# ISOMORPHISMS IN A CATEGORY OF PROPOSITIONS AND PROOFS

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I aim to show how a category of propositions and *classical* proofs can give rise to finely grained hyperintensional notions of sameness of content. One notion is *very* finely grained (distinguishing $p$ and $p \wedge p$), others less so. I show that one notion amounts to equivalence in Angell's logic of analytic containment [1].

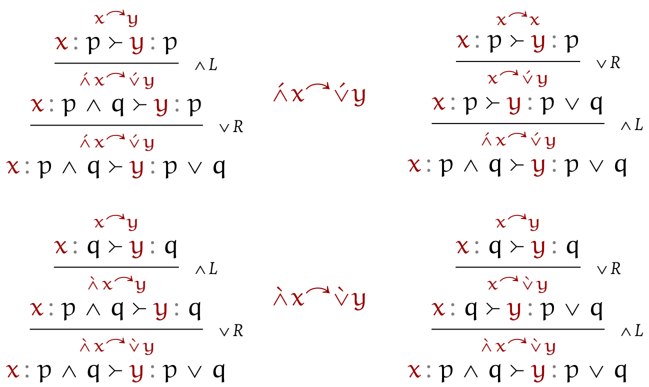
## 1 THE CATEGORY OF CLASSICAL PROOFS

Four different *derivations*, and two *proofs*.

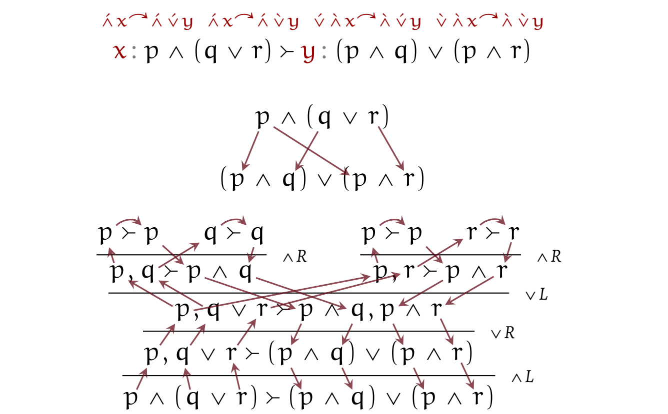
$$\dfrac{\dfrac{p \succ p}{p \wedge q \succ p}\,{\wedge L}}{p \wedge q \succ p \vee q}\,{\vee R} \quad\approx\quad \dfrac{\dfrac{p \wedge q}{p}}{p \vee q} \quad\approx\quad \dfrac{\dfrac{p \succ p}{p \succ p \vee q}\,{\vee R}}{p \wedge q \succ p \vee q}\,{\wedge L}$$

$$\dfrac{\dfrac{q \succ q}{p \wedge q \succ q}\,{\wedge L}}{p \wedge q \succ p \vee q}\,{\vee R} \quad\approx\quad \dfrac{\dfrac{p \wedge q}{q}}{p \vee q} \quad\approx\quad \dfrac{\dfrac{q \succ q}{q \succ p \vee q}\,{\vee R}}{p \wedge q \succ p \vee q}\,{\wedge L}$$

MOTIVATING IDEA: *Proof terms* are an *invariant* for derivations under rule permutation. $\delta_1$ and $\delta_2$ have the same *term* iff some permutation sends $\delta_1$ to $\delta_2$.



A *proof term* for $\Sigma \succ \Delta$ encodes the flow of information in a proof of $\Sigma \succ \Delta$. They can be represented as directed graphs on sequents [2].



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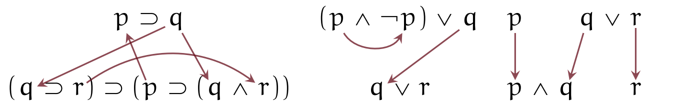
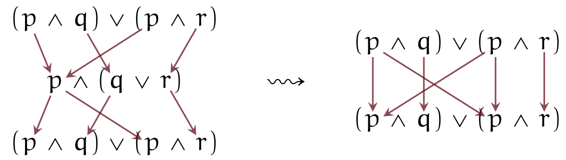
*More examples*:



Links wholly internal to a *premise* or a *conclusion* are called *cups* (⌣) and *caps* (⌢).

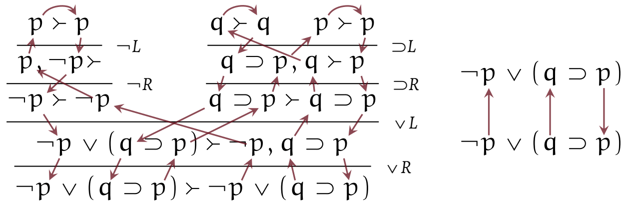
FACTS: Not every directed graph on occurrences of atoms in a sequent is a proof term. ¶ They *typecheck*. [An occurrence of $p$ is linked only with an occurrence of $p$.] ¶ They *respect polarities*. [Positive occurrences of atoms in premises and negative occurrences of atoms in conclusions are *inputs*. Negative occurrences of atoms in premises and positive occurrences of atoms in conclusions are *outputs*.] ¶ They must satisfy an "enough connections" condition, amounting to a non-emptiness under every *switching*. [e.g. the obvious linking between premise $p \vee q$ and conclusion $p \wedge q$ is not connected enough to be a proof term.]

*Cut* is chaining of proof terms, composition of graphs.



Cut elimination is *confluent* and *terminating*. [So it can be understood as a kind of *evaluation*.] ¶ Cut elimination for proof terms is *local*. [So it is easily made parallel.]

$\mathfrak{C}$ is the *Category of Classical Proofs*. *OBJECTS*: Formulas — $A$, $B$, etc. *ARROWS*: Cut-Free Proof Terms — $\pi : A \succ B$. *COMPOSITION*: Composition of derivations with the elimination of *Cut* — If $\pi : A \succ B$ and $\tau : B \succ C$ then $\tau \circ \pi : A \succ C$. *IDENTITY*: Canonical identity proofs — $\mathrm{Id}(A) : A \succ A$.



The category $\mathfrak{C}$ is *symmetric monoidal* and *star autonomous*, but not *cartesian*, with structural *monoids* and *comonoids*, and is enriched in *SLat* (the category of semilattices). Being enriched in *SLat* means that proofs terms come ordered by $\subseteq$, and compose under $\cup$, and these interact sensibly with composition.

$$\begin{aligned} \pi \subseteq \pi' &\quad\Rightarrow\quad \pi \circ \tau \subseteq \pi' \circ \tau \\ \tau \subseteq \tau' &\quad\Rightarrow\quad \pi \circ \tau \subseteq \pi \circ \tau' \\ \pi \circ (\tau \cup \tau') &\quad=\quad (\pi \circ \tau) \cup (\pi \circ \tau') \\ (\pi \cup \pi') \circ \tau &\quad=\quad (\pi \circ \tau) \cup (\pi' \circ \tau) \end{aligned}$$

$\mathfrak{C}$ is just *classical* propositional logic, in a categorical setting. (The sequent calculus is playing no essential role here. You can define proof terms on other proof systems, e.g. *natural deduction*, *Hilbert proofs*, *tableaux*, *resolution*.)

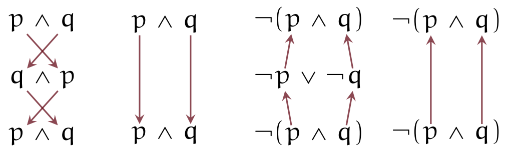
## 2 ISOMORPHISMS

$f : A \to B$ is an *isomorphism* in a category iff it has an *inverse* $g : B \to A$, where $g \circ f = id_A : A \to A$ and $f \circ g = id_B : B \to B$. (If $g$ and $g'$ are inverses, $g = id_A \circ g = (g' \circ f) \circ g = g' \circ (f \circ g) = g' \circ id_B = g'$, so any inverse is unique. We can call it $f^{-1}$.)

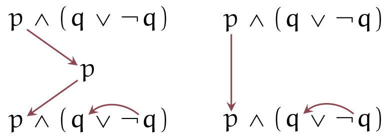
If $A$ and $B$ are isomorphic in a category $\mathcal{C}$, then what we can do with $A$ (in $\mathcal{C}$) we can do with $B$, too.

If $A$ and $B$ are isomorphic in $\mathfrak{C}$, then they agree not only on *provability*, but also, on *proofs*. The distinctions drawn when you analyse how something is *proved* (from premises), are not far from what you want to understand when you ask how something is *made true*.

*Isomorphisms in* $\mathfrak{C}$: $p \wedge q \cong q \wedge p$; $\neg(p \wedge q) \cong \neg p \vee \neg q$




*Non-isomorphisms in* $\mathfrak{C}$: $p \wedge (q \vee \neg q) \not\cong p$; $p \wedge p \not\cong p$; $p \wedge (q \vee r) \not\cong (p \wedge q) \vee (p \wedge r)$; $p \wedge (p \vee q) \not\cong p \vee (p \wedge q)$




*Occurrence Polarity Condition*: If $A$ is isomorphic to $B$ in $\mathfrak{C}$ then each variable occurs positively [negatively] in $A$ exactly as many times as it occurs positively [negatively] in $B$. (This condition is *necessary*, not *sufficient*: $p \wedge (p \vee q) \not\cong p \vee (p \wedge q)$.)

$A$ is *isomorphic to* $B$ iff $A$ and $B$ are equivalent in the following calculus:

$$\begin{array}{cc} A \wedge B \leftrightarrow B \wedge A, & A \wedge (B \wedge C) \leftrightarrow (A \wedge B) \wedge C. \\ A \vee B \leftrightarrow B \vee A, & A \vee (B \vee C) \leftrightarrow (A \vee B) \vee C. \\ \neg(A \vee B) \leftrightarrow \neg A \vee \neg B, & \neg(A \wedge B) \leftrightarrow \neg A \vee \neg B. \\ \neg\neg A \leftrightarrow A. & A \leftrightarrow B \Rightarrow C(A) \leftrightarrow C(B). \end{array}$$

(This allows for a *negation normal form*, but not DNF or CNF.)

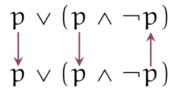
*Proof Sketch* (Došen and Petrić, 2012 [3]).

If $A \leftrightarrow B$ holds in the calculus, $A$ and $B$ are isomorphic. ¶ $A$ is isomorphic to $B$ iff there are *diversified* $A'$ and $B'$ where $A'$ and $B'$ are isomorphic, and $A = \sigma A'$ and $B = \sigma B'$ for some substitution $\sigma$. ¶ $A$ is isomorphic to $B$ iff their negation normal forms are isomorphic. (If $A$ is diversified, so is its negation normal form.) ¶ If $A$ and $B$ are diversified, isomorphic, and in negation normal form, if $l \wedge m$ is a conjunction in $A$ ($l$ and $m$, literals), a substitution argument (substituting $\top$ and $\bot$ for the *other* atoms) shows that $l$ and $m$ must be conjunctively joined in $B$, too. The same goes for $l \vee m$. ¶ Replace $l \wedge m$ by a new atom in both $A$ and $B$, and repeat. ¶ This shows how to reconstruct a proof of equivalence for $A$ and $B$ in the syntactic calculus for isomorphic formulas.

*Isomorphism* is a very tight constraint: If $A$ and $B$ are isomorphic, they can play *essentially* the same role in proof. ¶ Replacing $A$ by $B$ in a proof (as a premise or conclusion) not only gives you something that is also a proof (mere logical equivalence would do *that*), but it gives you a proof which is *essentially the same*. ¶ Not even $A$ and $A \wedge A$ are equivalent in *this* sense. ¶ Yet, $A$ and $A \wedge A$ seem to have identical *subject matter* (insofar as we understand that notion). ¶ Can we use the fine-grained tools of proof theoretical analysis to generalise this notion of subject matter to arbitrary statements?

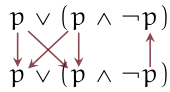
## 3 MORE PROOFS FROM $A$ TO $A$

$Id(p \vee (p \wedge \neg p))$



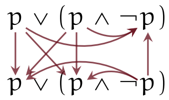

In $Id(A)$, each occurrence of an atom in the premise is linked with every its corresponding occurrence of in the conclusion. *Different occurrences of atoms in $A$ are treated differently.*

$Mx(p \vee (p \wedge \neg p))$




In $Hz(A)$, each positive [negative] occurrence of an atom in the premise is linked with every positive [negative] occurrence in the conclusion. *We treat occurrences of an atom in $A$—with the same polarity—equally.*

$Hz(p \vee (p \wedge \neg p))$




In $Mx(A)$, each syntactically possible linking is included. *We treat all occurrences of an atom in $A$ equally.*

*Note*: $Hz(A)$ is $Mx(A)$ with the caps and cups removed.

Let's look at relations like isomorphism, but which erase distinctions, up to *Hz* or *Mx*.

Let's say that $A$ and $B$ *Hz*-MATCH, when there are proofs $\pi : A \succ B$ and $\pi' : B \succ A$ where $\pi' \circ \pi = Hz(A)$ and $\pi \circ \pi' = Hz(B)$. We write "$\approx_{Hz}$" for the *Hz*-matching relation, and we write "$\pi, \pi' : A \approx_{Hz} B$" to say that $\pi : A \succ B$ and $\pi' : B \succ A$ define a *Hz*-match between $A$ and $B$.

Let's say that $A$ and $B$ *Mx*-MATCH, when there are proofs $\pi : A \succ B$ and $\pi' : B \succ A$ where $\tau \circ \pi = Mx(A)$ and $\pi \circ \pi' = Mx(B)$. We write "$\approx_{Mx}$" for the *Mx*-matching relation, and we write "$\pi, \pi' : A \approx_{Mx} B$" to say that $\pi : A \succ B$ and $\pi' : B \succ A$ define a *Mx*-match between $A$ and $B$.

*Isomorphism* $\subseteq$ *Hz-Matching*: If $\pi : A \succ B$ and $\pi^{-1} : B \succ A$, then consider $\pi' = Hz(B) \circ \pi \circ Hz(A)$ and $\tau' = Hz(A) \circ \pi^{-1} \circ Hz(B)$. These satisfy the *Hz*-matching criteria, $\tau' \circ \pi' = Hz(A)$ and $\pi' \circ \tau' = Hz(B)$.

*Hz-Matching* $\subseteq$ *Mx-Matching*: If $\pi, \pi' : A \approx_{Hz} B$, then consider $\tau = Mx(B) \circ \pi \circ Mx(A)$ and $\tau' = Mx(A) \circ \pi' \circ Mx(B)$. These satisfy the *Mx*-matching criteria, $\tau' \circ \pi' = Mx(A)$ and $\pi' \circ \tau' = Mx(B)$.

*Mx-Matching* $\subseteq$ *Logical Equivalence*: If $A \approx_{Mx} B$ then there are proofs $\pi : A \succ B$ and $\tau : B \succ A$.

*Matching Relations are Equivalences*: REFLEXIVE $Hz(A), Hz(A) : A \approx_{Hz} A$. $Mx(A), Mx(A) : A \approx_{Mx} A$. ¶ SYMMETRIC If $\pi, \pi' : A \approx_{Hz} B$, then $\pi', \pi : B \approx_{Hz} A$. If $\pi, \pi' : A \approx_{Mx} B$, then $\pi', \pi : B \approx_{Mx} A$. ¶ TRANSITIVE If $\pi, \pi' : A \approx_{Hz} B$ and $\tau, \tau' : B \approx_{Hz} C$, then $(\tau \circ \pi), (\pi' \circ \tau') : A \approx_{Hz} C$. If $\pi, \pi' : A \approx_{Mx} B$ and $\tau, \tau' : B \approx_{Mx} C$, then $(\tau \circ \pi), (\pi' \circ \tau') : A \approx_{Mx} C$.

*Matchings*: $p \vee p \approx_{Hz} p \approx_{Hz} p \wedge p$; $p \wedge (q \vee r) \approx_{Hz} (p \wedge q) \vee (p \wedge r)$.

*Mx-Matching* $\subset$ *Logical Equivalence*: If an atom $p$ occurs positively [negatively] in $A$ but not in $B$, then $A$ and $B$ do not *Mx*-match.

PROOF: $Mx(A) : A \succ A$ contains the link from [to] that occurrence of $p$ in the premise $A$ to [from] its corresponding occurrence in the conclusion $A$. ¶ No proof from $A$ to $B$ contains a link from [to] that occurrence to anything in $B$ (since there is no positive [negative] occurrence in $B$ at all). ¶ So, in the composition proof from $A$ to $A$, there is no link from [to] the premise occurrence to [from] the conclusion occurrence. No proof from $A$ to $B$ and back can recreate $Mx(A)$.

COROLLARY: $p \not\approx_{Mx} p \wedge (q \vee \neg q)$; $p \wedge \neg p \not\approx_{Mx} q \wedge \neg q$.

*Hz-matching* ⊂ *Mx-matching*: $(p \wedge \neg p) \wedge (q \vee \neg q) \approx_{Mx} (p \vee \neg p) \wedge (q \wedge \neg q)$.

$$\begin{array}{ccc} (p \wedge \neg p) \wedge (q \vee \neg q) & \quad & (p \wedge \neg p) \wedge (q \vee \neg q) \\ (p \vee \neg p) \wedge (q \wedge \neg q) & & \\ (p \wedge \neg p) \wedge (q \vee \neg q) & & (p \wedge \neg p) \wedge (q \vee \neg q) \end{array}$$

However, $(p \wedge \neg p) \wedge (q \vee \neg q) \not\approx_{Hz} (p \vee \neg p) \wedge (q \wedge \neg q)$. So:

*Isomorphism* ⊂ *Hz-Matching* ⊂ *Mx-Matching* ⊂ *Logical Equivalence*

## 4 MATCHING & LOGICS OF ANALYTIC CONTAINMENT

*Angell's Logic of Analytic Containment*: [AC1] $A \leftrightarrow \neg\neg A$ [AC2] $A \leftrightarrow (A \wedge A)$ [AC3] $(A \wedge B) \leftrightarrow (B \wedge A)$ [AC4] $A \wedge (B \wedge C) \leftrightarrow (A \wedge B) \wedge C$ [AC5] $A \vee (B \wedge C) \leftrightarrow (A \vee B) \wedge (A \vee C)$ [R1] $A \leftrightarrow B, C(A) \Rightarrow C(B)$

Here, $A \vee B$ is shorthand for $\neg(\neg A \wedge \neg B)$. You can define $A \to B$ as $A \leftrightarrow (A \wedge B)$.

The first degree fragment of *Parry's* Logic of Analytic Containment is found by adding $(A \vee (B \wedge \neg B)) \to A$ to Angell's Logic. (Parry's logic still satisfies this relevance constraint: $A \to B$ is provable only when the atoms in $B$ are present in $A$.)

*First Degree Entailment* (FDE) is found by adding $A \to (A \vee B)$ to Angell's Logic. ¶ FDE allows for a disjunctive (or conjunctive) normal form. The only difference from classical logic is that $p \vee \neg p$, and $q \wedge \neg q$ are both non-trivial, and ineliminable. ¶ A simple translation encodes FDE inside classical logic. Choose, for each atom $p$, a fresh atom $p'$, its *shadow*. For each FDE formula $A$, its translation is the formula $A'$ found by replacing the negative occurrences of atoms $p$ in $A$ by their shadows. An argument is FDE valid iff its translation is classically valid.

DEFINITION: $Mx(A, B)$ is the set of all possible linkings which could occur in any proof from $A$ to $B$. ¶ That is, it contains a link from {positive atoms in $A$, negative atoms in $B$} to matching {positive atoms in $B$, negative atoms in $A$}.

FACT: $Mx(A, B)$ is a proof iff there is some proof from $A$ to $B$. (And if so, it is the maximal such proof.)

$Mx(p \vee \neg p, p \wedge \neg q)$ is not a proof:

$$\begin{array}{c} p \vee \neg p \\ p \wedge \neg q \end{array}$$

LEMMA: If $A \approx_{Mx} B$, then $Mx(A, B)$ and $Mx(B, A)$ are proofs, and $Mx(A, B), Mx(B, A) : A \approx_{Mx} B$.

PROOF: If $\pi, \pi' : A \approx_{Mx} B$, then $\pi \subseteq Mx(A, B)$ and $\pi' \subseteq Mx(B, A)$, so $Mx(A, B)$ and $Mx(B, A)$ are both proofs. ¶ Since $\pi' \circ \pi = Mx(A)$, we have $Mx(A) = \pi' \circ \pi \subseteq Mx(B, A) \circ Mx(A, B) \subseteq Mx(A)$, and similarly, $Mx(B) = Mx(A, B) \circ Mx(A)$, so $Mx(A, B), Mx(B, A) : A \approx_{Mx} B$.

FACT: If $A$ is classically equivalent to $B$, and all atoms occurring positively [negatively] in $A$ also occur positively [negatively] in $B$, and *vice versa*, then $A$ and $B$ *Mx*-match—and conversely.

PROOF: If $A$ is logically equivalent to $B$, then $Mx(A, B)$ and $Mx(B, A)$ are both proofs. ¶ It suffices to show that $Mx(B, A) \circ Mx(A, B) = Mx(A)$ (and similarly for $B$). To show this, we need to show that each positive [negative] occurrence of an atom in $A$ is linked to any positive [negative] occurrence of that atom in $A$ by way of some link in $Mx(A, B)$ composed with a link in $Mx(B, A)$. But since that atom occurs positively [negatively] also in $B$ at least once, the links to accomplish this occur in $Mx(A, B)$ and $Mx(B, A)$. ¶ Conversely, if $A \approx_{Mx} B$, we have already seen that $A$ and $B$ must be equivalent, and no atom occurs positively [negatively] in $A$ but not $B$.

This is *not* Equivalence in Parry's Logic. $A$ is equivalent to $B$ in Parry's logic of analytic containment iff $A$ is classically equivalent to $B$ and the atoms present in $A$ are the atoms present in $B$. ¶ $(p \wedge \neg p) \wedge q \not\approx_{Mx} (p \wedge \neg p) \wedge \neg q$, but this pair satisfies Parry's variable sharing criteria.

QUESTION: Does the equivalence relation of *Mx*-matching occur elsewhere in the literature?

DEFINITION: $Hz(A, B)$ is the set of all possible linkings which could occur in any proof from $A$ to $B$, excluding caps and cups. ¶ That is, it contains a link from positive atoms in $A$ to corresponding positive atoms in $B$ and negative atoms in $A$ to corresponding negative atoms in $B$.

$Hz(p \wedge \neg p, q \vee \neg q)$ contains no links. $Hz(p \wedge \neg p, p \vee \neg p)$ is a proof, but not the maximal one:

$$\begin{array}{c} p \wedge \neg p \\ p \vee \neg p \end{array}$$

FACT: $Hz(A, B)$ is a proof iff $A$ entails $B$ in FDE.

PROOF: From FDE-validity to *Hz*-proof: straightforward induction on an FDE-axiomatisation. ¶ From the *Hz*-proof $Hz(A, B)$ to FDE-validity: Notice that no negative occurrences of atoms in $A$ or $B$ are linked to any positive occurrences of atoms in $A$ or $B$. So, there is another *Hz*-proof $Hz(A', B')$ for the FDE translations for $A$ and $B$.

LEMMA: If $A \approx_{Hz} B$, then $Hz(A, B)$ and $Hz(B, A)$ are proofs, and $Hz(A, B), Hz(B, A) : A \approx_{Hz} B$.

PROOF: If $\pi, \pi' : A \approx_{Hz} B$, then then since $\pi' \circ \pi = Hz(A)$ and $\pi \circ \pi' = Hz(B)$, $\pi$ and $\pi'$ are cap- and cup-free, so $\pi \subseteq Hz(A, B)$ and $\pi' \subseteq Hz(B, A)$, so $Hz(A, B)$ and $Hz(B, A)$ are both proofs. ¶ Since $\pi' \circ \pi = Hz(A)$, we have $Mx(A) = \pi' \circ \pi \subseteq Hz(B, A) \circ Hz(A, B) \subseteq Hz(A)$, and similarly, $Hz(B) = Hz(A, B) \circ Hz(A)$, so $Hz(A, B), Hz(B, A) : A \approx_{Mx} B$.

FACT: If $A$ is FDE-equivalent to $A$, and all atoms occurring positively [negatively] in $A$ also occur positively [negatively] in $B$, and *vice versa*, then $A$ and $B$ *Hz*-match — and conversely.

PROOF: If $A$ is FDE-equivalent to $B$, then $Hz(A, B)$ and $Hz(B, A)$ are both proofs. ¶ It suffices to show that $Hz(B, A) \circ Hz(A, B) = Hz(A)$ (and similarly for $B$). To show this, we need to show that each positive [negative] occurrence of an atom in $A$ is linked to any positive [negative] occurrence of that atom in $A$ by way of some link in $Hz(A, B)$ composed with a link in $Hz(B, A)$. But since that atom occurs positively [negatively] also in $B$ at least once, the links to accomplish this occur in $Hz(A, B)$ and $Hz(B, A)$. ¶ Conversely, if $A \approx_{Hz} B$, we have already seen that $A$ and $B$ must be FDE-equivalent, and no atom occurs positively [negatively] in $A$ but not $B$.

FACT: (Ferguson 2016 [4]; Fine [5]) $A$ is equivalent to $B$ in Angell's logic of analytic containment iff $A$ is FDE equivalent to $B$, and any atom occurs positively [negatively] in $A$ iff it occurs positively [negatively] in $B$.

So, *Hz-matching* ≡ *Angellic Equivalence*.

## 5 MATCHING AS ISOMORPHISM

*$Hz(A)$ and $Mx(A)$ are Idempotents*: $Hz(A) \circ Hz(A) = Hz(A)$, $Mx(A) \circ Mx(A) = Mx(A)$.

For any category $\mathcal{C}$, if $i_A$ is an idempotent for each object $A$, we can form a new category $\mathcal{C}_i$ with the same objects as $\mathcal{C}$, and with arrows $i_B \circ f \circ i_A : A \to B$. ¶ In this new category, the idempotents $i_A$ are the new identity arrows. ¶ So, $\mathfrak{C}_{Hz}$ and $\mathfrak{C}_{Mx}$ are both categories — like $\mathfrak{C}$, but less discriminating, with fewer arrows.

*Hz*-matching is *isomorphism* in $\mathfrak{C}_{Hz}$.

*Mx*-matching is *isomorphism* in $\mathfrak{C}_{Mx}$.

$\mathfrak{C}_{Mx}$ and $\mathfrak{C}_{Hz}$ are nontrivial, nonetheless.

$$
\begin{tikzcd}[column sep=tiny] p \arrow[d] & \wedge & q \\ p & \vee & q \end{tikzcd}
\qquad
\begin{tikzcd}[column sep=tiny] p \arrow[d] & \wedge & q \arrow[d] \\ p & \vee & q \end{tikzcd}
\qquad
\begin{tikzcd}[column sep=tiny] p & \wedge & q \arrow[d] \\ p & \vee & q \end{tikzcd}
$$

These are each different proofs in $\mathfrak{C}_{Mx}$ and $\mathfrak{C}_{Hz}$.

## 6 CONCLUSION

- Extending these results to include the units $\top$ and $\bot$ are not difficult. (They were left out only to ease the presentation).
- Proof theoretical resources *for classical logic* provide tools for fine-grained hyperintensional distinctions.
- One question is how to relate these results to *models* of logics of content.
- Another next step is these results to first order logic is an open question.

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