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Haptic Communication for Cooperative Object Manipulation

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Abstract: In this study, we focus on precise and natural cooperative object manipulation in a virtual space. We introduce two virtually expanded physical laws - virtual mechanical equilibrium on a rigid object and exclusive object arrangement - to create realistic cooperative manipulation. We have built a trial system according to our proposed design. This method is expected to allow users to exchange intended manipulation by haptic and visual channels.

1. Introduction

The 3D design system in a virtual space is one of the anticipated applications of VR technique. The ordinary designing procedure is done with a computer. Since designed objects are represented by numerical data on a computer, a designer can construct objects without physical limitations, such as weight, size, dimensions and time. Although it is necessary to manufacture a target by way of trial, it is a time- and cost- consuming job. In VR-based CAD, since the system presents the designer with a feeling of realistic manipulation for numerical data, s/he can confirm the virtual target as well as the real one without trying it.

Most VR systems are made up of input devices, world simulations, and output devices. For a user, the input and output devices compose interacting bidirectional media. Although many studies have been done in this field, it is difficult to construct an ultimate multipurpose media. Therefore, VR systems are generally made by using the most suitable method in according with the need.

In our research we focused on a cooperative object manipulating system using visual and haptic communication in virtual space. Generating a natural feeling of manipulation with enough precision, we introduced two virtually expanded physical laws. It is expected that the proposed method will allow users to handle one object together sharing their intended manipulation through natural sensations.

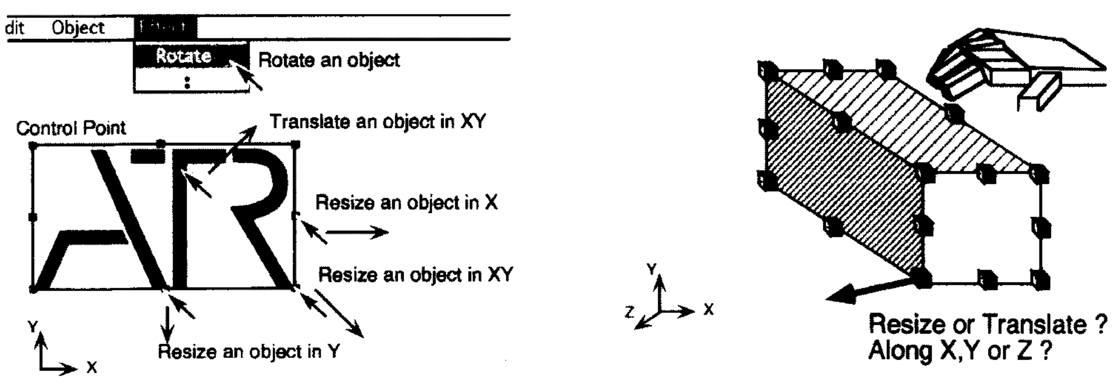
In this paper, we will begin by considering the necessity of manipulation media for multi-users, and the effectiveness of haptic and visual methods. Then we propose a virtual expansion of physics for precise and natural manipulation. Finally, we present problems and solutions to build up a trial system.

2. Cooperative object manipulation in virtual space

2.1 Issues in multi-hand manipulation

First, we would like to focus on the disadvantages of an interface using one hand.

Generally we are too bad to handle any object without



(a) Object manipulation in 2D GUI (b) Object manipulation in 3D virtual environment

Figure 1: Manipulating an object with one icon

haptic sensation. We, for example, need a ruler to draw straight line on a paper. In practical CAD systems using 2D GUI, the system offers a sophisticated precise manipulation with one mouse icon. As shown in fig. 1-a, a handled object has some control points that represent unique manipulating methods. Some of them allow the user to move an object exactly along the base line. Some effects are driven from the menu items previously selected. The reasons why such methods work successfully are because the motion of the target is limited in 2D and some specialized manipulation rules have been studied. In short, it employs some indirect manipulation for effective manipulation using the one mouse icon.

One of the most important features for manipulation in virtual space is that solid objects are manipulated in 3D space naturally and directly. Realizing precise manipulation for one hand icon, some control points could be defined around a 3D object as shown in fig. 1-b, but it is hard to assign a unique 3 dimensional manipulation independently as same as in the 2D-GUI style. Although combinations with some other method such as gestures, buttons and menus could be proposed to determine the unique manipulations, they are an unnatural studied rule that spoils immersive sensation into virtual space.

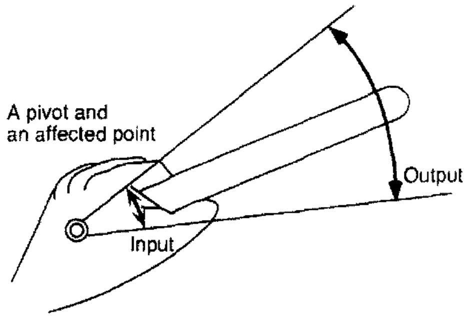
In daily life, we cooperate both hands. If targets are large, we ask assistance of cooperators. In this point, we proposed multi-hand manipulation as a solution for precise and natural object manipulation in virtual space. Of course, we do not have to simulate the negative features of real space. For example, a virtual desk can weights 0 kgf in a virtual space, so we do not have to work together to lift it as in daily life. We, however, can find the following advantages in the multi-hand manipulation.

a) Precise manipulation with a pivot

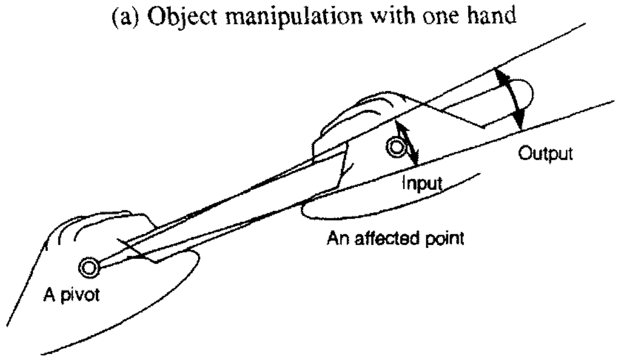
Fig. 2 shows typical manipulation for rotating object. Using only one hand, an affected point acts also as a pivot of manipulation, so it is difficult to adjust the end of the object precisely. On the other hand, in the case of two hands, one hand acts as a pivot, and the affected point is placed near the output. Therefore, the user can handle the object easier than in the case of one hand. In the case of the manipulation for translating object, one hand acts as a ruler and other hand acts as effector as same as the rotation.

b) Extension of the DOF (degree of freedom), volume of manipulation and functions

Using two hands, we can move two objects simultaneously, and the working volume is expanded by two times the maximum. By attaching some different functions to each hand, such as holding, drilling, cutting, melting and so on, it is expected that the working ability could be extended.



(a) Object manipulation with one hand



(b) Object manipulation with two hands

Figure 2: Precision in manipulation

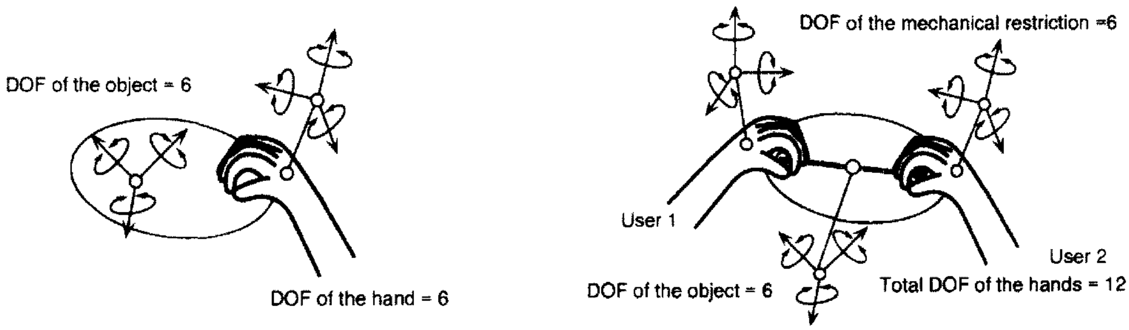
c) Effectiveness

The results from an ergonomic study show that manipulation with two hands is more effective than with one hand. For example, as mentioned previously, when we use one hand as the pivot and use other hand as the an effector to maintain precision in object placement with two hands, we often exchange the role of these hands as occasion may demand. Although the concept of a virtual pivot for one hand manipulation can be introduced, it requires extra steps (lock, move and lock). Therefore, it can be said that manipulation with multi-hands presents a user with continuous operation in virtual space.

2.2 Necessity of a haptic display.

2.2.1 Mechanical restriction of cooperative handling

In the real world, when an object is handled with only one hand (Fig. 3-a), the number of DOF of the hand is the same as the DOF of the object. So the object's DOF is determined by the input motion exactly. When **n** hands are handling one object simultaneously (Fig. 3-b), the number of DOF of the inputting hands are **6n**. If the object is rigid enough and positional relations between the hands are fixed, the status of the object is determined. When a user pushes the object, this action is transmitted to the other user through the object as a change of reaction force. In short, as long as they are holding the object, they can



(a) One user holds one object (b) Two users hold one object together

Figure 3: Degree of freedom of manipulation in real space

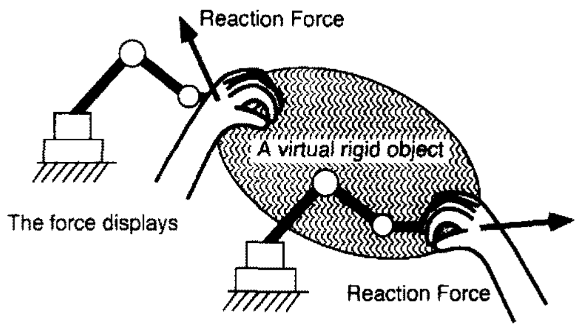


Figure 4: Virtual mechanical restriction by force display

Figure 5: The trial system for two users

handle it together sharing haptic sensation.

In the simplest VR system, using only a glove-like device and a magnetic positional sensor, the user gets only visual feedback from a visual display. Of course, such a system can not restrict the user's motion physically, so many of them disable the function of handling one object by multi-users.

In our proposal, we introduce a force display to restrict the users' motion physically. As shown in fig. 4, the force display generally looks like a mechanical robot arm and can generate reaction force to the user.

2.2.2 Mechanical limitation of force display

Many haptic feedback systems have been studied.[1,2,3] These results said that an ideal force display that simulate realistic haptic sensation requires a robot arm with the following features.

1) The ideal force display has to suppress the human muscles sufficiently.
2) The ideal force display has to follow the entire user's motion in the working area.
3) The ideal force display needs high-speed feedback for stability.

Therefore, it is generally difficult to realize such an ideal force display because of the physical limitations.

Fig. 5 shows a trial system described later. Two custom made force displays are used in this system. Each of them has three actuated joints to generate a maximum of 10N reaction force at a grip in the end. It is, however, insufficient to present a rigid mechanical restriction to the user's hand. Moreover, the grip is connected through unattached universal joints with three axes, so it can follow and measure a 6 DOF motion of a user's hand, but can not physically restrict rotational motion.

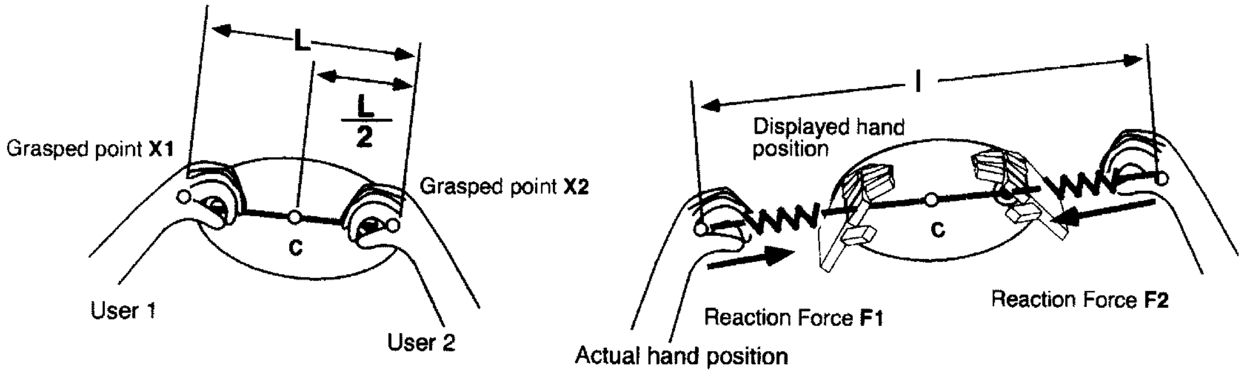
To solve these problems, we introduced virtually expanded two physical laws into a simulation of virtual object manipulation. This method allows users to manipulate one object together naturally and precisely with limited interface devices.

3. Proposed methods for haptic communication

In this section, we introduce two virtually expanded physical laws for the cooperative manipulation. They are 'virtual mechanical equilibrium on a rigid object' and 'exclusive object arrangement'. The former method allows users to handle one object together with realistic haptic communication, and the latter method realizes precise manipulation. The proposed methods present visual and haptic information that is retouched as occasion may require.

3.1 Virtual mechanical equilibrium on a rigid object

When users handle a rigid object in real space, the



(a) Start holding one object with two hands (b) Manipulating one object together

Figure 6: Virtual mechanical equilibrium on a rigid object

positional relations between the grabbing points are fixed. Each user, then, receives reaction force that is in the opposite direction, and equal to the acting force (the third law of motion). The motion of the object is determined by the equilibrium of the acted forces from the users.

As previously mentioned, insufficient force displays can not fix the positional relation exactly. Therefore, the proposed method fills the positional relation only visually in the virtual space, and the reaction force is determined in proportion to distance error as shown in fig. 6. In fig. 6-a, when the first user (user 1) is holding an object at **X1** and the second user (user 2) takes it at **X2**, a point **C** is fixed on the object as the middle point between **X1** and **X2**. While handling it together, point **C** is determined by the users' actual hand positions **P1** and **P2** in real space. In the case of two users, **C** is the middle point between **P1** and **P2**. However, the icons of the users' hands in virtual space are drawn at **X1** and **X2**. which are fixed on the object to satisfy the geometrical relation visually. At that time, each user receives the reaction force (F1 and F2) that is determined by these equations.

$$\mathbf{F1} = -\mathbf{F2} \quad (1)$$

$$|\mathbf{F1}| = |\mathbf{F2}| = |k \times (l - L)| \quad (2)$$

Where, **l** is the actual distance between the users' hands in real space and **L** is the same in virtual space. So the reaction forces F1 and F2 have opposite directions and are the same size in proportion to the distance error between **Xi** and **Pi** (**i**=1,2), as if they are holding the object using springs as illustrated in fig. 6-b. In this configuration, when one user pulls the object, the icon of the other user's hand is pulled visually and s/he receives this motion with haptic sensation at the same time.

3.2 Exclusive object arrangement[4]

When placing an cup on a table in real space, the cup being handled never overlaps the table. The user receives a suitable reaction force caused by the collision of the cup and the table, so s/he can place it on the table precisely without any special attention.

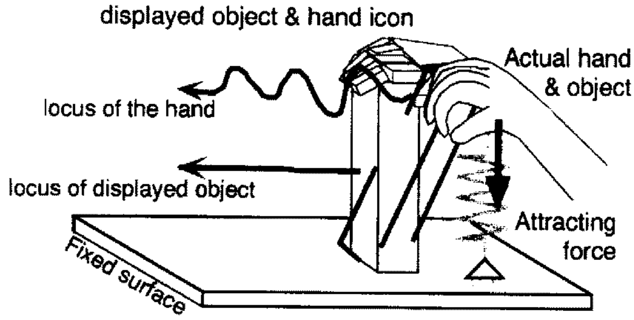


Figure 7: Exclusive object arrangement with visual and haptic methods

Realizing such exclusive object arrangement in virtual space, a VR system has to detect the complex collisions of the objects and present 6 DOF reaction force in real-time. As mentioned before, this requests time-consuming calculation and an ideal force displays.

Supporting such an natural placement task in virtual space with limited devices, we introduce visual and haptic feedback based constraints among object manipulation. The concept of this approach is shown in Fig. 7.

This method visually restricts the object's motion and hand icon in virtual space, but does not restrict the user's hand motion rigidly in real space. The original DOF of the virtual object is 6, and the DOF is restricted to 3 automatically to avoid overlap when the object is placed on other surface. While the handled object is restricted on the other surface, the reaction force attracts the user's hand to the constrained surface. In short, the user's hand is kept around the face without the user being aware of motion control. If the user want to lift the cup from the table, s/he has to intentionally pull it apart against the reaction force from the table more than the predefined threshold.

The status of constraint is controlled by the system semiautomatically. When the user approaches the cup

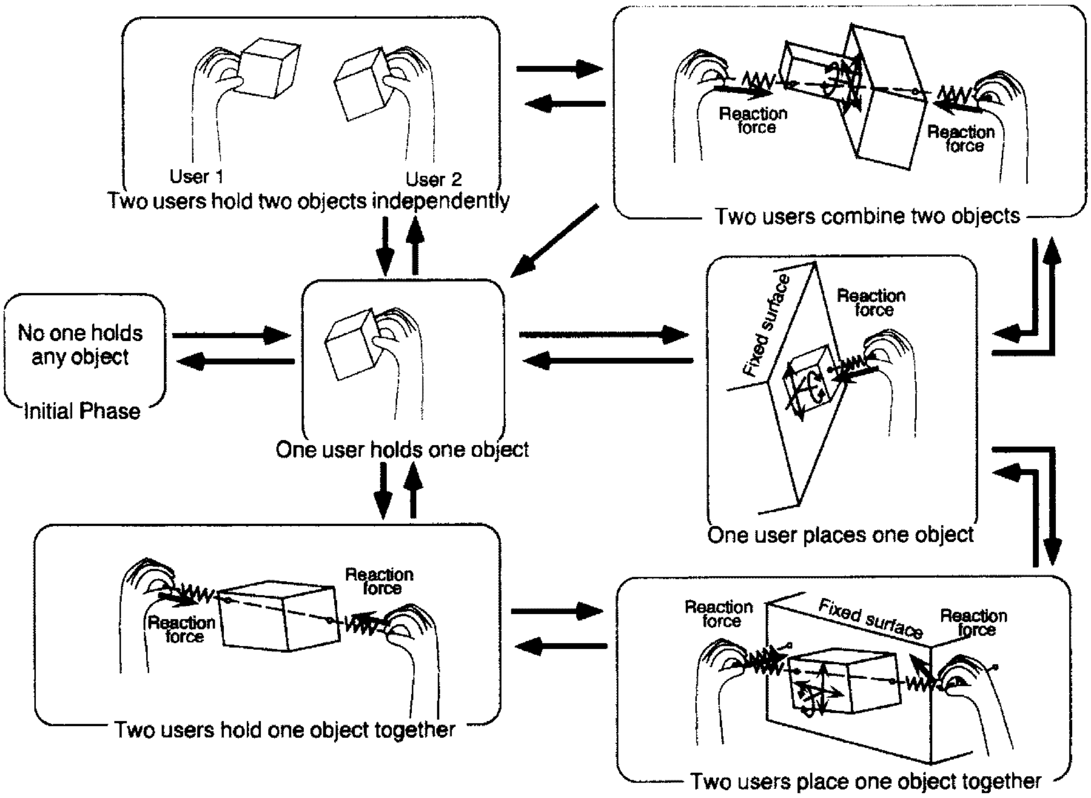


Figure 8: Transition diagrams of object manipulation in the case of two hands

on the table, the system estimates the best pair of the faces for each one and constrains them. Therefore, these two kinds of feedback based method presents the user with highly direct manipulation, and consequently s/he can pay attention to simply manipulating unrestricted DOF of the cup as s/he pleases.

4. Manipulation with two hands in the proposed method

To explain the proposed application, fig. 8 shows transition diagrams of object manipulation in the case of two hands. In these diagrams, all of the users' motions are directly reflected on the object being handled in the unshaded phases. In the shaded phases, the system retouches the motion of both handled objects and the icon of each hand according to the proposed methods. The illustrated hands represent the position of the actual hands for easier understanding. In virtual space, these hand icons are shown just where the hands are grabbing the object as long as they hold it.

First, when the user places the object being handed on another fixed surface, the manipulation phase transits from "*one user holds one object*" to "*one user places one object.*" In this phase, the method "Exclusive object arrangement" applies, so the motion of the object is constrained on the fixed surface and the user gets an attracting force from the surface.

In the phase "*two users hold one object together*", the method "Virtual mechanical equilibrium" allows them to cooperate in object manipulation by communicating their intentions through visual and haptic channels. Additionally, when moving the object to a fixed surface together, the phase transits to "*two users place one object together.*" Here, the method "Exclusive object arrangement" takes over, so each user receives the transmitted action from the other user and the attracting force from the fixed surface simultaneously. Of course, they do not have to be careful to place the object on the surface straightly.

From the phase "*two users hold two objects independently,*" they can combine these objects, In the phase, "*two users combine two objects together*", the method "Exclusive object arrangement" retouches the positional relation between these objects to prevent them from overlapping. Then, the method "Virtual mechanical equilibrium" determines the reaction forces for the users, transmitted through the constrained face.

In any phase, one user's motion is transmitted to the other user through the handled virtual object as a reaction force. Additionally, overlapping between virtual objects is automatically avoided. Therefore, it is expected that the users can handle virtual objects precisely with a successful feeling of manipulation.

5. Trial system

5.1 Configuration of the trial system

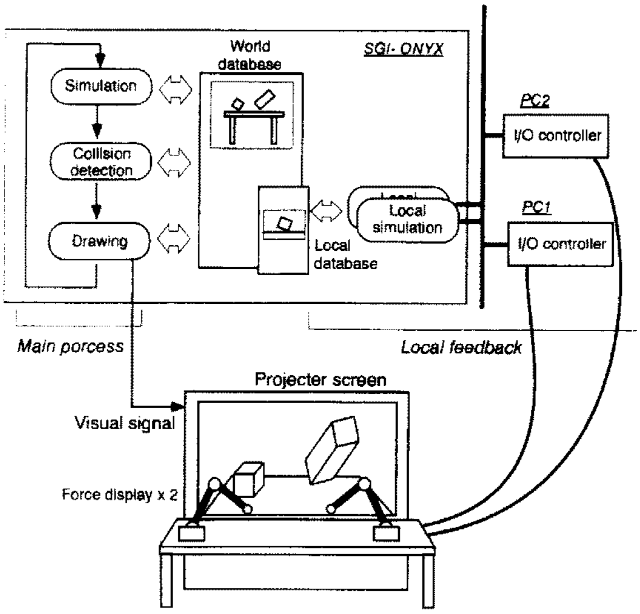


Figure 9: Block diagram of the trial system

Fig. 9 shows a block diagram of the trial system. All input and output devices and sensors were controlled by a SGI ONYX™ and PCs (P5,75MHz). Two 70-inch screen projectors were used to present stereoscopic images of virtual space. The system equipped two force displays, so two users' hands, or both hands of one user, can handle objects with the feeling of the cooperative manipulation through the visual and force display. When the user wants to grab a virtual object, s/he puts in the hand-shaped icons into the object and clicks button at the grip of the force display.

5.2 Issue of the update rate

The information updating rate is a serious problem for VR systems. It is well known that we can not distinguish a series of visual images being updated at a rate of more than about 12 Hz. The force display and simulation of dynamics, however, requires a higher update cycle than the updating cycle of visual information. [5] So we divided the trial system into time-consuming heavy process and high-speed light processes. (fig. 9)

The former is named 'main process' and consists of a virtual world simulating process that manages all objects, real-time collision detecting process, and a CG drawing process. Each subprocess places such a load of the CPU that they were carried out at an average of 30 Hz depending on the number of object and polygons. The numerical database of all virtual objects is maintained by the main process and the objects are shared with the latter subsystem.

The latter are named 'local feedback'. These subsystems were carried out higher than the main process unsynchronously. They were referencing the phase of manipulation, the actual position of the users' hands in real space, and were maintaining the local database of the objects around the users' hand icons. Using these data, they realize force feedback at enough high rate. The ONYX™ and PCs were connected by ethernet. In the trial system, they were carried out at about 300 Hz.

6. Conclusion

In this study, we focused on precise and natural cooperative manipulation in virtual space. Our system introduces two virtually expanded physical laws. The users manipulate a rigid object in virtual space visually, but the actual users' hands do not receive real reaction force. Here, the haptic communication channel is used as a realistic indicator for the retouched manipulation. Although our proposition is not to simulate real manipulation using VR in this point, we expected this method to achieve realistic cooperative manipulation.

According to the proposition, we have designed and built the trial system that allows two user to handle one object simultaneously. In the future work, we plan to exam the effectiveness of proposed method compared to manipulation in real space.

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