \vdash \Delta}\ \textsc{Exl}$$

$$\frac{\Gamma \vdash \Delta_1 \mid t_1 : A \mid t_2 : B \mid \Delta_2}{\Gamma \vdash \Delta_1 \mid t_2 : B \mid t_1 : A \mid \Delta_2}\ \textsc{Exr}$$

The Parl rule depends on a function let-pat $z\, p\, \Delta$. We define this function next.

Definition 6. *The function* let-pat $z\, p\, t$ *is defined as follows:*

$$\begin{array}{c} \text{let-pat}\, z\, (x \parr -)\, t = t \\ \textit{where } x \notin \mathsf{FV}(t) \\ \\ \text{let-pat}\, z\, (- \parr y)\, t = t \\ \textit{where } y \notin \mathsf{FV}(t) \\ \\ \text{let-pat}\, z\, p\, t = \mathsf{let}\, z\, \mathsf{be}\, p\, \mathsf{in}\, t \end{array}$$

We can then extend the previous definition to right-contexts as follows:

$$\begin{array}{l} \text{let-pat}\, z\, p \cdot = \cdot \\ \text{let-pat}\, z\, p\, (t : A) = (\text{let-pat}\, z\, p\, t) : A \\ \text{let-pat}\, z\, p\, (\Delta_1 \mid \Delta_2) = (\text{let-pat}\, z\, p\, \Delta_1) \mid (\text{let-pat}\, z\, p\, \Delta_2) \end{array}$$

The motivation behind this function is that it only binds the pattern variables in p in a term if and only if those pattern variables are free in the term. This over comes the counterexample given by Bierman in [1]. Throughout the sequel we will denote derivations of the previous rules by π.

2 Basic Results

In this section we simply list several basic results needed throughout the sequel:

Lemma 7 (Substitution Distribution)**.** *For any terms t, t_1, and t_2,* $[t_1/x][t_2/y]t = [[t_1/x]t_2/y][t_2/x]t$.

Proof. This proof holds by straightforward induction on the form of t. $\square$

3 Cut-elimination

The usual proof of cut-elimination for intuitionistic and classical linear logic should suffice for FILL. Thus, in this section we simply give the cut-elimination procedure for FILL following the development in [3]. However, there is one invariant that must be verified across each derivation transformation. The invariant is that if a derivation π is transformed into a derivation π', then the terms in π must be equivalent to the terms in π', but using what notion of equivalence?

Definition 8. *Equivalence on terms is defined as follows:*

$$\frac{y \notin \mathsf{FV}(t)}{t = [y/x]t}\ \textsc{Eq\_Alpha} \qquad \frac{}{(\lambda x.e)\ e' = [e'/x]e}\ \textsc{Eq\_Beta} \qquad \frac{}{(\lambda x.f\ x) = f}\ \textsc{Eq\_Eta}$$

$$\frac{}{\mathsf{let}\ *\ \mathsf{be}\ *\ \mathsf{in}\ e = e}\ \textsc{Eq\_I} \qquad \frac{}{\mathsf{let}\ u\ \mathsf{be}\ *\ \mathsf{in}\ [*/z]f = [u/z]f}\ \textsc{Eq\_Stp}$$

$$\frac{}{\mathsf{let}\ e \otimes t\ \mathsf{be}\ x \otimes y\ \mathsf{in}\ u = [e/x, t/y]u}\ \textsc{Eq\_T1} \qquad \frac{}{\mathsf{let}\ u\ \mathsf{be}\ x \otimes y\ \mathsf{in}\ [x \otimes y/z]f = [u/z]f}\ \textsc{Eq\_T2}$$

$$\frac{}{\mathsf{let}\ u \parr t\ \mathsf{be}\ x \parr -\ \mathsf{in}\ e = [u/x]e}\ \textsc{Eq\_P1} \qquad \frac{}{\mathsf{let}\ u \parr t\ \mathsf{be}\ - \parr y\ \mathsf{in}\ e = [t/y]e}\ \textsc{Eq\_P2}$$

$$\frac{}{(\mathsf{let}\ x\ \mathsf{be}\ x \parr -\ \mathsf{in}\ x) \parr (\mathsf{let}\ u\ \mathsf{be}\ - \parr y\ \mathsf{in}\ y) = u}\ \textsc{Eq\_P3} \qquad \frac{t = t'}{\lambda x.t = \lambda x.t''}\ \textsc{Eq\_Lam}$$

$$\frac{t_1 = t_1'}{t_1\ t_2 = t_1'\ t_2}\ \textsc{Eq\_App1} \qquad \frac{t_2 = t_2'}{t_1\ t_2 = t_1\ t_2'}\ \textsc{Eq\_App2} \qquad \frac{t_1 = t_1'}{t_1 \otimes t_2 = t_1' \otimes t_2}\ \textsc{Eq\_Ten1}$$

$$\frac{t_2 = t_2'}{t_1 \otimes t_2 = t_1 \otimes t_2'}\ \textsc{Eq\_Ten2} \qquad \frac{t_1 = t_1'}{t_1 \parr t_2 = t_1' \parr t_2}\ \textsc{Eq\_Par1} \qquad \frac{t_2 = t_2'}{t_1 \parr t_2 = t_1 \parr t_2'}\ \textsc{Eq\_Par2}$$

$$\frac{t = t'}{\mathsf{let}\ t\ \mathsf{be}\ p\ \mathsf{in}\ e = \mathsf{let}\ t'\ \mathsf{be}\ p\ \mathsf{in}\ e}\ \textsc{Eq\_Let1} \qquad \frac{e = e'}{\mathsf{let}\ t\ \mathsf{be}\ p\ \mathsf{in}\ e = \mathsf{let}\ t\ \mathsf{be}\ p\ \mathsf{in}\ e'}\ \textsc{Eq\_Let2} \qquad \frac{}{t = t}\ \textsc{Eq\_Refl}$$

$$\frac{t = t'}{t' = t}\ \textsc{Eq\_Sym} \qquad \frac{t_1 = t_2 \quad t_2 = t_3}{t_1 = t_3}\ \textsc{Eq\_Trans}$$

Throughout the remainder of this section we give each transformation of derivations, and then prove that the terms maintain equivalence across each transformation.

3.1 Commuting conversion cut vs cut (first case)

The following proof

$$\dfrac{\dfrac{\begin{array}{c}\pi_1\\ \vdots\end{array}}{\Gamma \vdash t : A \mid \Delta} \qquad \dfrac{\dfrac{\begin{array}{c}\pi_2\\ \vdots\end{array}}{\Gamma_2, x : A, \Gamma_3 \vdash t_1 : B \mid \Delta_1} \qquad \dfrac{\begin{array}{c}\pi_3\\ \vdots\end{array}}{\Gamma_1, y : B, \Gamma_4 \vdash t_2 : C \mid \Delta_2}}{\Gamma_1, \Gamma_2, x : A, \Gamma_3, \Gamma_4 \vdash \Delta_1 \mid [t_1/y]t_2 : C \mid [t_1/y]\Delta_2}\ \textsc{Cut}}{\Gamma_1, \Gamma_2, \Gamma, \Gamma_3, \Gamma_4 \vdash \Delta \mid [t/x]\Delta_1 \mid [t/x][t_1/y]t_2 : C \mid [t/x][t_1/y]\Delta_2}\ \textsc{Cut}$$

is transformed into the proof

$$\dfrac{\dfrac{\dfrac{\begin{array}{c}\pi_1\\ \vdots\end{array}}{\Gamma \vdash t : A \mid \Delta} \qquad \dfrac{\begin{array}{c}\pi_2\\ \vdots\end{array}}{\Gamma_2, x : A, \Gamma_3 \vdash t_1 : B \mid \Delta_1}}{\Gamma_2, \Gamma, \Gamma_3 \vdash [t/x]t_1 : B \mid [t/x]\Delta_1} \qquad \dfrac{\begin{array}{c}\pi_3\\ \vdots\end{array}}{\Gamma_1, y : B, \Gamma_4 \vdash t_2 : C \mid \Delta_2}}{\Gamma_1, \Gamma_2, \Gamma, \Gamma_3, \Gamma_4 \vdash \Delta \mid [t/x]\Delta_1 \mid ([[t/x]t_1/y]t_2) : C \mid [[t/x]t_1/y]\Delta_2}\ \textsc{Cut}$$

In order for the previous two proofs to be considered equal, we have to show that the final terms in the conclusion of the above derivations are equivalent. First, we know that the term $[t/x][t_1/y]t_2$ in the first derivation above is equivalent to $[[t/x]t_1/y][t/x]t_2$ by Lemma 7. Furthermore, by inspecting the first derivation we can see that $x \notin \mathsf{FV}(t_2)$, and thus, $[[t/x]t_1/y][t/x]t_2 = [[t/x]t_1/y]t_2$. This argument may be repeated for any term in Δ_2, and thus, we know $[t/x][t_1/y]\Delta_2 = [[t/x]t_1/y]\Delta_2$.

3.2 Commuting conversion cut vs. cut (second case)

The second commuting conversion on cut begins with the proof

$$\dfrac{\dfrac{\begin{array}{c}\pi_1\\ \vdots\end{array}}{\Gamma \vdash t : A \mid \Delta} \qquad \dfrac{\dfrac{\begin{array}{c}\pi_2\\ \vdots\end{array}}{\Gamma' \vdash t' : B \mid \Delta'} \qquad \dfrac{\begin{array}{c}\pi_3\\ \vdots\end{array}}{\Gamma_1, x : A, \Gamma_2, y : B, \Gamma_3 \vdash t_1 : C \mid \Delta_1}}{\Gamma_1, x : A, \Gamma_2, \Gamma', \Gamma_3 \vdash \Delta' \mid [t'/y]t_1 : C \mid [t'/y]\Delta_1}\ \textsc{Cut}}{\Gamma_1, \Gamma, \Gamma_2, \Gamma', \Gamma_3 \vdash \Delta \mid [t/x]\Delta' \mid [t/x][t'/y]t_1 : C \mid [t/x][t'/y]\Delta_1}\ \textsc{Cut}$$

is transformed into the following proof:

$$\dfrac{\dfrac{\dfrac{\begin{array}{c}\pi_2\\ \vdots\end{array}}{\Gamma' \vdash t' : B \mid \Delta'} \qquad \dfrac{\dfrac{\begin{array}{c}\pi_1\\ \vdots\end{array}}{\Gamma \vdash t : A \mid \Delta} \qquad \dfrac{\begin{array}{c}\pi_3\\ \vdots\end{array}}{\Gamma_1, x : A, \Gamma_2, y : B, \Gamma_3 \vdash t_1 : C \mid \Delta_1}}{\Gamma_1, \Gamma, \Gamma_2, y : B, \Gamma_3 \vdash \Delta \mid [t/x]t_1 : C \mid [t/x]\Delta_1}\ \textsc{Cut}}{\Gamma_1, \Gamma, \Gamma_2, \Gamma', \Gamma_3 \vdash \Delta' \mid [t'/y]\Delta \mid [t'/y][t/x]t_1 : C \mid [t'/y][t/x]\Delta_1}\ \textsc{Cut}}{\Gamma_1, \Gamma, \Gamma_2, \Gamma', \Gamma_3 \vdash [t'/y]\Delta \mid \Delta' \mid [t'/y][t/x]t_1 : C \mid [t'/y][t/x]\Delta_1}\ \textsc{Series of Exchanges}$$

Now, because we know $x, y \notin \mathsf{FV}(\Delta)$ by inspection of the first derivation, we know that $\Delta = [t'/y]\Delta$ and $\Delta' = [t/x]\Delta'$. Similarly, we know that $x, y \notin \mathsf{FV}(t)$ and $x, y \notin \mathsf{FV}(t')$. Thus, by this fact and Lemma 7, we know that $[t/x][t'/y]t_1 = [[t/x]t'/y][t/x]t_1 = [t'/y][t/x]t_1$. This argument can be repeated for any term in Δ_1, hence, $[t/x][t'/y]\Delta_1 = [t'/y][t/x]\Delta_1$.

3.3 The η-expansion cases

3.3.1 Tensor

The proof

$$\dfrac{}{x : A \otimes B \vdash x : A \otimes B}\ \textsc{Ax}$$

is transformed into the proof

$$\dfrac{\dfrac{}{y : A \vdash y : A}\ \textsc{Ax} \qquad \dfrac{}{z : B \vdash z : B}\ \textsc{Ax}}{\dfrac{y : A, z : B \vdash y \otimes z : A \otimes B}{x : A \otimes B \vdash \mathsf{let}\, x\, \mathsf{be}\, y \otimes z\, \mathsf{in}\, (y \otimes z) : A \otimes B}\ \textsc{Tl}}\ \textsc{Tr}$$

Now by the rule EQ_T2 we know $\mathsf{let}\, x\, \mathsf{be}\, y \otimes z\, \mathsf{in}\, (y \otimes z) = x$.

3.3.2 Par

The proof

$$\dfrac{}{x : A \parr B \vdash x : A \parr B}\ \textsc{Ax}$$

is transformed into the proof

$$\dfrac{\dfrac{}{y : A \vdash y : A}\ \textsc{Ax} \qquad \dfrac{}{z : B \vdash z : B}\ \textsc{Ax}}{\dfrac{x : A \parr B \vdash \mathsf{let}\, x\, \mathsf{be}\, (y \parr -)\, \mathsf{in}\, y : A \mid \mathsf{let}\, x\, \mathsf{be}\, (- \parr z)\, \mathsf{in}\, z : B}{x : A \parr B \vdash (\mathsf{let}\, x\, \mathsf{be}\, (y \parr -)\, \mathsf{in}\, y) \parr (\mathsf{let}\, x\, \mathsf{be}\, (- \parr z)\, \mathsf{in}\, z) : A \parr B}\ \textsc{ParR}}\ \textsc{ParL}$$

Just as we saw in the previous case by rule EQ_P3 we know $((\mathsf{let}\, x\, \mathsf{be}\, (y \parr -)\, \mathsf{in}\, y) \parr (\mathsf{let}\, x\, \mathsf{be}\, (- \parr z)\, \mathsf{in}\, z)) = x$.

3.3.3 Implication

The proof

$$\dfrac{}{x : A \multimap B \vdash x : A \multimap B}\ \textsc{Ax}$$

transforms into the proof

$$\dfrac{\dfrac{}{y : A \vdash y : A}\ \textsc{Ax} \qquad \dfrac{}{z : B \mid - z : B}\ \textsc{Ax}}{\dfrac{y : A, x : A \multimap B \vdash x\, y : B}{x : A \multimap B \vdash \lambda y.x\, y : A \multimap B}\ \textsc{ImpR}}\ \textsc{ImpL}$$

Finally, all terms in the two derivations are equivalent, because $(\lambda y.x\, y) = x$ by the EQ_ETA rule.

3.3.4 Tensor unit

The proof

$$\dfrac{}{x : I \vdash x : I}\ \textsc{Ax}$$

transforms into the proof

$$\dfrac{\dfrac{}{\cdot \vdash * : I}\ \textsc{Ir}}{x : I \vdash \mathsf{let}\, x\, \mathsf{be}\, *\, \mathsf{in}\, * : I}\ \textsc{Il}$$

Lastly, we know $x = \mathsf{let}\, x\, \mathsf{be}\, *\, \mathsf{in}\, *$ by EQ_I.

4 The axiom steps

4.1 The axiom step

The proof

$$\dfrac{\dfrac{}{x : A \vdash x : A}\ \textsc{Ax} \qquad \dfrac{\begin{matrix}\pi \\ \vdots\end{matrix}}{\Gamma_1, y : A, \Gamma_2 \vdash t : B \mid \Delta}}{\Gamma_1, x : A, \Gamma_2 \vdash [x/y]t : B \mid [x/y]\Delta}\ \textsc{Cut}$$

transforms into the proof

$$\dfrac{\begin{matrix}\pi \\ \vdots\end{matrix}}{\Gamma_1, y : A, \Gamma_2 \vdash t : B \mid \Delta}$$

By Eq_Alpha we know $t = [x/y]t$ and $\Delta = [x/y]\Delta$.

4.2 Conclusion vs. axom

The proof

$$\dfrac{\dfrac{\begin{matrix}\pi \\ \vdots\end{matrix}}{\Gamma \vdash t : A \mid \Delta} \quad \dfrac{}{x : A \vdash x : A}\ \textsc{Ax}}{\Gamma \vdash \Delta \mid [t/x]x : A}\ \textsc{Cut}$$

transforms into

$$\dfrac{\dfrac{\begin{matrix}\pi \\ \vdots\end{matrix}}{\Gamma \vdash t : A \mid \Delta}}{\Gamma \vdash \Delta \mid t : A}\ \textsc{Series of Exchanges}$$

By the definition of the substitution function we know $t = [t/x]x$.

4.3 The exchange steps

4.3.1 Conclusion vs. left-exchange (the first case)

The proof

$$\dfrac{\dfrac{\begin{matrix}\pi_1 \\ \vdots\end{matrix}}{\Gamma \vdash t : A \mid \Delta} \qquad \dfrac{\dfrac{\begin{matrix}\pi_2 \\ \vdots\end{matrix}}{\Gamma_1, x : A, y : B, \Gamma_2 \vdash t' : C \mid \Delta'}}{\Gamma_1, y : B, x : A, \Gamma_2 \vdash t' : C \mid \Delta'}\ \textsc{ExL}}{\Gamma_1, y : B, \Gamma, \Gamma_2 \vdash \Delta \mid [t/x]t' : C \mid [t/x]\Delta'}\ \textsc{Cut}$$

transforms into the proof

$$
\dfrac{\dfrac{\dfrac{\pi_1}{\vdots}}{\Gamma \vdash t : A \mid \Delta} \qquad \dfrac{\dfrac{\pi_2}{\vdots}}{\Gamma_1, x : A, y : B, \Gamma_2 \vdash t' : C \mid \Delta'}}{\dfrac{\Gamma_1, \Gamma, y : B, \Gamma_2 \vdash \Delta \mid [t/x]t' : C \mid [t/x]\Delta'}{\Gamma_1, y : B, \Gamma, \Gamma_2 \vdash \Delta \mid [t/x]t' : C \mid [t/x]\Delta'}\ \textsc{Series of Exchanges}}\ \textsc{Cut}
$$

Clearly, all terms are equivalent.

4.3.2 Conclusion vs. left-exchange (the second case)

The proof

$$
\dfrac{\dfrac{\dfrac{\pi_1}{\vdots}}{\Gamma \vdash t : B \mid \Delta} \qquad \dfrac{\dfrac{\dfrac{\pi_2}{\vdots}}{\Gamma_1, x : A, y : B, \Gamma_2 \vdash t' : C \mid \Delta'}}{\Gamma_1, y : B, x : A, \Gamma_2 \vdash t' : C \mid \Delta'}\ \textsc{ExL}}{\Gamma_1, \Gamma, x : A, \Gamma_2 \vdash \Delta \mid [t/y]t' : C \mid [t/y]\Delta'}\ \textsc{Cut}
$$

transforms into the proof

$$
\dfrac{\dfrac{\dfrac{\dfrac{\pi_1}{\vdots}}{\Gamma \vdash t : B \mid \Delta} \qquad \dfrac{\dfrac{\pi_2}{\vdots}}{\Gamma_1, x : A, y : B, \Gamma_2 \vdash t' : C \mid \Delta'}}{\Gamma_1, x : A, \Gamma, \Gamma_2 \vdash \Delta \mid [t/y]t' : C \mid [t/y]\Delta'}\ \textsc{Cut}}{\Gamma_1, \Gamma, x : A, \Gamma_2 \vdash \Delta \mid [t/y]t' : C \mid [t/y]\Delta'}\ \textsc{Series of Exchanges}
$$

Clearly, all terms are equivalent.

4.3.3 Conclusion vs. right-exchange

The proof

$$
\dfrac{\dfrac{\dfrac{\pi_1}{\vdots}}{\Gamma \vdash t : A \mid \Delta} \qquad \dfrac{\dfrac{\dfrac{\pi_2}{\vdots}}{\Gamma_1, x : A, \Gamma_2 \vdash \Delta_1 \mid t_1 : B \mid t_2 : C \mid \Delta'}}{\Gamma_1, x : A, \Gamma_2 \vdash \Delta_1 \mid t_2 : C \mid t_1 : B \mid \Delta'}\ \textsc{ExR}}{\Gamma_1, \Gamma, \Gamma_2 \vdash \Delta \mid [t/x]\Delta_1 \mid [t/x]t_2 : C \mid [t/x]t_1 : B \mid [t/x]\Delta'}\ \textsc{Cut}
$$

transforms into this proof

$$
\dfrac{\dfrac{\dfrac{\dfrac{\pi_1}{\vdots}}{\Gamma \vdash t : A \mid \Delta} \qquad \dfrac{\dfrac{\pi_2}{\vdots}}{\Gamma_1, x : A, \Gamma_2 \vdash \Delta_1 \mid t_1 : B \mid t_2 : C \mid \Delta'}}{\Gamma_1, \Gamma, \Gamma_2 \vdash \Delta \mid [t/x]\Delta_1 \mid [t/x]t_1 : B \mid [t/x]t_2 : C \mid [t/x]\Delta'}\ \textsc{Cut}}{\Gamma_1, \Gamma, \Gamma_2 \vdash [t/x]\Delta_1 \mid [t/x]t_2 : C \mid [t/x]t_1 : B \mid [t/x]\Delta'}\ \textsc{ExR}
$$

4.4 Principle formula vs. principle formula

4.4.1 Tensor

The proof

$$\dfrac{\dfrac{\dfrac{\pi_1}{\Gamma_1 \vdash t_1 : A \mid \Delta_1} \qquad \dfrac{\pi_2}{\Gamma_2 \vdash t_2 : B \mid \Delta_2}}{\Gamma_1, \Gamma_2 \vdash t_1 \otimes t_2 : A \otimes B \mid \Delta_1 \mid \Delta_2}\,\textsc{Tr} \qquad \dfrac{\dfrac{\pi_3}{\Gamma_3, x : A, y : B, \Gamma_4 \vdash t_3 : C \mid \Delta_3}}{\Gamma_3, z : A \otimes B, \Gamma_4 \vdash \mathsf{let}\, z\, \mathsf{be}\, x \otimes y\, \mathsf{in}\, t_3 : C \mid \mathsf{let}\, z\, \mathsf{be}\, x \otimes y\, \mathsf{in}\, \Delta_3}\,\textsc{Tl}}{\Gamma_3, \Gamma_1, \Gamma_2, \Gamma_4 \vdash \Delta_1 \mid \Delta_2 \mid [t_1 \otimes t_2/z](\mathsf{let}\, z\, \mathsf{be}\, x \otimes y\, \mathsf{in}\, t_3) : C \mid [t_1 \otimes t_2/z](\mathsf{let}\, z\, \mathsf{be}\, x \otimes y\, \mathsf{in}\, \Delta_3)}\,\textsc{Cut}$$

is transformed into the proof

$$\dfrac{\dfrac{\pi_1}{\Gamma_1 \vdash t_1 : A \mid \Delta_1} \qquad \dfrac{\dfrac{\pi_2}{\Gamma_2 \vdash t_2 : B \mid \Delta_2} \qquad \dfrac{\pi_3}{\Gamma_3, x : A, y : B, \Gamma_4 \vdash t_3 : C \mid \Delta_3}}{\Gamma_3, x : A, \Gamma_2, \Gamma_4 \vdash \Delta_2 \mid [t_2/y]t_3 : C \mid [t_2/y]\Delta_3}\,\textsc{Cut}}{\Gamma_3, \Gamma_1, \Gamma_2, \Gamma_4 \vdash \Delta_1 \mid \Delta_2 \mid [t_1/x][t_2/y]t_3 : C \mid [t_1/x][t_2/y]\Delta_3}\,\textsc{Cut}$$

Now we can see that $[t_1 \otimes t_2/z](\mathsf{let}\, z\, \mathsf{be}\, x \otimes y\, \mathsf{in}\, t_3) = \mathsf{let}\, t_1 \otimes t_2\, \mathsf{be}\, x \otimes y\, \mathsf{in}\, t_3$ by the definition of substitution, and by using the $\textsc{Eq\_T1}$ rule we obtain $\mathsf{let}\, t_1 \otimes t_2\, \mathsf{be}\, x \otimes y\, \mathsf{in}\, t_3 = [t_1/x][t_2/y]t_3$. This argument can be repeated for any term in $[t_1 \otimes t_2/z](\mathsf{let}\, z\, \mathsf{be}\, x \otimes y\, \mathsf{in}\, \Delta_3)$, and thus, $[t_1 \otimes t_2/z](\mathsf{let}\, z\, \mathsf{be}\, x \otimes y\, \mathsf{in}\, \Delta_3) = [t_1/x][t_2/y]\Delta_3$.

Note that in the second derivation of the above transformation we first cut on B, and then A, but we could have cut on A first, and then B, but this would yeild equivalent derivations as above by using Lemma 7.

4.4.2 Par

The proof

$$\dfrac{\dfrac{\dfrac{\pi_1}{\Gamma_1 \vdash \Delta_1 \mid t_1 : A \mid t_2 : B \mid \Delta_2}}{\Gamma_1 \vdash \Delta_1 \mid t_1 \parr t_2 : A \parr B \mid \Delta_2}\,\textsc{Parr} \qquad \dfrac{\dfrac{\pi_2}{\Gamma_2, x : A \vdash t_3 : C_1 \mid \Delta_3} \qquad \dfrac{\pi_3}{\Gamma_3, y : B \vdash t_4 : C_2 \mid \Delta_4}}{\Gamma_2, \Gamma_3, z : A \parr B \vdash \text{let-pat}\, z\, (x \parr -)\, t_3 : C_1 \mid \text{let-pat}\, z\, (- \parr y)\, t_4 : C_2 \mid \Delta_5}\,\textsc{Parl}}{\Gamma_2, \Gamma_3, \Gamma_1 \vdash \Delta_1 \mid \Delta_2 \mid [t_1 \parr t_2/z](\text{let-pat}\, z\, (x \parr -)\, t_3) : C_1 \mid [t_1 \parr t_2/z](\text{let-pat}\, z\, (- \parr y)\, t_4) : C_2 \mid [t_1 \parr t_2/z]\Delta_5}\,\textsc{Cut}$$

where $\Delta_4 = \text{let-pat}\, z\, (x \parr -)\, \Delta_3, \text{let-pat}\, z\, (- \parr y)\, \Delta_4$ is transformed into the proof

$$\dfrac{\dfrac{\dfrac{\dfrac{\pi_1}{\Gamma_1 \vdash \Delta_1 \mid t_1 : A \mid t_2 : B \mid \Delta_2} \qquad \dfrac{\pi_3}{\Gamma_3, y : B \vdash t_4 : C_2 \mid \Delta_4}}{\Gamma_3, \Gamma_1 \vdash \Delta_1 \mid t_1 : A \mid \Delta_2 \mid [t_2/y]t_4 : C_2 \mid [t_2/y]\Delta_4}\,\textsc{Cut} \qquad \dfrac{\pi_2}{\Gamma_2, x : A \vdash t_3 : C_1 \mid \Delta_3}}{\Gamma_2, \Gamma_3, \Gamma_1 \vdash \Delta_1 \mid \Delta_2 \mid [t_2/y]t_4 : C_2 \mid [t_2/y]\Delta_4 \mid [t_1/x]t_3 : C_1 \mid [t_1/x]\Delta_3}\,\textsc{Cut}}{\Gamma_2, \Gamma_3, \Gamma_1 \vdash \Delta_1 \mid \Delta_2 \mid [t_1/x]t_3 : C_1 \mid [t_2/y]t_4 : C_2 \mid [t_1/x]\Delta_3 \mid [t_2/y]\Delta_4}\,\textsc{Series of Exr}$$

First, $[t_1 \parr t_2/z](\text{let-pat}\, z\, (x \parr -)\, t_3) = \text{let-pat}\, (t_1 \parr t_2)\, (x \parr -)\, t_3$, and $\text{let-pat}\, (t_1 \parr t_2)\, (x \parr -)\, t_3 = [t_1/x]t_3$ if $x \in \mathsf{FV}(t_3)$ or $\text{let-pat}\, (t_1 \parr t_2)\, (x \parr -)\, t_3 = t_3$ otherwise. In the latter case we can see that $t_3 = [t_1/x]t_3$, thus, in both cases $\text{let-pat}\, (t_1 \parr t_2)\, (x \parr -)\, t_3 = [t_1/x]t_3$. This argument can be repeated for any terms in Δ_3, and hence, $[t_1 \parr t_2/z](\text{let-pat}\, z\, (x \parr -)\, \Delta_3) = \text{let-pat}\, (t_1 \parr t_2)\, (x \parr -)\, \Delta_3 = [t_1/x]\Delta_3$. We can apply a similar argument for $[t_1 \parr t_2/z](\text{let-pat}\, z\, (- \parr y)\, t_4)$ and $[t_1 \parr t_2/x](\text{let-pat}\, z\, (- \parr y)\, \Delta_4)$.

Note that just as we mentioned about tensor we could have first cut on A, and then on B in the second derivation, but we would have arrived at the same result just with potentially more exchanges on the right.

4.4.3 Implication

The proof

$$\dfrac{\dfrac{\dfrac{\pi_1}{\Gamma, x : A \vdash t : B \mid \Delta} \quad x \notin \mathsf{FV}(\Delta)}{\Gamma \vdash \lambda x.t : A \multimap B \mid \Delta}\textsc{ImpR} \quad \dfrac{\dfrac{\pi_2}{\Gamma_1 \vdash t_1 : A \mid \Delta_1} \quad \dfrac{\pi_3}{\Gamma_2, y : B \vdash t_2 : C \mid \Delta_2}}{\Gamma_1, z : A \multimap B, \Gamma_2 \vdash [z\, t_1/y]t_2 : C \mid [z\, t_1/y]\Delta_2 \mid \Delta_1}\textsc{ImpL}}{\Gamma_1, \Gamma, \Gamma_2 \vdash \Delta \mid [\lambda x.t/z][z\, t_1/y]t_2 : C \mid [\lambda x.t/z][z\, t_1/y]\Delta_2 \mid [\lambda x.t/z]\Delta_1}\textsc{Cut}$$

transforms into the proof

$$\dfrac{\dfrac{\dfrac{\dfrac{\pi_2}{\Gamma_1 \vdash t_1 : A \mid \Delta_1} \quad \dfrac{\pi_1}{\Gamma, x : A \vdash t : B \mid \Delta} \quad x \notin \mathsf{FV}(\Delta)}{\Gamma, \Gamma_1 \vdash \Delta_1 \mid [t_1/x]t : B \mid [t_1/x]\Delta}\textsc{Cut} \quad \dfrac{\pi_3}{\Gamma_2, y : B \vdash t_2 : C \mid \Delta_2}}{\Gamma_2, \Gamma, \Gamma_1 \vdash \Delta_1 \mid [t_1/x]\Delta \mid [[t_1/x]t/y]t_2 : C \mid [[t_1/x]t/y]\Delta_2}\textsc{Cut}}{\Gamma_1, \Gamma, \Gamma_2 \vdash [t_1/x]\Delta \mid [[t_1/x]t/y]t_2 : C \mid [[t_1/x]t/y]\Delta_2 \mid \Delta_1}\textsc{Series of Exchanges}$$

First, by hypothesis we know $x \notin \mathsf{FV}(\Delta)$, and so we know $\Delta = [t_1/x]\Delta$. Now we can see that $[\lambda x.t/z][z\, t_1/y]t_2 = [(\lambda x.t)\, t_1/y]t_2 = [[t_1/x]t/y]t_2$ by using the congruence rules of equality and the rule Eq_Beta. This argument can be repeated for any term in $[\lambda x.t/z][z\, t_1/y]\Delta_2$, and so $[\lambda x.t/z][z\, t_1/y]\Delta_2 = [[t_1/x]t/y]\Delta_2$. Finally, by inspecting the previous derivations we can see that $z \notin \mathsf{FV}(\Delta_1)$, and thus, $\Delta_1 = [\lambda x.t/x]\Delta_1$.

4.4.4 Tensors Unit

The proof

$$\dfrac{\dfrac{}{\cdot \vdash * : I}\textsc{Ir} \quad \dfrac{\dfrac{\pi}{\Gamma \vdash t : A \mid \Delta}}{\Gamma, x : I \vdash \mathsf{let}\, x\, \mathsf{be}\, *\, \mathsf{in}\, t : A \mid \mathsf{let}\, x\, \mathsf{be}\, *\, \mathsf{in}\, \Delta}\textsc{Il}}{\Gamma \vdash [*/x](\mathsf{let}\, x\, \mathsf{be}\, *\, \mathsf{in}\, t) : A \mid [*/x](\mathsf{let}\, x\, \mathsf{be}\, *\, \mathsf{in}\, \Delta)}\textsc{Cut}$$

is transformed into the proof

$$\dfrac{\pi}{\Gamma \vdash t : A \mid \Delta}$$

We can see that $[*/x](\mathsf{let}\, x\, \mathsf{be} * \mathsf{in}\, t) = \mathsf{let} * \mathsf{be} * \mathsf{in}\, t = t$ by the definition of substitution and the Eq_I rule. This argument can be repeated for any term in $[*/x](\mathsf{let}\, x\, \mathsf{be}\, *\, \mathsf{in}\, \Delta)$, and hence, $[*/x](\mathsf{let}\, x\, \mathsf{be}\, *\, \mathsf{in}\, \Delta) = \Delta$.

4.4.5 Pars Unit

The proof

$$\dfrac{\dfrac{\dfrac{\pi}{\Gamma \vdash \Delta}}{\Gamma \vdash \circ :\perp \mid \Delta}\textsc{Pr} \quad \dfrac{}{x :\perp \vdash \cdot}\textsc{Pl}}{\Gamma \vdash \Delta \mid [\circ/x]\cdot}\textsc{Cut}$$

transforms into the proof

$$\frac{\begin{array}{c}\pi \\ \vdots\end{array}}{\Gamma \vdash \Delta}$$

Clearly, $[\circ/x]\cdot = \cdot$.

References

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[2] Martin Hyland and Valeria de Paiva. Full intuitionistic linear logic (extended abstract). *Annals of Pure and Applied Logic*, 64(3):273 – 291, 1993.

[3] Paul-Andre Mellies. *Categorical Semantics of Linear Logic*. 2009.

A The full specification of FILL

$$
\begin{array}{llll}
\mathit{term\_var},\ w,\ x,\ y,\ z,\ v & & & \\
\mathit{index\_var},\ i,\ j,\ k & & & \\
\mathit{form},\ A,\ B,\ C,\ D,\ E & ::= & & \\
 & | & I & \\
 & | & \perp & \\
 & | & A \multimap B & \\
 & | & A \otimes B & \\
 & | & A \parr B & \\
 & | & (A) & \mathsf{S} \\
 & & & \\
\mathit{patterns},\ p & ::= & & \\
 & | & * & \\
 & | & x & \\
 & | & p_1 \otimes p_2 & \\
 & | & p_1 \parr p_2 & \\
 & | & - & \\
 & | & (p) & \mathsf{S} \\
 & & & \\
\mathit{term},\ t,\ e,\ d,\ f,\ g,\ u & ::= & & \\
 & | & x & \\
 & | & * & \\
 & | & \circ & \\
 & | & e_1 \otimes e_2 & \\
 & | & e_1 \parr e_2 & \\
 & | & \lambda x.t & \\
 & | & \mathsf{let}\ t\ \mathsf{be}\ p\ \mathsf{in}\ e & \\
 & | & f\ e & \\
 & | & \text{let-pat}\ t\ p\ e & \mathsf{M} \\
 & | & [t/x]t' & \mathsf{M}
\end{array}
$$

	$\vert$	$[t/x, e/y]t'$	M
	$\vert$	(t)	S
	$\vert$	t	M
	$\vert$	t	M
Γ	$::=$		
	$\vert$	$x : A$	
	$\vert$	$\cdot$	
	$\vert$	Γ, Γ'	
	$\vert$	$x : A$	
Δ	$::=$		
	$\vert$	$t : A$	
	$\vert$	$\cdot$	
	$\vert$	$\Delta \mid \Delta'$	
	$\vert$	Δ	
	$\vert$	Δ, Δ'	
	$\vert$	$[t/x]\Delta$	
	$\vert$	$\mathsf{let}\ t\ \mathsf{be}\ p\ \mathsf{in}\ \Delta$	
	$\vert$	(Δ)	
	$\vert$	let-pat $t\ p\ \Delta$	M
$formula$	$::=$		
	$\vert$	$judgement$	
	$\vert$	$formula_1 \quad formula_2$	
	$\vert$	$(formula)$	
	$\vert$	$x \notin \mathsf{FV}(\Delta)$	
	$\vert$	$x \in \mathsf{FV}(t)$	
	$\vert$	$x, y \notin \mathsf{FV}(\Delta)$	
	$\vert$	$x \notin \mathsf{FV}(t)$	
	$\vert$	$x, y \notin \mathsf{FV}(t)$	
	$\vert$	$\Delta_1 = \Delta_2$	
	$\vert$	$\mathsf{FV}(t)$	
	$\vert$	$\mathsf{FV}(\Delta)$	
$InferRules$	$::=$		
	$\vert$	$\Gamma \vdash \Delta$	
	$\vert$	$f = e$	
$judgement$	$::=$		
	$\vert$	$InferRules$	
$user\_syntax$	$::=$		
	$\vert$	$term\_var$	
	$\vert$	$index\_var$	

$|$ *form*
$|$ *patterns*
$|$ *term*
$|$ Γ
$|$ Δ
$|$ *formula*

$\boxed{\Gamma \vdash \Delta}$

$$\frac{}{x : A \vdash x : A} \quad \textsc{Ax}$$

$$\frac{\Gamma \vdash t : A \mid \Delta \quad y : A, \Gamma' \vdash \Delta'}{\Gamma, \Gamma' \vdash \Delta \mid [t/y]\Delta'} \quad \textsc{Cut}$$

$$\frac{\Gamma \vdash \Delta}{\Gamma, x : I \vdash \mathsf{let}\, x\, \mathsf{be}\, * \,\mathsf{in}\, \Delta} \quad \textsc{Il}$$

$$\frac{}{\cdot \vdash * : I} \quad \textsc{Ir}$$

$$\frac{\Gamma, x : A, y : B \vdash \Delta}{\Gamma, z : A \otimes B \vdash \mathsf{let}\, z\, \mathsf{be}\, x \otimes y\, \mathsf{in}\, \Delta} \quad \textsc{Tl}$$

$$\frac{\Gamma \vdash e : A \mid \Delta \quad \Gamma' \vdash f : B \mid \Delta'}{\Gamma, \Gamma' \vdash e \otimes f : A \otimes B \mid \Delta \mid \Delta'} \quad \textsc{Tr}$$

$$\frac{}{x : \perp \vdash \cdot} \quad \textsc{Pl}$$

$$\frac{\Gamma \vdash \Delta}{\Gamma \vdash \circ : \perp \mid \Delta} \quad \textsc{Pr}$$

$$\frac{\Gamma, x : A \vdash \Delta \quad \Gamma', y : B \vdash \Delta'}{\Gamma, \Gamma', z : A \parr B \vdash \text{let-pat}\, z\, (x \parr -)\, \Delta \mid \text{let-pat}\, z\, (- \parr y)\, \Delta'} \quad \textsc{Parl}$$

$$\frac{\Gamma \vdash \Delta \mid e : A \mid f : B \mid \Delta'}{\Gamma \vdash \Delta \mid e \parr f : A \parr B \mid \Delta'} \quad \textsc{Parr}$$

$$\frac{\Gamma \vdash e : A \mid \Delta \quad \Gamma', x : B \vdash \Delta'}{\Gamma, y : A \multimap B, \Gamma' \vdash \Delta \mid [y\ e/x]\Delta'} \quad \textsc{Impl}$$

$$\frac{\Gamma, x : A \vdash e : B \mid \Delta \quad x \notin \mathsf{FV}(\Delta)}{\Gamma \vdash \lambda x.e : A \multimap B \mid \Delta} \quad \textsc{Impr}$$

$$\frac{\Gamma, x : A, y : B \vdash \Delta}{\Gamma, y : B, x : A \vdash \Delta} \quad \textsc{Exl}$$

$$\frac{\Gamma \vdash \Delta_1 \mid t_1 : A \mid t_2 : B \mid \Delta_2}{\Gamma \vdash \Delta_1 \mid t_2 : B \mid t_1 : A \mid \Delta_2} \quad \textsc{Exr}$$

$\boxed{f = e}$

$$\frac{y \notin \mathsf{FV}(t)}{t = [y/x]t} \quad \textsc{Eq\_Alpha}$$

$$\frac{}{(\lambda x.e)\ e' = [e'/x]e} \quad \textsc{Eq\_Beta}$$

$$\frac{}{(\lambda x.f\ x) = f} \quad \textsc{Eq\_Eta}$$

$$\frac{}{\mathsf{let}\ *\ \mathsf{be}\ *\ \mathsf{in}\ e = e}\ \textsc{Eq\_I}$$

$$\frac{}{\mathsf{let}\ u\ \mathsf{be}\ *\ \mathsf{in}\ [*/z]f = [u/z]f}\ \textsc{Eq\_Stp}$$

$$\frac{}{\mathsf{let}\ e \otimes t\ \mathsf{be}\ x \otimes y\ \mathsf{in}\ u = [e/x, t/y]u}\ \textsc{Eq\_T1}$$

$$\frac{}{\mathsf{let}\ u\ \mathsf{be}\ x \otimes y\ \mathsf{in}\ [x \otimes y/z]f = [u/z]f}\ \textsc{Eq\_T2}$$

$$\frac{}{\mathsf{let}\ u \parr t\ \mathsf{be}\ x \parr -\ \mathsf{in}\ e = [u/x]e}\ \textsc{Eq\_P1}$$

$$\frac{}{\mathsf{let}\ u \parr t\ \mathsf{be}\ - \parr y\ \mathsf{in}\ e = [t/y]e}\ \textsc{Eq\_P2}$$

$$\frac{}{(\mathsf{let}\ x\ \mathsf{be}\ x \parr -\ \mathsf{in}\ x) \parr (\mathsf{let}\ u\ \mathsf{be}\ - \parr y\ \mathsf{in}\ y) = u}\ \textsc{Eq\_P3}$$

$$\frac{t = t'}{\lambda x.t = \lambda x.t''}\ \textsc{Eq\_Lam}$$

$$\frac{t_1 = t_1'}{t_1\ t_2 = t_1'\ t_2}\ \textsc{Eq\_App1}$$

$$\frac{t_2 = t_2'}{t_1\ t_2 = t_1\ t_2'}\ \textsc{Eq\_App2}$$

$$\frac{t_1 = t_1'}{t_1 \otimes t_2 = t_1' \otimes t_2}\ \textsc{Eq\_Ten1}$$

$$\frac{t_2 = t_2'}{t_1 \otimes t_2 = t_1 \otimes t_2'}\ \textsc{Eq\_Ten2}$$

$$\frac{t_1 = t_1'}{t_1 \parr t_2 = t_1' \parr t_2}\ \textsc{Eq\_Par1}$$

$$\frac{t_2 = t_2'}{t_1 \parr t_2 = t_1 \parr t_2'}\ \textsc{Eq\_Par2}$$

$$\frac{t = t'}{\mathsf{let}\ t\ \mathsf{be}\ p\ \mathsf{in}\ e = \mathsf{let}\ t'\ \mathsf{be}\ p\ \mathsf{in}\ e}\ \textsc{Eq\_Let1}$$

$$\frac{e = e'}{\mathsf{let}\ t\ \mathsf{be}\ p\ \mathsf{in}\ e = \mathsf{let}\ t\ \mathsf{be}\ p\ \mathsf{in}\ e'}\ \textsc{Eq\_Let2}$$

$$\frac{}{t = t}\ \textsc{Eq\_Refl}$$

$$\frac{t = t'}{t' = t}\ \textsc{Eq\_Sym}$$

$$\frac{t_1 = t_2 \quad t_2 = t_3}{t_1 = t_3}\ \textsc{Eq\_Trans}$$