Efficiently Planning Coherent Visual Discourse

Michelle X. Zhou **Steven K. Feiner**
Department of Computer Science
Columbia University
500 West 120th St., 450 CS Building
New York, NY 10027
+1 212 939 7000

{zhou, feiner}@cs.columbia.edu

Abstract

A visual discourse is a series of connected visual displays. A coherent visual discourse is characterized by smooth transitions between displays, consistent design within and across displays, and successful integration of new information into existing displays. We use a top-down, hierarchical-decomposition, partial-order planner to efficiently construct a visual discourse from scratch, taking advantage of parametrized primitive visual objects that serve as building blocks in the design process. Visual representations are modeled as visual objects, graphical techniques are employed as planning operators, and design policies are encoded as constraints. This approach not only improves computational efficiency compared to search-based approaches, but also facilitates knowledge encoding, and ensures global coherency.

Keywords: Top-down hierarchical planning, automated graphics generation, knowledge-based user interfaces.

1 Introduction

Much of the research done in automated graphics generation has been focused on designing individual presentations (e.g., [12, 17]) or planning sequences of static presentations (e.g., [6, 19]). In contrast, designing coherent visual discourse has not received the full attention that it deserves. We use the term *visual discourse* to refer to a series of connected visual displays. A *coherent* visual discourse is one that has smooth transitions between displays, consistent design within and across displays, and visually effective integration of new information into existing displays. Cognitive psychology studies have demonstrated that incoherent visual discourse can greatly impair user performance: The user might be "lost" in a display network [24], confused due to inconsistent design [13], or overwhelmed by information overload caused by a lack of efficient information integration [16].

We present a top-down hierarchical planning approach for automatically designing coherent visual discourse. To achieve coherency, we introduce three effectiveness criteria: *continuity*, *consistency*, and *unity*. *Continuity* guarantees smooth spatial or temporal transitions, *consistency* ensures a consistent design within and across displays, and *unity* addresses how to unify individual components into a coherent whole [15].

In our approach, a visual discourse is a sequence of visual actions. A *visual action* is an encoded graphic design technique (e.g., moving an object). We use a hierarchical planner [5] to generate the sequence of actions. Compared to search-based approaches, hierarchical planning achieves computational efficiency by reducing the amount of search needed [25]. It also eases the task of knowledge encoding [21] by reusing the actions that are common to many design tasks. In addition, we adopt a top-down hierarchical decomposition strategy [26] to facilitate the interleaving of planning and execution [21] and to ensure both local and global coherency within a visual discourse.

First, the system sketches a visual discourse design that is complete but too vague to be realized; then it refines the vague parts of the design into more detailed subdesigns until the design has been refined to a sequence of primitive visual actions. During this design process, the design constraints are incrementally specified at each level, and the constraints must be satisfied before the design can be further refined. In contrast, in a bottom-up approach (e.g., [12]), partial designs are generated at the primitive level, and then are composed together to form composite designs. Without considering the design constraints at a higher-level, the partial designs are prone to failure and usually require redesign. In the worst case, satisfying all local design constraints cannot even guarantee the satisfaction of the global design constraints.

As the planning process progressively refines the high-level vague visual descriptions, a complex visual presentation is recursively built using fully specified primitive visual objects. Instead of constructing these primitive visual objects from scratch, we store a collection of parametrized primitive visual objects as a *visual lexicon*, and directly use them as building blocks to increase design efficiency [29].

In the rest of this article, following a brief discussion of related work in Section 2, we present our top-down hierarchical planning approach in Section 3. We identify various types of visual objects, and then we introduce visual actions that are used as planning operators. We also briefly describe the representation of

the visual lexicon and its important role in visual design process. Next, we focus on several key design stages to explain how our approach works. Our approach has been used in a computer network management domain to automatically generate visual presentations for different network management tasks. Two major tasks are exploring internal structures of various network entities (e.g., network nodes and links), and monitoring network traffic status (e.g., traffic load on a particular link). In Section 4, We elaborate the design process using an example from the network domain. Finally, we present our conclusions and discuss future improvements in Section 5.

2 Related Work

Friedell [7] presents a system for automatically synthesizing graphical objects from object descriptions. He employs a top-down approach in which complex objects are decomposed into simpler subobjects. Structural relations are used to relate objects and their subobjects and specify how the subobjects are oriented with respect to each other. APT [12] and SAGE [17] generate 2D visual presentations of quantitative information. Both systems adopt a bottom-up strategy in which partial designs corresponding to various data relations are planned first; then all partial designs are composed together to construct a complete design based on design constraints. All three systems focus on designing individual presentations. They do not address either design consistency in consecutive displays, or how to integrate new designs into existing ones.

APEX [6] can automatically create pictorial explanations to depict actions in a 3D world, generating a series of pictures to depict a sequence of actions. Both IBIS [19] and WIP [1] use a generate-and-test approach to design a sequence of static visual displays for procedural explanations. They all maintain a certain degree of consistency for related images (e.g., using a consistent view specification when appropriate). They also achieve continuity by arranging the images in a logical order (e.g., the order in which depicted procedures are to be performed). However, they only address a limited set of transition issues concerning camera specification. Moreover, the generate-and-test approach often results in a large search space [2].

ESPLANADE [9] employs a hierarchical planning approach to automatically generate animated presentations using film-making heuristics. It ensures smooth frame-to-frame transitions by exploiting stan-

dard film-making techniques such as dissolve, fade in, and fade out. Like IBIS and WIP, it uses realistic images of physical objects and generates presentations with little user interaction. Thus, it does not deal with consistency issues at the symbol encoding level (e.g., mapping object attributes to visual variables) and unity issues such as integrating new information into the current scenario.

3 Approach

In a planning approach, problem-solving operators are applied to various objects to accomplish planning tasks. In the context of visual design, the objects refer to both domain and visual objects. Visual actions are graphical techniques that are used as planning operators to design or manipulate visual objects. First, we introduce visual objects and visual actions. Then we illustrate how the objects and actions are utilized in the design process.

3.1 Visual Objects

Our system supports five types of visual objects: visual primitives, visual unities, visual structures, visual frames, and visual discourse. These form a hierarchy, as shown in Figure 1 (****** Figure 1 near here*******).

Visual Hierarchy

At the bottom of the hierarchy are *visual primitives,* which are individual visual variables: shape, material, texture, size, position, and orientation [3].

Next come *visual unities*, which are constructed from visual primitives and other visual unities. For example, a red plastic cube is a visual unity that is formed by two visual variables (cuboid shape and red plastic material).

Above the visual unities are *visual structures*. Visual structures spatially organize various visual unities and other visual structures in a specific way to convey abstract concepts or explain how processes work [22]. For example, a 2D line graph that plots height against age is composed of line segments and two orthogonal axes with textual labels. This plot indicates how height changes with the age. Conventional visual structural classification used in cognitive psychology studies [23] identifies three basic structures that fall between text and realistic images: charts, graphs, and diagrams. Based on the visual representation

classification proposed by Lohse [11], we have extended our visual structure classification. For example, graphs are further partitioned into scatter plots, bar graphs, etc. A visual structure could also be a cartogram (i.e., a spatial map overlaid with visual objects, such as dot maps that use symbols to show the location of individual objects on the map), which does not quite fit into any of the three basic categories. The visual structures that can be automatically designed by our system are shown in Figure 2 (****** Figure 2 near here ******).

Visual frames contain single or multiple visual structures. For example, a visual frame representing a computer network's topological structure and its traffic statistics over a time interval could include a cartogram (network nodes and links overlaid on a geographical map) and a textual table chart. The cartogram represents the topological structure, and the table chart conveys the traffic information.

Visual discourse is a cohesive formation of a series of visual frames. Suppose we need to show network traffic statistics over a long time period that is divided into several shorter time intervals. One visual frame can display traffic statistics for one short time interval, while all visual frames are connected to form a visual discourse that shows the network traffic statistics over a long time period.

Syntax and Semantics

To automatically compose visual discourse, we must specify both syntax and semantics for visual objects [14]. Syntax specifies how a visual object should be constructed. For example, the syntax for constructing a table chart must indicate the spatial relations among the rows and columns, and how the rows and columns are formed. In contrast, semantics defines the meaning of an object's syntactic features. For example, each division of a pie chart specifies a *part-whole* relationship between the object represented by the division and the object represented by the whole pie.

To synthesize a visual object, syntax is used as both layout constraints (e.g., all elements within a table column must be vertically aligned) and pattern constraints (e.g., a 2D bar graph uses the same line width for both axes). Semantics, on the other hand, is employed to ensure that syntactically valid visual objects are also conceptually correct [10], based on domain information characteristics [28]. Figure 3 (****** Figure 3 near here ******) is a cartogram that represents a network's topological structure. In this example, semantic constraints make sure that similar objects have similar visual appearance—spheres and cones

represent switch and router nodes, respectively, while thin cylinders depict links. In a top-down approach, the task of designing a visual object is refined to designing its components. For example, designing a bar graph is refined to designing its bars, axes and textual labels. Here, the syntax of the visual object is used to limit the possible combinations of its lower-level components. For example, the syntax for a 2D bar graph specifies that the two axes must have similar visual appearance. If the line color and width for one axis is decided, then the same visual properties will be applied to the other. Thus, there is no need to design the visual properties for two axes separately.

3.2 Visual Actions

In our system, we encode graphical techniques as visual actions that are used as planning operators.

Categorization

Visual actions are categorized based on their functionality. There are three types of visual actions: *formational actions*, *transformational actions*, and *camera actions*. *Formational actions* design visual objects from scratch by mapping information to visual objects. In contrast, *transformational actions* modify existing visual objects in two ways: *appearance transformations* (e.g., Transfigure changes an object's material) and *geometry transformations* (e.g., Scale modifies an object's size). While the first two types of actions act upon the domain and visual objects, *camera actions* involve *viewing specification* (e.g., Set camera position or orientation) and *viewing modification* (e.g., camera Zoom). Table 1 (******Table 1 near here******) shows the set of *primitive* visual actions currently identified and implemented in our system.

Representation

A general visual action is defined in a format shown in Figure 4(a) (****** Figure 4 hear here******), while a more specific type of visual action can be represented as a subclass of ACTION (Figure 4b). In this case, ANIMATED-ACTION is a type of actions with temporal constraints, which is represented as a time interval that is specified by its start and stop times. In fact, this is the type of action that is used to achieve smooth transitions between visual displays. For example, a *geometric transition* is a smooth transformation from one geometric configuration to another (e.g., Move or Align), while a *visual appearance transition* is a smooth transformation from one appearance to another (e.g., gradually making an object

transparent). These actions interpolate between the old and new values (e.g., position or transparency value) over time to achieve a smooth transition. To achieve appealing animation effects, we use conventional animation techniques such as slow-in, and slow-out [4]. Therefore, the interpolation usually is not linear. In a visual discourse, the current display might be replaced by a completely different display. To maintain aesthetic continuity [27], we adopt conventional film transition techniques such as dissolve, fade in, and fade out (as used in [9]) to achieve smooth transitions between displays.

As shown in Figure 4(a), each action has a set of operands that it acts upon. All preconditions must be true before an action can be executed and all postconditions become true after the action is executed. Each action is also associated with a set of parameters. For example, action Move has parameters source and destination (Figure 4c). Preference indicates how preferable the action is in the current design context. How the preference of an action is determined is described in the following section.

A visual action is either *primitive* or *composite*. Primitive visual actions, such as Enlarge (i.e., Scale action with scaleFactor greater than 1), can be executed by the rendering component directly. In contrast, composite actions are represented by a set of partial plans, which will eventually be decomposed into primitive actions. Each partial plan is represented using a decomposition schema [26]. Hence, each composite action is associated with a set of decomposition schemata. A decomposition schema specifies subactions that are used to accomplish the composite action, and partial orders and causal relations among the subactions (Figure 5b ******Figure 5 near here******). As shown in Figure 5(a), a composite action has three extra slots: decompositionSchemata, decompositionPreferences (discussed later), and currentDecomposition. For example, the composite operator RevealInternal has two decomposition schemata as shown in Figure 6 (******Figure 6 near here******).

In DecompositionSchema1, RevealInternal can be decomposed into three subactions: Focus on ?objX (to emphasize the selected object), DesignVisObject (see next section), and Open ?objX (to expose its internal structures). Moreover, the partial-Orders limit the order of the three actions to be applied: both Focus and DesignVisObject must precede Open. Similarly, DecompositionSchema2 states that the action RevealInternal can also be achieved by another combination of three actions. In this decomposition, ShowInset replaces Open to display ?objX and its internals in an inset window. We will discuss how a decomposition schema is

selected later.

There are two distinct advantages to having both primitive and composite actions. First, composite actions can be used by the hierarchical planner at a high level to sketch an abstract design without worrying about computationally overwhelming details. For example, at a high level, the design task of "comparing the traffic load of two network nodes" could be solved by a very abstract plan that includes two composite actions: Focus on the two nodes and Show the traffic load within these two nodes. At this level, the plan is not concerned with how to focus on the nodes or how to show the traffic load. A more detailed plan will be constructed later through decomposition. The second advantage is that only a small set of primitive actions need to be implemented in the rendering component. Primitive actions can be reused in a wide range of combinations to specify different composite actions. For example, Enlarge is used as one of the subactions for the composite action Focus to achieve the focusing effect by enlarging the object. The same action is also used in the composite action Distinguish to distinguish an object by increasing its size.

In the following section, we explain in detail how a design task is accomplished using the visual hierarchy and visual actions.

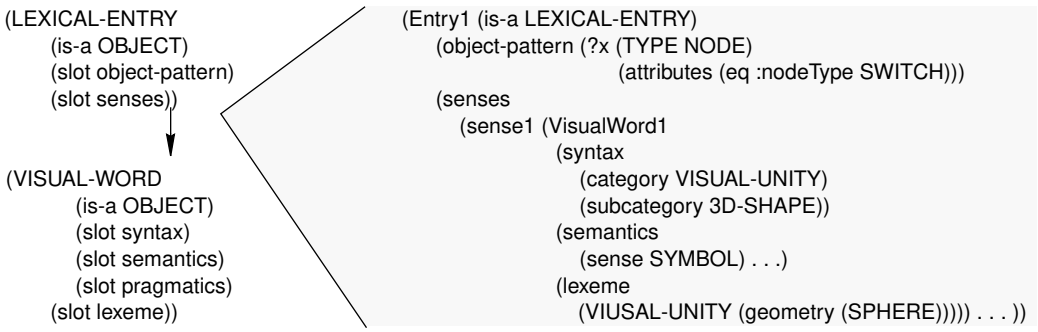
3.3 Visual Lexicon

As mentioned earlier, a visual lexicon is a collection of parametrized primitive visual objects. The *visual lexicon* provides a foundation on which more complex designs can be built so that it is not always necessary to design everything from scratch [29]. To conform with the overall constructive planning approach, the system uses the visual lexicon to represent only atomic objects, while it builds visual representations of composite objects from scratch by gluing together various visual primitive objects. We use the term *visual word* or *visual lexical item* to refer to a collection of information that encodes a specific graphical expression (*lexeme*) and its *syntax*, *semantics* and *pragmatics.* A visual word always represents one type of object, but one type of object can be mapped to more than one visual word. To gain generality and compactness, we use *object patterns* to represent objects that share the same type or attributes; for example, all network NODE objects whose nodeType are SWITCH can be represented as:

```
(object-pattern (?x (TYPE NODE) (attributes (eq :nodeType SWITCH))))
```

To facilitate information storage and retrieval, we index the visual lexicon by object patterns and group

together all visual words that represent the same object pattern under the slot sense. Thus, a generic visual lexical entry and an example of it are represented as follows:



Very much like exploiting syntactic, semantic and pragmatic information of various visual objects in assembling high-level visual presentations, the system selects the right visual word by matching its syntactic, semantic, and pragmatic information against the constraints formulated in the design process [29]. For example, if a syntactic constraint requires that an atomic object be represented using a TEXT object, then the syntax of the selected visual word should indicate this constraint is indeed satisfied.

As the visual word represents only atomic objects, determining which visual word to use usually happens at a latter planning stage since higher-level plans usually deal with abstract actions and composite objects, which will be gradually replaced by their atomic components in a top-down planning fashion. We will see an example of this type of *object decomposition* later in Section 4.

3.4 Design Stages

The input to our system is a design task which is represented as communicative goals. The hierarchical planner starts to plan based on the current input. A planning cycle oscillates among four steps: selecting an action to accomplish a task, decomposing a composite action, resolving conflicts, and checking whether the planning process is finished. Here we focus on two key steps: action selection and action decomposition. These two steps together determine how a design is constructed and how the search space is pruned.

Action Selection

One of the major steps in planning is to find an action that can accomplish the current task. The planner compares the design task with the postconditions of visual actions. If one of an action's postconditions matches the task, then the action becomes a candidate to accomplish the current task. A candidate action

could be either a brand new action that has never been instantiated before, or a used action that was instantiated earlier for accomplishing another task. Usually, there is more than one candidate action. Nondeterministically choosing one of them might result in later planning failure. Therefore, several heuristic preference constraints are employed to rank the candidate actions. The higher the action is ranked, the more preferable it is.

Currently five types of preference constraints are used in our system: *achievability*, *consistency*, *unity*, *sharing,* and *availability.*

Achievability ranks the actions based on the fact that some actions will lead to a more effective design than others for a particular task. For example, DesignLineGraph is ranked higher than DesignBarGraph if the task is to compare different sets of numerical data emphasizing a trend over time [8]. Achievability is specified in the action's postconditions. The following representation shows that DesignLineGraph ranks higher than DesignBarGraph when the postcondition is ShowTrend:

```
(DesignLineGraph (is-a CompositeAction)
    (. . .)
    (postconditions
        (postcondition1 (ShowTrend (rank 10)))) )
```

```
(DesignBarGraph (is-a CompositeAction)
    (. . .)
    (postconditions
        (postcondition1 (ShowTrend (rank 5)))) )
```

Consistency asserts that if an action was used before to accomplish a similar task in a similar situation, then it is preferable. The consistency preference not only applies to the action selection process, but also affects action instantiation. For example, assume that the current user dialogue is shown in Figure 7 (****** Figure 7 near here ******), which uses colors to encode different types of network traffic in a link. Suppose the user wants to examine the traffic in a different link. Unless there is a good reason to do otherwise, not only should the color encoding action be used, but the action should also be instantiated to use the same color code. To accomplish this, we use a history list to record the dialogue's tasks and solutions.

Unity states that if an action leads to a design that can be better integrated with the existing design than other actions, then this action is preferable. Figure 7 shows a network with traffic load information in a link. The stacked bars inside the link represent the traffic load. A regular bar graph can also be used to display the traffic information. However, in this example, the design task is to show the link's traffic status without comparing different links. Therefore, the oriented stacked bar graph conveys the needed informa-

tion and can be better integrated with the selected link than a bar graph. Thus, DesignStackBar is preferred over DesignBarGraph.

Within the same planning process and concerned with the same object(s), *sharing* states that if one of several competing actions has already been *used* and others have not, then the used action is more preferable since it can be shared by the previous and current task [18]. For example, if the current subtask is Distinguish (objectX), both Enlarge (objectX) and Highlight (objectX) are among the choices. But suppose Enlarge (objectX) is instantiated earlier in the same planning process to accomplish another subtask Identify (objectX). In that case, Enlarge is a better candidate than the unused action Highlight since it can be shared by both subtasks Distinguish (objectX) and Identify (objectX).

Availability specifies that an action is more preferable if it has more satisfied preconditions than another action. For example, Enlarge and Highlight could both be used to distinguish an object. If two of the preconditions of Enlarge are already satisfied, and none of the preconditions in Highlight has been satisfied yet, then Enlarge is preferred to Highlight. At one extreme, under an availability preference, actions without any preconditions are always preferable to actions that require preconditions.

Preference constraints not only improve performance by avoiding backtracking, but they also ensure the satisfaction of certain effectiveness criteria (e.g., consistency, unity). Moreover, preferences themselves can be ranked based on their importance when multiple preferences can be applied at the same time. The current ranking in a descending order is: achievability, consistency, unity, sharing and availability. Our ranking is based on the fact that ensuring the selection of an effective design (achievability) is most important. Next come consistency and unity criteria to support overall cohesiveness. Finally, sharing and availability preference constraints complement the design process as performance tuning factors (e.g., availability will favor actions with fewer unsatisfied preconditions). The preference slot will hold the computed ranking based on preference constraints.

The preference constraints not only guide the selection of visual action, but also aid in determining the appropriate visual word for representing a particular atomic domain object. However, the evaluation of the preference constraints might be slightly different for these two situations. For example, the evaluation of achievability preference for visual word selection takes into account all syntactic, semantic and pragmatic

information of the word, while the evaluation for visual action selection examines the information held in the postconditions slot of the visual actions.

Once an action is selected, it will be processed. If it is a composite action, it will be decomposed using one of its decomposition schemata. If it is a primitive action, all its preconditions are checked to see whether they are satisfied. Next, we focus on action decomposition.

Action Decomposition

A composite action must be decomposed into subactions before a complete plan can be constructed. Just as arbitrarily choosing an action might result in later plan failure, randomly selecting a decomposition schema in action decomposition could also cause plan failure. Hence, we attach a set of decomposition preference constraints to a composite action to guide the decomposition. We use two types of preference constraints: *achievability* and *consistency.* Similar to the achievability preference in action selection, the *achievability* constraint states that under conditionX, a decomposition schema is preferred since it leads to a more effective design. The *consistency* constraint aims to maintain design consistency by favoring a decomposition schema that was used in previous dialogues.

The two types of preference constraints themselves can also be ordered. Our system gives priority to the achievability preference. Recall that RevealInternal has two decomposition schemata as shown in Figure 6. Preference1 asserts that if the operand ?objX is likely to intersect with other objects and it has a small 2D bounding box (the size of the inset window created by ShowInset is proportional to the bounding box), then DecompositionSchema2 should be used. Here, "small" is interpreted to mean that either dimension of the bounding box does not span more than 1/3 of the full display window. In a network application, some nodes are very likely to intersect with other nodes nearby especially when they get enlarged. In this case, the second decomposition schema should be selected.

In our top-down approach, an abstract design is sketched at a high level using composite visual actions. Thus, action decomposition can also be considered as design refinement. Through action decomposition, a rough design is refined. Moreover, design consistency is ensured through the refinement. Suppose we want to design a network diagram to represent a computer network. At a high level, the DesignNetworkDiagram action is selected. It is specified as follows where diagram1 is an instantiation of the network diagram class

to represent this particular network instance network1:

```
(DesignNetworkDiagram                          (diagram1
        (is-a COMPOSITE-ACTION)                        (is-a NETWORK-DIAGRAM)
        (operand                                       (nodes)
              (operand1 network1)                      (links)
              (operand2 diagram1))                     (. . .))
        (. . .))
```

At this stage, the representations for nodes and links are still empty. Later, DesignNetworkDiagram is decomposed into two types of DesignVisObject actions: one for every node in the network and one for every link:

```
. . .                                          . . .
(DesignVisObject (is-a COMPOSITE-ACTION)       (DesignVisObject (is-a COMPOSITE-ACTION)
        (operands                                      (operands
              (operand1 node32)                              (operand1 link10)
              (operand2 node32VisRep))                       (operand2 link10VisRep))
        (. . .))                                       (. . .))

. . .                                          . . .
```

Note that the decomposition not only decomposes the composite action DesignVisObject (network1, diagram1) into various subactions, but it also refines the operands network1 using the individual network entities: nodes and links. Thus, action decomposition also carries out *object decomposition* when it is necessary. Suppose one material should be consistently applied to all nodes. Then each node will have a similar representation:

```
(node32 (is-a NODE)                            (node32VisRep
        (id 32)                                        (is-a VISUAL-OBJECT)
        (. . .)                                        (material ?node_material)
        (representation node32VisRep))                 (. . .))
```

At this point, diagram1 is refined accordingly:

```
(diagram1 (is-a NetworkDiagram)
        (nodes node1VisRep node2VisRep . . . node32VisRep . . . )
        (links)
        (. . .)
        (variable-list (?node_material (binding NONE)))
```

Here, the variable ?node_material serves as a global variable in the network diagram design. If ?node_material in one of the node is instantiated later to some actual material value, then all nodes will have the same material because of the variable binding. The ability to use variables is an important feature in a planner [21]. Using variables in abstract visual presentations ensures consistent design within a display, and also defers some detailed decisions at the high level to avoid costly redesigns. In this example, deciding which color to use is really not important at this level—the link representation has not been designed

yet and the system knows nothing about the background color either. An arbitrary early decision will likely lead to a failure. For example, if the system arbitrarily assigns the color white for the nodes, it might determine later that white is inappropriate due to a white background.

Conflict Resolution

Before a plan can be further refined, all conflicts at this level must be resolved. Conflict resolution involves detecting potential conflicts (e.g., one action's postcondition might deny another action's precondition), formulating new constraints to avoid potential conflicts, and ensuring that the constraints are likely to be satisfiable. Currently, we use a straightforward approach to solve simple constraints: we exhaustively check each constraint in the constraint network. A more sophisticated constraint solver could be used to replace the current one in the future.

Completion Checking

This step checks if a plan is finished. A plan is finished if and only if:

1. All preconditions for every action are satisfied,

2. there is no composite action in the plan, and

3. there is no conflict in the plan.

Any precondition that has not yet been satisfied becomes a subtask that needs to be achieved before a complete plan can be formed.

To complete the design process, visual word selection and instantiation also occur at this stage. Visual word selection tries to find the most appropriate visual representation for an atomic object based on the preference constraints mentioned earlier. The instantiation of a visual word involves two subtasks: substituting the variables in the visual word expression with the matched object instances, and supplying the unspecified parameter values of the selected word [29]. For example, a visual word (highlighted segment) in the following entry is selected. This word consists of a VISUAL-UNITY, which represents a network NODE (e.g., node32) by using SPHERE and TEXT objects:

```
(entry1
      (object-pattern (?x (TYPE NODE)))
      (senses
            (visual-word
                  . . .
                  (lexeme (VISUAL-UNITY (geometry
                                    (TEXT (string (get-nodeName ?x)))
```

(SPHERE (radius 1.0))))))

))

To choose the desired visual word, the system first needs to match the entry's object-pattern with the NODE instance (i.e., node32). Once the match is sucessful, then all the visual words under this object pattern become candidates. Then the system evaluates which word would be most preferrable by taking into account a wide variety of factors, including the word's syntax, semantics, pragmatics, and various preference constraints [29]. Once a visual word is determined, every object variable ?x specified in this visual word should be replaced by node32 in the instantiation process. Moreover, to render the visual word, unspecified parameter values of the VISUAL-UNITY such as size, color of the TEXT or SPHERE should be supplied based on various effectiveness constraints (e.g., consistency). Conforming with the main theme of the least-commitment algorithm, no instantiation is carried out unless there is enough information to support such a decision.

4 Example

In our computer network domain, a network link contains a set of *virtual path segments*. Each segment has attributes such as capacity and utilization. To reveal the internals of a link is to display all virtual path segments inside the link. In addition, those segments are distinguished by their capacities. In this section, we describe how a visual discourse is planned to fulfill the task of revealing the internals of a selected link. This is a much simplified version of the actual planning process, which fires 210 rules.

In Figure 8 (****** Figure 8 here******), suppose that the user has selected link23, which is between node1 (Austin) and node7 (Tucson). The system formulates the task as:

(Task (ShowInternal link23))

The planner seeks actions that have a postcondition that matches the task description. In this case, the planner selects the composite action RevealInternal. Next, RevealInternal is decomposed using one of its decomposition schemata. In our example, the selected link's bounding box is too big to satisfy the preference condition for DecompositionSchema2. Therefore, the default decomposition schema is used. Thus, RevealInternal is decomposed into three subactions: Focus (link23), DesignVisObject (link23-vpathSegments), and Open (link23).

Among the three subactions, only action Open is a primitive action; the other two are composite actions

and need to be further decomposed. Focus is decomposed into Extract (extract link23 from the rest of the network1). This decision is made based on the fact that a link is likely to intersect with other objects and Extract separates intersected objects or prevents the potential intersections while achieving focusing. Focusing by Enlarge increases the intersection possibility, and focusing by Highlight does not fix or prevent any intersection.

In our example, the application requires the internal objects of link23 (i.e., a set of virtual path segments) and their attributes *capacities* to be displayed *symbolically*. DesignVisObject is refined into two actions:

```
DesignVisObject (is-a COMPOSITE-ACTION)
      (operands
            (operand1 link23-vpathSegments)
            (operand2 link23-vpathSegmentsVisRep))
. . .
```

```
DesignVisObject (is-a COMPOSITE-ACTION)
      (operands
         (operand1 (relation1
                     (relationType attributive)
                     (object link23-vpathSegments)
                     (attribute link23-vpathSegs-capacity)))
         (operand2 relation1VisRep))
. . .
```

The first is concerned with designing the visual representation of the internal objects, while the second takes care of building visual displays for representing the attributive relationships between the internal objects and their capacities. Since vpathSegments is a *composite* object which consists of several individual virtual path segments, its visual representation is further refined to define the visual expressions for *each* individual virtual path segment. In this case, the planner chooses to decompose the action by refining its composite operands (e.g., link23-vpathSegments) using their components (e.g., individual vpathSegments) instead of replacing the action itself as it did before (e..g, using Extract, Open to replace RevealInternal). In fact, this is a good example that demonstrates that action decomposition not only reasons about decomposing an action into subactions, but is also concerned with decomposing composite objects into subobjects. A similar decomposition method is applied to the second DesignVisObject, of which operands realtion1 will be decomposed into simpler relations, each of which deals with *one* virtual path segment and its capacity.

Now that the individual virtual path segment is an *atomic* object, the planner determines its visual representation by searching through the visual lexicon. In the network domain, we have stored visual words that specify various visual expressions for CONNECTION objects. To represent CONNECTION objects symbolically, an entry recording a VISUAL-UNITY with cylindrical shape would be appropriate. Moreover, the system knows that the internal objects within a link are one type of CONNECTION and needs to be represented sym-

bolically. Thus, the visual representation for the internal objects are directly retrieved from the matched lexical entry. In our example, the VISUAL-UNITY with cylindrial shape is selected. Regarding the visual representation for the vpathSegment-capacity attributive relationship, the system decides to map the capacity to one of the visual attributes (diameter) of the internal objects' visual reprepsenation (cylinder) based on data characteristics (e.g., capacity is a quantitative measurement). Therefore, the capacity is signified by the thickness of the cylinder that is used to represent the virtual path segments (Figure 9c ******Figure 9 near here******).

At this point of planning, let us assume all preconditions but one are satisfied and no conflicts need to be resolved. The only precondition that is not true at this stage comes from the action Open. One precondition for Open requires that the object be large enough so that the opening effect is recognizable. Scale is selected to establish the causal link for this precondition of Open.

At this stage, Extract is the only non-primitive action. It is then replaced by Align and Move. Align rotates the whole network so it is laid down (Figure 9a), while Move moves the link and its two end nodes away from the rest of the network (Figure 9b), and Open cuts the link open to reveal its internal structures (Figure 9c).

Figure 10 (****** Figure 10 near here *******) shows all planning levels. Each level is a complete plan, and is a refined version of the level above it. At each level, each action precedes the action to its right (e.g., Focus precedes DesignVisObject), while all actions in the same column are not ordered (e.g., Move, Scale etc. at the last level). In the final plan, a complete sequence of actions is not necessarily a linear sequence. For example, actions Move and Scale are executed simultaneously in this example (Figure 9b).

5 Implementation

Our system is written in C++ and the CLIPS production system language [20]. We have implemented the hierarchical-decomposition partial-order planner using CLIPS, based in part on the research of [21, 26]. We use the SGI Open Inventor 3D graphics toolkit to implement the rendering component. It takes approximately 2.8 seconds to plan the whole design for the example mentioned in the previous section, running on a 250 MHZ R4400 SGI Indigo2.

6 Conclusions and Future Work

We are building a system that can automatically generate a connected sequence of visual displays to form a coherent visual discourse. In addition to the effectiveness criteria used for designing individual presentations, we introduce three effectiveness criteria to ensure visual cohesiveness: continuity, consistency, and unity.

We use a top-down hierarchical planning design approach. This approach is computationally efficient compared to a search-based or non-hierarchical planning approach [25]. It eases knowledge-encoding through reuse of primitive actions. More importantly, its top-down design assures global coherence, and facilitates interleaving of planning and execution [21]. To gain more design efficiency, we have also stored a collection of primitive visual objects in a visual lexicon and directly employ them as building blocks to assemble higher-level visual presentations.

Currently, we are working on several ways to improve the current system so that it can automatically design timely, coherent visual discourse in an interactive environment. The unity criterion is still fuzzy, and it needs to be refined so that it is computationally measurable (currently it is specified as heuristic rules). We are also working on interruptible visual discourse. This is essential in an interactive environment in which the user may want to stop or resume the ongoing discourse at any time. In addition, we are studying how to interleave planning and execution to reduce response time, which is important in an interactive environment.

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