Non-Adjunctive Inference and Classical Modalities

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November 24, 2003

Technical Report No. CMU-PHIL-150

Philosophy

Methodology

Logic

Carnegie Mellon

Pittsburgh, Pennsylvania 15213

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Abstract. The article focuses on representing different forms of non-adjunctive inference as sub-Kripkean systems of *classical modal logic*, where the inference from $\Box A$ and $\Box B$ to $\Box(A \wedge B)$ fails. In particular we prove a completeness result showing that the modal system that Schotch and Jennings derive from a form of non-adjunctive inference in (Schotch-Jennings, 1980) is a classical system strictly stronger than **EMN** and weaker than **K**.[1] The unified semantical characterization in terms of neighborhoods permits comparisons between different forms of non-adjunctive inference. For example, we show that the non-adjunctive logic proposed in (Schotch-Jennings, 1980) is not adequate in general for representing the logic of high probability operators. An alternative interpretation of the forcing relation of Schotch and Jennings (more in line with the initial ideas of Jaskowski in (Jaskowski, 1969)) is derived from the proposed unified semantics and utilized in order to propose a more fine-grained measure of epistemic coherence than the one presented in (Schotch-Jennings, 1980).

Keywords: Classical modal logic, Epistemic logic, High probability operators, Paraconsistent logic, Non-Adjunctive logic

1. Introduction

Non-Adjunctive logical systems are those where the inference from A and B to $A \wedge B$ fails. As is indicated in (Priest-Tanaka, 2000) the first of these systems to be produced was also the first formal *paraconsistent logic*. This was Jaskowski's *discussive* (or *discursive*) logic (Jaskowski, 1969). The central idea in discussive logic is to formalize the process of pooling (and reasoning from) the consistent (but possibly contradictory) views of various agents. Most applications of non-adjunctive inference are epistemically motivated.

As a concrete example, various authors have suggested that formalizing the logic of high probability requires the use of non-adjunctive inference (or the use of some form of paraconsistent formalism). Views pro and con are discussed in (Kyburg, 1995). A related, but slightly different argument proposes that 'it is highly probable that' should be formalized as an epistemic modal operator. It is quite obvious that $A \wedge B$ might fail to be highly probable, even when A and B are highly probable. Under this construal what fails is not the inference from A

[1] Following the notation for classical modalities presented in (Chellas, 1980).

and B to $A \wedge B$, but the inference from $\Box A$ and $\Box B$ to $\Box(A \wedge B)$, where '$\Box$' is the monadic operator of high probability.

Formalizing this latter account possesses also significant challenges. In fact, the weakest of the system of modal logics endowed with a Kripkean semantics, the system **K**, satisfies the schema:

(C) $(\Box(A) \wedge \Box(B)) \rightarrow \Box(A \wedge B)$

So, this suggests that studying a logical system where failures of this modal form of Adjunction occur requires a generalization of the standard Kripke semantics for modal operators. This generalization, even though less carefully studied than its Kripkean counterpart, has indeed been proposed (independently) by Dana Scott (Scott, 1970) and Richard Montague (Montague, 1970). A systematic presentation of this semantics and of the systems of *classical modal logic* that correspond to them is offered in Part III of (Chellas, 1980) - this includes work first presented in (Segerberg, 1971). Brian Chellas calls this generalization of Kripke semantics *minimal models.* They are otherwise known as *neighborhood models*, and this will be the terminology adopted here. (Arló-Costa, 2002) proposes the use of the family of sub-Kripkean *classical* logics in order to formalize epistemic operators where different failures of logical omniscience occur. In particular it is suggested the possibility of using some of these systems in order to model monadic operators of high probability. The logical focus of (Arló-Costa, 2002) is to study a first order extension of some of the classical modal systems weaker than **K**. Kyburg and Teng (Kyburg-Teng, 2002) have focused on the propositional level and on applications considering high probability. They identify the logical system **EMN** as the one involved in representing high probability operators. Classical systems can be introduced succinctly as follows (we will provide more background below):

DEFINITION 1.1. *A system of modal logic is* classical *if and only if it contains the axiom* $\Diamond A \leftrightarrow \neg\Box\neg A$*, and is closed under the rule of inference* **RE**, *according to which* $\Box A \leftrightarrow \Box B$ *should be inferred from* $A \leftrightarrow B$.

In addition **EMN** satisfies the axioms:

(M) $\Box(A \wedge B) \rightarrow (\Box A \wedge \Box B)$

as well as:

(N) $\Box(True)$

The weakest Kripkean system, the system **K**, is equivalent to **EMCN**, so **EMN** is one of the sub-Kripkean systems which fail to satisfy the modal counterpart of adjunction. It is not difficult to see that the remaining axioms and rules are naturally motivated for an operator of high probability.

One of the virtues of the previous account is the natural intuitiveness of the use of a modal operator in order to represent qualitative probability. Another virtue is the fact that the analysis can be carried out by using an extension of classical logic, without modifying the underlying notion of logical consequence. Of course, the analysis still requires using a generalization of Kripke semantics in order to understand the nature of the modal operator '$\Box$'.

There is, nevertheless, an intimate connection between non-adjunctive inference and non-Kripkean modal operators (where (C) fails), which we intend to study in detail here. As has happened in other areas of philosophical logic, connections between non-standard logical systems and extensions of classical logic illuminate the nature of both (an example is given by the connections between intuitioninsm and the modal system S4).

Schotch and Jennings have offered in (Schotch-Jennings, 1980) one of the standard contemporary systems of non-adjunctive inference, and in the process of doing so, they also derived a modal system from the non-adjunctive notion of consequence (the *forcing* relation) used in their analysis. Nevertheless, the nature of this modal operator and its eventual relationships with the epistemic $\Box$ axiomatized by **EMN** is not immediate. They offer a semantics, which they see as a generalization of Kripke semantics. One of my goals here is to show that their modal operator has neighborhood models of the type proposed by Scott and Montague. I shall provide closure conditions on neighborhoods that completely characterize Schotch and Jennings' modal operator. The semantics allows us to locate Schotch and Jennings' modal system as a classical system of modal logic stronger than **EMN** and weaker than **K**. The system in question has not been independently studied by modal logicians. I shall also study a natural strengthening of their logic, also weaker than **K**.

Even when the resulting classical modal system is an **EMN**-system, I shall show via examples that it is not adequate to represent operators of high probability. This, in turn, sheds some light concerning the nature of the forcing relation proposed by Schotch and Jennings. Even when the notion in question admits an epistemic interpretation, I shall argue that the interpretation in question is very different from the one required for monadic operators of high probability. The nature of non-adjunctive inference in Schotch and Jennings' system, as well as various strengthenings studied here, seem to be more naturally related to the first systems developed by Jaskowski.

I shall proceed as follows. First, I shall introduce the forcing relation of Schotch and Jennings as well as their derived modal operator. Then I shall enter the details of neighborhood semantics and I shall prove that the axiomatization of Schotch and Jennings' is complete with respect to the proposed neighborhood model. Once this is done we will use the models in question in order to show that operators of high probability need not meet the constraints on neighborhoods needed for Schotch and Jennings' operators (with the exception of some limit cases). Finally a strengthening of Schotch and Jennings' modal logic will be considered. I shall close with some philosophical remarks concerning the epistemic nature of the forcing relation and I shall utilize them in order to motivate a new measure of coherence of information.

2. Measures of coherence and non-adjunctive inference

The central idea behind Schotch and Jennings' notion of forcing is their proposal for measuring the coherence of a set of sentences. Their *coherence function* c is a function having as its domain the set of all finite sets of sentences and as a codomain the set $Nat \cup \{w\}$, where *Nat* is the set of natural numbers.

DEFINITION 2.1. *For* **false** $\notin \Gamma$, $c(\Gamma) = m$ *if and only if* m *is the least integer such that there are sets*

$a_1, ..., a_m$, *with* $a_i \nvdash$ **false** $(1 \leq i \leq m)$

and $\cup_{i=1}^{m} a_i = \Gamma$

where $\vdash$ *is the classical notion of consequence and where* $c(\Gamma) = w$ *by convention if* **false** $\in \Gamma$

Now we can define a notion of derivability in terms of this notion of levels of coherence. The *forcing relation* $[\!\vdash$ is characterized as a relation between finite sets of sentences and sentences and defined as follows:

DEFINITION 2.2. *For* $c(\Gamma) = n(w)$, $\Gamma \; [\!\vdash A$ *if and only if for every* n*-fold* (w*-fold*) *decomposition* $a_1, ..., a_n$, *of* Γ, *there is some* i *such that* $a_i \vdash A (1 \leq i \leq n(w))$.

The forcing relation obeys the following structural rules (as the classical notion of consequence $\vdash$):

(Ref) $A \in \Gamma \rightarrow \Gamma [\!\vdash A$

(Mon) $\Gamma [\!\vdash A \rightarrow \Gamma \cup \Delta [\!\vdash A$, when $c(\Gamma \cup \Delta) = c(\Gamma)$.

(Trans) $\Gamma \cup \{A\} [\!\vdash B$ and $\Gamma [\!\vdash A \rightarrow \Gamma [\!\vdash B$

We need an additional structural rule as well, which depends on the previous concept of m-cluster. For a any finite set we say that $C \subseteq 2^a$ is an *m-cluster* if and only if $m \in Nat$ and:

For all $f \in m^a$, there is $x \in C$, and there is $y \leq m$: $x \subseteq f^{-1}[y]$.

In words: for any way of dividing a into m subsets there is a member x of C such that x is included in at least one of the m subsets into which a has been divided.

(Clus) If $C = \{c_1, ..., c_n\}$ is an m-cluster constructed out of $A_1, ..., A_k \in \Gamma$ and $c(\Gamma) = m$, then $(c_1 [\!\vdash B, c_2 [\!\vdash B, ..., c_n [\!\vdash B) \rightarrow \Gamma [\!\vdash B$

In addition we have the usual rules for introducing and eliminating connectives, with the notable exception that the rule for introducing conjunction only holds for sets Γ, such that $c(\Gamma) = 1$. In other words, from $\Gamma [\!\vdash A$ and $\Gamma [\!\vdash B$ it no longer follows that $\Gamma [\!\vdash (A \wedge B)$, unless $c(\Gamma) = 1$.

We can now introduce a generalization of the standard (logical) notion of *theory*. The most immediate definition is an obvious generalization of the classical notion:

DEFINITION 2.3. *Δ is a m-theory if and only if $c(\Delta) = m$ and $\Delta [\!\vdash A$ entails $A \in \Delta$.*

The notion of m-theory can also be expressed via two closure conditions, without appealing to a direct use of '$[\!\vdash$'.

DEFINITION 2.4. *Δ is a m-theory if and only if*

(a) $A \in \Delta$ and $\vdash A \rightarrow B$, entail that $B \in \Delta$

(b) If $\{c_1, ..., c_k\} \subseteq 2^\Delta$ is an m-cluster, then $\vee_1^k\{\wedge c_1, ..., \wedge c_k\} \in \Delta$, where $\wedge c_i$ denotes '$A_{i1}, ..., A_{ij}$' for $c_i = \{A_{i1}, ..., A_{ij}\}$.

This notion of m-theory, which generalizes the standard notion of theory, will be useful in order to introduce the necessity operator that Schotch and Jennings derive from the forcing relation. This derivation will be the focus of the next section.

3. Necessity derived from the forcing relation

The first step in the derivation is to enlarge the language of the propositional calculus PC with a new connective $\Box$. A *pre-model* $\mathcal{B}$ for the enlarged language $PC(\Box)$ is a standard model (U, P) of a non-empty set U and a valuation P mapping the atoms of the language to events in 2^U. P is extended (uniquely) to a function $||.||^{\mathcal{B}}$ which evaluates all sentences of the language by means of classical truth conditions. So, we have $||A \wedge B||^{\mathcal{B}} = ||A||^{\mathcal{B}} \cap ||B||^{\mathcal{B}}$, etc.

No specific truth conditions are introduced for '$\Box$' aside from stipulating that $||\Box(A)||^{\mathcal{B}} \in 2^U$, for all A. So, '$\Box$' is not really behaving as a logical constant at this stage. Still the $\Box$-operator can be used in order to 'guard' inconsistent formulae. So, even when $||\{A, \neg A\}||^{\mathcal{B}} = \emptyset$, we have $||\{\Box(A), \Box(\neg A)\}||^{\mathcal{B}} \neq \emptyset$.

The second step in the derivation of a model for the $\Box$-operator will be to restrict the class of pre-models to a special subclass called *full pre-models*.

DEFINITION 3.1. *$\mathcal{B}$ is a full $PC(\Box)$ pre-model if and only if, $\mathcal{B}$ is a pre-model and for all u such that $\Box(u)^{\mathcal{B}} = \{A | \models_u^{\mathcal{B}} \Box A\}$ is an n-theory, $a \subseteq \Box(u)^{\mathcal{B}}$, such that $a \not\vdash$ **false**, $a \subseteq b$ and $b \not\vdash$ **false**, then $||b||^{\mathcal{B}} \neq \emptyset$.*

Now as a final step of the construction we derive the underlying structure of the desired model and the truth conditions for $\Box A$ form the restrictions imposed by $[\vdash$. This is done in two steps, the first of which is to define a n-natural relation.

DEFINITION 3.2. *Let $\mathcal{B}$ be a full $PC(\Box)$ pre-model. For each $n \in \mathrm{Nat}$ let r be a function r: $\{x | c(\Box(x)^{\mathcal{B}}) = n\} \to U^n$. Let u be an element of U such that $c(\Box(u)^{\mathcal{B}}) = n$. Further let $\Delta(u) = \{\delta | \delta : c(\Box(u)^{\mathcal{B}}) \to n\}$ be the set of non-trivial n-fold decompositions of $c(\Box(u)^{\mathcal{B}})$.*

Then $r(u) = \{\langle x_1, ..., x_n\rangle | x_i \in ||\delta^{-1}[i]||^{\mathcal{B}}$ $(1 \leq i \leq n)$ for some $\delta \in \Delta(u)\}$. Finally if $\langle x_1, ..., x_n\rangle \in r(u)$ we write $uRx_1, ..., x_n$ and call R the n-natural relation of u.

Now we can prove the following theorem stating the desired truth conditions for the derived modal operator:

THEOREM 3.1. *(Schotch and Jennings) If $\mathcal{B}$ is a full $PC(\Box)$ pre-model and $\Box(u)^{\mathcal{B}}$ is an n-theory and R the n-natural relation, then $\models_u^{\mathcal{B}}$ $\Box A$ if and only if for all $x_1, ..., x_n$, if $uRx_1, ..., x_n$, then $\models_{x_1}^{\mathcal{B}} A$ or ... or $\models_{x_n}^{\mathcal{B}} A$.*

Schotch and Jennings comment that their semantics is a generalization of Kripke semantics. Nevertheless, the presentation is non-standard and dependent of the notion of pre-model. It would be nice to see whether the proposed semantics can be classified in terms of some of the well-known generalizations of Kripkean semantics. I shall focus on this topic in section 4.

3.1. THE LOGIC K_n

The goal of Schotch and Jennings is to show that the class of structures generated in the previous section determine a modal logic extending the non-adjunctive logic presented above. The logic in question is obtained by supplementing the axioms and rules constraining the $[\!\vdash$ relation with the following rule:

(RK_n) If $c(\Gamma) = n$, and $\Gamma [\!\vdash B$, then $\Box[\Gamma] \vdash \Box(B)$, where $\Box[\Gamma] = \{\Box(A) | A \in \Gamma\}$.

Schotch and Jennings built a canonical model for the resulting logic K_n, and they prove that the model is a full $PC(\Box)$ pre-model, satisfying the closure restriction used in the theorem presented above.

In the following sections I shall proceed as follows. First I shall provide some background about neighborhood models of modalities. Then I shall introduce a constraint on neighborhoods, called *clustering*, and I shall show that this constraint is a 'natural' semantic counterpart of the notion of m-theory. This introductory result might help connecting the new neighborhood structures with the ones built up by Schotch and Jennings. Then I shall prove a general representation result for K_n in terms of neighborhood models, which does not require using the full $PC(\Box)$ pre-models of Schotch and Jennings.

4. Neighborhood models for modalities

We will introduce here the basis of the so-called *neighborhood semantics* for propositional modal logics. We will follow the standard presentation given in Part III of (Chellas, 1980).

DEFINITION 4.1. *$\mathcal{M} = \langle W, N, P \rangle$ is a neighborhood model if and only if:*

(1) W is a set

(2) N is a mapping from W to sets of subsets of W

(3) P is a standard valuation mapping the atoms of the language to subsets of W.

Of course the pair $\mathcal{F} = \langle W, N\rangle$ is a *neighborhood frame*. The following definition makes precise the notion of truth in a model.

DEFINITION 4.2. Truth in a neighborhood model*: Let u be a world in a model $\mathcal{M} = \langle W, N, P\rangle$. P is extended (uniquely) to a relation $\models_u$ (where $\mathcal{M} \models_u A$ states that A is true in the model $\mathcal{M}$ at world u). The extension is standard for Boolean connectives. Then the following clauses are added in order to determine truth conditions for modal operators.*

(1) $\mathcal{M} \models_u \Box(A)$ if and only if $||A||^{\mathcal{M}} \in N(u)$

(2) $\mathcal{M} \models_u \Diamond(A)$ if and only if $||\neg \text{A}||^{\mathcal{M}} \notin N(u)$

where, $||A||^{\mathcal{M}} = \{u \in W\colon \mathcal{M}, \models_u A\}$

$||A||^{\mathcal{M}}$ is called A's *truth set.* Intuitively $N(u)$ yields the propositions that are necessary at u. Then $\Box A$ is true at u if and only if the 'truth set' of A (i.e. the set of all worlds where A is true) is in $N(u)$. If the intended interpretation is epistemic $N(u)$ contains a set of propositions understood as epistemically necessary. This can be made more precise by determining the exact nature of the epistemic attitude we are considering. $N(u)$ can contain the known propositions, or the believed propositions, or the propositions that are considered highly likely, etc. Then the set $P = \{A \in W\colon \models_u \Diamond(A)\}$ determines the space of epistemic possibilities with respect to the chosen modality - knowledge, likelihood, etc.

Clause (2) forces the duality of possibility with respect to necessity. It just says that $\Diamond(A)$ is true at u if the denial of the proposition expressed by A (i.e. the complement of A's true set) is not necessary at u. $N(u)$ is called the *neighborhood* of Γ.

4.1. Augmentation

The following conditions on the function N in a neighborhood model $\mathcal{M} = \langle W, N, P\rangle$ are of interest. For every world u in $\mathcal{M}$ and every proposition (set of worlds) X, Y in $\mathcal{M}$:

(m) If $X \cap Y \in N(u)$, then $X \in N(u)$, and $Y \in N(u)$.

(c) If $X \in N(u)$, and $Y \in N(u)$, then $X \cap Y \in N(u)$.

(n) $W \in N(u)$

When the function N in a neighborhood model satisfies conditions (m), (c) or (n), we say that the model is *supplemented*, is *closed under intersections*, or *contains the unit* respectively. If a model satisfies (m) and (c) we say that it is a *quasi-filter*. If all three conditions are met it is a *filter*. Notice that filters can also be characterized as non-empty quasi-filters - non-empty in the sense that for all worlds u in the model $N(u) \neq \emptyset$.

DEFINITION 4.3. *A neighborhood model* $\mathcal{M} = \langle W, N, P \rangle$ *is* augmented *if and only if it is supplemented and, for every world* u *in it:*

$$\cap N(u) \in N(u).$$

Now we can present an observation (established in (Chellas, 1980), section 7.4), which will be of heuristic interest in the coming section.

OBSERVATION 4.1. *$\mathcal{M}$ is augmented just in case for every world u and set of worlds X in the model: (a) $X \in N(u)$ if and only if $\cap N(u) \subseteq X$.*

It easy to see that every augmented model is a filter: supplemented, closed under intersections and possessed of the unit. Moreover, every finite filter is augmented. This suggests a tight relationships between neighborhood and Kripke models: a Kripke model is essentially an augmented neighborhood model.

4.2. Epistemic interpretation of augmentation

In recent work in epistemic logic it is quite usual to represent agents by *acceptance sets* or *belief sets*, obeying certain rationality constraints. If the representation is linguistic the agent is represented by a logically closed set of sentences. If the representation is done in a σ-field or relative to a universe of possible worlds, the agent is represented by a set of points such that all propositions accepted (believed) by the agent are supersets of this set of points. Adopting either representation is tantamount to imposing logical omniscience as a rationality constraint.

When a neighborhood frame is augmented we have the guarantee that, for every world u, its neighborhood $N(u)$ contains a smallest proposition, composed of the worlds that are members of every proposition in $N(u)$. In other words, for every u we know that $N(u)$ always contains $\cap N(u)$ and every superset thereof (including W).

We will propose to see the intersection of the neighborhood of a world as an acceptance set for that world, obeying the rationality constraints required by logical omniscience. The following results help to make this idea more clear.

OBSERVATION 4.2. *If $\mathcal{M}$ is augmented, then for every u in the model: (1) $\models_u \Box A$ iff and only if $N(u) \subseteq ||A||^{\mathcal{M}}$, and (2) $\models_u \neg\Box(A)$ iff and only if $N(u) \not\subseteq ||A||^{\mathcal{M}}$.*

Epistemic possibility is, in this setting, understood in terms of compatibility with the belief set $\cap N(u)$. In other words $\models_u \Diamond(A)$ if and only if $||A||^{\mathcal{M}} \cap (\cap\, N(u)) \neq \emptyset$. This in turn means that, when the model $\mathcal{M}$ is augmented, $\models_u \Diamond(A)$ holds whenever $||A||^{\mathcal{M}}$ is logically compatible with *every* epistemically necessary proposition in the neighborhood.

This epistemic interpretation of augmentation can be extended to the case of neighborhoods that are not augmented. The basic idea is to extend the previous account even for inconsistent neighborhoods with empty intersection:

DEFINITION 4.4. *(Poss) $\mathcal{M} \models_u \Diamond(A)$ if and only if for every X in $N(u)$, $||A||^{\mathcal{M}} \cap X \neq \emptyset$*

The central idea being that an (unclosed) inconsistent set of statements can be used in order to establish what is possible as follows: if a statement contradicts *a member* of the set, then it is not possible. For certain standard of quality control, that one of the pieces has passed my inspection is not OK is not a serious possibility. And at the same time, it is not a serious possibility that all the inspected pieces are OK. A detailed analysis of the logical consequences of adopting this extended notion of epistemic possibility for first order languages, as well as some consequences concerning the lottery paradox, is presented in (Arló-Costa, 2002).

4.3. The level of coherence of neighborhoods

The previous remarks bring us directly to the fact that most of the sub-Kripkean classical models will contain inconsistent neighborhood models. We can measure the level of coherence of these neighborhoods as we can measure the level of coherence of a set of sentences.

DEFINITION 4.5. *A set of propositions N has level of coherence m if and only if m is the least integer such that there is a sequence of sets of propositions $X_1, ..., X_m$, such that $\emptyset \neq \cap X_i$ and $\cup_i X_i = N$. Each of the sequences $X_1, ..., X_m$ will be called an m-decomposition of N.*

This is a straightforward adaptation of the ideas of Schotch and Jennings presented above. We can add a bit of useful notation here:

DEFINITION 4.6. *If a set of propositions N has degree of coherence m, and $X_1, ..., X_m$ is an m-decomposition of N, then the sets $G_1 = \cap X_1, ..., G_m = \cap X_m$, are called a set of m-generators of N.*

Now the following closure condition on neighborhoods, which we can call *clustering* is of interest:

DEFINITION 4.7. *A neighborhood model $\mathcal{M} = \langle W, N, P \rangle$ is* m-clustered *if and only if for every $u \in W$, and for every $X \subseteq 2^W$, if $N(u)$ has level of coherence m,*

$X \in N(u)$ if and only if for all generators $G_1, ..., G_m$ for $N(u)$, either $G_1 \subseteq X, or ..., or G_m \subseteq X$

We will say that a neighborhood of level of coherence m in a clustered model is m-clustered. It is not difficult to see that a clustered neighborhood is supplemented and possesses the unit, even though it need not be closed under intersections. The next section will be devoted to show that clustering is the counterpart for neighborhoods of the syntactic notion of m-theory.

5. From pre-models to neighborhood models

Now we can proceed independently of pre-models. Let $\mathcal{N} = \langle U, N, P \rangle$ be a neighborhood model. We can then prove the following result about clustering:

THEOREM 5.1. *Let $\mathcal{N}$ be a neighborhood model and let $\Box(u)^{\mathcal{N}}$ be an m-theory. Then $N(u)$ is m-clustered.*

Proof. Assume that X $= ||A||^{\mathcal{N}} \in N(u)$. Then, by the truth conditions of the $\Box$-operator, $A \in \Box(u)^{\mathcal{N}}$. Therefore, $\Box(u)^{\mathcal{N}}$ $[\vdash A$ (by $[Ref]$). So, for all m-decompositions δ of $\Box(u)^{\mathcal{N}}$, there is i, $||\delta^{-1}[i]||^{\mathcal{N}} \subseteq ||A||^{\mathcal{N}}$.

Since $\Box(u)^{\mathcal{N}}$ is an m-theory, $N(u)$ has level of coherence m and all m-generators of $N(u)$ are given by the sets $||\delta^{-1}[1]||^{\mathcal{N}}$, ..., $||\delta^{-1}[m]||^{\mathcal{N}}$ for each δ. So, we have that for all sets of m-generators $G_1, ..., G_m$ for the neighborhood, there is G_i in the set entailing X, and this is enough to establish the LTR part of the proof.

For the RTL part of the proof assume that $X = ||A||^{\mathcal{N}} \notin N(u)$. Then we have that $A \notin \Box(u)^{\mathcal{N}}$ and since $\Box(u)^{\mathcal{N}}$ is, by hypothesis, a m-theory, $\Box(u)^{\mathcal{N}}$ $\not[\vdash A$. Therefore there is $\delta \in \Delta(u)$: for all i $(1 \leq i \leq n)$

$||\delta^{-1}[i]||^{\mathcal{N}} \not\subseteq ||A||^{\mathcal{N}}$. For the reasons invoked in the first part of the proof, this means that there is a set of m-generators of $N(u)$, $||\delta^{-1}[1]||^{\mathcal{N}}$, ..., $||\delta^{-1}[n]||^{\mathcal{N}}$ such that neither of them entails $||A||^{\mathcal{N}}$. This completes the proof.

The proof is more direct than a similar proof in terms of the m-natural relation, offered by Schotch and Jennings. The reason for this directness is the fact that m-clustering seems to be a more 'natural' semantic counterpart for the syntactic notion of m-theory.

6. Completeness in terms of canonical neighborhood models

A direct completeness proof in terms of canonical neighborhood models proceeds as follows. The construction of the canonical model is standard. Let Σ be a system of classical modal logic. Then let $Max_{\Sigma}\Gamma$ denote a maximal and consistent set of sentences of Σ. Let p_n denote the atoms of the language. In addition we have the notation $|A|_{\Sigma} = \{Max_{\Sigma}|A \in \Gamma\}$, where $|A|_{\Sigma}$ is A's *proof set* for the system Γ. The canonical model $\mathcal{N} = \langle W, N, P\rangle$ is built up as follows:

(1) $W = \{\Gamma | Max_{\Sigma}\Gamma\}$

(2) For all $u \in \mathcal{N}$, $\Box(A) \in u$ if and only if $|A|_{\Sigma} \in N(u)$

(3) $P_n = |p_n|_{\Sigma}$, for n = 0, 1, ...

I shall not repeat here the main results about canonical models for classical systems, which can be found in (Chellas, 1980). The result that interest us in order to prove a determination result for the logic K_n is the following one:

THEOREM 6.1. *Let $\mathcal{N} = \langle W, N, P\rangle$ be the smallest canonical neighborhood model for the classical system containing the rule RK_n. Then for every u in $\mathcal{N}$ such that $N(u)$ has degree of coherence n, $N(u)$ is n-clustered.*

Proof. Let Σ be a system of classical logic containing the rule RK_n and let $\mathcal{N}$ be the smallest canonical neighborhood model for Σ, i.e. a model such that $N(u) = \{|A|_{\Sigma}|\Box(A) \in u\}$. Assume for arbitrary u that $N(u)$ has degree of coherence n. Assume in addition that $X \in N(u)$. Then, $X = |A|_{\Sigma}$, for $\Box(A) \in u$.

Since $\Box(A) \in u$ we have that $A \in \Box(u)^{\mathcal{N}} = \{A|\Box(A) \in u\}$. This indicates, by Reflexivity of $[\vdash$, that $\Box(u)^{\mathcal{N}}$ $[\vdash A$. So, for all n-decompositions δ of $\Box(u)^{\mathcal{N}}$, there is i, $\delta^{-1}[i] \vdash A$. Now, all the n-generators of $N(u)$

are the sets:

$|\delta^{-1}[1]|_\Sigma$, ..., $|\delta^{-1}[n]|_\Sigma$ for some decomposition δ of $\Box(u)^{\mathcal{N}}$.

So, we know that for any arbitrary set of n-generators $G_1, ..., G_n$ for $N(u)$ where:

$G_1 = |\delta^{-1}[1]|_\Sigma$, ..., $G_n = |\delta^{-1}[n]|_\Sigma$ for some decomposition δ of $\Box(u)^{\mathcal{N}}$.

there should be i, such that $G_i = |\delta^{-1}[i]|_\Sigma \subseteq |A|_\Sigma$.

On the other hand, if we assume that for all n-generators $G_1, ..., G_n$ of $N(u)$ there is at least one G_i entailing $|A|_\Sigma$; this is tantamount to assume that $\Box(u)^{\mathcal{N}}$ $[\vdash A$. So, by the rule RK_n, Γ' $= \{x|\ x = \Box(B)$ and $\Box(B) \in u\} \vdash \Box(A)$. Therefore $\Box(A) \in u$, which entails that $|A|_\Sigma \in N(u)$, as needed.

7. High probability neighborhoods and clustering

Let $\mathcal{N}_\mathcal{P} = \langle U, N_P, V\rangle$ be a high n-probability model, where U is the universe, V a valuation and P a probability function defined on a Boolean sub-algebra of the power set of U. In addition, N_P is defined as follows:

DEFINITION 7.1. $N_P(u) = \{X|P(X) \geq n\}$

As we reported above, it is clear from the work of Kyburg and Teng (Kyburg-Teng, 2002) that high probability models are supplemented and possess the unit, and they are not closed under intersections. In addition, we can apply Schotch and Jennings' ideas here by measuring the coherence of high probability neighborhoods.

Some salient cases are immediate. High n-probability neighborhoods which contain a point $w \in U$ such that $P(\{w\}) \geq n$ are augmented with $\cap N(u) = \{w\}$. Nevertheless, high probability neighborhoods are not in general clustered:

EXAMPLE 7.1. *Consider a .6-probability neighborhood where U contains four points, and let $P(\{w_1\}) = .5$, $P(\{w_2\}) = .1$, $P(\{w_3\}) = .3$, $P(\{w_1\}) = .1$. This neighborhood has level of coherence 1 with only one generator in $\{w_1\}$. Nevertheless, the neighborhood is not clustered, because $\{w_1\} \notin N(u)$.*

The example gives some hints about the nature of the notion of clustering itself and about the nature of the non-adjunctive logics based on it. There are, of course, a variety of possible epistemic interpretations for the notion. I am interested here on the fact that clustering admits an interpretation, which is compatible with endorsing the most demanding standards of epistemic rationality in terms of logical closure. Here is the basis of this account of clustering (comparisons with the logic of high probability will flow naturally from the interpretation itself).

The gist of the idea is to see clustering as an account of epistemic indeterminacy prompted by data, which can be incoherent. An alternative example will help motivating the idea.

EXAMPLE 7.2. *Consider a .6-probability neighborhood where U contains four points, and let $P(\{w_1\}) = .4$, $P(\{w_2\}) = .3$, $P(\{w_3\}) = .2$, $P(\{w_1\}) = .1$. This neighborhood has level of coherence 2. Possible generators include $G_1 = \{w_2\}$, $G_2 = \{w_3\}$; $G_1 = \{w_1\}$, $G_2 = \{w_2, w_3\}$; $G_1 = \{w_1\}$, $G_2 = \{w_4, w_2, w_3\}$; $G_1 = \{w_1\}$, $G_2 = \{w_2\}$; $G_1 = \{w_1\}$, $G_2 = \{w_3\}$.*

A cluster *in the sense of Schotch and Jennings is: $C_1 = \{w_1, w_2\}$, $C_2 = \{w_1, w_3\}$, $C_3 = \{w_4, w_2, w_3\}$. So we have that $N(u) = \{X|$ either $C_1 \subseteq X$, or $C_2 \subseteq X$, or $C_3 \subseteq X\}$.*

Even when the last example was generated by utilizing high probability, I ask the reader to abstract from that fact and to just consider the data in the neighborhood as a possible data set independently of its origin. An agent facing the set of possible 2-decompositions of the data can be seen as being in doubt between various ways of articulating the data as the pooled knowledge of two consistent, but unclosed views. So the idea of forcing can be articulated as a form of cautious inference, where one should be committed to infer something from the data as long as it follows from any of the possible manners of articulating the data. So, for example, one of the generators will be in the neighborhood as long as it is a conclusion inferable from all possible articulations of the data.

So, clustering can be seen as a condition which requires the maximum degree of logical perfection as is compatible with the degree of indeterminacy represented in the neighborhood. If, as in the first example, there is no degree of indeterminacy, and the level of coherence is one, then the agent should be logically omniscient, i.e. the neighborhood should be augmented. Of course, this is a requirement which clashes with the logic of high probability, which permits augmentation only in some limit cases, but that establishes its own standard of rationality, not necessarily coherent with logical closure (seen as an ideal of rationality).

8. A more fine-grained measure of coherence?

The previous epistemic account of clustering suggests, in turn, that Schotch and Jennings' measure of coherence might not be fine-grained enough to reflect an intuitive notion of coherence in terms of epistemic determinacy. It seems that there are cases where neighborhoods, which intuitively bear different degree of coherence, receive nevertheless the same measure. For example, consider the following class of neighborhoods of level of coherence n:

DEFINITION 8.1. *A neighborhood $N(u)$ is* closed under a set of m-generators $G_1, ..., G_m$ *if and only if* $N(u)$ *can be represented as* $\{X \subseteq 2^U | G_1 \subseteq X\} \cup ... \cup \{X \subseteq 2^U | G_m \subseteq X\}$.

It is clear that neighborhoods closed under m-generators have level of coherence m. Nevertheless, of two neighborhoods of level of coherence m it seems that if one is closed under generators and the other is not, the one which is closed is epistemically more determinate (and intuitively more coherent) than the one which is unclosed. For example, consider the following modification of our second example:

EXAMPLE 8.1. *Consider a neighborhood $N(u)$ which is closed under the generators $G_1 = \{w_2\}$, $G_2 = \{w_3\}$ in the example 7.2.*

Certainly there are grounds here in order to make a logical distinction. The models whose neighborhoods are closed under generators are a strict subclass of the clustered models. Syntactically the requirement can be expressed by constraining further the forcing relation:

(CG) If $a_1, ..., a_n$ is an n-decomposition of Γ, then $\Gamma [\!\vdash \wedge a_i$, for all i, $1 \leq i \leq n$.

A possible improvement on the measure of coherence we have been using can be to define:

DEFINITION 8.2. *For consistent Γ, $c(\Gamma) = m.n$ if and only if m is the least integer such that there are sets*

$a_1, ..., a_m, a_i \nvdash$ **false** *($1 \leq i \leq m$)*

and $\cup_{i=1}^{m} a_i = \Gamma$

where $\vdash$ is the classical notion of consequence, where $c(\Gamma) = w$ if **false** $\in \Gamma$, *and where n is the number of possible m-decompositions of Γ.*

So, according to this proposal, the coherence of the neighborhood in example (7.1) is 1; the coherence of the neighborhood in example (7.2) is 10; and the coherence of the neighborhood in example (8.1) is 2.

9. Closure under generators

Neighborhood models closed under generators have applications that have been considered previously by paraconsistent logicians. Here is the gist of the idea behind the *discussive* logics of Jaskowski.

> In a discourse, each participant puts forward some information, beliefs, or opinions. What is true in a discourse is the sum of opinions given by participants. Each participant's opinions are taken to be self-consistent, but may be inconsistent with those of others. To formalise this idea, take an interpretation, I, to be one for a standard modal logic, say **S5**. Each participant's belief set is the set of sentences true in a possible world in I. Thus, A holds in I iff A holds at *some* world in I. Clearly, one may have both A and $\neg A$ (but not $A \wedge \neg A$) holding in an interpretation (Priest-Tanaka, 2000).

Neighborhood semantics is a generalization of Kripke semantics. So, we can obtain the entire Kripkean family of modal systems by adding appropriate constraints on neighborhoods. Here is a list of those constraints for the standard schemas D, T, B, 4 and 5 (in epistemic logic 4 is called KK o positive introspection, etc). The constraints are conditions on a model $\mathcal{M} = \langle U, N, P \rangle$, for every world u and proposition X in $\mathcal{M}$.

(d) If $X \in N(u)$, then $X^c \notin N(u)$

(t) If $X \in N(u)$, then $u \in N(u)$

(b) If $u \in N(u)$, then $\{w \in \mathcal{M} | \ X^c \notin N(w)\} \in N(u)$

(iv) If $X \in N(u)$, then $\{w \in \mathcal{M} | \ X \in N(w)\} \in N(u)$

(iv) If $X \notin N(u)$, $\{w \in \mathcal{M} | \ X \notin N(w)\} \in N(u)$

Now consider the following constraint on neighborhoods:

DEFINITION 9.1. *(J-Σ) $X \in N_Y(u)$ if and only if $X \in \cup\{N(w) \mid w \in Y \subseteq U$ and $N(w)$ is a neighborhood in a model of a classical system $\Sigma\}$*

When Σ is any normal Kripkean system, (J-Σ) seems to model constraints inspired by Jaskowski's ideas.[1] (J-Σ)-neighborhoods represent the sum of the beliefs of n participants in a 'discussion' (where n is the cardinality of Y). The set of beliefs of each participant $w \in Y$ is represented by the propositions in $N_Y(u)$. The standards of rationality of participants are given by the constraints imposed by Σ.

Notice that as long as Σ is any Kripkean system, a model closed under (J-Σ) is clustered, closed under generators and of level of coherence n, where n is the number of participants. In fact, since in this case we have $\mathbf{K} \subseteq \Sigma$, the corresponding model of Σ is augmented, with $\emptyset \neq \cap N_Y(u) \in N(w)$ for each w. Therefore each $\cap N_Y(u)$ is a generator.

It seems that most of the studied systems of non-adjunctive logic have modal counterparts that live between **EMN** and **K**. There is a hierarchy of models closed under generators which obey (J-Σ) for the various possible Kripkean Σ.

Of course, we can consider as well the possibility of studying models constrained by (J-Σ), where Σ is classical, but not Kripkean. This possibility, apparently not considered by Jaskowski, yields a class of models that need not be closed under generators.

10. Conclusion

Some of the best known non-adjunctive logics have neat modal counterparts as sub-Kripkean systems of classical modal logic. The relationship is tight. If $\mathcal{N} = \langle W, N, P \rangle$ is the smallest canonical neighborhood model for the classical system containing the rule RK_n, we have that for all u, $\Box(u)^{\mathcal{N}}$ is an n-theory, and moreover:

If $\Box(u)^{\mathcal{N}}$ $[\!\vdash A$, then $\models_u^{\mathcal{N}} \Box(A)$

[1] Our goal in this section is to motivate the interest of a family of logics which require closure under generators. The motivation appeals to ideas first presented by Jaskowski. Further work is needed in order to determine whether some of the systems actually axiomatized by Jaskowski, like the system $\mathcal{J}$, has neighborhood models requiring closure under generators. Some of the recent axiomatizations of $\mathcal{J}$, like the one presented in (da Costa-Dubikajtis, 1977), are natural candidates for studying this problem. In fact, the axiomatization presented in Lemma B of this paper proceeds by adding only a monadic modal operator to the classical propositional language. It is an open problem whether this operator is a classical modality and if this were the case, it is also an open problem to determine where it is located in the hierarchy of classical systems presented in this paper. Part of my motivation here is to suggest that the methodology used here in order to present a neighborhood semantics for Schotch and Jennings's system can be extended in order to classify and unify the semantics of a larger set of non-adjunctive and paraconsistent systems.

Schotch and Jennings established a similar result by utilizing their models, which they propose as generalizations of Kripke semantics. Our results permit to identify these models as neighborhood models. This has various advantages. One the one hand, it seems that proofs and definitions are simpler. On the other hand, there are, as we have seen, different kinds of neighborhood models which are not closed under intersections. While the models which are supplemented and possess the unit seem reasonable to model operators of high probability; clustered models seem to encode a different type of epistemic modality naturally related to Schotch and Jennings's forcing relation. And, in the same manner that we can identify an interesting sub-class of models which are supplemented and possess the unit (clustered models), there is also a salient sub-class of those, the ones which are closed under generators. In the latter case we can see the models as rationalizing the data contained in the neighborhood in terms of the pooled knowledge of n agents who are fully rational. Each generator is the strongest proposition believed by one of these agents. As we explained above, clustered models seem to reflect a modality that has little to do with high probability. Our account in terms of epistemic determinacy suggested also a new measure of coherence, which seems to improve on the one offered by Schotch and Jennings (quite independently of the epistemic construal which motivated it).

The connection between non-adjunctive logics and classical modal logics seems to be mutually beneficial. On the one hand we learn more about the many possible sub-Kripkean classical logics. On the other hand, neighborhood models seem to offer good both conceptual and logical models of the particular form of paraconsistent inference under study.

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