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Collaborative Object Grouping in Graphics Editing Systems

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Abstract

Object grouping is an effective means for managing the complexity in graphics editing. However, research on collaborative object grouping has not been adequate. In this paper, we contribute a novel collaborative object grouping technique, called CoGroup. CoGroup can achieve maximal combined effects among compatible operations and preserve all users’ work in the face of conflict without the overhead of undoing and redoing conflict operations as in existing serialization approaches. CoGroup has been implemented in collaborative word processing (CoWord) and slide authoring (CoPowerPoint) systems and is generally applicable to a range of off-the-shelf commercial graphics applications, particularly CAD/CASE tools.

1. Introduction

Object-based graphics editing systems are a special type of graphics editing systems. A document of such systems consists of a collection of graphic objects like lines, circles, text boxes, etc. Each object has a set of attributes, such as color, size, position, etc. Users are allowed to create, delete objects or modify object attributes. Object-based graphics editing is the foundation of a wide range of off-the-shelf commercial applications, including slide authoring systems (e.g. Microsoft PowerPoint), word processors (e.g. Microsoft Word), CAD systems (e.g. AutoCAD) and CASE systems (e.g. Rational Rose). The goal of our research is to apply the Transparent Adaptation (TA) approach [16] to convert existing single-user graphics editing applications into real-time collaborative systems without changing their source code.

Documents of graphics editing applications (e.g. CAD systems) often contain a large number of objects with complex logical structures. Managing complex structures on the basis of individual object would cost significant efforts or sometimes may be infeasible. Object grouping, which packs multiple logically related objects into a single group-object and vice versa, is an effective means to help manage the complexity of graphics editing. When objects are grouped, they behave like a single object in response to modifications to any attribute. At the same time, some attributes (e.g. fill color) of group members can still be modified individually. Furthermore, a group-object can be a member in another group-object, which provides a multi-level hierarchical structure for managing complex documents. In summary, object grouping can not only prevent mistaken actions from breaking the logical relationship among group members, but also provide the convenience of modifying group members individually. Object grouping is a practically useful and frequently used function in existing single-user graphics editing applications, and thus must also be supported in TA-based multi-user collaborative versions.

Supporting collaborative object grouping is nontrivial due to the increased complexity in both the data model and the operation model of the collaborative graphics editing technique. First, existing collaborative graphics editing techniques often treat graphic objects as independent entities, but object grouping introduces the group relationships among graphic objects. Second, existing collaborative graphics editing techniques focus on supporting three types of basic operations: a CreateObj operation creates a new object (e.g. a line, circle, square, or textbox); a DeleteObj operation removes an existing object; and a ChangeAtt operation changes an attribute (e.g. size, color, or position) of an existing object. Object grouping requires support for two additional operations: a Group operation packs a collection of objects into a single group-object; and an Ungroup operation unpacks a group-object into a collection of member objects. We shall use the term grouping operation to mean either a Group or an Ungroup operation. The main technical challenge here is conflict resolution and consistency maintenance in the presence of group-objects and grouping operations in a TA-based real-time collaborative environment.

While collaborative editing has been an active area of research in the past decades, little has been done on the techniques for supporting collaborative object grouping. To our knowledge, there is only one prior work on collaborative object grouping in graphics editing systems, which is based on operation serialization [5]. In this work, undo and redo strategies are used to reorder operations for consistency maintenance in the face of conflict. Apart from the inherent high complexity and overhead involved in operation serialization, the work in [5] is incapable of preserving all users’ work in the face of conflict and is not suitable for application to existing graphics editing systems (detailed analysis and comparison shall be given in Section 5). In this paper, we contribute a novel collaborative object grouping technique, called CoGroup, which is based on the Operational Transformation (OT) technique [12][14][15] and on the TA approach [16]. The use of OT enables the CoGroup technique to resolve conflicts among grouping operations without using internal undo/redo; and the TA approach makes the CoGroup technique applicable to a wide range of existing graphics editing systems without changing their source code. The CoGroup work is the first collaborative...
object grouping technique based on OT and TA, and has been implemented in the CoWord and CoPowerPoint systems [16]. This paper reports the main research findings in designing and implementing the CoGroup technique.

The rest of this paper is organized as follows. Section 2 introduces background knowledge about OT and TA. Section 3 defines the conflict relations and MVSD combined effects among conflict and/or compatible basic and grouping operations. Section 4 discusses technical issues and solutions in supporting object grouping in the TA framework. In Section 5, the CoGroup approach is compared with related work. Finally, contributions and future work are summarized in Section 6.

2. Background on OT and TA

2.1 Basics of the OT Technique

OT was originally designed to support multiple users to insert and delete characters in replicated text documents concurrently and consistently [3][12][14]. The basic idea of OT is to transform an editing operation defined on a previous document state according to the effects of executed concurrent operations, so that the transformed operation can achieve the correct effect in the current document state. Despite its text editing origine, OT is independent of text documents and text editing, and has been applied to support consistency maintenance and user-initiated undo in collaborative editing of both text and graphics documents [1][8][10][15][16].

There are two underlying models in the OT technique: one is the data address model which defines the way data objects in a document are addressed by operations; the other is the operation model which defines the set of operations that can be directly transformed by OT functions. Different OT techniques may have different data and operation models.

In this paper, we assume the OT data address model is a tree of multiple linear address domains [2], as shown in Figure 1. In this model, a data object is mapped to a position in a linear addressing domain only if it has the position number as its address in this domain. A data object is a terminal object if it has no internal data structure or its internal data structure is not addressable. A data object is an intermediate object if it has an addressable internal data structure. A terminal object has no link leading to a lower level addressing domain, which represents this object’s internal addressing space. An object in this data address model can be uniquely addressed by a vector of position integers: \( \nu_p = [p_0, p_1, ..., p_i, ..., p_k] \) where \( \nu_p[i] = p_i, 0 \leq i \leq k \), represents one addressing point at level i.

The OT operation model assumed in this paper consists of three generic Primitive Operations (PO) [15]:
1. Insert \([pos, obj]\) denotes inserting object \(obj\) at position \(pos\).
2. Delete \([pos, obj]\) denotes removing object \(obj\) at position \(pos\).
3. Update \([pos, key, old_value, new_value]\) denotes changing the attribute \(key\), from \(old_value\) to \(new_value\), of an object at position \(pos\).

These POs are generic in the sense that they are independent of object types. With these POs, OT does not need any application-specific knowledge to do its work.

2.2 Basics of the TA Approach

TA is an innovative approach to converting single-user applications for multi-user real-time collaboration, without changing the source code of the original application [16]. The TA approach is based on a replicated system architecture where the shared single-user application is replicated at all collaborating sites, the use of the single-user application’s API (Application Programming Interface) to intercept and replay the user’s interactions with the shared application, and the use of the OT technique to manipulate the intercepted user operations for supporting responsive and unconstrained (i.e. concurrent and free) multi-user interactions with the shared application. The central idea of the TA approach is to adapt the data address and operation models of the shared application’s API to that of the OT technique.

More precisely, the TA approach can be described by a reference model, as shown in Figure 2. This reference model consists of three components: Single-user Application (SA), Collaboration Adaptor (CA), and Generic Collaboration Engine (GCE). The main functionalities of these components are sketched below.

The SA component provides conventional single-user interface features and functionalities. This component can be either an existing commercial off-the-shelf single-user application, or a new single-user functionality component in a multi-user collaborative system, but this component itself has no knowledge about multi-user collaboration.

The CA component provides application-specific collaboration capabilities and plays a central role in adapting the SA for collaboration. This component has the knowledge of the SA API but not its internals. At the center of this component is the module of Adapted Operation (AO), which represents the SA functionalities exposed by the API. The AO can be generated by the Local Operation Handler (LOH) module by intercepting local user’s interactions, or received by the Remote Operation Handler (ROH) module from remote users. With the AO residing between the API and OT, the task of adaptation between the API and OT is decomposed into two modules:

![Figure 1. The OT address model.](image-url)
Two operations \( O_1 \) and \( O_2 \) cannot belong to two different result objects, and concurrent operations may conflict with each other if they target common objects since their effects cannot be accommodated in the target or result objects at the same time. Moreover, two concurrent operations cannot be accommodated within the same target object at the same time. Consequently, two concurrent operations conflict since their effects cannot be accommodated in the target or result objects at the same time. These concurrent operations conflict since their effects cannot be accommodated within the same target object at the same time. Moreover, two concurrent operations may also conflict with each other if they target common objects since these common objects cannot belong to two different result objects at the same time. In [11] and [15], we have discussed in detail how to define and resolve conflicts among \( \text{ChangeAtt} \) operations. In this paper, we extend our prior work on conflict definition and resolution to grouping operations.

To define the conflict relation, we use the following notions: (1) \( \text{Type}(O) \) denotes the type of operation \( O \); (2) \( \text{Target}(O) \) denotes the set of identifiers of target objects of operation \( O \); and (3) \( \text{Att.Key}(O) \) denotes the attribute type of operation \( O \) if \( O \) is a \( \text{ChangeAtt} \) operation.

**Definition 1.** Conflict relation “\( \bigcirc \)”: Two operations \( O_1 \) and \( O_2 \) conflict with each other, expressed as \( O_1 \bigcirc O_2 \), if and only if (1) \( O_1 \) and \( O_2 \) are concurrent; (2) \( \text{Target}(O_1) \cap \text{Target}(O_2) \neq \emptyset \); and (3)

\[
\begin{align*}
& a. \quad \text{Type}(O_1) = \text{Type}(O_2) = \text{Group}; \text{ or} \\
& b. \quad \text{Type}(O_1) = \text{Type}(O_2) = \text{ChangeAtt} \text{ and } \text{Att.Key}(O_1) = \text{Att.Key}(O_2) .
\end{align*}
\]

**Definition 2.** Compatible relation “\( \bigodot \)”. Two operations \( O_1 \) and \( O_2 \) are compatible, expressed as \( O_1 \bigodot O_2 \), if and only if they do not conflict with each other; that is, \( \neg(\bigcirc) \).

According to the above definitions, sequential operations are compatible; operations without common target objects are compatible; and operations of different types are compatible. Conflict relations occur only between a pair of \( \text{Group} \) operations or a pair of \( \text{ChangeAtt} \) operations under the conditions specified in Definition 1. The conflict/compatible relations among the three basic operations and the two grouping operations are summarized in Table I (called a conflict relation triangle in [11]). The meaning of shaded cells will be explained in Section 4.6.

<table>
<thead>
<tr>
<th>Operation Types</th>
<th>CreateObj</th>
<th>DeleteObj</th>
<th>ChangeAtt</th>
<th>Group</th>
<th>Ungroup</th>
</tr>
</thead>
<tbody>
<tr>
<td>CreateObj</td>
<td>( \bigodot )</td>
<td>( \bigcirc )</td>
<td>( \bigcirc )</td>
<td>( \bigodot )</td>
<td>( \bigodot )</td>
</tr>
<tr>
<td>DeleteObj</td>
<td>( \bigodot )</td>
<td>( \bigcirc )</td>
<td>( \bigcirc )</td>
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<tr>
<td>ChangeAtt</td>
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</tr>
<tr>
<td>Ungroup</td>
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</tr>
</tbody>
</table>

### 3.2 Conflict Resolution by MVSD

For compatible operations, they can be applied without any special treatment and their effects can be combined in the target objects even if they target common objects. For conflict operations, however, special treatment is needed to resolve their conflict and maintain system consistency.

There are three possible ways of resolving operation conflict while maintaining consistency [11][15]:

1. **Null-effect**: none of the conflict operations has any final effect on the target object.
2. **Single-operation-effect**: only one operation has a final effect on the target object.
3. **All-operations-effect**: all operations have final effects on the target objects.

In [11] and [15], a Multi-Version Single-Display (MVSD) technique has been devised to achieve the all-operations-effect: multiple versions of the common target objects are created to accommodate the effects of all conflict operations, but only one version is displayed at the user interface. Users are allowed to...
choose to display any version at a time by using the system undo facility or a multi-version management tool [15].

The multi-versioning technique is capable of preserving all users’ work even in the face of conflict; the single-display strategy matches the single-user interface of existing graphic editing applications, and lends itself to integration with OT [15].

3.3 Combined Effects for Conflict and Compatible Operations

Based on the conflict/compatible relations given in Table I and the MVSD technique, we specify the combined effects among the five operations: CreateObj, DeleteObj, ChangeAtt, Group, and Ungroup, in this subsection.

According to Table I, a CreateObj operation is always compatible with all operations, including another CreateObj operation because the object to be created cannot be targeted by another concurrent operation.

A DeleteObj operation is always compatible with all other operations as well because the effect of a DeleteObj operation can be combined with the effect of any other concurrent operation targeting the same object.

1. The combined effect with another DeleteObj operation is the deletion of the target object (Figure 3-(b)). Their effects have been combined in the sense that the deleted object can be recovered only after undoing both operations [15].

2. The combined effect with a ChangeAtt operation is the change of the attribute and the deletion of the target object (Figure 3-(c)).

3. The combined effect with a Group operation is the creation of a group-object containing all member objects targeted by the Group operation, except the member object targeted by the DeleteObj operation (Figure 3-(d)).

4. The combined effect with an Ungroup operation is the unpacking of the member objects in the group-object targeted by the Ungroup operation and the deletion of the member object targeted by the DeleteObj (Figure 3-(e)).

5. The combined effect with another concurrent operation targeting the same object.

A ChangeAtt operation may conflict with another ChangeAtt operation under the condition specified in Definition 1; but it is always compatible with other operations because the effect of a ChangeAtt operation can be combined with the effect of any other concurrent operation targeting the same object.

1. The combined effect with a DeleteObj operation is illustrated in Figure 3-(c).

2. The combined effect with a Group operation is the creation of a group-object containing all target member objects, and the change of the attribute of one member object targeted by the ChangeAtt operation (Figure 3-(f)).

3. The combined effect with an Ungroup operation is the unpacking of all member objects inside the target group-object, and the change of attribute of the member object targeted by the ChangeAtt operation (Figure 3-(g)).

Examples for illustrating the combined MVSD effects of conflicting ChangeAtt operations targeting common non-group objects can be found in [11] and [15]. An example for the combined MVSD effects of conflicting ChangeAtt operations targeting group-objects shall be given in Section 4.2.

A Group operation may conflict with another concurrent Group operation if they target common objects; but it is always compatible with other operations because the effect of a Group operation can be combined with the effect of any other concurrent operation targeting the same object.

1. The combined effect with a DeleteObj or a ChangeAtt operation has been illustrated in Figure 3-(d) and Figure 3-(f), respectively.

2. The combined effect with an Ungroup operation is the unpacking of all member objects inside the target group-object (a member object targeted by the Group operation as well) targeted by the Ungroup operation (Figure 3-(h)).

An example for illustrating the combined MVSD effects of two conflict Group operations is given in Figure 4. Initially, the document contains five objects: G1, G2, ..., G5, and suppose two operations O1 = Group(G1, G5), O2 = DeleteObj(G2), O3 = DeleteObj(G2), O4 = ChangeAtt(G2, FillColor, red), O5 = Ungroup(G5), O6 = Ungroup(G5).

According to Table I, O3 and O4 are generated concurrently, as shown in Figure 4-(a). Since O1 and O2 target a common object G3, they conflict with each other. To achieve the MVSD effect, two versions G3O2 and G3O3 should be created to accommodate the effects of both O1 and O2, but only G3O2 is displayed in the group-object created by O1 (Figure 4-(b)), provided that O1 has a higher priority than O2 [15]. The version G3O3 is maintained internally in the group-object created by O2 but is invisible at the single-display strategy due to the single-display strategy. However, after O1 is undone, G3O2 shall become visible as shown in Figure 4-(c).
4. Supporting object grouping in the TA framework

In this section, we shall discuss the technical issues and solutions involved in supporting object grouping by means of OT in the TA framework.

4.1 The Group Objects Address Model

The first issue is how to map graphics objects, particularly group-objects, into an object address model that is compatible with that of OT as shown in Figure 1.

A wide range of graphics editing applications have provided varieties of mechanisms (in their APIs) for mapping any graphic objects, including group-objects, into a tree of linear addressing domains [16]. To illustrate this address mapping, consider the following example: Figure 5-(a) shows a graphic document when viewed from the user interface; and Figure 5-(b) shows the mapping of the graphic objects in this document to a tree of linear addressing domains when viewed from the API. In this example, the top three objects (G1, G2, and G3) are mapped into the top-level linear addressing domain in the tree; the member objects in the two group-objects G2 and G3 are mapped into two second-level addressing domains, respectively; and the member objects in group-object G4 are further mapped into a third-level addressing domain. As shown in this example, member objects of a group-object forms a separate linear addressing domain; a group-object (e.g. G4) can be a member object of a higher level group-object (e.g. G2), allowing multiple levels of object grouping.

Under the address model in Figure 5-(b), any graphic object can be accessed with the vector address used in OT (see Figure 1). For example, the address of the pentagon can be expressed as a vector address [2, 0, 1], where “2” refers to the group-object G3, “0” refers to the group-object G4; and “1” refers to the pentagon object.

![Figure 5. The group objects address model.](image)

4.2 Basic AOs targeting Group-Objects

In the TA framework (see Section 2.2), the user’s interactions with the single-user application are intercepted and expressed as Adapted Operations (AO). For the three basic operations, we have three corresponding basic AOs: CreateObjAO, DeleteObjAO, and ChangeAttAO. Effects of these basic AOs in the group-object address model can be fully captured by POs, so the built-in mechanisms of OT are capable of resolving conflicts among basic AOs without any additional mechanisms at the AO level.

A example of resolving conflicts among ChangeAttAOs targeting group-objects is shown in Figure 6. From the initial document state (Figure 6-(a)), three operations are generated concurrently: O1 = ChangeAttAO([0, 0], FillColor, red) to change the color of non-group object G1 into red, O2 = ChangeAttAO([0, 0], FillColor, green) to change the color of group-object G5 to green, and O3 = ChangeAttAO([0], FillColor, blue) to change group-object G6 to blue. According to the conflict definition, these three AOs conflict. Assume their priority relation is O1 > O2 > O3.

![Figure 6. A scenario of three conflict ChangeAttAOs.](image)

The conflicts among these AOs can be detected in OT from their common PO types (all are type Update), target attribute types (all are FillColor), and overlapping addresses, (O3.addr is the prefix of O2/O1.addr, and O2.addr is the prefix of O1.addr). These conflicts are solved with the conflict resolution algorithm for the Update PO [15] and the combined MVSD effects, shown in Figure 6-(b), is achieved. In this result, multiple versions for objects targeted by conflict AOs are created, but only the versions created by AOs with the highest priorities (e.g. G1O1, G2O2 and G3O2) are displayed.

4.3 Grouping AO Representation

For object grouping, we have two grouping AOs, named as GroupAO and UngroupAO, respectively. To determine the representation of these grouping AOs, it is necessary to analyze their effects on both the real objects (visible from the user interface) and the object address model (visible from the API).

As illustrated in Figure 7, the effect of a GroupAO on the real objects is to pack multiple target objects into a single group-object, and its effects on the internal addressing model include: (1) inserting a group-object in the current addressing domain (at the position before the first target object); and (2) moving all target objects into a lower level addressing domain (linked to the group-object). In moving these target objects, their original relative sequence relationships are preserved (see Figure 7-(b)).

The effect of an UngroupAO on the real objects is to unpack the target group-object into multiple member objects; and its effects on the address model include: (1) moving all member objects to the position of the target group-object in the higher...
level addressing domain; and (2) deleting the target group-object (see Figure 7-(c)).

(a) The initial state  (b) The state after grouping  (c) The state after ungrouping

Figure 7. Effects of GroupAO and UngroupAO.

It should be pointed out that after executing the UngroupAO operation, the document state returns to the previous state before the execution of the GroupAO operation at the user interface; but the internal addresses of these objects are not restored, as can be seen by comparing Figure 7-(a) and (c). These object grouping effects are supported by the APIs of all existing single-users applications we have investigated, including MS Word, MS PowerPoint and OpenOffice Presentation.

To facilitate grouping AOs adaptation, their representations must capture their effects on both the data objects (needed for replaying their effects in AO-API Adaptation (see Figure 2)), and on the object addressing space (needed for OT-processing in AO-PO Adaptation (see Figure 2)). Since both GroupAO and UngroupAO have the effect of moving existing objects between different addressing domains, we introduce a new operation, named MoveAO, to represent this effect. The MoveAO can be represented as follows:

- MoveAO(from, to, obj) denotes the effects of deleting the object obj at the address from and inserting the same obj at the address to.

Based on the basic AOs and MoveAO, the two grouping AOs can be represented as follows:

1. GroupAO(CreateObjAO(addr, go), MoveAO(from-1, to-1, obj-1), ..., MoveAO(from-n, to-n, obj-n)) denotes the effects of creating a group-object go at address addr and moving the target member objects obj-1, ..., obj-n from addresses from-1, ..., from-n, to new addresses to-1, ..., to-n at a higher level addressing domain.

2. UngroupAO(DeleteObjAO(addr, go), MoveAO(from-1, to-1, obj-1), ..., MoveAO(from-n, to-n, obj-n)) denotes the effects of deleting the target group-object go at address addr and moving the member objects obj-1, ..., obj-n from addresses from-1, ..., from-n, to new addresses to-1, ..., to-n at a higher level addressing domain.

It should be stressed that the object addresses used in all AOs are positional references in the tree of linear addressing domains (see Figure 1), rather than the visual locations of the data objects at the user interface.

4.4 Grouping AO Translation

OT works on an operation model that includes only three POs (see Section 2.1). For conflict resolution and consistency maintenance by OT, all AOs, including grouping AOs, must be translated into suitable POs according to their effects on the OT-related address model. Translation of the basic AOs is straightforward: a CreateObjAO has the effect of inserting an object in the address model, so it can be translated into an Insert PO; a DeleteObjAO has the effect of deleting an object from the address model, so it can be translated into a Delete PO; a ChangeAttAO has the effect of changing an attribute of an object in the address model, so it can be translated into an Update PO.

On the other hand, GroupAO and UngroupAO are compound AOs in the sense that they cannot be translated into a single PO. The translation of a compound AO consists of translating each composing AO into a list of POs.

Definition 3. Translation Rules for Grouping AOs. For each composing AO in a grouping AO, it is translated as follows:

1. if the composing AO is a basic AO: CreateObjAO/ DeleteObjAO/ChangeAttAO, then it is translated into a single PO: Insert/Delete/Update PO;

2. if the composing AO is MoveAO, then it is translated into a pair of POs: Delete and Insert, where the two POs must refer to the same object (which is different from a pair of independent Delete and Insert).

Let GroupAO-POList denote the translated PO list for GroupAO, UnGroupAO-POList denote the translated PO list for UngroupAO. Based on the translation rules in Definition 3, we have:

1. GroupAO-POList = [Insert(go-addr, go-ref), Delete(from-1, moref-1), Insert(to-1, moref-1), ..., Delete(from-n, moref-n), Insert(to-n, moref-n)].

2. UngroupAO-POList = [Delete(go-addr, go-ref), Delete(from-1, moref-1), Insert(to-1, moref-1), ..., Delete(from-n, moref-n), Insert(to-n, moref-n)].

It should be stressed that the translated PO list captures only part of the grouping AO effect (including the timestamps for detecting concurrency [14]) and priorities), which are needed for generic OT processing. Additional application-specific mechanisms are needed to detect and resolve operation conflict at the AO level, which are discussed in the following subsections.

4.5 Grouping AO Conflict Detection

Based on the AO representation and translation schemes discussed in Sections 4.3 and 4.4, conflicts among basic AOs can be fully detected and resolved by the mechanisms built in the generic OT technique [15]. However, detection of conflicts among GroupAOs requires the knowledge of operation type Group (see Definition 1), which is unknown to the OT component in GCE (see Figure 2). Therefore, conflict detection in the presence of grouping AOs requires additional mechanisms at the AO level.

According to Definition 1, a pair of GroupAOs may conflict under three conditions: (1) they are concurrent; (2) they have overlapping target objects; and (3) they have the same operation type GroupAO. OT is able to detect the first two conditions by examining the POs translated from GroupAOs, but the third condition must be checked at the AO level. To facilitate the check of the third condition and to propagate the concurrency and overlapping conditions result from the PO level to the AO level, we have established bi-directional references between each AO and its translated POs. A routine GetAO(P0) is provided to get the AO associated with the PO. Moreover, the underlying OT functions have been extended as follows: when a PO1 is transformed against a concurrent PO2 and found to have
overlapping target objects with PO2, this finding and PO2’s reference to its associated AO must be recorded in the transformed PO1. At the AO level, a routine POConcurrentAndOverlapping(PO1) is provided to check whether PO1 has been found to be concurrent and overlapping with another operation, and another routine GetCOAO(PO1) is provided to get the AO associated with PO2. Based on the above extensions, we are able to determine whether a GroupAO is in conflict with another GroupAO by invoking the GAOConflictDetection() routine defined in Figure 8.

4.6 Conflict Resolution and Combined Effects

4.6.1. The Need for AO-level mechanisms. OT is able to resolve conflicts among basic AOs, but additional mechanisms at the AO level are needed to resolve conflicts among GroupAOS. This is because resolving GroupAO conflicts requires semantic knowledge of the GroupAO and its representation, which are not captured by individual POs and hence unknown to the OT component in GCE. For the same reason, to achieve combined effects among compatible AOs in the presence of grouping AOs, additional mechanisms at the AO level are also needed. In other words, resolving conflicts among conflict operations and achieving the combined effects among compatible operations require the interaction and collaboration between the underlying generic OT component and the AO-PO Adaptation module in the TA framework (Figure 2).

An overall picture of the responsibility distribution between these two components is shown in Table I (see Section 3.1): the non-shaded cells indicate the sole responsibility areas of the generic OT component for resolving conflicts and achieving the defined combined effects among basic AOs; the shaded cells correspond to joint responsibility areas of OT plus additional AO-level mechanisms (in the AO-PO Adaptation module) for resolving conflict and achieving combined effects in the presence of grouping AOs.

The rest of this section shall focus on mechanisms for resolving conflicts and achieving combined effects for the shaded cells in Table I.

In the following discussion, we shall use the following auxiliary functions: (1) GetMove(POx) returns the composing MoveAO from which the PO POx is translated; and (2) GetCOMove(POx) returns the composing MoveAO of the grouping AO whose reference is recorded in the PO POx. Implementation of these functions is straightforward based on the AO-PO association and AO reference recorded in a transformed PO. Furthermore, we use the term Common Target MoveAO (CT-MoveAO) to mean a composing MoveAO of a grouping AO that moves a common target object targeted by another concurrent AO.

4.6.2. Resolving GroupAO Conflicts. According to the MVSD combined effect defined in Section 3.3, the conflict between two GroupAOS is resolved based on their priorities. Given two conflict GroupAOS: O1 with a higher priority and O2 with a lower priority, their common target objects should be packed in the group-object created by O1 and excluded from the group-object created by O2.

In the GroupAO representation, the effects of moving target objects are represented by composing MoveAOS. Therefore, for a pair of conflicting GroupAOS O1 and O2, there must be a CT-MoveAO in each of them, which target a common target object. Based on this observation, the strategy of resolving the conflict between O1 and O2 is as follows:

1. if the O1 is executed after O2, the from parameter of the CT-MoveAO of O1 should be set to the to parameter of the CT-MoveAO of O2, so that the common target object shall be moved to the group-object created by O1.
2. if O2 is executed after O1, the CT-MoveAO of O2 should be cancelled so that the common target object is excluded from the group-object created by O2.

Based on the above strategy, the routine GAOConflictResolution(TPO) is defined (Figure 9) for resolving the conflict between the GroupAO (obtained by calling GetAO) from which the TPO was translated and the GroupAO (obtained by calling GetCOAO) with which TPO was associated due to concurrency and overlapping relationship.

```c
if(GetAO(TPO).priority > GetCOAO(TPO).priority)
    GetMove(TPO).from = GetCOMove(TPO).to;
else
    GetMove(TPO).cancelled = true;
```

Figure 9. The routine for resolving conflicts among GroupAOS.

Based on the MVSD effect, our conflict resolution approach also supports selectively displaying versions that are hidden by default. Assume that between the two conflict GroupAOS O1 and O2, O1 has a higher priority than O2. According to the MVSD effect, two versions of the common target object are created, but only the version created by O1 is displayed. To display the version created by O2, a simple strategy is to undo O1. The disadvantage of this strategy is that all O1’s object-packing effects are unnecessarily discarded, including those non-common objects that are not targeted by O2. To preserve O1’s effects to the maximum extent, a better strategy is to partially undo the composing CT-MoveAO of O1. From the adjustment to this MoveAO while resolving the conflict between O1 and O2, it is clear that the effect of this undo is only to move the common target object from O1’s group-object into O2’s, while all other member objects in O1’s group-object are intact. A detailed discussion on this partial-undo based version selection scheme is beyond the scope and space limitation of this paper. The reader is referred to [15] for a detailed discussion on a full-undo based version selection scheme.

4.6.3. Achieving Combined Effects for Compatible Operations in the Presence of GroupAOS. According to the combined effects of concurrent and compatible operations
defined in Section 3.3 (see Figure 3), their effects should be accommodated on the common target object at the same time.

Here we shall focus in scenarios in which two concurrent and overlapping compatible AOs are involved and at least one of them is a grouping AO. Given a pair of AOs, O1 and O2 involved in such a scenario, suppose O1 is executed after O2. When O1 is executed, its parameters need to be adjusted according to the changes caused by O2 to achieve the combined effect. Next, we shall discuss adjustment strategies for different AO type combinations.

In the routines discussed in this section, the input parameter TPO is the transformed PO of the currently processed AO (i.e. O1). With TPO, O1 can be obtained by calling GetAO; O2 can be obtained by calling GetCOAO; the CT-MoveAO of O1 can be obtained by calling GetMove if O1 is a grouping AO; and the CT-MoveAO of O2 can be obtained by calling GetCOMove if O2 is a grouping AO.

Consider the scenario in which O1 is a GroupAO and O2 is a DeleteObjAO. When O1 is executed, the common target object has been deleted by O2. Therefore, this object should be excluded from the group-object created by O1. From the GroupAO representation, we know that the effect of moving the common target object is represented by the CT-MoveAO of O1, so our strategy for this scenario is to cancel the CT-MoveAO of O1. This strategy also applies to the AO combinations of UngroupAO versus DeleteObjAO (the DeleteObjAO targets a member object of the UngroupAO target group-object) and UngroupAO versus UngroupAO.

On the other hand, if O1 is a DeleteObjAO and O2 is a GroupAO, when O1 is executed, its target object has been moved into the group-object created by O1. Based on the GroupAO representation, we know that the current address of the common target object is indicated by the to parameter of O2's CT-MoveAO, so our strategy for this scenario is to set O1's address to the to parameter of O2's CT-MoveAO. This strategy also applies to AO combinations ChangeAttAO/DeleteObjAO versus UngroupAO (the ChangeAttAO/ DeleteObjAO targets a member object of the UngroupAO target group-object), DeleteObjAO versus GroupAO, and UngroupAO versus GroupAO.

Based on the above strategies, the routine for achieving combined effects for concurrent and overlapping GroupAO and DeleteObjAO is shown in Figure 10.

Figure 10. The routine for achieving combined effects for GroupAO and DeleteObjAO.

Consider the scenario in which O1 is a ChangeAttAO, O2 is an UngroupAO and they both target the same group-object. When O1 is executed, the common target group-object has been unpacked into a continuous range of multiple objects by O2 (see Figure 7-(c)). From the UngroupAO representation, we know that the address and length of the unpacked object range are indicated by O2's composing MoveAOs. Therefore, our strategy for this scenario is to set O1's effect range (i.e. address and length) to cover all unpacked objects. This strategy also applies to AO combinations DeleteObjAO versus UngroupAO (the DeleteObjAO targets the same group-object as the UngroupAO) and GroupAO versus UngroupAO.

In the scenario in which O1 is a GroupAO and O2 is a ChangeAttAO, when O1 is executed, O2 has applied its effect on all member objects of the target group-object. To make sure that after ungrouping, all the unpacked objects will still have O2's effect, our strategy is to apply O2's effect to data objects of all O1's composing MoveAOs.

4.7 Grouping AO-PO Adaptation Algorithm

With the routines discussed above, the AO-PO Adaptation in the TA framework can be extended to support grouping AOs, as shown in Figure 12.

First, the input AO is translated into a series of POs saved in a PO list. Then, each PO in the list is processed as follows. The PO is first transformed in OT. Then, if this AO involves in a GroupAO conflict, the conflict resolution routine is invoked. Otherwise, if this AO is overlapping with another concurrent compatible AO and at least one of them is a grouping AO, the CompatibleGAOCombinedEffects routine is invoked to apply AO level mechanisms for achieving combined effects for compatible AOs. In the CompatibleGAOCombinedEffects routine, suitable routines discussed in Section 0 are invoked according to AO type combinations.

Figure 12. The routines for adapting AOs in the presence of grouping AOs.

5. Comparison to Related Work
The CoGroup technique reported in this paper is the first collaborative object grouping technique based on the OT technique and designed in the TA framework. This work made important extensions to our prior work on OT and TA in order to support collaborative object grouping. Particularly, this work contributes a new definition of conflict/compatible relations among graphic editing operations in the presence of object grouping operations, new definitions of desirable combined effects among a mixture of basic and grouping operations to maximize the natural combination of compatible operations and to preserve all users work in the face of conflict, and novel data and operation adaptation techniques to bridge the gap between grouping operations and OT-supported primitive operations in the TA framework. These extensions are essential to apply OT and TA to a wider range of commercial off-the-shelf editing systems, particularly CAD/CASE applications.

To the best of our knowledge, the operation serialization technique reported in [5] is the only prior work on collaborative object grouping in graphic editing systems. Both the CoGroup work in this paper and the work in [5] address similar issues involved in conflict resolution for a similar collection of graphics editing operations, but these two work are very different in their approaches to conflict definitions, combined effects among conflicting/compatible operations, and techniques for conflict resolution.

The notion of conflict in CoGroup is based on the conditions that operations are concurrent, target common objects, and cannot be accommodated in the common target objects. Under this conflict definition, conflict may occur only between ChangeAtt operations or between Group operations, and the relations among all other operations are compatible (as shown in Table I). Operation conflicts are resolved by an all-operations-effect technique: multiple versions of the common target objects are created to preserve the effects of all operations, but one version at a time is displayed at the user interface (the MVSD technique). CoGroup is based on and extends OT for conflict resolution and consistency maintenance.

The notion of conflict in [5] is based on the conditions that operations are concurrent and do not commute. Under this conflict definition, conflict may occur not only between ChangeAtt operations and between Group operations, and the relations among all other operations are compatible (as shown in Table I), but also among other operations, as shown Table II (in which the ChangeAtt operation represents the setColor, SetBckColour, setZ, SetText, translate, scale operations in [5]).

### Table II. Conflict relation triangle of five operation types in the prior work [5].

<table>
<thead>
<tr>
<th></th>
<th>CreateObj</th>
<th>DeleteObj</th>
<th>ChangeAtt</th>
<th>Group</th>
<th>Ungroup</th>
</tr>
</thead>
<tbody>
<tr>
<td>CreateObj</td>
<td></td>
<td></td>
<td></td>
<td>❌</td>
<td>❌</td>
</tr>
<tr>
<td>DeleteObj</td>
<td>❌</td>
<td></td>
<td></td>
<td>❌</td>
<td>❌</td>
</tr>
<tr>
<td>ChangeAtt</td>
<td>❌</td>
<td>❌</td>
<td></td>
<td>❌</td>
<td>❌</td>
</tr>
<tr>
<td>Group</td>
<td>❌</td>
<td>❌</td>
<td>❌</td>
<td>❌</td>
<td>❌</td>
</tr>
<tr>
<td>Ungroup</td>
<td>❌</td>
<td>❌</td>
<td>❌</td>
<td>❌</td>
<td>❌</td>
</tr>
</tbody>
</table>

For the purpose of resolving operation conflict, two types of conflict are further distinguished in [5]: real conflicts are those which can be resolved by preserving the effect of one of the conflict operations (or none of them); and resolvable conflicts are those which can be resolved by combining partial effects of conflict operations. Regardless whether the conflict is real or resolvable, conflict resolution is based on operation serialization, which achieves the defined effects either by using operation-specific ordering rules (specified in [5]) for resolvable conflicts, or by using any priority scheme for real conflicts. Serialization is essentially a single-operation-effect or null-effect conflict resolution technique [11].

It is well known that the combined effects achievable by an all-operations-effect technique cover all combined effects achievable by a single-operation-effect technique, but the inverse is not true [11]. Furthermore, some combined effects among conflict Group operations achievable by CoGroup are not achievable by the serialization work in [5]. For example, when two concurrent Group operations target some common and non-common objects, they are regarded as conflict operations in both CoGroup and [5] (a real conflict). The combined effects in CoGroup is following: both Group operations shall succeed in creating their result group-objects; both group-objects contain their non-common target objects, but only one of them has the common target objects displayed (see Figure 4). However, the combined effects in [5] is the following: one of the two Group operations shall win and create the group-object containing all target objects, but the other one shall lose completely and has no any effect (not even the effect of grouping the non-common target objects).

In [5], achieving the partially combined effects for some resolvable conflicts is the main motivation for disqualifying OT from being applied for this purpose and for devising the new operation serialization technique. As shown in the example in Figure 6, however, the partially combined effect in [5] can be achieved by using the generic OT technique without additional application-level support, and more comprehensive MVSD combined effects can be achieved by extending OT with the application-level adaptation. A major problem with operation serialization is its undoing and redoing conflict operations when they are executed out of the correct conflict resolution order, which may cause potential interface disruption (when the undo/redo effects are visible at the user interface) and major performance overheads. It should be pointed out that the undo/redo involved in operation serialization is different from the collaborative undo capability in OT: the former is initiated by the internal system out of the necessity for resolving conflict among grouping operations, but the latter is initiated by the external user for the purpose of eliminating the effect of error grouping operations [13].

Last but not least, CoGroup is designed in the TA framework so it can be applied to a wide range of commercial off-the-shelf graphics editing systems (and this generality has been tested by its successful application in CoWord2 and CoPowerPoint3, whereas the work in [5] was designed in the context of a collaboration-aware graphics editing system and its applicability to collaboration-transparent applications is unknown.

It is worth pointing out that there exist other alternative approaches to conflict resolution based on locking (e.g. Ensemble [9] and GroupDraw [4]) or different kinds of serialization (e.g. GroupDesign [7] and LICRA [6]), but none of them addressed the issues related to collaborative object

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grouping. The reader is referred to [11] and [15] for detailed comparisons between the multi-versioning approach, on which CoGroup is based, and these alternative approaches.

6. Conclusions and Future Work

In this paper, we have contributed a novel technique, called CoGroup, to supporting collaborative object grouping in graphics editing systems. The CoGroup technique is the first collaborative object grouping technique based on the OT technique in the TA framework. Major technical contributions of this work include new definitions of conflict/compatible relations among graphics editing operations in the presence of object grouping operations, new definitions of desirable combined effects among basic and grouping operations to maximize the natural combination of compatible operations and to preserve all users' work in the face of conflict, and novel data and operation adaptation techniques to bridge the gap between grouping operations and OT-supported primitive operations in the TA framework. The collaborative object group capability provided by CoGroup is essential to expand the application scope of OT and TA to a wider range of commercial off-the-shelf editing systems, particularly CAD/CASE applications, which are the new targets of our research plan.

7. Reference


