Base-extension Semantics for Intuitionistic Linear Logic

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Goals for this talk

- To introduce Intuitionistic Linear Logic and a natural deduction system for it.
- Present a Base-extension Semantics for Intuitionistic Linear Logic.
- Talk about some of the difficulties involved the process of developing such a semantics.

Presentation root directory

Presentation root directory

Notation

- $\mathbb{A}$ represents a fixed, countably infinite set of propositional atoms.
- Lower case latin letters represent propositional atoms.
- Upper case latin letters represent finite multisets of propositional atoms.
- Atomic multiset is taken to mean multiset of propositional atoms.
- The sum of two multisets P and Q is denoted $P \fatsemi Q$.
- Lower case greek letters represent ILL formulas.
- Upper case greek letters represent ILL finite multisets thereof.

Formulas of Intuitionistic Linear Logic

Definition

Formulas of ILL are defined inductively as follows:

$$\mathrm{Form} \ni \varphi, \psi ::= p \in \mathbb{A} \mid \top \mid 0 \mid 1 \mid \varphi \multimap \psi \mid \varphi \otimes \psi \mid \varphi \,\&\, \psi \mid \varphi \oplus \psi \mid \,!\,\varphi$$

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Definition (Sequent)

A sequent is a pair (Γ, φ).

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Definition (Sequent)

A sequent is a pair (Γ, φ).

An example ILL sequent is $(\{\varphi, \varphi \multimap \psi\}, \psi \otimes \chi)$

A natural deduction system for ILL

$$\frac{}{\varphi \vdash \varphi}\ \mathsf{Ax}$$

$$\frac{\Gamma \,, \varphi \vdash \psi}{\Gamma \vdash \varphi \multimap \psi}\ \multimap\text{-I} \qquad \frac{\Gamma \vdash \varphi \multimap \psi \qquad \Delta \vdash \varphi}{\Gamma \,, \Delta \vdash \psi}\ \multimap\text{-E}$$

$$\frac{\Gamma \vdash \varphi \qquad \Delta \vdash \psi}{\Gamma \,, \Delta \vdash \varphi \otimes \psi}\ \otimes\text{-I} \qquad \frac{\Gamma \vdash \varphi \otimes \psi \qquad \Delta \,, \varphi \,, \psi \vdash \chi}{\Gamma \,, \Delta \vdash \chi}\ \otimes\text{-E}$$

$$\frac{}{\vdash 1}\ 1\text{-I} \qquad \frac{\Gamma \vdash \varphi \qquad \Delta \vdash 1}{\Gamma \,, \Delta \vdash \varphi}\ 1\text{-E}$$

$$\frac{\Gamma \vdash \varphi \qquad \Gamma \vdash \psi}{\Gamma \vdash \varphi \,\&\, \psi}\ \&\text{-I} \qquad \frac{\Gamma \vdash \varphi_0 \,\&\, \varphi_1}{\Gamma \vdash \varphi_i}\ \&\text{-E}_i$$

$$\frac{\Gamma \vdash \varphi_i}{\Gamma \vdash \varphi_0 \oplus \varphi_1}\ \oplus\text{-I}_i \qquad \frac{\Gamma \vdash \varphi \oplus \psi \qquad \Delta \,, \varphi \vdash \chi \qquad \Delta \,, \psi \vdash \chi}{\Gamma \,, \Delta \vdash \chi}\ \oplus\text{-E}$$

$$\frac{\Gamma_1 \vdash \varphi_1 \qquad \ldots \qquad \Gamma_n \vdash \varphi_n}{\Gamma_1 \,, \cdots \,, \Gamma_n \vdash \top}\ \top\text{-I} \qquad \frac{\Gamma \vdash 0}{\Gamma \vdash \varphi}\ 0\text{-E}$$

A natural deduction system for ILL (cont.)

$$\frac{\Gamma_1 \vdash\, !\psi_1 \qquad \ldots \qquad \Gamma_n \vdash\, !\psi_n \qquad !\psi_1 \,;\, \ldots \,;\, !\psi_n \vdash \varphi}{\Gamma_1 \,;\, \ldots \,;\, \Gamma_n \vdash\, !\varphi}\ \text{!-Promotion}$$

$$\frac{\Gamma \vdash\, !\varphi \qquad \Delta \,;\, \varphi \vdash \psi}{\Gamma \,;\, \Delta \vdash \psi}\ \text{!-Dereliction}$$

$$\frac{\Gamma \vdash\, !\varphi \qquad \Delta \vdash \psi}{\Gamma \,;\, \Delta \vdash \psi}\ \text{!-Weakening}$$

$$\frac{\Gamma \vdash\, !\varphi \qquad \Delta \,;\, !\varphi \,;\, !\varphi \vdash \psi}{\Gamma \,;\, \Delta \vdash \psi}\ \text{!-Contraction}$$

What is the general form of an inference figure?

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$$\frac{\Gamma \vdash \varphi_1 \qquad \Delta \vdash \varphi_2}{\Gamma \,;\, \Delta \vdash \varphi_1 \otimes \varphi_2} \otimes\text{-I}$$

What is the general form of an inference figure?

$$\frac{\Gamma \vdash \varphi_1 \qquad \Gamma \vdash \varphi_2}{\Gamma \vdash \varphi_1 \,\&\, \varphi_2}\ \&\text{-I}$$

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$$\frac{\Gamma_1 \vdash \varphi_1 \qquad \dots \qquad \Gamma_n \vdash \varphi_n}{\Gamma_1 \,,\, \cdots \,,\, \Gamma_n \vdash \psi}$$

$$\frac{\Gamma \vdash \varphi_1 \qquad \dots \qquad \Gamma \vdash \varphi_n}{\Gamma \vdash \psi}$$

What is the general form of an inference figure?

$$\frac{\Gamma_1 \vdash \varphi_1 \qquad \ldots \qquad \Gamma_n \vdash \varphi_n}{\Gamma_1 \fatsemi \cdots \fatsemi \Gamma_n \vdash \psi} \qquad\qquad \frac{\Gamma \vdash \varphi_1 \qquad \ldots \qquad \Gamma \vdash \varphi_n}{\Gamma \vdash \psi}$$

$$\frac{\Gamma \vdash \varphi_1 \oplus \varphi_2 \qquad \Delta \fatsemi \varphi_1 \vdash \chi \qquad \Delta \fatsemi \varphi_2 \vdash \chi}{\Gamma \fatsemi \Delta \vdash \chi}\ \oplus\text{-E}$$

What is the general form of an inference figure?

$$\frac{\Gamma \vdash \varphi_1 \oplus \varphi_2 \qquad \Delta \,⨾\, \varphi_1 \vdash \chi \qquad \Delta \,⨾\, \varphi_2 \vdash \chi}{\Gamma \,⨾\, \Delta \vdash \chi} \oplus\text{-E}$$

What is the general form of an inference figure?

$$\frac{\Gamma \vdash \varphi_1 \oplus \varphi_2 \qquad \Delta\{\varphi_1 \vdash \chi \qquad \varphi_2 \vdash \chi\}}{\Gamma \,;\, \Delta \vdash \chi} \oplus\text{-E}$$

What is the general form of an inference figure?

$$\frac{\Gamma\{\varnothing \vdash \varphi_1 \oplus \varphi_2\} \qquad \Delta\{\varphi_1 \vdash \chi \qquad \varphi_2 \vdash \chi\}}{\Gamma \mathbin{⨟} \Delta \vdash \chi}\ \oplus\text{-E}$$

What is the general form of an inference figure?

$$\dfrac{\Gamma\{\varnothing \vdash \varphi_1 \oplus \varphi_2\} \qquad \Delta\{\varphi_1 \vdash \chi \qquad \varphi_2 \vdash \chi\}}{\Gamma \fatsemi \Delta \vdash \chi}\ \oplus\text{-E}$$

What is the general form of an inference figure?

$$\frac{\Gamma\{\varnothing \vdash \varphi_1\} \qquad \Delta\{\varnothing \vdash \varphi_2\}}{\Gamma \,⨾\, \Delta \vdash \varphi_1 \otimes \varphi_2} \otimes\text{-I}$$

$$\frac{\Gamma\{\varnothing \vdash \varphi_1 \qquad \varnothing \vdash \varphi_2\}}{\Gamma \vdash \varphi_1 \,\&\, \varphi_2} \&\text{-I}$$

What is the general form of an inference figure?

$$\frac{\ldots \qquad \Gamma_i \;\{\Delta_{i_1} \vdash \varphi_{i_1} \qquad \ldots \qquad \Delta_{i_{l_i}} \vdash \varphi_{i_{l_i}}\} \qquad \ldots}{\Gamma_1 \,⁏\, \cdots \,⁏\, \Gamma_n \vdash \psi}$$

What is the general form of an inference figure?

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Almost! What about:

$$\frac{\Gamma_1 \vdash\, !\,\psi_1 \qquad \ldots \qquad \Gamma_n \vdash\, !\,\psi_n \qquad !\,\psi_1 \,⨾\, \ldots \,⨾\, !\,\psi_n \vdash \varphi}{\Gamma_1 \,⨾\, \ldots \,⨾\, \Gamma_n \vdash\, !\,\varphi}\ \text{!-Promotion}$$

What is the general form of an inference figure?

$$\dfrac{\Gamma_1\{\varnothing \vdash\, !\psi_1\} \quad \ldots \quad \Gamma_n\{\varnothing \vdash\, !\psi_n\} \quad !\psi_1 \,⨾\, \ldots \,⨾\, !\psi_n \vdash \varphi}{\Gamma_1 \,⨾\, \ldots \,⨾\, \Gamma_n \vdash\, !\varphi}\ \text{!-Promotion}$$

Presentation root directory

Substructural atomic derivability

Definition (Basic rule)

Basic rules take the following form:

$$\{(P_{1_i} \Rightarrow q_{1_i})\}_{i=1}^{l_1}, \ldots, \{(P_{n_i} \Rightarrow q_{n_i})\}_{i=1}^{l_n} \Rightarrow r$$

- Each $(P_i \Rightarrow q_i)$ is a pair (P_i, q_i) called an atomic sequent.
- Each collection $\{(P_{i_1} \Rightarrow q_{i_1}), \ldots, (P_{i_{l_i}} \Rightarrow q_{i_{l_i}})\}$ is called an atomic box.

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Definition (Base)

A base $\mathscr{B}$ is a **SET** of basic rules.

Substructural atomic derivability

Definition (Basic derivability relation)

The relation of derivability in a base $\mathscr{B}$, is defined inductively as so:

Ref $p \vdash_{\mathscr{B}} p$

App Given that $(\{(P_{1_i} \Rightarrow q_{1_i})\}_{i=1}^{l_1}, \ldots, \{(P_{n_i} \Rightarrow q_{n_i})\}_{i=1}^{l_n} \Rightarrow r) \in \mathscr{B}$ and atomic multisets C_i such that the following hold:

$$C_i \fatcomma P_{i_j} \vdash_{\mathscr{B}} q_{i_j} \text{ for all } i = 1, \ldots, n \text{ and } j = 1, \ldots, l_i$$

Then $C_1 \fatcomma \ldots \fatcomma C_n \vdash_{\mathscr{B}} r$.

Example derivations

Example (Derivation terminations)

Let $\mathscr{B} = \{(\Rightarrow a), (\{\Rightarrow a\}, \{\Rightarrow b\} \Rightarrow c)\}$

$$\dfrac{\dfrac{}{b \vdash_{\mathscr{B}} b}\,\mathrm{Ref} \qquad \dfrac{}{\vdash_{\mathscr{B}} a}\Rightarrow a}{b \vdash_{\mathscr{B}} c}\,\{\Rightarrow a\}, \{\Rightarrow b\} \Rightarrow c$$

Therefore, in $\mathscr{B}$, the atom c is derivable from b.

Example derivations

Example (Invalid derivation)

By the definition of $\vdash_{\mathscr{B}}$, deriving a from $a \mathbin{⨟} a$ in the empty base is not possible, i.e. $a \mathbin{⨟} a \vdash_{\varnothing} a$ is not possible.

Example derivations

Example (Invalid derivation)

By the definition of $\vdash_{\mathscr{B}}$, deriving a from $a \fatsemi a$ in the empty base is not possible, i.e. $a \fatsemi a \vdash_{\varnothing} a$ is not possible.

Example (Invalid derivation 2)

Let $\mathscr{B} = \{(\{\Rightarrow a\} \Rightarrow c), (\{a \Rightarrow c\} \Rightarrow b)\}$

$$\dfrac{\dfrac{\dfrac{\times}{a \fatsemi a \vdash_{\mathscr{B}} a}}{a \fatsemi a \vdash_{\mathscr{B}} c}\{\Rightarrow a\} \Rightarrow c}{a \vdash_{\mathscr{B}} b}\{a \Rightarrow c\} \Rightarrow b$$

We see that in this base, a is not derivable from $a \fatsemi a$.

Example derivations

Example (A possible fix for invalid derivation 2)

Let $\mathscr{C} = \{(\{\Rightarrow a\} \Rightarrow c), (\{a \Rightarrow c\} \Rightarrow b), (\{\Rightarrow a\}, \{\Rightarrow a\} \Rightarrow a)\}$

$$
\begin{prooftree}
\AxiomC{}
\RightLabel{Ref}
\UnaryInfC{$a \vdash_{\mathscr{C}} a$}
\AxiomC{}
\RightLabel{Ref}
\UnaryInfC{$a \vdash_{\mathscr{C}} a$}
\RightLabel{$\{\Rightarrow a\}, \{\Rightarrow a\} \Rightarrow a$}
\BinaryInfC{$a , a \vdash_{\mathscr{C}} a$}
\RightLabel{$\{\Rightarrow a\} \Rightarrow c$}
\UnaryInfC{$a , a \vdash_{\mathscr{C}} c$}
\RightLabel{$\{a \Rightarrow c\} \Rightarrow b$}
\UnaryInfC{$a \vdash_{\mathscr{C}} b$}
\end{prooftree}
$$

Note that $\mathscr{C} \supset \mathscr{B}$!!

Example derivations

Example (Another possible fix for invalid derivation 2)

Let

$\mathscr{D} = \{(\{\Rightarrow a\} \Rightarrow c), (\{a \Rightarrow c\} \Rightarrow b), (\{\Rightarrow d\}, \{\Rightarrow d\} \Rightarrow a), (\{\Rightarrow a\} \Rightarrow d)\}$

$$\dfrac{\dfrac{\dfrac{\dfrac{}{a \vdash_{\mathscr{D}} a}\,\text{Ref}}{a \vdash_{\mathscr{D}} d}\,\{\Rightarrow a\} \Rightarrow d \qquad \dfrac{\dfrac{}{a \vdash_{\mathscr{D}} a}\,\text{Ref}}{a \vdash_{\mathscr{D}} d}\,\{\Rightarrow a\} \Rightarrow d}{\dfrac{a \,⨾\, a \vdash_{\mathscr{D}} a}{a \,⨾\, a \vdash_{\mathscr{D}} c}\,\{\Rightarrow a\} \Rightarrow c}\,\{\Rightarrow d\}, \{\Rightarrow d\} \Rightarrow a}{a \vdash_{\mathscr{D}} b}\,\{a \Rightarrow c\} \Rightarrow b$$

Example derivations

Example (A live complicated derivation!)

Consider a base $\mathscr{B}$ with only the following rules:

- $\{\Rightarrow c\}, \{\Rightarrow y\} \Rightarrow f$
- $\Rightarrow z$
- $\{\Rightarrow a\}, \{\Rightarrow b\}, \{\Rightarrow z\} \Rightarrow h$
- $\{\Rightarrow h\} \Rightarrow g$
- $\{\Rightarrow x\}, \{\Rightarrow g\} \Rightarrow e$
- $\{x \Rightarrow e\}, \{y \Rightarrow f\} \Rightarrow d$

is there a derivation of d from the multiset $a \mathbin{,} b \mathbin{,} c$ in $\mathscr{B}$?

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is there a derivation of d from the multiset $a \mathbin{,} b \mathbin{,} c$ in $\mathscr{B}$?

Disclaimer: The fact I couldn't fit this derivation on the slide has nothing to do with why we are doing this derivation live :-)

Example derivations

Example (A very interesting derivation)

Let $\mathscr{B} = \{(\{\Rightarrow b\} \Rightarrow c), (\{\Rightarrow a\}, \{b \Rightarrow c\} \Rightarrow d), (\{\Rightarrow d, \Rightarrow a\} \Rightarrow e), (\{a \Rightarrow e\} \Rightarrow f)\}$

$$\dfrac{\dfrac{\dfrac{}{a \vdash_{\mathscr{B}} a}\,\text{Ref} \qquad \dfrac{\dfrac{}{b \vdash_{\mathscr{B}} b}\,\text{Ref}}{b \vdash_{\mathscr{B}} c}\,\{\Rightarrow b\} \Rightarrow c}{a \vdash_{\mathscr{B}} d}\,\{\Rightarrow a\}, \{b \Rightarrow c\} \Rightarrow d \qquad \dfrac{}{a \vdash_{\mathscr{B}} a}\,\text{Ref}}{\dfrac{a \vdash_{\mathscr{B}} e}{\vdash_{\mathscr{B}} f}\,\{a \Rightarrow e\} \Rightarrow f}\,\{\Rightarrow d, \Rightarrow a\} \Rightarrow e$$

An interesting property of $\vdash_{\mathscr{B}}$

Lemma (Substitution lemma)

The following are equivalent for arbitrary atomic multisets $P \fatsemi S$, atom q, and base $\mathscr{B}$, where we assume $P = \{p_1, \ldots, p_n\}$:

- $P \fatsemi S \vdash_{\mathscr{B}} q$
- *For every* $\mathscr{C} \supseteq \mathscr{B}$*, atomic multisets* $T_1, \ldots, T_m$ *where* $T_1 \vdash_{\mathscr{C}} p_1, \ldots, T_n \vdash_{\mathscr{C}} p_m$*, then* $T_1 \fatsemi \cdots \fatsemi T_m \fatsemi S \vdash_{\mathscr{C}} q$

(At)	$\Vdash^{L}_{\mathscr{B}} p$	iff	$L \vdash_{\mathscr{B}} p$
$(\multimap)$	$\Vdash^{L}_{\mathscr{B}} \varphi \multimap \psi$	iff	$\varphi \Vdash^{L}_{\mathscr{B}} \psi$
$(\otimes)$	$\Vdash^{L}_{\mathscr{B}} \varphi \otimes \psi$	iff	for any $\mathscr{C}$ such that $\mathscr{B} \subseteq \mathscr{C}$, atomic multisets K and any $p \in \mathbb{A}$, if $\varphi \,,\, \psi \Vdash^{K}_{\mathscr{B}} p$ then $\Vdash^{L,K}_{\mathscr{C}} p$
(1)	$\Vdash^{L}_{\mathscr{B}} 1$	iff	for any $\mathscr{C}$ such that $\mathscr{B} \subseteq \mathscr{C}$, atomic multisets K and any $p \in \mathbb{A}$, if $\Vdash^{K}_{\mathscr{B}} p$ then $\Vdash^{L,K}_{\mathscr{C}} p$
$(\top)$	$\Vdash^{L}_{\mathscr{B}} \top$	iff	always
$(\&)$	$\Vdash^{L}_{\mathscr{B}} \varphi \,\&\, \psi$	iff	$\Vdash^{L}_{\mathscr{B}} \varphi$ and $\Vdash^{L}_{\mathscr{B}} \psi$
$(\oplus)$	$\Vdash^{L}_{\mathscr{B}} \varphi \oplus \psi$	iff	for any $\mathscr{C}$ such that $\mathscr{B} \subseteq \mathscr{C}$, atomic multisets K and any $p \in \mathbb{A}$, if $\varphi \Vdash^{K}_{\mathscr{C}} p$ and $\psi \Vdash^{K}_{\mathscr{C}} p$, then $\Vdash^{L,K}_{\mathscr{C}} p$
(0)	$\Vdash^{L}_{\mathscr{B}} 0$	iff	$\Vdash^{L}_{\mathscr{B}} p$ for any $p \in \mathbb{A}$
$(!)$	$\Vdash^{L}_{\mathscr{B}} !\,\varphi$	iff	for any $\mathscr{C}$ such that $\mathscr{B} \subseteq \mathscr{C}$, atomic multisets K and any $p \in \mathbb{A}$, if for any $\mathscr{D}$ such that $\mathscr{C} \subseteq \mathscr{D}$, (if $\Vdash^{\varnothing}_{\mathscr{D}} \varphi$ then $\Vdash^{L}_{\mathscr{D}} p$) then $\Vdash^{L,K}_{\mathscr{C}} p$
$(,)$	$\Vdash^{L}_{\mathscr{B}} \Gamma \,,\, \Delta$	iff	there exists multisets K and M such that $L = K \,,\, M$ and $\Vdash^{K}_{\mathscr{B}} \Gamma$ and $\Vdash^{M}_{\mathscr{B}} \Delta$
(Inf)	$!\,\Delta \,,\, \Theta \Vdash^{L}_{\mathscr{B}} \varphi$	iff	for any $\mathscr{C}$ such that $\mathscr{B} \subseteq \mathscr{C}$, atomic multisets K, if $\Vdash^{\varnothing}_{\mathscr{C}} \Delta$ and $\Vdash^{K}_{\mathscr{C}} \Theta$ then $\Vdash^{L,K}_{\mathscr{C}} \varphi$

Base-extension Semantics for ILL

Note the clause for (!) could be written as:

- $\Vdash^{L}_{\mathscr{B}} !\,\varphi$ iff for any $\mathscr{C}$ such that $\mathscr{C} \supseteq \mathscr{B}$, atomic multisets K and any $p \in \mathbb{A}$, if $!\,\varphi \Vdash^{K}_{\mathscr{C}} p$ then $\Vdash^{L,K}_{\mathscr{C}} p$.

Notes on $\Vdash^{L}_{\mathscr{B}}$

- The sequent (Γ, φ) is said to be valid if and only if $\Gamma \Vdash^{\varnothing}_{\varnothing} \varphi$ holds.

Notes on $\Vdash^{L}_{\mathscr{B}}$

- The sequent (Γ, φ) is said to be valid if and only if $\Gamma \Vdash^{\varnothing}_{\varnothing} \varphi$ holds.
- We frequently write this as $\Gamma \Vdash \varphi$.

Notes on $\Vdash^{L}_{\mathscr{B}}$

- If $\Vdash^{L}_{\mathscr{B}} \varphi$ then for all $\mathscr{C} \supseteq \mathscr{B}$ we have $\Vdash^{L}_{\mathscr{C}} \varphi$.
- Given $\Gamma \Vdash^{L}_{\mathscr{B}} \varphi$ and $\Vdash^{K}_{\mathscr{B}} \Gamma$, then it holds that $\Vdash^{L \fatsemi K}_{\mathscr{B}} \varphi$.

Soundness

Theorem (Soundness)

If $\Gamma \vdash \varphi$ *then* $\Gamma \Vdash \varphi$

Soundness

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If $\Gamma \vdash \varphi$ *then* $\Gamma \Vdash \varphi$

- The strategy is to show every rule of the natural deduction system presented previously is semantically expressible.
- This suffices by induction to prove this theorem as now we can encode any deduction into a series of semantic proofs.

A reminder of the rules of natural deduction for ILL

$$\frac{}{\varphi \vdash \varphi}\ \mathsf{Ax}$$

$$\frac{\Gamma \,,\, \varphi \vdash \psi}{\Gamma \vdash \varphi \multimap \psi}\ \multimap\text{-I} \qquad \frac{\Gamma \vdash \varphi \multimap \psi \qquad \Delta \vdash \varphi}{\Gamma \,,\, \Delta \vdash \psi}\ \multimap\text{-E}$$

$$\frac{\Gamma \vdash \varphi \qquad \Delta \vdash \psi}{\Gamma \,,\, \Delta \vdash \varphi \otimes \psi}\ \otimes\text{-I} \qquad \frac{\Gamma \vdash \varphi \otimes \psi \qquad \Delta \,,\, \varphi \,,\, \psi \vdash \chi}{\Gamma \,,\, \Delta \vdash \chi}\ \otimes\text{-E}$$

$$\frac{}{\vdash 1}\ 1\text{-I} \qquad \frac{\Gamma \vdash \varphi \qquad \Delta \vdash 1}{\Gamma \,,\, \Delta \vdash \varphi}\ 1\text{-E}$$

$$\frac{\Gamma \vdash \varphi \qquad \Gamma \vdash \psi}{\Gamma \vdash \varphi \,\&\, \psi}\ \&\text{-I} \qquad \frac{\Gamma \vdash \varphi_0 \,\&\, \varphi_1}{\Gamma \vdash \varphi_i}\ \&\text{-E}_i$$

$$\frac{\Gamma \vdash \varphi_i}{\Gamma \vdash \varphi_0 \oplus \varphi_1}\ \oplus\text{-I}_i \qquad \frac{\Gamma \vdash \varphi \oplus \psi \qquad \Delta \,,\, \varphi \vdash \chi \qquad \Delta \,,\, \psi \vdash \chi}{\Gamma \,,\, \Delta \vdash \chi}\ \oplus\text{-E}$$

$$\frac{\Gamma_1 \vdash \varphi_1 \qquad \ldots \qquad \Gamma_n \vdash \varphi_n}{\Gamma_1 \,,\, \cdots \,,\, \Gamma_n \vdash \top}\ \top\text{-I} \qquad \frac{\Gamma \vdash 0}{\Gamma \vdash \varphi}\ 0\text{-E}$$

Reminder (cont.)

$$\frac{\Gamma_1 \vdash\, !\,\psi_1 \qquad \ldots \qquad \Gamma_n \vdash\, !\,\psi_n \qquad !\,\psi_1 , \ldots , !\,\psi_n \vdash \varphi}{\Gamma_1 , \ldots , \Gamma_n \vdash\, !\,\varphi} \text{ !-Promotion}$$

$$\frac{\Gamma \vdash\, !\,\varphi \qquad \Delta , \varphi \vdash \psi}{\Gamma , \Delta \vdash \psi} \text{ !-Dereliction}$$

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Completeness

Theorem (Completeness)

If $\Gamma \Vdash \varphi$ *then* $\Gamma \vdash \varphi$.

Completeness

Theorem (Completeness)

If $\Gamma \Vdash \varphi$ *then* $\Gamma \vdash \varphi$*.*

- Define two functions $(\cdot)^\flat$: Form $\to \mathbb{A}$ and $(\cdot)^\natural$: $\mathbb{A} \to$ Form.
- Show that any valid sequent remains valid when “atomised”.
- Construct a base $\mathscr{N}$ whose rules simulate the natural deduction rules of ILL.
- Show that every derivation in this simulation base is equivalent to a corresponding derivation in ILL.
- Show we can go from a valid derivation to a derivation in ILL.

The Simulation Base

Consider the valid sequent $\Gamma \Vdash \varphi$. Let α, β range over all subformulas of this sequent.

- To construct $\mathscr{N}$ we simulate all possible ND-rules of our system.
- This means $\mathscr{N}$ contains the introduction and elimination rules governing $\alpha \circ \beta$, where $\circ \in \{\otimes, \&, \oplus, \multimap\}$, governing α where $\alpha \in \{1, 0, \top\}$ and all rules governing α where $\alpha = !\,\beta$.
- Thus, rules include but, of course, are not limited to:
  - $\{\alpha^\flat \Rightarrow \beta^\flat\} \Rightarrow (\alpha \multimap \beta)^\flat$
  - $\{\Rightarrow (\alpha \multimap \beta)^\flat\}, \{\Rightarrow \alpha^\flat\} \Rightarrow \beta^\flat$
  - $\{\Rightarrow \alpha^\flat\}, \{\Rightarrow \beta^\flat\} \Rightarrow (\alpha \otimes \beta)^\flat$
  - $\{\Rightarrow (\alpha \otimes \beta)^\flat\}, \{\alpha^\flat \,,\, \beta^\flat \Rightarrow p\} \Rightarrow p$

The Simulation Base: An explaination

Recall the *flattened* form of the introduction and elimination rules for the tensor:

- $\{\Rightarrow \alpha^\flat\}, \{\Rightarrow \beta^\flat\} \Rightarrow (\alpha \otimes \beta)^\flat$
- $\{\Rightarrow (\alpha \otimes \beta)^\flat\}, \{\alpha^\flat \mathbin{,} \beta^\flat \Rightarrow p\} \Rightarrow p$

The Simulation Base: An explaination

Recall the *flattened* form of the introduction and elimination rules for the tensor:

- $\{\Rightarrow \alpha^\flat\}, \{\Rightarrow \beta^\flat\} \Rightarrow (\alpha \otimes \beta)^\flat$
- $\{\Rightarrow (\alpha \otimes \beta)^\flat\}, \{\alpha^\flat \mathbin{,} \beta^\flat \Rightarrow p\} \Rightarrow p$

Another way of writing these rules would be as follows:
Let $\alpha^\flat = x$, $\beta^\flat = y$ and $(\alpha \otimes \beta)^\flat = z$. Then:

- $\{\Rightarrow x\}, \{\Rightarrow y\} \Rightarrow z$
- $\{\Rightarrow z\}, \{x \mathbin{,} y \Rightarrow p\} \Rightarrow p$

The Simulation Base: A quiz

Example

Given that $a = \alpha^\flat$ and $b = \beta^\flat$, which ILL formula is being simulated by the atom x in the following rules?

- $\{\Rightarrow a, \Rightarrow b\} \Rightarrow x$
- $\{\Rightarrow x\} \Rightarrow a$
- $\{\Rightarrow x\} \Rightarrow b$

The Simulation Base: A quiz

Example

Given that $a = \alpha^\flat$ and $b = \beta^\flat$, which ILL formula is being simulated by the atom x in the following rules?

- $\{\Rightarrow a, \Rightarrow b\} \Rightarrow x$
- $\{\Rightarrow x\} \Rightarrow a$
- $\{\Rightarrow x\} \Rightarrow b$

Thats right! It's $\alpha \,\&\, \beta$

Presentation root directory

What of the exponential?

The exponential is hard...

What of the exponential?

The exponential is hard...

But we finally understand it!

Why was it so hard?

$$\frac{\Gamma_1 \vdash\, !\psi_1 \qquad \ldots \qquad \Gamma_n \vdash\, !\psi_n \qquad !\psi_1 , \ldots , !\psi_n \vdash \varphi}{\Gamma_1 , \ldots , \Gamma_n \vdash\, !\varphi}\ \text{!-Promotion}$$

$$\frac{\Gamma \vdash\, !\varphi \qquad \Delta , \varphi \vdash \psi}{\Gamma , \Delta \vdash \psi}\ \text{!-Dereliction}$$

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Why was it so hard?

$$\frac{!\,\psi \vdash !\,\psi \qquad !\,\psi \vdash \varphi}{!\,\psi \vdash !\,\varphi}$$

What do we have now?

(!) $\Vdash^{L}_{\mathscr{B}} !\,\varphi$ iff for any $\mathscr{C}$ such that $\mathscr{C} \supseteq \mathscr{B}$, atomic multisets K and any $p \in \mathbb{A}$, if $!\,\varphi \Vdash^{K}_{\mathscr{C}} p$ then $\Vdash^{L,K}_{\mathscr{C}} p$.

(Inf) $!\,\Delta \,\text{,}\, \Theta \Vdash^{L}_{\mathscr{B}} \varphi$ iff for all $\mathscr{C} \supseteq \mathscr{B}$, atomic multisets K, if $\Vdash^{K}_{\mathscr{C}} \Theta$ and $\Vdash^{\varnothing}_{\mathscr{C}} \Delta$ then $\Vdash^{L,K}_{\mathscr{C}} \varphi$.

What we had last year

(Inf) $\Gamma \Vdash^{L}_{\mathscr{B}} \varphi$ iff for all $\mathscr{C} \supseteq \mathscr{B}$, atomic multisets K, if $\Vdash^{K}_{\mathscr{C}} \Gamma$ then $\Vdash^{L,K}_{\mathscr{C}} \varphi$.

What do we know?

Two important identities from Intuitionistic Linear Logic:

- $!\,\varphi \Vdash \varphi \otimes \ldots \otimes \varphi$
- $!(\varphi \mathbin{\&} \psi) \equiv\, !\,\varphi \otimes\, !\,\psi$

Expanding what we know

$!\,\varphi \Vdash \varphi \otimes \ldots \otimes \varphi$ iff

for all bases $\mathscr{B}$ and atomic multisets L, such that $\Vdash^{L}_{\mathscr{B}} !\,\varphi$ then $\Vdash^{L}_{\mathscr{B}} \varphi \otimes \ldots \otimes \varphi$

Expanding what we know

- So when does $\Vdash^{L}_{\mathscr{B}} \varphi \otimes \ldots \otimes \varphi$ hold?

Expanding what we know

Considering the case when $\varphi = p$ for simplicity we get the following:

Expanding what we know

Considering the case when $\varphi = p$ for simplicity we get the following:

- Given a base $\mathscr{B}$ such that $\vdash_{\mathscr{B}} p$ and $L = \varnothing$.

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Considering the case when $\varphi = p$ for simplicity we get the following:

- Given a base $\mathscr{B}$ such that $\vdash_{\mathscr{B}} p$ and $L = \varnothing$.
- Then we have that $\Vdash^{L}_{\mathscr{B}} p \otimes \ldots \otimes p$.

Expanding what we know

Considering the case when $\varphi = p$ for simplicity we get the following:

- Given a base $\mathscr{B}$ such that $\vdash_{\mathscr{B}} p$ and $L = \varnothing$.
- Then we have that $\Vdash^{L}_{\mathscr{B}} p \otimes \ldots \otimes p$.
- Examples of such bases:
  - $\mathscr{B} = \{\Rightarrow p\}$
  - $\mathscr{B} = \{\Rightarrow q, \{\Rightarrow q\} \Rightarrow p\}$

Expanding what we know

Inferring from $!\,\varphi$ *should imply that* $\Vdash^{\varnothing}_{\mathscr{B}} \varphi$.

A proof-theoretic flavour of the !

We now consider the second identity: $\Vdash^{L}_{\mathscr{B}} !(\varphi \,\&\, \psi)$ iff $\Vdash^{L}_{\mathscr{B}} !\varphi \otimes !\psi$ with $\psi = \top$. Furthermore since $\varphi \,\&\, \top \equiv \varphi$ we go as follows:

$\Vdash^{L}_{\mathscr{B}} !\varphi$ iff $\Vdash^{L}_{\mathscr{B}} !\varphi \otimes !\top$

iff for all $\mathscr{C} \supseteq \mathscr{B}$, K and $p \in \mathbb{A}$, $!\varphi \,⨾\, !\top \Vdash^{K}_{\mathscr{C}} p$ implies $\Vdash^{L ⨾ K}_{\mathscr{C}} p$

iff for all $\mathscr{C} \supseteq \mathscr{B}$, K and $p \in \mathbb{A}$,

if (for all $\mathscr{D} \supseteq \mathscr{C}$, if $\Vdash^{\varnothing}_{\mathscr{D}} \varphi$ and $\Vdash^{\varnothing}_{\mathscr{D}} \top$ then $\Vdash^{K}_{\mathscr{D}} p$) then $\Vdash^{L ⨾ K}_{\mathscr{C}} p$

iff for all $\mathscr{C} \supseteq \mathscr{B}$, K and $p \in \mathbb{A}$,

if (for all $\mathscr{D} \supseteq \mathscr{C}$, if $\Vdash^{\varnothing}_{\mathscr{D}} \varphi$ then $\Vdash^{K}_{\mathscr{D}} p$) then $\Vdash^{L ⨾ K}_{\mathscr{C}} p$

Gracias!

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