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Prototyping of Designs in Virtual Reality

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Abstract

Conventional CAD systems have not yet proven their ability to provide support for activities which characterise the early conceptual phase of design. We propose to refer to this set of capabilities of the human designer in conventional design as, design prototyping. We define the theoretical limitations of current CAD systems for supporting design prototyping, and postulate the potential of functionally dedicated, task related, CAD modules in Virtual Reality as a means to provide a unique form of a knowledge-based, visual design support environment for design prototyping support. We are currently engaged in a research program in which we explore CAD as a medium to support early conceptual design through rapid prototyping of architectural form. Furthermore we are exploring Virtual Reality as a potential design prototyping environment in which prototypes of designs can be constructed, communicated and visually evaluated at a high level of verisimilitude. In the first phase we have built the prototype system VIDE. This system has been used for extensive internal evaluation. In the ongoing second phase we are constructing an empirical research to observe designers at work on design prototyping in the Virtual Reality environment.

1. Introduction

Commercial CAD system producers appear unaware that the activity of design generation is structurally different from conventional drawing or modelling. Many so-called computer-aided design systems really expect designers to come to them with ideas already formed in considerable detail. But the amounts of information these systems require could not possibly be provided at an early design stage. Systems like these are therefore misnamed and should be thought of primarily as computer-aided presentation or production drawing systems (Lansdown 1994).

In the following section, we identify the problems underlying this inability of conventional CAD systems to provide support for activities which characterise the early conceptual phase of design. In section three, we indicate how Virtual Reality (VR) can potentially contribute to a solution of these problems. Finally, in section four, we describe the prototype system which has been developed for experimenting with conceptual design support in VR.

2. CAD systems in the early, conceptual phase of the design process

2.1 Design Prototyping

Current CAD systems have little functionality to support early design (Akin 1986). During this stage the objects, or elements, of the design are not yet defined. We may refer to these objects of the design in the terms of Schön as the "materials" of the design problem (Schön 1983). The materials are the elements through which the design is manipulated in the designer’s mind, through which the design problem space can be explored, and through which a design solution can be expressed. Without some definition of these materials of early design, we have no ability to employ CAD systems as "design sketching systems". How, therefor, can CAD be made to support prototyping of designs in an early conceptual stage?

One approach to the provision of such an ability to generate designs quickly which is conventional in current CAD systems is that of the "library". The library approach provides a choice of elements existing in the memory of the computer which can be copied into the new design. Engineering symbols in engineering design, or furniture in architectural design are examples of such elements in a library. Generally, library elements are statically defined, but some might also be parametrical, such as window and door elements for architectural design..

Another approach comparable to the library is to provide a vocabulary of procedural elements. This approach we might term, the "menu" approach. It provides a menu of elements and also a range of possible procedural operations upon those elements. This approach is common to all computer graphics systems. In order to make an analogy to the problem of design prototyping these procedural elements would be "higher level" design elements rather than simply the geometric primitives currently provided by CAD system. That is, they would be the elements and procedures through which the design is manipulated in the designer’s mind and through which a design solution can be expressed. In Schön’s terms, these procedural elements would be the materials of the problem. They would be "task specific", in the sense that they would be the content of particular design problem sub-tasks. For example, in the design of a specific architectural space, the system would provide floor, walls, openings, lighting. Next to the task-specific materials, the prototyping environment would also have to provide some degree of "intelligence" with respect to operations upon these materials. We might refer to this as "task-specific knowledge", in which the system contains certain higher level knowledge of the design task. For example knowledge of room design, in the room design task.

2.2 Visual Reasoning in Design Generation in CAD Systems

The second important characteristic of the early design stage is that it is highly conceptual. The sketch as a medium supports visual reasoning in early design (Oxman 1994) (Goldschmidt 1994a). Computer systems lack the "perceptual interactivity" of the sketch in supporting early design. The sketch also supports creative phenomena such as abstraction (Arnheim 1974)(Finke et al. 1992). Therefore in a design prototyping environment which employs a task-specific, intelligent menu approach, the acceptable operations and manipulations provided by the system become significant with respect to supporting design. Definition of the elements, the parametric and non-parametric variables for their modifications, the field, or background, upon which they are manipulated may provide certain of the attributes of the sketch as a conceptual design medium.

2.3 Interactivity as a Characteristic of Design Media

Recursive sketching though modifications of "successive multiple representations" is one characteristic of interacting with the materials of the problem. This attribute of design as a process of "re-representation" usually is enabled by transparent sketching paper. One interacts with designs by re-forming the representation. Further, designers often think of new concepts or variations while making one particular sketch. They either make a textual note on the side, decide to make the other sketch, or try to remember the new concept or variation (Stuyver and Hennessey 1994).

2.4 Evaluation in Early Design

A final problem related to the use of computer systems as a medium for conceptual design relates to a general problem of design rather than of design media. We generally first create a symbolic design representation (Habraken 1985) which later is modified to another form of representation (manufacturing specification), which later is materialised as a physically realised object. Thus design, particularly design in the early conceptual stages, is removed from the reality of making and of the reality of context.

It is important to evaluate the design in the early phases of the design process because the decisions made at that point exert an extensive influence on the quality of the final product. Unfortunately, quality information is rare at the early design phase. Evaluation is made even harder by symbolic representations because they hide much of the information.

Design evaluation can be supported by computational design simulation. Visual quality for instance, can be supported by presenting simulated pictures with a high level of verisimilitude ; economical evaluation can be supported by early cost calculations; etc. Simulation techniques for many building aspects are currently available. Simulation results immediately confront the designer with the consequences of his design decisions.

2.5 Summary

We have identified four problems as underlying the inability to use CAD systems in the early, conceptual phase of the design process:

1. prototyping capability
2. visual reasoning
3. interactivity
4. evaluation support

It is our assumption, that given proper theoretical formulation of these problems, it is possible to develop the capability for support of early conceptual design in CAD systems. We have referred to this as "Design Prototyping". Our current research experiments with theoretical foundations of the development of design support systems for early conceptual design in CAD environments.

Furthermore, we believe that VR will provide one possible design environment for the integration of all the necessary media attributes for the support of Design Prototyping. In the next section, we will show how VR environments can contribute to some fundamental aspects of the problems of visual reasoning, interactivity, and evaluation.

3. Design Prototyping Environment

3.1 Direct Manipulation

Before we analyse the environmental demands of the problems which we have discussed above, we will briefly discuss "direct manipulation theory". Research projects in various application domains have proved that interfaces with a clear direct character, have important performance advantages in comparison with indirect interfaces. This appears specifically the case for tasks with complex cognitive operations (Ballas et al. 1992). Direct manipulation theory is used as a basic theoretical foundation for the development of the design prototyping environment.

Direct manipulation interfaces are characterised according to a model world metaphor. The user interacts with an interface that represents the task domain itself, the domain objects and the effect of user operations on those objects (Hutchins et al.,1986). This, in comparison with the command language interface which behave according to a conversational metaphor: the user and the interface have a conversation about the application domain. As a result, the user has the feeling of interacting indirectly, through an intermediary.

Two aspects are important for an interface's directness. The first aspect is the information processing distance between the user's intentions and the facilities provided by the machine. This is related to both the match or mismatch of the user's intentions and the available materials (semantic distance), as well as with the match of the representation and the content of the materials (articulary distance). The second aspect of direct interfaces is engagement, e.g. the involvement that comes when the user is able to interact directly with the application domain and the objects within it rather than interacting through an intermediary. Whereas semantic distance is related to the definition of the design "materials" (which will not further be discussed here), both semantic distance and engagement are related to the design environment.

The key to direct engagement is the communications medium with which an explicit view of the task domain is presented, and with which the designer interacts (Draper 1986). In ordinary computer systems the shared medium is a 2D visual display, organised according to the desktop metaphor. The direct manipulation is visualised as a 'point and click' manipulation by using a cursor, controlled by a mouse. A much higher level of engagement can be reached with VR systems which are controlled by natural movements of the user's hand or head, leading to "virtual presence". (Smets 1994). VR systems can also decrease the interfaces articulary distance through representing the architectural task domain with a high level of verisimilitude. The user is put inside the task domain represented in it's natural appearance. This is especially important with respect to visual design evaluation.

3.2 Design Representation for the Support of Visual Reasoning

In the ongoing architectural practice, designers typically make sketches using pen and paper in the conceptualisation phase of the design process. Sketch activity helps generating new ideas. According to Goldschmidt (Goldschmidt 1994a), there are two kinds of interwoven sketch activities: (A) committing thoughts that are already in the mind to paper, this is making symbolic representations ; (B) sketching to help generate new ideas ; this is visual reasoning. Visual reasoning is a prominent strategy in the solving of ill-structured problems such as we find in discovery, invention, and design.

Visual reasoning makes use of mental imagery and visual analogical transfer. All kinds of pictural images can be instrumental to these phenomena (Goldschmidt 1994b), but self-made sketches prove particularly instrumental.

The ambiguity and indeterminacy of the sketch is indicated by several authors as the reason for its idea stimulating capability (Scrivener and Clark 1994). The vague two-dimensional representations allow the designer to ignore features of the represented elements. Such abstractions allows imaging the element as something else (imagery) as well as the discovery of structural relations between elements (analogy). Ambiguity proves instrumental to visual reasoning.

From the above, we can deduce that a computational design environment can empower visual thinking, if it succeeds in stimulating the designer in achieving various classes of abstraction.

As with sketches, this could be accomplished by presenting vague, ambiguous representations of the design. We refer to this approach as vague design representation. Another approach could be to computationally generate abstractions and present them in large numbers to the designer. The designer would explore hidden qualities in his design through navigating through these abstracted representations at a high speed. Here, ambiguity is created through the simultaneous presentation of multiple interpretations of the same design. We refer to this approach as multiple abstracted design representation.

Whatever the case, the support of visual reasoning requires some form of ambiguous image of the design. One observes the structural difference between this kind of design representation, and the highly realistic view, desirable for visual design evaluation.

3.3 Design Representation for the Support of Early Evaluation

Evaluation is an essential part of design processes. A design is thoroughly evaluated at a number of stages of the design process. These are the occasions when designer and other involved persons discuss the actual design and decide together whether this is the directionto proceed. Evaluation is also a continuous process for the designer. He evaluates each of his attempts to answer one or more demands of the design task at hand with respect to the actual partial design, the other demands, the context, etc.

Calibre has been researching the usefulness of VR techniques as a presentation medium in the later stages of the design process in the Asterisk project (Smeltzer et al. 1994). Real time visual simulation software has been developed for the generation of highly realistic visual images. See figure 1. These VR presentations were used as the final check of the appearance of a design or as a presentation medium to the principles and future occupants. However, this research has not addressed the usability of VR during the design generation process.

Figure 1: Presentation of a design for visual evaluation.

During the generation of the design, the designer needs to evaluate his decision on a number of aspects. Some of these aspects, such as visual appearance, acoustic quality, hydro- thermal performance, cost, etc. , can currently be relatively easily simulated by computers. At each moment, real time simulation processes can provide the designer information on the quality of his design.

The major problem that would arise with a such a system is that of overloading the designer with data that are difficult to understand. In order not to disturb the visual reasoning process, this data should be presented : (A) only when the designer requests to do so, and (B) in an easily interpretable format.

VR experts agree on the notion that VR interfaces have the potential of providing more information in an easily understandable form (Benedikt 1994), (Biocca and Levi 1995). VR interfaces can display things/concepts/data in a way much closer to their nature than by means of other symbols, such as words (Lanier and Biocca 1992). For example, on this moment, the information on heat-loss generated by a thermal simulation program is presented to the designer by means of a graph and words. See figure 2. With VR this could also be done by presenting this information as a specific 3D visual representation of his design in which the major places of heat loss are highlighted with a bright colour. See figure 3.

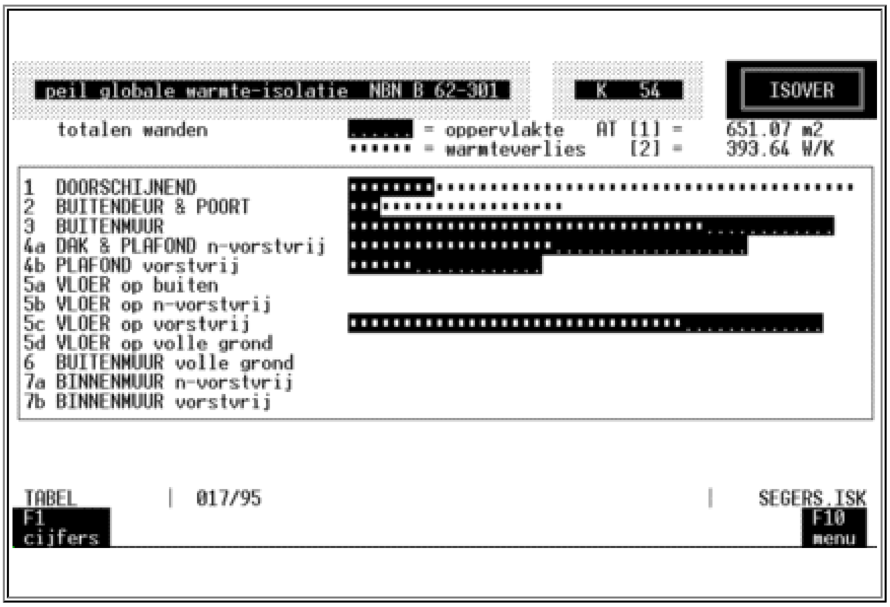

Figure 2: Conventional presentation of thermal simulation data.

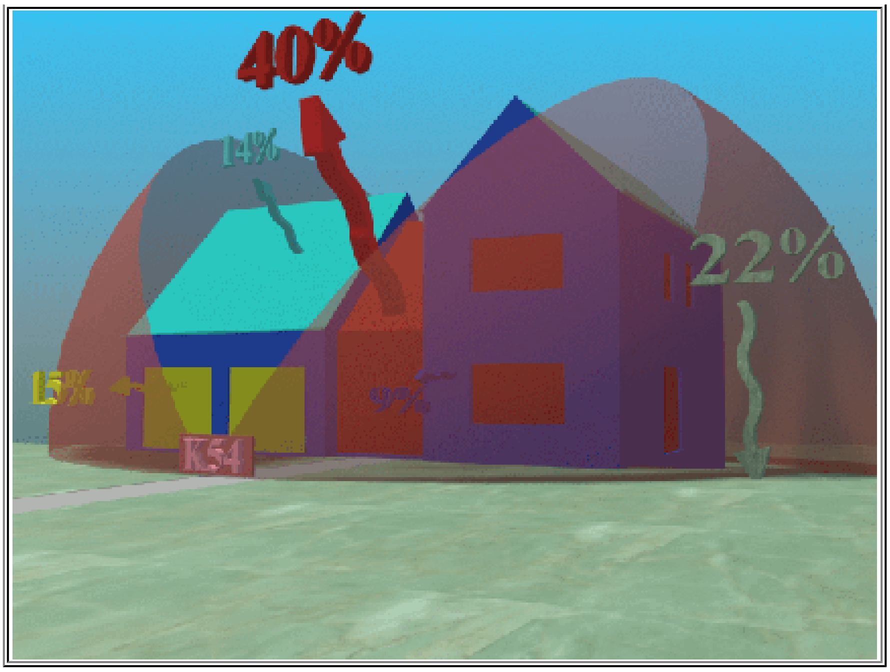

Figure 3: VR presentation of thermal simulation data.

3.4 Interactive Design

Design is characterised by a process of re-representation. One interacts with designs by re-forming the representation. Re-representation is externalisation of design thought. Through externalisation, visual reasoning processes are re-stimulated by the results of previous reasoning cycles. Designing is interpreting, externalising interpretations, re-interpreting, …

Sketching supports this recursive process because it's easy, and quick. It is automatic in the sense that the projection from idea to external representation is realised through the unconscious execution of a programme of motor actions. Marks of different type (e.g. pictorial and textual) can be produced with great rapidity and in rapid succession. As such there is limited interference between the act of sketching and the cognitive processes of creation, retention, manipulation, comparison, and evaluation. (Scrivener and Clark 1994)

If we compare the act of sketching with the act of designing with current CAD systems, we must conclude that the current CAD interface is difficult to use and takes to much time. Simply compare the mental effort needed to draw a line with a pen on a paper and the mental effort needed to draw a similar line on a CAD system. The CAD system requires our explicit attention to activate the "line" command, independent of the fact whether this must be done by selecting a screen button or by hitting a key. The time required to select a new command and the explicit need to shift attention from the design task to the interaction task, are features that are likely to interfere with and compete for the resources available to visual reasoning (Scrivener and Clark 1994).

A design system should be quick and intuitive, capturing the flow of concepts as quickly and naturally as possible. In the terminology of direct manipulation theory : it should make possible the "engagement" of the user with his design tools. Current menu, arrow and mouse-based computer interfaces do not completely meet this requirement. A better interface must be developed for our CAD systems.

Stuyver and Hennessey (Stuyver and Hennessey 1994) emphasise the benefit of relating specific hardware tools with specific functions. Through replacing screen menus with a set of hardware devices, the visual reasoning interfering point-and-click act is replaced by a the more natural action of physically taking a new tool.

But which commands should then be supplied to the designer? In analogy to pencil sketching, CAD systems require multi-functional interactive commands. While drawing a line with a pencil, we can easily control several line parameters: curvature, intensity, width. Notice that most designers prefer sketching with a pencil over pen because the pencil provides more control over line intensity, texture and width. Notice also that these parameters are interactively controlled: when a line has been started unintentionally too dark, the designer quickly releases pencil pressure in order to draw the rest of the line with the right intensity. Current CAD commands usually do not allow the changing of parameters during the execution of the command. Separated commands must be given for each modification. This clearly slows things down, and it makes drawing harder because the designer’s visual reasoning is interrupted several times.

In analogy to pencil sketching, drawing procedures for CAD systems must provide interactive control over the most relevant modes and settings. Earlier, J. Mantelers has explored this approach for conventional (mouse and keyboard) CAD interface (Calibre 19xx). We are now exploring 3D design procedures for some VR devices. VR devices have the advantage that they sense all the characteristics of the movement of the users hand and/or head in 3D. Their 3D sensing makes them obviously more suitable for interacting with a 3D design environment. But they also facilitate multifunctional commands better because they sense more aspects of the users gestures, e.g. when using a "flying joystick" as input device, not only the position of the sensor is scanned (as with a conventional mouse), but also the joystick’s orientation, speed, and specific path. We can exploit this extra information to let the designer control command modes and settings.

The following provides a simple example. As most design actions, stretching only requires input on the change of a 3D position. To stretch an object in the 3D design space, the flying joystick is used to virtually grab the corner of the object and relocate it. While stretching, the orientation of the joystick could be monitored to select the stretching mode: if held vertically, the wall is stretch orthogonally, if held horizontally, the wall stretches skew.

3.5 Summary

We have presented several reasons for the use of VR as a design prototyping environment:

- Direct manipulation theory indicates a structural improvement for VR based interfaces because they can provide high engagement and the possibility of a low articulary distance representation.
- Both visual reasoning support and evaluation support require multiple design representations. With respect to interface directness, a VR interface appears to be an excellent environment for the presentation of these views.
- Interactive designing requires the exploitation of the human skill of unconsciously performing actions and gestures. This is better facilitated by VR environments than in conventional 2D mouse based interfaces.

We are experimentally testing how these conclusions can be realised. We have developed and tested a first prototype system called VIDE, the acronym for Virtual Interactive Design Environment.

4. VIDE

4.1 Description of the System

The development of this first VIDE prototype was mainly an investigation on the technical practicability of a Virtual Reality based Design Support System. See also (Coomans 1996).

4.1.1 Materials of the system

The VIDE design system is devoted to the room design task. Room design involves space boundaries design, boundary penetrations, and furnishing. Because we had to develop a working design system from scratch, the materials of the system had to very limited in order to restrict the needed development time. We have chosen to take the parameters of the TUE full-scale physical modelling system as a frame for our Design Prototyping System.

For several decades, various educational institutions have concieved and built systems with which architectural spaces can be modelled on full scale. In each case, spaces can be modelled using building blocks. In the case of the TUE system, wall components of 30,60 and 90 cm width can be located between a fixed floor and ceiling. Furthermore, kinds of furnishings can be added. This small vocabulary set is task specific, because it clearly relates to the space design task. The operations on these components are restricted to adding, removing, and relocation. The system also contains some task specific intelligence in the form of a 30 cm orthogonal grid which is visible on the floor and ceiling, and according to which the wall components must be placed.

We have developed a menu of objects and operations similar to the objects and operations of the TUE full-scale modelling system. As a result, our VIDE system has the same target-group of users as the full-scale modelling system: inexperienced designers for which it is difficult to deduce spatial quality from a plan.

4.1.2 Interface

VIDE has been built to test the following postulations:

1. The ability to develop an instinctive interface through the implementation of natural object behaviour and natural user interaction.
2. The usefulness of a mixed plan-view and rendered photo-realistic interface.

Because we wanted to create an instinctive interface, we exploited people's skill of performing simple gestures and actions with their hands. In addition, we wanted to test the advantage of natural behaviour of objects in response to the user's actions: objects fall down when released in the air; objects collide when they collide with other objects; objects do not appear and disappear suddenly, but they grow and shrink; or they are taken from a stock and put back if no longer needed.

We attempted to support both design generation and visual design evaluation. To support visual evaluation, we had to provided a (more or less) photo-realistic view of the design. This perspective photo-realistic representation would not support design activity because it does not provide a good view of the design as a whole, as it is too unambiguous and thus does not support idea generation. To support design reasoning, we added a conventional plan view representation of the design. See figure 4.

4.2 Conclusions of the project

The VIDE project has led to the following conclusions on VR-based architectural design systems:

1. Materials

The simple materials provided did give the system the same easily comprehensible outlook as the physical full-scale modelling system. New users instantly understood the task it was meant for, and the constraints within which could be designed.

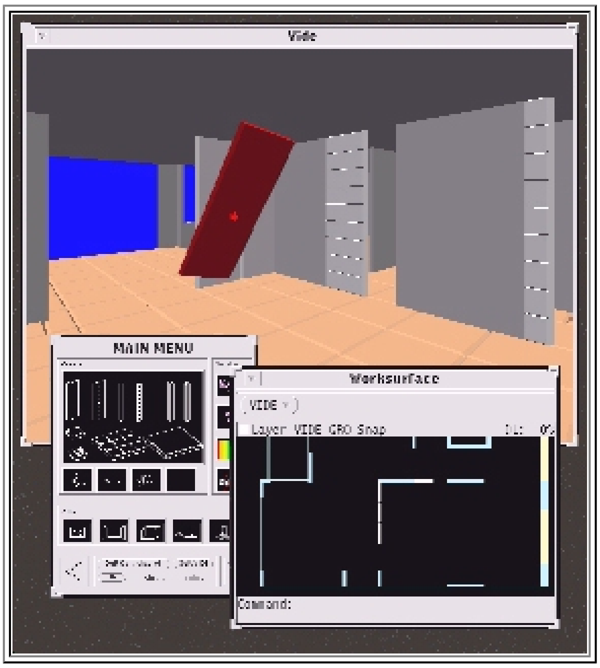

Figure 4: VIDE interface.

2. Instinctive interface

The system did demonstrate that Virtual Reality techniques can be used to create an interface that allows modelling in an instinctive way through the sensing of simple user's gestures such as grabbing and relocating objects in 3D. Furthermore, the interface provides predictable and recognisable characteristics through the imitation of behavioural aspects of the real world, such as objects's gravity, collision, growth, etc.

3. Current technical restrictions

The program has uncovered technical restrictions for a Virtual Reality based interface: the inaccuracy of 3D hand and head trackers and the poor visual quality of Head Mounted Displays do not currently alllow detailed work in 3D. These technical restrictions can be considered temporary.

4. Mixed plan-view / rendered perspective view.

The two types of representations proved complementary during design activities as was expected. However, we experienced problems in relating the two views, e.g. it sometimes appeared difficult for users to keep track of the camera point, from which the realistic view was presented.

4.3 Further Experiments: VIDE-2

Currently, we are working on a second Design Prototyping system: VIDE-2. Unlike the first VIDE system, VIDE-2 will be aimed at professional architectural designers. Furthermore the system will have alternative interface devices.

VIDE has been used for extensive internal evaluation. We will test VIDE-2 by observing and studying actual designer's behaviour. A selection of suitable candidates will be made for the empirical studies. These will include, among others, experienced designers.

5. Conclusions

We have identified the problems underlying the inability to use CAD systems in the early, conceptual phase of the design process. By analysing these problems we have shown that a VR environment can support the early design process better than the conventional desktop based computer interfaces. It achieves this result by offering a higher interactivity and by its potential of presenting highly complex information in an easily understandable form.

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