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Compositional Natural Language Semantics using Independence Friendly Logic or Dependence Logic

Abstract. Independence Friendly Logic, introduced by Hintikka, is a logic in which a quantifier can be marked for being independent of other quantifiers. Dependence logic, introduced by Väänänen, is a logic with the complementary approach: for a quantifier it can be indicated on which quantifiers it depends. These logics are claimed to be useful for many phenomena, for instance natural language semantics. In this contribution we will compare these two logics by investigating their application in a compositional analysis of the *de dicto* - *de re* ambiguity in natural language. It will be argued that Independence Friendly logic is suitable, whereas Dependence Logic is not.

Keywords: Independence friendly Logic, Dependence Logic, *de dicto de re*, Compositionality, Meaning representation, IF, DL.

1. The *de dicto* - *de re* ambiguity

The sentence

(1) *Mary believes that a stranger crippled John's cow*

is ambiguous. In one reading, called *de dicto* reading, the sentence means that Mary does not have a particular person in mind, but that she believes that whatever precisely happened, it must be some stranger who crippled John's cow. In the other reading, the *de re* reading, the sentence means that there is a particular person, say a stranger Mary saw last night, of whom she believes that he crippled John's cow. The *de dicto* - *de re* ambiguity has a long history in philosophy (see e.g. [21]), but that history will not be considered here.

One might characterize this ambiguity in two — alternative — ways.

1. It is a phenomenon of independence. In one reading Mary suspects a particular person, independent of her beliefs on what happened precisely. In the other reading the person is not independent of Mary's

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belief: depending on what happened precisely, it may concern another stranger.

2. It is a phenomenon of dependence. In one reading it depends on the belief of Mary on what happened precisely which stranger it is. In the other reading it does not depend on Mary's belief on what happened precisely which stranger she suspects.

These two characterizations reflect the perspective of respectively Independence Friendly Logic and Dependence Logic; henceforth abbreviated as IF and DL. In the next sections the two logics will be introduced, and a representation of the two readings in these logics will be given. These representations do not constitute the main issue in this article, but the question how to obtain them in a compositional way.

A standard principle in logical semantics is the 'Principle of Compositionality', which reads, in a formulation due to Partee [25]:

The meaning of a compound expression is a function of the meanings of its parts and of the way they are syntactically combined.

This roughly says that we have to assign meanings to words, and when words or phrases are combined to larger syntactic units, their meanings are combined as well. An important argument in favor of the principle is that it explains how we can produce and understand sentences we have never heard before.

The principle is fundamental for the formal approach to semantics of natural languages. In the *Handbook of Logic and Language* one of the methodological chapters is about compositionality [18], also in the *Handbook of Philosophy of Language* [6] there is such a chapter. The most important papers by B. Partee are collected in a book entitled 'Compositional Semantics' [26], conferences are devoted to the subject [32], and a handbook will appear [31]. However, from this list one should not conclude that the principle is accepted by everyone: there are many variants, discussions and opponents. We will adopt the formal version that is standard in the logical approach (see Sect. 3). The (not compositional) approach in linguistics will be considered briefly in Sect. 4.

The aim of this paper is to argue that by using IF a compositional semantics can be given for the *de dicto* - *de re* ambiguity, whereas by using DL this is not possible.

2. The representations of the *de dicto* - *de re* readings

In this section an intuitive explanation of IF and DL will be given that is sufficient to understand representations that we will use later for the meanings of (1); about the formal aspects of the interpretation more will be said in Sect. 3.

IF was introduced by Hintikka (see e.g. [13] or [15]). In this extension of predicate logic it can be indicated that a quantifier is independent of some of the quantifiers with larger scope. An example of an IF sentence is $\forall x \forall y \exists z_{/x} [z \neq x \wedge z > y]$. The quantifier $\exists z_{/x}$ says that the choice for z must be made independently of x . The traditional semantics for IF is defined by means of games, and says that the strategy function for z does not have x as argument (but may have any other variable as argument). For the present example there exists no function that does not have x as argument and at the same time guarantees that $z \neq x$; therefore the sentence is not true. The sentence is also not false (in models with at least two elements) because there are no values of x and y that guarantee that for any value of z the subformula $z \neq x$ is false. This illustrates that IF logic is not two-valued (an aspect that plays no role in our discussions).

DL was introduced by Väänänen [30]. It is an extension of predicate logic with a complementary approach: for a quantifier it can be indicated on which subset of quantifiers it depends exactly (from the quantifiers that have scope over it). An example is $\forall x \forall y \exists z [= (y, z) \wedge z \neq x \wedge z > y]$. The phrase $=(y, z)$ says that z depends only on y , hence not on x . Also this sentence is not true (nor false). A special case of dependency would be $=(z)$, indicating that z does not depend on any other variables.

IF is claimed to be useful for many phenomena. The first example (in 1974) concerned natural language semantics: the branching quantifier sentences [12]. Later the *de dicto* - *de re* ambiguity and other scope ambiguities were mentioned, and as examples in mathematics the definitions of *continuity* and *uniform continuity* [13]. Many more examples of applications are given in [13]. Also DL is said to be applicable to many phenomena (introduction of [30]), but specific examples are rarely mentioned.

The claim that IF is suitable for the *de dicto* - *de re* ambiguity is not worked out, so the formalization in this paper is my own. One aspect of its meaning will not be considered: since tense is not relevant for our problem, it will not be taken into account. The focus will be on the *de dicto* - *de re* ambiguity, and other kinds of ambiguity are not considered (e.g. *John's cow* is in all worlds assumed to be John's real cow).

The meaning of a sentence will be formalized as the set of possible worlds in which the sentence is true. Hence a variable for possible worlds will occur in the predicates, typically w and v will be used. The meaning of *John loves Suzy*, viz. $Love(w, J, S)$, will hold for some values of w , and not for other values. The meanings of the predicates are assumed to be given (since lexical semantics is not our aim). The representations of the meanings of sentences will (in general) contain a free variable for possible worlds, and the world with respect to which we perform the interpretation determines whether for that value the sentence is true or not. Following Montague [24] and others, the set of individuals is the same in all worlds, and proper names such as *John* and *Suzy* are rigid: they denote with respect to all worlds the same individual.

The verb *believe* will get a modal interpretation (this type of interpretation is introduced by Hintikka [14], and is standard in epistemic logic [7]). The sentence *Mary believes that John loves Suzy* is understood as the statement that according to Mary's beliefs *John loves Suzy* is true. Mary may have more beliefs (e.g. about Suzy loving John), but probably not concerning all statements (e.g. not concerning Suzy loving Mary, or not concerning Goldbach's conjecture). So there is set of possible worlds that is in accordance with the beliefs Mary has in possible world v . This set is denoted by $Bel(v, M)$, and is called the 'set of belief alternatives of Mary' (in v). The meaning with respect to v of *Mary believes that John loves Suzy* is denoted by $\forall w \in Bel(v, M) Love(w, J, S)$. An alternative formulation would be $\forall w [w \in Bel(v, M) \rightarrow Love(w, J, S)]$, and still another variant is used by Montague [24] where the meaning of *belief* is expressed as a relation between Mary and the set of worlds in which $Love(w, J, S)$ holds.

First the meaning representation in IF for the two readings of (2) is given, followed by some explanation.

(2) *Mary believes that a stranger crippled John's cow.*

(3) de re (IF):

$$\forall w \in Bel(v, M) \exists x_{/w} [Str(w, x) \wedge \exists y_{/w} [Cow(w, y, J) \wedge Cr(w, x, y)]]$$

(4) de dicto (IF):

$$\forall w \in Bel(v, M) \exists x [Str(w, x) \wedge \exists y_{/w} [Cow(w, y, J) \wedge Cr(w, x, y)]]$$

With $\forall w \in Bel(v, M)$ in (3) and (4) it is indicated that all possible worlds w are considered from the belief alternatives which Mary has in v . The variable v gets as value the world with respect to which we interpret the formula. In (3) the $\exists x_{/w}$ says that the x is chosen independently of w , so it is some particular person, whereas in (4) the $_{/w}$ does not occur with $\exists x$, so x may depend on w , i.e. on the belief alternative under consideration.

Next the representations in DL are given, followed by some explanation.

$$(5) \text{ de re (DL): } \forall w_{\in Bel(v,M)} \exists x [= (x) \wedge Str(w, x) \wedge \exists y [= (y) \wedge Cow(w, y, J) \wedge Cr(w, x, y)]]$$

$$(6) \text{ de dicto (DL): } \forall w_{\in Bel(v,M)} \exists x [Str(w, x) \wedge \exists y [= (y) \wedge Cow(w, y, J) \wedge Cr(w, x, y)]]$$

In (5) the $=(x)$ formalizes that x does not depend on any other variable, hence not on w . So x denotes the same person in all belief alternatives. The $=(y)$ in (5) and in (6) formalizes that in all belief alternatives y denotes the same cow.

This shows that the two readings of this sentence can be represented without any problem in both logics – the issue is how to obtain them in a compositional way.

3. The Principle of Compositionality

As said in Section 1, we will obey the principle of compositionality. This principle has a mathematical formalization that is given by Montague in his ‘Universal Grammar’ [23]. It says that the syntax has to be an algebra, semantics a similar algebra, and that meaning assignment a homomorphism from the syntactic term algebra to the semantic algebra. In [17, 18] and [34] mathematical properties are discussed (e.g. generative capacity).

The principle speaks about meanings, and these are formalized by set theoretic notions, such as relations and functions. In principle one could refer directly to such entities. This is done in [22], but, as it is explained in [23] and illustrated in [18], this is not handsome. It is more perspicuous to use a logical language to represent meanings, and to denote operations on meanings by operations on formulas. This perspective implies a restriction on the operations: they should correspond with operations on meanings. For a discussion with examples from the literature that are excluded by this requirement, see [18].

The above means that it is essential for our application that the logics have a compositional semantics. IF has been presented (e.g. in [13] and [15]) with a semantics that is not compositional. For instance, the interpretation of the sentence $\exists x_{/z} \phi$ is not obtained from the interpretation of ϕ , but from the interpretation of $\phi[c/x]$, where constant c is found by application of a certain game strategy. Carefully, meanings are assigned only to sentences, not to open formulas. Hintikka [13, p. 110] claimed that a compositional interpretation for IF would not be possible or in any case very unnatural.

Hodges considered this as a challenge, and provided a compositional semantics for IF [16]. The crucial step was that the interpretation of a formula was not with respect to an assignment (as in predicate logic) but with respect to a *set* of valuations (assignments defined for a finite set of variables). The approach is known as ‘trump semantics’. His definition is corrected for some details in [4], where also the equivalence is proven with a game interpretation.

Besides IF we will also use DL. For this logic a compositional semantics has always been used. The interpretation is defined with respect to a team, again a set of valuations.

On the basis of the mentioned compositional interpretations a notion of meaning might be defined that can be used in a compositional semantics for these logics.

Before we discuss the issue from natural language semantics, we first consider an example from mathematics that illustrates the issue in a simple way. It concerns the phrases *function f is continuous* and *function f uniformly continuous*. These phrases are represented in predicate logic by the well known ϵ - δ definitions (7) and (8).

$$(7) \quad \forall \epsilon \forall x \exists \delta \forall y [|x - y| < \delta \rightarrow |f(x) - f(y)| < \epsilon]$$

$$(8) \quad \forall \epsilon \exists \delta \forall x \forall y [|x - y| < \delta \rightarrow |f(x) - f(y)| < \epsilon]$$

One sees that replacement of the word *continuous* by *uniformly continuous* results in a change in the quantifier structure of the logical sentence.

A compositional approach asks that a local change in the sentence corresponds with a local change in the logical representation, instead of changing the structure of the logical sentence. In IF this is possible. Then replacing $\exists \delta$ by $\exists \delta_{/x}$ yields the desired result: (9) formalizes *uniformly continuous* and corresponds with (8) .

$$(9) \quad \forall \epsilon \forall x \exists \delta_{/x} \forall y [|x - y| < \delta \rightarrow |f(x) - f(y)| < \epsilon]$$

This example is mentioned by Hintikka in [13, p. 9]. He also discusses comparable notions such as (*uniformly*) *differentiable* [13, p. 74].

A consequence of compositionality is that representations can be used in all contexts, for instance to express that *all functions g from class G are uniformly continuous*. All that has to be said is that δ is independent of x ; the dependence of δ on g follows from the quantifier structure.

DL follows the opposite approach, and indicates for *uniformly continuous* on which variables δ depends:

$$(10) \quad \forall \epsilon \forall x \exists \delta [=(\epsilon, \delta) \wedge \forall y [|x - y| < \delta \rightarrow |f(x) - f(y)| < \epsilon]]$$

For *continuity* the $=(\epsilon, \delta)$ has to be omitted. Although in DL the difference between *continuous* and *uniformly continuous* can be expressed locally, there is a fundamental difference with IF: (10) *cannot* be used in other contexts. If one wants to express that all functions g from class G are uniformly continuous, then the δ has to be dependent on g , and therefore we have to use $=(\epsilon, g, \delta)$ instead of $=(\epsilon, \delta)$. This shows that DL does not provide a meaning representation for *uniformly continuous* that may be used in a compositional way.

In mathematics the principle of compositionality does not have the status it has in natural language semantics, so we will focus with the *de dicto* - *de re* ambiguity. It will be shown that this *de dicto* - *de re* ambiguity can be dealt with in a compositional way using IF logic, but *not* using DL. The source of the problem is in essence the same as above.

4. On the history of scope in logical semantics

In Montague's famous article *On the proper treatment of quantification in ordinary English* [24] several scope ambiguities are dealt with, and one of those is the *de dicto* - *de re* ambiguity. In his paper the *de re* reading of (1) is obtained by substituting *a stranger* for he_1 in (11).

(11) *Mary believes that he_1 crippled John's cow.*

With the same technique, called 'quantifying in', the wide scope reading of *a woman* in *Every man loves a woman* is obtained.

Sentence (11) is not an English sentence due to the artificial pronoun he_1 ; moreover no syntactic theory would consider (11) as a part of the *de dicto* - *de re* sentence. Montague's technique of 'quantifying in' was not appreciated, and alternatives were looked for.

The first development that has led away from Montague's original proposal was so called Cooper-storage [5]. In this approach the standard meanings of noun phrases (e.g. *a stranger* and *every man*) are used, but these are put into a store from which each can be taken out in arbitrary order. A later approach was to consider the noun phrases as ambiguous. Their ambiguity was systematic: there are rules that 'lift' the meaning of a noun phrase to another level which cause differences in scope (see [11]). In Kamp's discourse representation theory the way of embedding the noun phrase meanings in the discourse structure causes the difference in scope (see [9]). In the approach 'direct compositionality' [1] no decision is made, but one of the above methods is assumed to be used.

A second development that has led away from Montague's original proposal was that different meanings of determiners were distinguished. Some examples. *A man is brave* has a generic meaning, so this *a* has something like a universal meaning. In *All men lifted the piano* a collective reading of *all* is most plausible, whereas in *All men sneezed* the distributive reading seems preferable. The duplication of the article corresponding to *a* indicates in Hungarian the dependent reading (i.e. a narrow scope reading), whereas without duplication there is an ambiguity; an example is (12).

- (12) *Minden gyerek olvasott egy-egy könyvet.*
Every child read a - a book

These Hungarian phenomena suggest that *egy-egy* should get a narrow scope reading as lexical element. In [2] and [3] it is proposed to treat this and related phenomena with IF logic. The many possibilities of the meanings of articles are analyzed by e.g. [33] and [27].

This sketch of the developments in the field illustrates why the method of 'quantifying in' (with its substitution) is almost abandoned. As syntactic structure for the *de dicto - de re* sentence we should take a natural structure without artificial words, and the source of the ambiguity (viz. *a*) should, preferably, be assigned two meanings.

Linguistic theories, in particular those in the tradition of Chomsky, would follow a completely different approach. A structured sentence is input for a series of movement transformations until something is reached that is called the 'Logical Form'. In such a process the *de re* reading is obtained by moving *a stranger* to the leftmost position. Three remarks on this approach. 1) It is not a compositional process because the meaning of the sentence is not built from the meanings of its words. 2) It is not possible to attach a meaning to the movement transformation because the effects of moving a quantifier can vary considerable. 3) The 'Logical Form' is not given a formal (e.g. model theoretic) interpretation.

5. Compositional derivation of the *de dicto - de re* sentence

In line with the developments sketched in the previous section, we take as structure for the *de dicto - de re* sentence:

- (13) [*Mary* [*believes that* [[*a stranger*] [*crippled* [*John's cow*]]]]]

The smallest parts are not indicated, for instance *a stranger* has *a* and *stranger* as parts.

We will show how the *de dicto* and of the *de re* reading in IF and DL can be produced, starting from the parts of the sentence and their meaning representations. We start with the meaning of the smallest sentence it contains: *a stranger crippled John's cow*. Of course, its meaning has to be formed from the meanings of the words from which it is built, but then we have to explain what the meanings of noun phrases are and how these are used to produce the meaning of a basic sentence. The technique is standard (see an introduction like [8] or [10]), and the details are not relevant for the purpose of this article. Roughly speaking, a determiner denotes a generalized quantifier and a noun a set of entities, and the representation of the *de re* reading of *a* would be, in an extension of IF with lambda's, $\lambda P \lambda Q [\exists x_{/w} [P(w, x) \wedge Q(w, x)]]$.

First we give the meaning representations for the *de re* reading of (14), thereafter some explanation follows.

(14) *A stranger crippled John's cow.*

(15) *de re* (IF): $\exists x_{/w} [Str(w, x) \wedge \exists y_{/w} [Cow(w, y, J) \wedge Cr(w, x, y)]]$

(16) *de re* (DL): $\exists x [= (x) \wedge Str(w, x) \wedge \exists y [= (y) \wedge Cow(w, y, J) \wedge Cr(w, x, y)]]$

Both (15) and (16) contain a free variable w denoting the world with respect to which we interpret this sentence. If the sentence occurs as main sentence, that will be the actual world, but embedded after *believe* it can be a belief alternative. Other aspects are already explained in Section 2.

The next step is to embed (14) under *believe*, yielding (17).

(17) *believe that a stranger crippled John's cow.*

(18) *de re* (IF): $\forall w_{\in Bel(v, p)} \exists x_{/w} [Str(w, x) \wedge \exists y_{/w} [Cow(w, y, J) \wedge Cr(w, x, y)]]$

(19) *de re* (DL): $\forall w_{\in Bel(v, p)} [\exists x [= (x) \wedge Str(w, x) \wedge \exists y [= (y) \wedge Cow(y, J) \wedge Cr(w, x, y)]]]$

Both in (18) and (19) the variable w is now bound by $\forall w$, i.e. we consider all worlds that are possible according to the belief alternatives in world v of person p , where v and p are variables.

Next we combine (17) with *Mary*. For the meaning representation this means that (18) is conjoined with $p = M$. The result is equivalent with (21). The same is done for (19), resulting in a formula equivalent with (22).

(20) *Mary believes that a stranger crippled John's cow.*

(21) *de re* (IF): $\forall w_{\in Bel(v, M)} \exists x_{/w} [Str(w, x) \wedge \exists y_{/w} [C(w, y, J) \wedge Cr(w, x, y)]]$

$$(22) \text{ de re (DL): } \forall w \in \text{Bel}(v, M) \exists x [= (x) \wedge \text{Str}(w, x) \wedge \exists y [= (y) \wedge C(w, y, J) \wedge Cr(w, x, y)]]$$

Thus we have obtained in a compositional way the meaning representations we aimed at.

The *de dicto* reading of (20) can be produced in an analogous way, but then in all stages of the derivation the variable x for the stranger has to depend on the world under consideration. So for IF the $\exists x_{/w}$ must be replaced by $\exists x$, and for DL the $= (x)$ must be removed.

6. The problem with compositionality for DL

In the previous section we have produced a sentence with the representations of its meanings. It is a consequence of compositionality that the same parts can be used for the production of other sentences. For instance, we may combine *believes that a stranger crippled John's cow* as well with *every woman*, yielding:

$$(23) \text{ Every woman believes that a stranger crippled John's cow.}$$

This sentence has the same ambiguity as we have discussed in the first section: the stranger may either depend on the belief alternatives of the woman under consideration (the *de dicto* reading), or be independent of those alternatives (the *de re* reading), but still dependent on which woman is considered. There also is a reading in which all women suspect the same individual, but that reading will not be considered here.

We obtain the *de re* the reading of (23) in the same way as the *de re* the reading of (20). We have not specified the meaning of *every* nor of *every woman*, but the final result will not be surprising. That is equivalent with:

$$(24) \text{ de re (IF): } \forall z [W(v, z) \rightarrow \forall w \in \text{Bel}(v, z) \exists x_{/w} [\text{Str}(w, x) \wedge \exists y_{/w} [\text{Cow}(w, y, J) \wedge Cr(w, x, y)]]]$$

This shows that in IF the *de re* reading of (23) can easily be obtained in a compositional way.

Next we follow the same procedure in DL: combine the *de re* reading (19) with the meaning of *every woman*. This yields a result that is equivalent with

$$(25) \text{ de re (DL): } \forall z [W(v, z) \rightarrow \forall w \in \text{Bel}(v, z) \exists x [= (x) \wedge \text{Str}(x) \wedge \exists y [= (y) \wedge \text{Cow}(y, J) \wedge Cr(w, x, y)]]]$$

This result does *not* represent the desired meaning. It says, due to $=(x)$, that x does not depend on other variables, hence that for determining the stranger it is not relevant which belief alternative, nor which woman is considered: all women hold a suspicion against the same stranger. This is incorrect; we aimed at obtaining the reading that each woman may have her own suspect.

This incorrect result is a consequence of the meaning assigned to the *de re* reading of *believe that a stranger crippled John's cow*: in (19) it is formalized by $=(x)$ that the stranger does not depend on anything, and thus $\exists x$ is impeded for any influence of other variables. This shows that DL is *not* suitable for obtaining the *de re* meaning of (20) and (23) in a compositional way. For the *de dicto* reading there is no problem because then $=(x)$ does not occur, hence x may depend on z .

The problem can easily be generalized. We might add another factor which has influence on the choice of the stranger. For instance:

(26) *In every town every woman believes that a stranger crippled John's cow.*

In IF logic we can use the meaning of (23) and embed that under the scope of the quantifier for *every town*. In DL that does not work: $\exists x$ is protected against influence of *every town*, hence all women in all towns have the same suspect.

An issue that is related with our discussion is the translation between IF and DL. In [30] a translation is given between sentences of DL and Σ_1^1 (in both directions). In [15] translating between sentences of IF and Σ_1^1 is said to be simple. By combining these translations one obtains a translation between sentences of the two logics. But our discussion shows that translating between formulas is not possible:

THEOREM 6.1. There exists no meaning preserving translation between formulas of IF and of DL.

PROOF. Consider:

(27) IF: $\forall y \exists z_{/x} [z \neq x]$

(28) DL: $\forall y \exists z [= (y, z) \wedge z \neq x]$

The first formula says that z is independent of x . So z may depend on any other variable, even on variables that do not occur in the formula. There are infinitely many candidates. In DL it cannot be expressed that a variable depends on an infinite set of variables, it can only be said to depend on some finite fixed set. So there is in DL no formula that is equivalent with (27).

The analogous reciprocal problem arises. In (28) z only depends on y , so z is independent of all other variables, which are infinitely many. But in IF this cannot be expressed. So in IF there is no formula equivalent with (28). ■

COROLLARY 6.2. There is no compositional meaning preserving translation between IF and DL.

In [19] a meaning preserving translation is defined between formulas of IF and DL for the case that only a fixed finite set of variables is considered; the same restriction is used by Mann [20]. This restriction is understandable because it makes the mathematical theory easier. However, it takes away an essential feature of IF. Our application would no longer be possible because it exploits the IF property that it a variable can be declared to be independent of some variables, but at the same time can depend on any quantifier that will arise in any context in which the formula is used.

7. Conclusion

Suppose that in the analysis of a natural language sentence the existence of an individual (or entity) is stated. Then several factors (place, time, person, someone's belief alternatives, ...) may have influence on which individual is intended. In most sentences these factors are not mentioned explicitly, and assumed to be fixed and given by context. But in case a factor is mentioned explicitly and happens to be universally quantified (e.g. by *every woman* or *in every town*), the different values of this factor determine different individuals. Compositionality requires that the meaning for the expression without the explicit quantification can also be used when the factor is universally quantified and thereby becomes dependent of that factor. We have seen that IF logic has this property, whereas DL does not have it, because the dependence statements impedes other dependencies. Therefore IF is suitable whereas DL is *not* suitable for compositional semantics of natural language. In a compositional approach to natural language semantics, the notion 'independence' must be the fundamental notion, and not 'dependence'.

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