# Extending Telepresent Walking by Motion Compression

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**Abstract**

*Telepresent walking allows visiting remote places such as museums, exhibitions or industrial sites with a high degree of realism. While walking freely around in the user environment, the user sees the remote environment "through the eyes" of a remote mobile teleoperator. For that purpose, the user's motion is tracked and transferred to the teleoperator. Without additional processing of the motion data, the size of the remote environment to be explored is limited to the size of the user environment. This paper proposes an extension of telepresent walking to arbitrarily large remote or virtual spaces based on compressing wide area motion into the available user space. Motion Compression is a novel technique and does not make use of scaling or walking-in-place metaphors. Turning angles and travel distances are mapped with ratio 1:1.*

## 1 Introduction

Visiting remote environments from your living room would be a convenient alternative to being physically present on scene. For that purpose, a mobile teleoperator is required that moves under user control in the remote environment. The teleoperator is equipped with a stereo camera pair that transfers the perceived image stream to the user's current location,i.e., the user "sees through the eyes" of the teleoperator.

Telepresent walking induces the impression of walking through a remote target environment while being physically located in the user environment. This is achieved by tracking the physical motion of the user, who walks freely about the user environment. The teleoperator's motion is then controlled to replicate the user's motion. This approach to telepresent walking provides the most consistent perception of motion in the target environment by adding realisitic vestibular and kinesthetic cues to vision.

However, without additional processing of the user's motion data, the size of the target environment, that can be explored, is limited to the size of the available user environment.

This paper introduces a new paradigm called Motion Compression (MC), which allows strolling through an arbitrarily large target environment by actually walking in a much smaller user environment. This is achieved by transforming remote environment motion to a corresponding motion in the available user space, Fig. 2. The transformation does not make use of scaling and is selected such that degradation of realism is minimized.

MC is not limited to the control of the locomotion of a mobile teleoperator. In fact, it can readily be applied to locomotion in large *virtual* environments. Both a remote real environment and a virtual environment will be called *target environment* in the remainder of this paper. The teleoperator and the virtual representation of the user in a virtual target environment (avatar) will both be denoted as *proxy.*

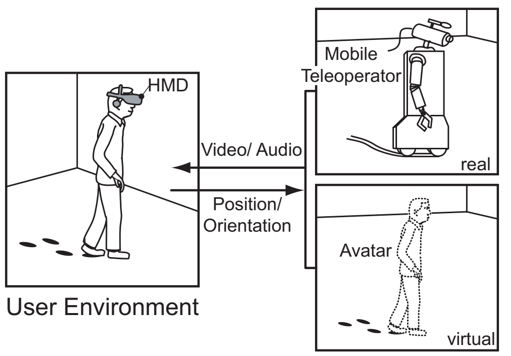


**Figure 1:** *Telepresent walking: The user controls locomotion in the target environment (real or virtual) by actually walking in the user environment.*

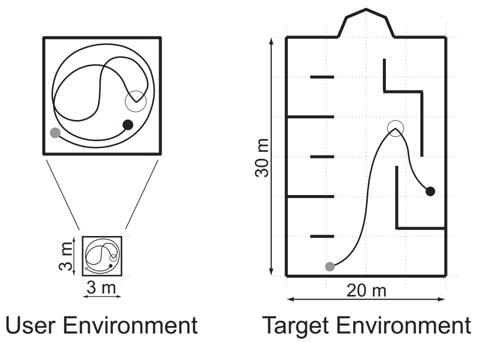


**Figure 2:** *Example of Motion Compression: The user physically walks along the convoluted path in the user environment (left). Visual perception, however, creates the impression of walking along the straight path in the target environment (right).*

## 2 Related Work

A great variety of approaches to teleoperated locomotion of mobile robots can be found in the literature. A good overview is given in [1]. However, most current approaches do *not* provide a realistic sensation of self-motion.

Locomotion in large virtual environments is also addressed in a variety of research projects. In many cases, the focus is on designing realistic interfaces trying to create a "perfect" sensation of self-motion. Examples are 2D-treadmills [2,3] or the tracking of physical user locomotion [4, 5]. A more abstract metaphor based on extracting the user's intended locomotion from physical in-place walking and stepping motion is presented in [6]. In [7], a Step WIM (World in Miniature) has been implemented to allow users to travel large distances in virtual environments.

Another approach to wide area locomotion in virtual environments, which is similar to Motion Compression is taken by [8]. It is based on the same idea of exploiting the human user's tolerance with respect to a certain amount of inconsistency between visual and proprioceptive perception of self-motion. However, their method relies on a predefined target path with a sufficient number of direction changes. By modifying angular motion mainly during these turns, turning angles are not mapped with ratio 1:1 as in the proposed approach.

The effects of the various stimuli conveying information about self-motion on the human navigation and orientation capabilities have been studied by many researchers. Results in [9] show that kinesthetic feedback among vestibular feedback and visual flow provides the most reliable and accurate data for path integration. Nevertheless, vestibular perception is essential for accurate path integration, too, [10,11]. The work of [12] suggests locomotion interfaces which use real translational and rotational user motion as input for tasks involving spatial orientation.

## 3 Basic Concept of Motion Compression

A user, who is wearing a head mounted display (HMD) and whose physical head motion is tracked in six degrees of freedom, can be immersed into a target environment by providing visual cues consistent with the detected head motion. The user receives the impression of walking in the target environment. MC extends this most realistic locomotion interface to target environments of much larger size than the available size of the user environment.

The basic concept of MC is to *guide* the user on a path in the user environment (user path) which is a transformed version, i.e., an image of the path the user travels in the target environment (target path), Fig. 3. As a simple example, the user is physically walking along a circle while the proxy moves along a straight line. The user's visual sensation is consistent with motion in the target environment (straight line), whereas proprioceptive, i.e., vestibular and kinesthetic, sensation reflects motion in the user environment (circle). In other words, MC provides the correct visual stimuli corresponding to motion in the target environment but can only approximate proprioceptive stimuli. Experiments demonstrate that the user tolerates a certain amount of inconsistency between visual and proprioceptive sensation of motion, see Sec. 5. This inconsistency results from the differences in curvature between the target and the user path.

MC comprises three main components. First, prediction of the intended locomotion of the user in the target environment (path prediction). The result is a predicted target path or, in general, a set of target paths. Second, transformation of the predicted set of target paths into the user environment (path transformation). For that purpose, an angle *and* distance preserving transformation is employed that produces an image of the set of target paths fitting into the user environment. Third, tracking of the user position and orientation with respect to the user environment and transformation back into the target environment. As a result, the user is guided on the user path (user guidance), Fig. 3.

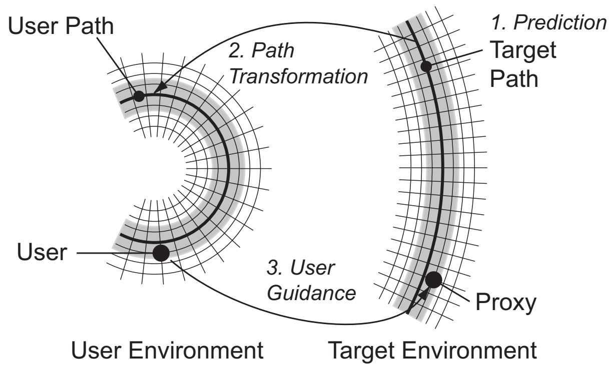


**Figure 3:** *Motion Compression: User locomotion is mapped from the user environment to the target environment in such a way that the user's path tracking feedback-control results in the user being guided on the user path. The condition of angle* and *distance preservation holds only in a narrow region left and right of the nominal paths (shaded area).*

# 4 Motion Compression for General Target Environments

In a general target environment there is a continuum of paths the user may move along. Off-line transformation of all possible paths becomes impractical. Hence, one path or one set of paths is considered at a time and path prediction as well as path transformation must be performed on-line.

## 4.1 Path Prediction

Reliable path prediction is vital for MC with minimum degradation of realism. Unpredicted changes of the user's motion direction may result in strongly curved user paths as indicated by the example in Fig. 4. Strongly curved user paths are experienced as the target environment spinning around the user. This undesired behaviour creates confusion and disorientation due to high inconsistency between vision and proprioception.

Two approaches exist for path prediction. First, a path prediction algorithm can be based on current and past position/ orientation data of the proxy. Such an algorithm would then make use of some model of human locomotion to predict future motion. It is obvious that this locomotion based approach can only offer short term prediction because it does not use information about the users global goal of locomotion. Sudden changes of the travel direction can often not be predicted.

Second, long term prediction is possible if the user's intention to head for a particular point or landmark in the target environment can be recognized. Intention recognition must be based on a model of the target environment from which information about potential goals of locomotion can be extracted.

## 4.2 Path Transformation

The basic idea of path transformation is to take the predicted target path and bend it such that it fits into the user environment. The result is the user path, a transformed version of the target path. As stated above, the inconsistency between the visually perceived target path and the proprioceptively perceived user path results only from the deviation of curvature. Therefore, the fundamental goal of path transformation is to minimize curvature deviation.

Path transformation could then be understood as a dynamic optimization problem with the path variable $s$ as the independent variable. The predicted path is given by the function

$$\kappa_T = \kappa_T(s) \quad s = 0 \ldots s_E \qquad (1)$$

where $\kappa_T$ is the target path curvature, $s$ the distance along the path and $s_E$ the total length of the path. Starting position and orientation of the target path are of no interest for the transformation.

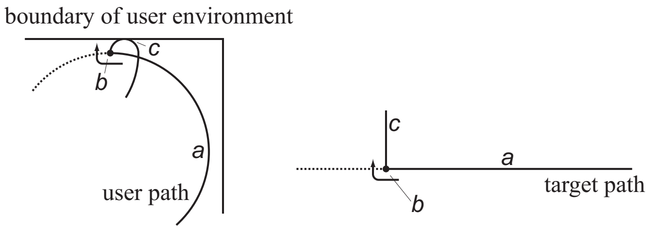


**Figure 4:** *Worst case situation: The user leaves the predicted target path (a) turning towards the limit of the user environment at (b). This results in a strongly curved user path (c) and thus high inconsistency between vision and proprioception.*

The optimal user path to be found will be given by the function

$$\kappa = \kappa(s) \quad s = 0 \dots s_E \tag{2}$$

together with its starting position and orientation

$$x_0, \quad y_0 \quad \text{and} \quad \varphi_0. \tag{3}$$

An obvious objective functional for minimizing overall curvature deviation is

$$J_1 = \int_0^{s_E} \frac{1}{2} (\kappa - \kappa_T)^2 \, ds. \tag{4}$$

The user path is subject to the following equality constraints describing the relationship of curvature, orientation and position

$$\frac{dx}{ds} = \dot{x} = \cos\varphi \tag{5}$$

$$\frac{dy}{ds} = \dot{y} = \sin\varphi \tag{6}$$

$$\frac{d\varphi}{ds} = \dot{\varphi} = \kappa \tag{7}$$

and a set of inequalitiy contraints describing the feasible space in the user environment

$$\underline{g}(x, y) \geq 0 \tag{8}$$

In general, the terminal position of the user path should be located as far away from the user environment boundaries as possible. This gives the user the freedom to set off in any direction from there. Therefore, a penalty term for the terminal condition is added to the objective functional leading to

$$J_2 = J_1 + \Phi\left[x(s_E), y(s_E), \varphi(s_E)\right]. \tag{9}$$

This general optimization problem can only be solved numerically. Depending heavily on the initial guess, different suboptimal solutions or no solutions are found, Fig. 5. Therefore, robust algorithms for finding good initial guesses will be the focus of future research work. One particular method will be presented in Sec. 4.4.

### 4.3 User Guidance

The user guidance component of MC maps the measured user position and orientation from the user environment to the position and orientation of the proxy in the target environment. The mapping is defined by the target and the user path. The basic idea of

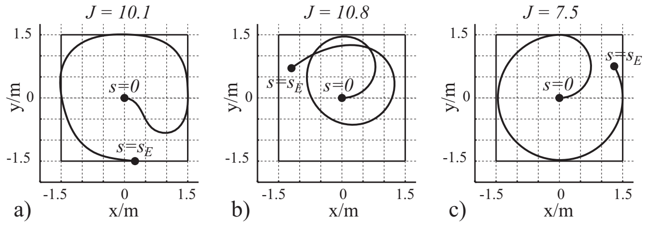


**Figure 5:** *Sample solutions of path transformation: The target path is a straight line of 10 meters length. Samples a) and b) are numerical solutions of the dynamic optimization problem using different initial guesses. Sample c) is the result of the semicircle-algorithm (see Sec. 4.4). J is the value of the objective functional.*

user guidance is to make use of the user's path tracking feedback-control. Position and orientation in the target environment is calculated such that the resulting visual feedback guides the user on the transformed (user) path.

One obvious method is obtained by specifying the following properties for the mapping (see also Fig. 4.3):

- Positions on the user path are mapped to positions on the target path, with the distance the user moved along the user path ($s_U$) equal to the distance along the target path ($s_T$).
- Positions off the user path are mapped to positions off the target path, with the perpendicular distance from the user to the user path ($d_U$) equal to the distance of the proxy to the target path ($d_T$).
- User orientation tangential to the user path is mapped to proxy orientation tangential to the target path or more general the angle between user orientation and the tangent of the user path ($\theta_U$) equals the angle between proxy orientation and target path ($\theta_T$).

These properties are taken into account by introducing two local Cartesian coordinate frames $S_{LU}$ and $S_{LT}$ in addition to the global frames $S_{OU}$ and $S_{OT}$. The origin of $S_{LU}$ is on the user path at position $s_U$ and its x-axis tangential to the user path. The origin of $S_{LT}$ is on the target path at position $s_T = s_U$ and its x-axis tangetial to the target path, Fig. 6. From the above specified properties follows

$$^{LU}T_U = {^{LT}T_T}, \tag{10}$$

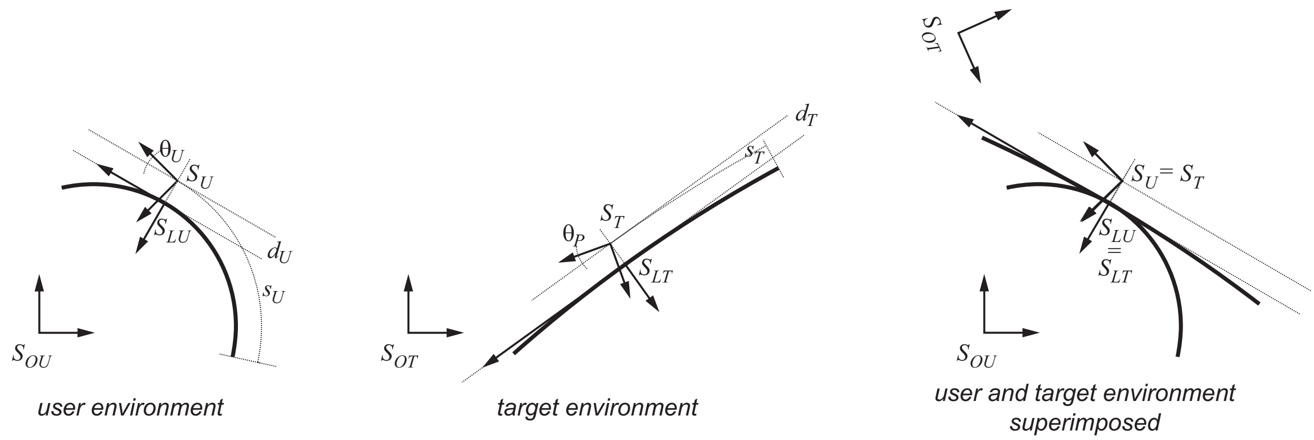


**Figure 6:** *User guidance: The measured position and orientation of the user is mapped to the position and orientation of the proxy. Superimposing user and target environment illustrates the relationship between environments.*

where the Homogenous Transformation ${}^{LU}T_U$ denotes the user's position and orientation with respect to $S_{LU}$ and ${}^{LT}T_T$ is the proxy's position and orientation in $S_{LT}$.

The position and orientation of the proxy with respect to $S_{OT}$ (${}^{OT}T_T$) are calculated from the measured position and orientation of the user with respect to $S_{OU}$ (${}^{OU}T_U$) by

$$ {}^{OT}T_T = {}^{OT}T_{LT} \underbrace{{}^{LU}T_{OU}\,{}^{OU}T_U}_{{}^{LT}T_T}. \tag{11} $$

From this equation, the transformation from user to target environment or vice versa is obtained as

$$ {}^{OT}T_{OU} = {}^{OU}T_{OT}^{-1} = {}^{OT}T_{LT}\,{}^{LU}T_{OU}. \tag{12} $$

This transformation describes position and orientation of the target environment with respect to the user environment, Fig. 6.

The transformation ${}^{OU}T_{LU}$ can be obtained from the measured position of the user in $S_{OU}$ by dropping a perpendicular from the user position onto the user path. The foot of the perpendicular is the origin of ${}^{OU}T_{LU}$ and thus determines the path variable $s_U$. Note that the perpendicular from the user position onto the path is not always unique.

## 4.4 Implemented Solutions

In the preceding subsections, we presented the methodology for the design of MC. For some of the related problems solutions are not known yet or difficult to implement. Therefore, we will introduce some simplifying assumptions and detail practical solutions.

**Path prediction.**

For path prediction both a locomotion based and a target based algorithm have been implemented and tested successfully.

The locomotion based algorithm rests on the following simple model of human locomotion: "future walking direction equals gaze direction." In this case, the predicted path is always a straight line starting at the proxy's position and running in the direction of its gaze. The endpoint of the predicted path is undetermined. Thus, a corresponding path transformation algorithm cannot optimize the endpoint of the user path but must anticipate unpredicted changes of the direction of locomotion.

The implemented target based algorithm is equally simple. From the geometrical model of the target environment, objects of interest are offline and manually identified as potential goals of locomotion. One of these potential goals is then selected online as the endpoint of the predicted path. The selection is based again on gaze direction. The longer the user remains looking at a potential goal, the more likely the object is the user's goal. This likelihood is expressed by a coefficient $w_i \in [-1; 1]$ assigned to every potential goal. $w_i$ is increased when the corresponding object is within the field of view and decreased otherwise. The object with the highest $w_i$ is selected and the predicted path is the straight line from the user to the selected goal.

**Path transformation.**

By neglecting the inequality constraints (8) and assuming the target path to be a straight line, the optimization problem from Sec. 4.2 reduces to finding the minimum of

$$J_3 = \int_0^{s_E} \frac{1}{2} \dot{\varphi}^2 ds. \quad (13)$$

By calculus of variation, the necessary condition for a minimum is given by

$$-\frac{d}{ds}\dot{\varphi} = -\frac{d^2\varphi}{ds^2} = 0. \quad (14)$$

Paths satisfying this equation are either circular arcs or straight lines. For that reason and because circles are convenient to deal with, path transformation is reduced to finding an appropriate circular arc.

A first heuristical solution, which incrementally transforms a target path to a user path, is based on the following assumptions: (1) The predicted path is a straight line starting at the proxy's position. (2) The predicted path has no fixed endpoint. (3) The user environment is a convex polygon.

Then the user path is a circular arc satisfying the following conditions: (1) The starting point is the user position. (2) The starting direction coincides with the direction of the target path mapped into the user environment. (3) The arc is the *largest semicircle* fitting into the boundaries of the user environment. Fig. 7 gives some examples with varied user positions and target path directions in a square user environment.

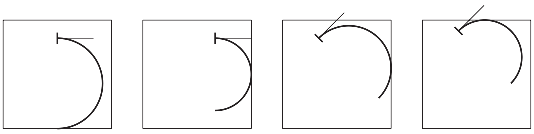

**Figure 7:** *Largest semicircles fitting into a square user environment for different given starting positions and directions.*

User path arcs are determined successively according to the conditions above for short sections of the target path. Thus, only a short section of each user path arc is actually used and the total user path is a chain of short circular arcs. Thanks to the second condition stated above, transitions between all circular arcs forming the user path are smooth with continuous orientation but discontinuities in curvature.

Fig. 5 shows a user path created with the semicircle-algorithm. The target path is a straight line with a length of 10 m. The transformation was achieved by successively transforming fractions of 1 cm length.

In the experimental setup, the semicircle-algorithm is executed concurrently with user tracking. A new circular arc is determined with every new measurement from the tracking system and every update of the predicted target path. Thus, the user path is planned incrementally and not in advance. Nevertheless, the semicircle-algorithm features a predictive behaviour which is accounted for by considering the boundaries of the user environment before they are actually hit.

The semicircle-algorithm cannot only be applied to direct path transformation as described in the preceding paragraph. It is also a reliable method for calculating initial guesses for the dynamic optimization problem discussed in Sec. 4.2.

**User guidance.**

The mapping from measured user coordinates to the proxy's position and orientation follows exactly the method described in Sec. 4.3.

# 5 Experiments

## 5.1 Experimental Setup

Experiments described in the following sections have been carried out in a user environment of 4.0 m by 4.0 m floor space. The algorithm uses a 3.0 m by 3.0 m area to ensure some safety margin to the physical walls. An Ascension Flock of Birds magnetic tracking system with a long range transmitter is employed for user tracking [13].

The user wears a V8 HMD by Virtual Research Systems, Inc., which displays stereo images of the target environment at standard VGA resolution. The virtual target environments are rendered on a Pentium III/ 800 equipped with two Voodoo2 3D-accelerators. The virtual environments were implemented with Maverik [14].

A photograph of the user environment is shown in Fig. 8.

## 5.2 Visiting a Virtual Museum

The MC algorithm is applied to visiting a large room in a virtual museum. The layout of the virtual hall is shown in Fig. 2. The size of the hall is 30 m by 20 m. Fig. 9 shows a screen shot of the virtual museum. Although the available user environment is 3 m by 3 m only and thus user path curvature is usually $> 0.3\ m^{-1}$, strolling through the virtual museum is

**Figure 8:** *User environment used in the experiments. Available floor space is about 4 m by 4 m. The user wears a HMD and head motion is tracked by a extended range magnetic tracker.*

found very comfortable and intuitive by most test subjects. As long as the user decides for one piece of art and walks there on a straight target path, no peaks of curvature deviation occur and subjects quickly accustom to the inconsistency of visual and proprioceptive perception. Test persons are observed to reach normal walking speed after a few cautious initial steps. However, peak curvature and changes of direction of curvature are likely to occur when the user decides for a new goal of locomotion at some unfavourable position. The inconsistency, although soon becoming almost unnoticeable, causes cyber-sickness and problems walking straight after the experiment.

## 6 Conclusion

A novel general and systematic method for compressing large scale voluntary locomotion into much smaller available space has been presented. The method does *not* rely on scaling. Rather, Motion Compression (MC) is based on the modification of path curvature. Turning angles and distances are transformed with ratio 1:1. However, MC can be combined with scaling in order to magnify or reduce target environments which otherwise would not be accessible by human walking. Consider for instance walking through a biological cell or through a solar system.

The advantage over conventional interfaces for locomotion in virtual or remote real environments (target environments) is that MC provides the "feeling" of motion by approximating proprioceptive cues.

MC can be applied to telepresent locomotion in virtual as well as real target environments. In case of virtual environments, the user controls the motion of a virtual representation of himself, thus getting the impression of being immersed in the virtual environment. In case of real target environments, a mobile teleoperator is controlled according to the user's physical motion.

Virtual environment applications include large virtual meeting places, virtual museums and visiting virtual prototypes of architecture. A real target environment could also be a museum, offering mobile teleoperators which people from other parts of the world can log into.

In our laboratory a HMD and magnetic tracking is used as human system interface. However, the method can readily be applied to other visual displays and tracking systems, like e.g. a CAVE [15].

In the future MC will be extended to 3D environments including stairs, ladders and slopes. Another extension is to share the user environment with its infrastructure (floorspace, tracking system, ...) among several users. Path transformation in this multi-user scenario not only has to consider the boundaries and static obstacles of the room but must also provide reliable user-to-user collision avoidance measures.

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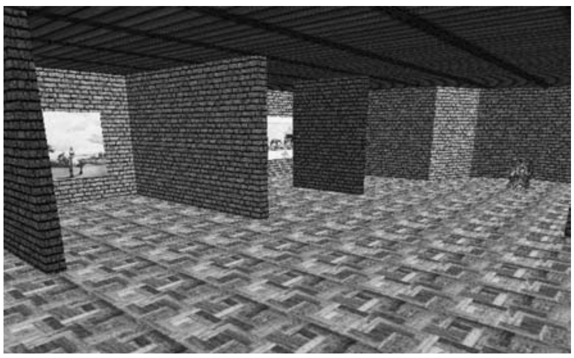

**Figure 9:** *Screen shot of the virtual museum used in the experiment.*

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