

Anaphora Resolution: A Centering Approach

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Abstract

We start by describing the problem of anaphora resolution and discuss approaches to modeling this problem. Centering Theory (CT), which is an approach to modeling certain aspects of local coherence in discourse, includes within it the component that models anaphora resolution. However, CT itself is not a theory of anaphora resolution. It was developed as part of a theory of local coherence. Subsequently many researchers have attempted to use CT or some modified versions of CT for anaphora resolution. This has led to some very interesting work but also raised issues and questions as to what CT is about. We attempt to clarify some of these issues.

1. Anaphora Resolution with Centers of Attention

Anaphora resolution in discourse - a coherent sequence of utterances - is the task or process of identifying the referents of expressions which we use to denote discourse entities, i.e., objects, individuals, properties and relations that have been introduced and talked about in the prior discourse. The importance of modeling this process cannot be overstated. Computing the meaning of a discourse is commonly understood as partly the process of connecting the information in the upcoming utterance with the information

contained in the prior discourse. Before we can do this, however, we need to assign an interpretation to all the elements of the utterance and then to the utterance as a whole. In many cases, the interpretation of some elements in the sentence can only be assigned relative to the prior discourse context – *anaphoric expressions* comprise one such class of elements.

In early approaches to anaphoric reference in AI and linguistics, the task of anaphora resolution was relegated to syntax, which provided filters such as grammatical agreement constraints, and open-ended semantic inference that drew on, among other things, world knowledge and inference procedures to identify the appropriate referent. However, it was soon recognized that while syntactic constraints were very limited in constraining the search for anaphoric referents on the one hand, the mechanism of open-ended semantic inference, on the other hand, was too knowledge intensive and complex - requiring reasoning over the entire space of discourse at once - and therefore computationally unfeasible.

In 1977, a different view to anaphora resolution arose out of the work of Barbara Grosz (Grosz, 1977) which rests on a fundamental and singularly important assumption regarding the attentional status of discourse entities: at any given point of the discourse, the discourse participants' attention is centered on a set of entities, a proper subset of all the entities being talked about in the discourse. Furthermore, for a given utterance, the discourse participants' attention is centered on a singleton entity, and the rest of the utterance makes a predication about this entity. The notion of the center of attention specific to utterances is very similar to the notion of "topic" in linguistics, where it is defined as what is "talked about" in the utterance. The approach for anaphora resolution with this centering view is that the search for the referents of anaphoric expressions should be restricted to the set of centered entities, the assumption being that in discourse, it is these entities that we are most likely to continue to talk about and refer to with the use of anaphoric expressions. Furthermore, a partial ordering is imposed on the elements of the set, so that some entities are more centered than others. Such a preference ordering on the possible candidate referents for anaphoric expressions significantly simplifies the "nature" of inference that would be needed and at the same time minimizes the "amount" of inference. Another significant proposal was that the set of centered entities can be partially determined by the linguistic structure of the utterance itself. The consequences for all these ideas were tremendous because it meant that it was possible to set aside, to a significant extent, the role of open-ended inferencing for anaphora resolution and look instead to more easily identifiable surface features of the utterance as the solution and explanation for at least part of the problem.

While Grosz laid out the general framework for the Centering process, her work did not suggest the exact mechanisms whereby the centered entities could be identified. In 1979, Candy Sidner extended Grosz's framework by precisely defining the notion of the utterance-based center linguistically and also provided a mechanism for using centers to identify referents of pronouns.

Sidner invoked several Centering structures - singleton sets called “discourse focus” and “actor focus”, and a set called the “potential foci” which can contain one or more elements. The “discourse focus” is equivalent to the center of the utterance, i.e., the entity about which some predication is made by the utterance. The “actor focus” is the discourse entity that is predicated as the agent of the event in the utterance. The “discourse focus” is identified using a set of rules that refer to the linguistic structure of the utterance as well as the state of the existing data structures when the utterance containing the pronoun is processed. A referent for a pronoun is identified primarily with the actor focus or the discourse focus, unless it is ruled out by some specified criteria, in which case an alternate candidate referent is considered from the set of “potential foci”, which contains entities other than the two primary foci. A significant aspect of Sidner’s work is that she does not rule out the role of inference in pronoun interpretation, but instead only constrains it in nature and amount. The nature of inference needed is different from earlier open-ended inference systems because it only involves checking for contradictions once a candidate referent is chosen using the structurally determined preference ordering; this allows for a much simpler knowledge base and reasoning procedures. The amount of inference needed is also reduced because of the preference ordering, so that as soon as an entity is identified for which no contradictions arise, no other inferencing is needed.

2. Centering Theory: Modeling Local Coherence with Centers of Attention

Centering Theory arose from the work of Aravind Joshi and Steve Kuhn in 1979 (Joshi and Kuhn, 1979), where the concepts of the “center” and “Centering” were first introduced as a way to specify an almost monadic calculus approach to discourse interpretation. Joshi and Kuhn showed that inferences of a certain class are more easily computed by using a monadic representation for utterances. However, they were also interested in computing the difficulty of deriving the necessary inferences.

While not explicitly stated by Joshi and Kuhn, the Centering process was assumed to be a local phenomenon operating over successive utterances. In the meantime, Grosz’s work on global and local discourse processing had also been formalized by Grosz and Sidner (Grosz and Sidner, 1986) and it was possible to place CT in its proper place in a complete theory of discourse processing. Grosz and Sidner provided a framework for discourse structure as a composite of three interacting constituents: a linguistic structure, an intentional structure, and an attentional state. The linguistic structure is determined by the intentional structure and comprises the utterances of the discourse grouped together hierarchically into discourse segments. The attentional state is an abstraction of the discourse participants’ center of attention as the discourse unfolds. Each discourse segment is associated with a fixed attentional state relevant to the overall discourse – the

global attentional state. A local attentional state is associated with each utterance within the segment. The local attentional state is inherently dynamic and can remain constant or change from utterance to utterance within the segment.

Centering Theory (Grosz, Joshi and Weinstein, 1983;1986;1995) was proposed as a model of the local attentional state, i.e., of the dynamic attentional state within the discourse segment. Following up on the concerns of Joshi and Kuhn, it explicates more clearly and formally the particular linguistic and attentional state factors that contribute to the ease or difficulty in interpreting a discourse segment. The notion of inferential complexity or difficulty was recast as the term of “coherence”. The first factor that contributes to coherence is given as a further explication of Joshi and Kuhn’s “change of center” rule, and accounts for the difference in coherence between the following two discourse segments:

1. (a) John went to his favorite music store to buy a piano.
(b) He had frequented the store for many years.
(c) He was excited that he could finally buy a piano.
(d) He arrived just as the store was closing for the day.
2. (a) John went to his favorite music store to buy a piano.
(b) It was a store John had frequented for many years.
(c) He was excited that he could finally buy a piano.
(d) It was closing just as John arrived.

Discourse (1) is intuitively more coherent than discourse (2). This difference may be seen to arise from the number of changes in the center. Discourse (1) centers a single individual ‘John’, describing various actions he took and his reactions to them. In contrast, discourse (2) seems to flip back and forth between ‘John’ and ‘the store’. These “changes in aboutness” or “changes of centers” makes discourse (2) less coherent than discourse (1).

The second observation that CT captures with discourses (1) and (2) establishes the correlation of center changes and the degree of coherence with the linguistic form of the utterances. Both discourses convey the same information, but in different ways. They differ not in content or what is said, but in expression or how it is said. The variation in “changes of attentional state” that they exhibit arises from different choices of the way in which they express the same propositional content. The different linguistic choices further engender different inference demands on the hearer or reader, and these differences in inference load underlie certain differences in coherence between them.

In addition to the different linguistic choices pertaining to the realization of the propositional content of the utterance as a whole, CT also identifies different linguistic choices made for realizing particular elements within the propositional content of the

utterance. These are choices in referring expression form. Pronouns and definite descriptions are not equivalent with respect to their effect on coherence. CT characterizes the perceived coherence of the use of pronouns and definite descriptions by relating different choices to the inferences they require the hearer or reader to make. The following variations of a discourse illustrate this relationship:

3. (a) Terry really goofs sometimes.
- (b) Yesterday was a beautiful day and he was excited about trying out his new sailboat
- (c) He wanted Tony to join him on a sailing expedition.
- (d) He called him at 6 A.M.
- (e) He was sick and furious at being woken up so early.
- (e')) Tony was sick and furious at being woken up so early.
- (f) He told Terry to get lost and hung up.
- (g) Of course, he hadn't intended to upset Tony.
- (g') Of course, Terry hadn't intended to upset Tony.
- (g'') Of course, Terry hadn't intended to upset him.

In discourse (3), it is the use of the pronoun in utterance (3e) that is in question. While we can tell that the pronoun *He* refers to 'Tony', the use of the pronoun here is potentially confusing. CT claims that this is because, until utterance (3d), 'Terry' has been the "center of attention", and therefore the most likely referent of the pronoun. This claim rests on the assumption that hearers expect speakers to continue talking about the entity that is in the "center of attention". The confusion therefore results because we tend to assign the reference of the pronoun to the center of attention as soon as we encounter it but have to backtrack (a phenomenon called "garden-path") when we process the rest of the sentence and find something that contradicts our assumption. In this particular example, we backtrack when we get to the word *sick* and from the prior utterances in the discourse, reason that it must be 'Tony' and not 'Terry' who is sick. As the careful reader will have noticed, the assumed preferences for determining the referents of pronouns in CT is reminiscent of Sidner's model. We will return to this comparison at the end of this section where we discuss the relation between anaphora resolution and Centering theory.

The confusion arising from (3e) is removed if the pronoun is replaced with the full noun phrase 'Tony' as shown in (3e'). The conjecture in CT, therefore, is that when the center of attention shifts to another entity, the form of referring expression used to denote the new centered entity has consequences for the processing load required for interpreting the utterance. A pronoun used to refer to the new centered entity increases the processing load because it causes backtracking from the interpretation of the old centered entity and thus from the interpretation of the utterance itself. A full noun phrase on the other hand shifts the center of attention before the rest of the utterance is processed and therefore entails less processing.

The three variants (3g), (3g') and (3g'') provide an illustration of yet another type of difference in coherence due to the form of referring expression. This arises when multiple entities are talked about from one utterance to the next. By the time (3f) is processed, the center has shifted from 'Terry' to 'Tony', so that in (3g), we expect 'Tony' to be the center of attention. This expectation is borne out in (3g) since 'Tony' is indeed mentioned again. However, what makes this sentence very odd and hard to process is that 'Terry' is also mentioned in (3g), but while the centered 'Tony' is referred to with a full noun phrase, the non-centered 'Terry' is referred to with a pronoun. This increased processing is reduced when a full noun phrase is used for 'Terry' instead of the pronoun, as in (3g') or (3g''), so that we are able to shift the center before processing the rest of the utterance, thus avoiding any backtracking. The type of coherence variation found in these utterances is due to the fact that both the centered entity in (3f) as well as another entity are mentioned again in (3g) and its variants, but in (3g), it is the non-centered entity from (3f) that is referred to with a pronoun.

CT provides a set of definitions, constraints and rules to formalize the three-way relationship discussed above, i.e., the relationship between attentional state, the degree of coherence and linguistic form (for the realization of full propositional content as well as for the realization of discourse entities). The CT definitions, constraints and rules are given below.

Definitions:

- (D1.) Each utterance U in a discourse segment is assigned a set of *forward-looking centers*, $C_f(U)$, where *centers* are discourse entities realized in the utterance.
- (D2.) Each utterance other than the segment-initial utterance is assigned a single *backward-looking center*, $C_b(U)$.
- (D3.) The *backward-looking center* of utterance U_{n+1} connects with one of the *forward-looking centers* of U_n .
- (D4.) The elements of $C_f(U_n)$ are partially ordered to reflect relative prominence or salience in U_n . In English, the C_f is ordered according to grammatical role.
- (D5.) The more highly ranked an element of $C_f(U_n)$, the more likely it is to be $C_b(U_{n+1})$.
- (D6.) The most highly ranked element of $C_f(U_n)$ is called the *preferred center*, $C_p(U_n)$.
- (D7.) A transition relation holds between each utterance pair U_n and U_{n+1} in a segment. There are four types of transitions, which describe center continuation, center retention, and two types of center shifting. The transitions are shown in Table 1.

Constraints:

- (C1.) There is precisely one backward-looking center $C_b(U_n)$.
 - (C2.) $C_b(U_{n+1})$ is the highest ranked element of $C_f(U_n)$ that is realized in U_{n+1} .
- Constraint C1 says that there is one central discourse entity that the utterance is about. Constraint C2 states that the ranking or ordering of the forward-looking centers in U_n

determines which of them realized in U_{n+1} will become the backward-looking center of U_{n+1} .

Rules.

(Rule 1.) If some element of $C_f(U_n)$ is realized as a pronoun in U_{n+1} then so is $C_b(U_{n+1})$.

(Rule 2.) With respect to Table 1, sequences of the CONTINUE transition are preferred to sequences of the RETAIN transition, which are preferred to sequences of the SMOOTH-SHIFT transition, which are preferred to sequences of the ROUGH-SHIFT transition.

Rule 1 is often called the “Pronoun Rule”. It is important to note that the inference load due to Rule 1 is not part of the inference load characterized by the transitions. Rule 1 is thus independent of the transitions. This independence of Rule 1 is an important consideration when thinking of the relation between CT and anaphora resolution. The inference load due to Rule 1 can be regarded as a binary measure, simply stating whether or not Rule 1 has been violated. With this rule, we can now explain the varying degrees of coherence for utterances (3g-3g’’) in discourse (3). The centering analysis for this discourse is shown in Table 4. After ‘Tony’ is established as the center (the C_b) in (3e), this center continues in (3f), but with the re-introduction of ‘Terry’ as a potential center. In (3g), both ‘Tony’ and ‘Terry’ are mentioned but since ‘Tony’ is higher ranked than ‘Terry’ in (3f), it is ‘Tony’ that is retained as the C_b in (3g). However, this utterance creates a Rule 1 violation because the C_b , ‘Tony’, is not realized with a pronoun whereas ‘Terry’, which is not the C_b , is. The only difference between (3g) and (3g’-3g’’) is that the latter does not violate Rule 1, the transitions remaining the same. The oddness of (3g) is therefore explained by Rule 1.

Rule 2 provides a formal characterization of the perceived differences in coherence for discourse segments in terms of an ordering on transition sequences. The less frequent the shifts in a discourse, the more coherent it is. Discourse (1) above is characterized by Continue transitions throughout the segment (Continue, Continue, Continue – see Table 2) describing a highly coherent discourse, whereas discourse (2) is characterized by switches between Retain and Continue (Retain, Continue, Retain – see Table 3), describing a less coherent discourse.

3. Centering Theory and Anaphora Resolution

As stated right in the beginning, the main goal of CT is to characterize certain aspects of local coherence. Differences in coherence result from changes in the center of attention, captured by the Centering transitions and transition ordering, and from the different expressions in which centers are realized. In particular, pronouns and definite descriptions engender difference inference demands on the hearer. CT, however, is not to be seen as a theory of anaphora resolution. The incorporation of referring expressions in

the account of local coherence has led many researchers to use the CT as part of anaphora resolution algorithms. This has led to some very interesting research. At the same it has led to some confusion in the literature associated with CT.

The first point to appreciate is that there is undoubtedly a very relevant connection between CT and anaphora resolution. As the careful reader will have deduced, the garden-path effects with the interpretation of the pronouns illustrated in discourse (3) is reminiscent of the preference ordering utilized by Sidner for the reference resolution of pronouns. In Sidner's model, the "center of attention" is equivalent to the "discourse focus" and like Sidner, CT utilizes this preference for the "center of attention" to continue over successive utterances. The relative preference of the "actor focus" as the next center of attention is also captured with the "preferred center" in CT. At a first look, it may seem that Sidner's use of the "center of attention" to determine the referents of pronouns and CT's use of the same to explain how incorrect referents are assigned to pronouns results in a paradox. But a closer look shows that it isn't really so, because like CT, Sidner also allows for garden-paths on the referents of pronouns by further invoking inference procedures (albeit unspecified) to check for contradictions. So Sidner's goals and CT's goals are very much alike, in that they both assume very similar preference for the "initial" resolution of pronouns which can be contradicted with further information. The difference between the two is that CT goes further to formalize the nature and difficulty of the contradictory inferences in terms of utterance pair transitions and uses the formal system as a way to compute the degree of coherence of a discourse segment.

Anaphora resolution algorithms that want to obviate the need for inference procedures and want to model the preferential rules for pronoun resolution should use the common part underlying the two described models. Sidner's inference rules for computing contradictions should be left out (or at least relegated to another interacting component) as should the part in CT that deals with the computation of coherence with the transitions and transition orderings. More formally, the common aspect of Sidner's model and CT are captured in CT with (i) the list of *forward-looking centers*, (ii) the *backward-looking center*, (iii) the *preferred center*, and (iv) Rule 1, the "Pronoun Rule". These data structures and rules are sufficient to set the initial preference for the referents of pronouns. Furthermore, corpus studies and studies of naturally occurring data of the form of referring expressions have shown that to a large extent speakers adhere to the preference orderings and Rule 1, so that much mileage can be achieved by building in these preferences into anaphora resolution algorithms, as Sidner had conjectured. However, while some anaphora resolution algorithms have used these very data structures and shown good results, others have used CT in totality, i.e., together with the transitions and transition orderings, to compute the referents of pronouns (for example, the centering algorithm – called the BFP algorithm - for pronoun resolution in Brennan et al., 1987). In addition to being theoretically misguided, the latter approach also yields contradictory results for the initial preferential resolution of pronouns (Kehler, 1997). An Optimality theory based version of the BFP algorithm and a comprehensive overview of

Centering together with a historical development of Centering Theory and its applications can also be found in Beaver (2004).

4. Unspecified Aspects of Centering

Some parameters and constants in Centering, both from the perspective of anaphora resolution and local coherence were left unspecified in the original models. Two of these in particular have led to a great deal of research.

The first is determination of the preference ordering on the list of forward-looking centers or determination of relative salience of discourse entities in an utterance. This is crucial for the initial interpretation assignments for pronouns. Cross-linguistic investigation of the mechanisms that languages use to realize discourse functions like “topic” shows that different ranking criteria need to be used for different languages. In English, relative salience is largely predicted by grammatical role, as was correctly assumed in CT. Other languages use other mechanisms. In Japanese, which uses the morphemes *wa* and *ga* to distinguish topics and subjects and special forms of the verb for marking empathy, topic and empathy marked entities are ranked higher than subjects. German uses word order in some syntactic contexts to indicate salience, positioning higher ranked entities before lower ranked ones. Other languages on which such research has been conducted include Finnish, Greek, Hindi, Italian, Russian and Turkish.

The second is the specification of what constitutes the *utterance*, which in CT is the linguistic locus of the local attentional state. Discourse centers, both backward-looking and forward-looking, are computed for each utterance. That is, each utterance serves as a center update unit. In attempting to characterize the linguistic encoding of a center update unit, complications rise from complex sentence structures. Up-to-date research on this issue suggests that complex sentences may project different center update units depending on their internal structure.

In early theoretical work on characterizing the center update unit in Centering, it was suggested that complex sentences be broken in clauses each of which forms an autonomous center update unit, with the possible exception of relative clauses and complement clauses. Treating adverbial clauses as autonomous center update units predicts that a pronoun in a fronted adverbial clause, as in (4c) below, is anaphorically dependent on an entity already introduced in the immediately prior discourse and not on the subject of the main clause it is attached to:

4. (a) (Jim) Kern_i began reading a lot about the history and philosophy of Communism
(b) but never 0_i felt there was anything he as an individual could do about
(c) When he_i attended the Christina Anti-Communist Crusade school here about

six months ago

(d) Jim_i (Kern) became convinced that he as an individual could do something constructive in the ideological battle

(e) and 0_i set out to do it

This view on backward anaphora was also professed in earlier work by Kuno, who asserted that there was no *genuine* backward anaphora: the referent of an apparent cataphoric pronoun must appear in the previous discourse. Empirical data later showed that this view of backward anaphora cannot be maintained. Corpus studies show that cataphoric pronouns can appear discourse initially.

Experimental work focusing on complex sentences of the type that includes adverbial clauses suggests that adverbial clauses are processed as a single unit with the matrix clause. Specifically, native speakers of English tend to interpret the ambiguous subject pronoun in (5) as *the groom*, i.e., the subject of the preceding clause, even when the adverbial in the second main clause is semantically varied (*however, as a result, moreover, then* etc). This pattern contrasts with the interpretation of the subject pronoun (6) for which no consistent tendency is identified, indicating that in this case the interpretation of the pronoun is most likely determined by the semantics of the predicates of the main and adverbial clause and the relation between them.

5. The groom hit the best man. *However*, he...

6. The groom hit the best man *although* he...

Other experimental work on the interpretation of a subject pronoun following a complex sentence indicates that referents in subject position in adverbial clauses are not favored for the interpretation of a subsequent pronoun. In (7) and (8), for example, the subject pronoun is interpreted as *the conductor*, i.e., the referent of the matrix clause, even when the adverbial clause is postposed with respect to the main clause.

7. After the tenor opened his music store the conductor sneezed three times. He...

8. The conductor sneezed three times after the tenor opened his music score. He...

Data such as the above would be a challenge for a Centering-based anaphora resolution algorithm which processes one clause at a time because there is no way of distinguishing between (5) and (6). At the same time, these data are consistent with Centering and Centering's Pronoun rule under the assumption that adverbial clauses are not processed as independent update units. Under this assumption, Centering would predict the pattern observed in (5), (7) and (8). Centering's pronoun rule would not make a prediction for (6) with respect to the entities introduced in the main clause because they belong to the same unit as the pronoun. Additional evidence for treating the entire sentence as a single update unit comes from corpus work exploring various parameters that can be set for

Centering and the number of Centering rules that they would violate. This type of work suggests that overall treating the whole complex sentence as a center update unit leads to fewer violations of the Pronoun rule.

Studies of Centering in relative clauses present conflicting results which need further research to be reconciled. On the one hand are discourses like (9) that suggest that entities mentioned in relative clauses (9b) are less salient than in the main clause (9a), as indicated by the use of the subsequent use of full noun phrase in (9c). In fact, a pronoun used instead of the full noun phrase would probably be interpreted as Mr. Taylor, i.e., the entity in the main clause.

9. (a) Mr. Taylor_i, 45 years old, succeeds Robert D. Kilpatrick_j, 64,
(b) who_j is retiring, as reported earlier.
(c) Mr. Kilpatrick_j will remain a director.
(d) He_i ...#He_j...

On the other hand are discourses like (10) showing the opposite pattern from that in (9). Such data comes from work that looks at different types of relative clauses, specifically non-restrictive and restrictive with a definite or indefinite head. Complementary patterns in the use of pronouns and definite descriptions shows that non-restrictive clauses and restrictive clauses with an indefinite head pattern alike, and form an autonomous (but embedded and accessible) center update unit. In example (10), the subject pronoun in (10c) refers, without any garden-path effects, to the subject referent of the preceding relative clause and not the subject referent of the main clause, indicating that in this case the relative clause probably introduces a new update unit that is accessible to (10c) for center establishment.

10. (a) This Moses_i was irresistible to a man like Simkin_j
(b) who_j loved to pity and to poke fun at the same time.
(c) He_j was a reality-instructor.

5. Applications of Centering Theory as a model of Local Coherence

Some research illustrates the appropriate and correct application of Centering Theory. The four Centering transitions shown in Table 1 define four degrees of coherence within a discourse segment. A textual segment characterized by a sequence of Continue transitions demonstrates the highest degree of coherence and is perceived as a segment focusing on a single entity. Topic retains and smooth shifts to new topics are captured in the Retain and Smooth-Shift transitions. Indeed, numerous corpus studies have identified Continue, Retain and Smooth-Shift transitions. As expected, Rough-Shift transitions are rarely identified in corpora of written text which presumably maintain a high level of coherence. An exception to this pattern is observed in texts whose coherence is under

evaluation and therefore cannot be assumed. A typical kind of this type of text is student essays. Indeed, in a study of essays written by students, it has been shown that excessive number of Rough-Shift transitions per paragraph in students' essays correlates with low essay scores provided by writing experts .

A closer analysis of the essays reveals that the incoherence detected by a Rough-Shift measure is not due to violations of Centering's Pronominal Rule or other infelicitous uses of pronominal forms. The distribution of nominal and pronominal forms over Rough-Shift transitions reveals that in fact pronominal forms are avoided in Rough-Shift transitions. This observation indicates that the incoherence found in student essays is not due to the processing load imposed on the reader to resolve anaphoric references. Instead, the incoherence in the essays is due to discontinuities caused by introducing a rapid succession of new, undeveloped topics with no links to the prior discourse. In other words, Rough-Shifts pick up textual incoherence due to topic discontinuities.

Studies such as the one just described are supportive of the formulation of Centering as a model of local discourse coherence. They also show that the Centering model can be used successfully for practical applications, e.g., to improve automated systems of writing evaluation in testing and education. In fact, it has been shown that adding a Centering-based metric of coherence to an existing electronic essay scoring system (the system e-rated developed at the Educational Testing Service) improves the performance of the system by better approximating human expert scores. In addition, a Centering-based system of writing evaluation has exceptional pedagogical value. This is because the models offers the capability of directing students' attention to specific locations within an essay where topic discontinuities occur. It can illuminate broken topic and focus chains within the text of an essay by drawing the student's attention to the noun phrases playing the roles of C_b 's and C_p 's. Supplementary instructional comments could guide the student into revising the relevant section paying attention to topic discontinuities.

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	$C_b(U_{i+1}) = C_b(U_i)$ OR $C_b(U_i) = [?]$	$C_b(U_{i+1}) \neq C_b(U_i)$
$C_b(U_{i+1}) = C_p(U_{i+1})$	CONTINUE	SMOOTH-SHIFT
$C_b(U_{i+1}) \neq C_p(U_{i+1})$	RETAIN	ROUGH-SHIFT

Table 1: Centering Transitions

<p>(1a) John went to his favorite music store to buy a piano. $C_f = \{\text{John, store, piano}\}$, $C_p = \text{John}$, $C_b = ?$, Transition = undef.</p>
<p>(1b) He had frequented the store for many years. $C_f = \{\text{John, store}\}$, $C_p = \text{John}$, $C_b = \text{John}$, Transition = Continue</p>
<p>(1c) He was excited that he could finally buy a piano. $C_f = \{\text{John, piano}\}$, $C_p = \text{John}$, $C_b = \text{John}$, Transition = Continue</p>
<p>(1d) He arrived just as the store was closing for the day. $C_f = \{\text{John, store}\}$, $C_p = \text{John}$, $C_b = \text{John}$, Transition = Continue</p>

Table 2: Centering Analysis for Discourse (1)

<p>(2a) John went to his favorite music store to buy a piano. $C_f = \{\text{John, store, piano}\}$, $C_p = \text{John}$, $C_b = ?$, Transition = undef.</p>
<p>(2b) It was a store John had frequented for many years. $C_f = \{\text{store, John}\}$, $C_p = \text{store}$, $C_b = \text{John}$, Transition = Retain</p>
<p>(2c) He was excited that he could finally buy a piano. $C_f = \{\text{John, piano}\}$, $C_p = \text{John}$, $C_b = \text{John}$, Transition = Continue</p>
<p>(2d) It was closing just as John arrived. $C_f = \{\text{store, John}\}$, $C_p = \text{store}$, $C_b = \text{John}$, Transition = Retain</p>

Table 3: Centering analysis for Discourse (2)

<p>(3a) Terry really goofs sometimes. $C_f = \{\text{Terry}\}$, $C_p = \text{Terry}$, $C_b = ?$, Transition = undef.</p>
<p>(3b) Yesterday was a beautiful day and he was excited about trying out his new sailboat. $C_f = \{\text{Terry, sailboat}\}$, $C_p = \text{Terry}$, $C_b = \text{Terry}$, Transition = Continue</p>
<p>(3c) He wanted Tony to join him in a sailing expedition. $C_f = \{\text{Terry, Tony, expedition}\}$, $C_p = \text{Terry}$, $C_b = \text{Terry}$, Transition = Continue</p>
<p>(3d) He called him at 6 A.M. $C_f = \{\text{Terry, Tony}\}$, $C_p = \text{Terry}$, $C_b = \text{Terry}$, Transition = Continue</p>
<p>(3e) He was sick and furious at being woken up so early. $C_f = \{\text{Tony}\}$, $C_p = \text{Tony}$, $C_b = \text{Tony}$, Transition = Smooth-shift</p>
<p>(3e') Tony was sick and furious at being woken up so early. $C_f = \{\text{Tony}\}$, $C_p = \text{Tony}$, $C_b = \text{Tony}$, Transition = Smooth-shift</p>
<p>(3f) He told Terry to get lost and hung up. $C_f = \{\text{Tony, Terry}\}$, $C_p = \text{Tony}$, $C_b = \text{Tony}$, Transition = Continue</p>
<p>(3g) Of course, he hadn't intended to upset Tony. $C_f = \{\text{Terry, Tony}\}$, $C_p = \text{Terry}$, $C_b = \text{Tony}$, Transition = Retain</p>
<p>(3g') Of course Terry hadn't intended to upset Tony. $C_f = \{\text{Terry, Tony}\}$, $C_p = \text{Terry}$, $C_b = \text{Tony}$, Transition = Retain</p>
<p>(3g'') Of course, Terry hadn't intended to upset him. $C_f = \{\text{Terry, Tony}\}$, $C_p = \text{Terry}$, $C_b = \text{Tony}$, Transition = Retain</p>

Table 4: Centering analysis for Discourse (3)

KEYWORDS:

Anaphora resolution
Pronoun resolution
Centering
Discourse
Discourse structure
Linguistics
Pragmatics
Processing complexity
Inference
Topic
Coherence
Referring expressions
Discourse salience
Utterance
Complex sentences
Attentional state