TRAJECTORY DESIGN AND STATIONKEEPING
FOR MULTIPLE SPACECRAFT IN FORMATION
NEAR THE SUN-EARTH L₁ POINT

K. C. Howell* and B. T. Barden†
School of Aeronautics and Astronautics, Purdue University
West Lafayette, Indiana USA

Abstract
The concept of flying multiple spacecraft in formation near libration points in the three-body problem offers new technical challenges. Investigations thus far have centered on methods to compute trajectories for formations in a region of space that is inherently unstable. This study utilizes the previous efforts for a preliminary investigation of issues associated with the control of such formations. First, the critical issues in trajectory design for multiple spacecraft in this regime are presented. Then, stationkeeping methods that have been successful in controlling spacecraft in more standard libration point trajectories are considered within the context of formation flying. Finally, results from Monte Carlo simulations with various error levels are presented.

INTRODUCTION
Recently, interest in missions that utilize libration point trajectories has increased. A number of proposals for NASA’s Discovery and Midex programs have been based on mission concepts that arise from trajectory options available in the region of space near the Sun-Earth/Moon collinear libration points. To compliment this interest, numerical capabilities for computing libration point trajectories, as well as transfers to and from such orbits, have improved greatly. Exploitation of the expanded numerical capabilities, coupled with the application of Dynamical Systems Theory (DST), has provided a means to develop new trajectory concepts. Specifically, flying multiple spacecraft in some predetermined configuration in the vicinity of a libration point is a recent result of these efforts.

Formation flying is a challenging problem in any regime. Some of the complexities that arise are addressed, for example, in the design of the Space Technology 3 and LISA missions, both of which involve flying two or more spacecraft that operate cooperatively in an essentially two-body regime. However, some design and control issues associated with formation flying are further complicated when the vehicles spend considerable time in the region of space near the collinear libration points, that is, three of the five equilibrium points that exist when the problem is defined within the context of a three-body system. Beyond the known complexities that surface even in the computation of a single nominal trajectory in this region of space, the inherent instability of these types of trajectories – coupled with typical mission constraints – makes control of the relative configuration a particularly challenging problem.

In this study, then, the primary goal is an understanding of the issues involved in establishing and maintaining formations of spacecraft near the collinear libration points. To that end, different scenarios are generated to provide a setting for experimentation and, thus, to expose a number of the significant issues that impacts the process of stationkeeping various formations of spacecraft. The control environment is structured to either take advantage of the natural dynamics in this region of space or, alternately, to ignore the dynamical coupling and rely exclusively on a firm, active controller. Of course, a large number of factors contribute to the successful maintenance of a satellite formation. The focus of this investigation includes maneuver (ΔV) costs as well as robustness of the maneuver strategies in the presence of uncertainties. The mission scenarios all involve clusters of multiple spacecraft near the L₁ libration point in the Sun-
Earth/Moon system; all of the formations must be maintained for approximately four years. In this study, the trajectory simulations incorporate full ephemerides for the positions of the Sun, Earth, and Moon. Then, the stationkeeping analyses allow the evaluation of different constraints and error levels. This investigation, therefore, offers some benchmark in the consideration of other control options for libration point trajectories, as applied to this type of formation.

**TRAJECTORY DESIGN**

For any potential mission involving multiple spacecraft in a three-body regime, the first step is the formulation of a methodology for the design of baseline trajectories specifically for formations of spacecraft near libration points. Initial progress in this problem resulted from important insights that became apparent when Dynamical Systems Theory (DST) was first applied to the three-body problem. In a recent effort by Barden and Howell, DST is applied as a tool to expand the current understanding of the fundamental motions near libration points. A significant result from that investigation is a set of observations that suggests a dynamical approach to initiate the construction of successful spacecraft formations in the vicinity of libration point trajectories. From fundamental motions that lie in the center manifold near periodic orbits associated with the collinear libration points, a periodic closed curve can be isolated that evolves on a torus. The torus itself is related to an underlying periodic halo orbit. This relationship, outlined in Barden and Howell and Gómez et al., is the key component for successful construction of a dynamical formation in this regime. Particles initially placed on the curve will then remain on the curve throughout the dynamical evolution of the system. A demonstration of this motion on the torus in the circular restricted three-body problem is presented in Figure 1 where six uniquely colored particles (possibly representing spacecraft) have been placed on the curve. The collective formation of particles is isolated at six locations, each marked by $C(t_i)$, as the curve proceeds in time along the torus in the direction of motion of the underlying halo orbit. There are certain aspects of the evolution of this curve that are of particular interest. The curve, when viewed independently of the torus, appears simply closed and nearly circular in configuration space. When the amplitude, or pseudo-radius, of the curve is “small”, i.e., in the linear range (less than 1000 km, perhaps more), the curve is considered to be planar. However, as the curve evolves, it changes size and shape. This is apparent in Figure 2 where the curve is plotted at eight different locations (equally spaced in time) throughout one period of the underlying halo orbit. In each instance, the orientation of the plane containing the formation is first identified; then the curve defined by the six particles is viewed from a point along the normal to the plane. Thus, each image in Figure 2 illustrates the changing characteristics of the curve in its own plane. The first location in time along the halo orbit is represented in Figure 2(a), corresponding to the maximum $z$ excursion on the halo orbit; then the evolution is tracked chronologically in Figures 2(b), 2(c), etc. (Again, recall that the plane itself changes orientation as motion proceeds along the torus.) In addition to the flux in size and shape, there is a winding aspect of the motion that can also be seen in Figure 2 and proceeding as before, a clockwise rotation is clearly visible. This type of natural formation has been demonstrated to exist in a more complicated dynamical model that includes ephemeris information for the positions of the planets, the Moon, and the Sun.

This type of natural motion as an option for formation flying is very appealing from a dynamical perspective. From a practical standpoint, however, this formation will likely not meet the constraints and scientific requirements of a generic mission. The likely scenario is that some pre-specified formation will be mandated. Thus, other formations must also be considered. In the previous example, a natural solution for multiple spacecraft moving in a fixed relative configuration within this dynamical system is isolated. Thus, no significant deterministic maneuvers are necessary and all particles/spacecraft proceed naturally and independently along their respective paths. However, in forcing a specified configuration, independent of the dynamics, it becomes necessary to insert deterministic maneuvers to maintain the formation. The frequency and location of these maneuvers depend upon the specific specifications for the formation, as well as the libration point trajectory that serves as the dynamical framework to support the cluster of particles/spacecraft in the formation. The issue of the required deterministic maneuvers will be addressed later. First, it is necessary to briefly review the construction of the supporting libration point trajectory.
A general approach for the design of formations in this region of space does not exist. However, some straightforward considerations can be made to provide a means of making significant progress in this arena. The design process begins with a baseline Lissajous trajectory in the vicinity of a libration point. This can be accomplished using the methodology described in Howell and Pernicka. A quasi-periodic Lissajous trajectory near the $L_1$ libration point in the Sun-Earth/Moon system appears in Figure 3, and this is the baseline trajectory that is used throughout this study. This trajectory possesses an out-of-plane $A_z$ amplitude of 200,000 km and an in-plane $A_y$ amplitude of approximately 740,000 km and is presented in the usual rotating libration point coordinates. (Note that all simulations and trajectory computations are computed in a dynamical model that uses the Jet Propulsion Laboratory DE405 ephemeris for values of the mass as well as the locations of the Sun, Earth and Moon.) Note that a periodic (or nearly periodic) reference trajectory is necessary to compute the natural motions discussed previously in order to satisfy the appropriate conditions for the application of DST. Of course, no requirements for periodicity of the reference orbit exist to propagate arbitrary initial conditions for a set of particles; however, a cluster of particles/spacecraft will the
Figure 2 Evolution of the Invariant Curve
Formations can now be defined relative to this periodic or quasi-periodic trajectory. As a general example, consider a formation that requires some number of spacecraft to lie in an arbitrary fixed plane. As mentioned previously, deterministic maneuvers must be included; thus, any formation can be enforced at the maneuver locations. However, there are deviations from the specified formation between the maneuvers. This situation cannot be avoided if the formation is defined independent of the natural dynamics. Therefore, the formation is classified as “non-natural.” It would be necessary to apply continuous control to maintain the formation at all times. The justification for this observation originates with the analysis of the invariant subspaces associated with the underlying Lissajous trajectory (and it can be verified numerically). The behavior of the trajectories in the phase space near the reference quasi-periodic Lissajous trajectory can be approximated via the variational matrix. Assuming periodicity (a reasonable assumption under certain circumstances), any state nearby the reference trajectory can be expressed as a linear combination of the invariant subspaces associated with the monodromy matrix, i.e., the variational matrix after one (assumed) period of the motion. For fixed points associated with periodic and quasi-periodic solutions in this region of space, there is a one-dimensional stable subspace, a one-dimensional unstable subspace, and a four-dimensional center subspace. The natural formation discussed earlier lies strictly in the center subspace and, thus, ideally does not have an unstable component. The general nature of the non-natural formations clearly implies that, given the arbitrary geometry, some component in the unstable direction will always exist. Additionally, in contrast to the motions that coincide with the natural formation, the geometry of these non-natural formations clearly indicates that they are not themselves solutions to the differential equations and, thus, the enforcement of the non-natural formations essentially suppresses the natural dynamics. Thus deviations from the specified formation between maneuvers are unavoidable.

Some examples of non-natural formations will demonstrate these issues more clearly. In the first case, consider six spacecraft evenly distributed on a circle of radius 100 km in a plane coincident with the rotating libration point (RLP) coordinates $y$ and $z$. 

![Figure 3 Baseline Lissajous Trajectory](image)
Figure 4 Out-of-Plane Components for Non-natural Formation in $yz$–plane

i.e., parallel to the $yz$–plane. Thus, at each maneuver, the formation is enforced, but there will be out-of-plane excursions for each of the spacecraft between the maneuvers; note also that the amplitude will vary for each vehicle. Such excursions appear in Figure 4. Each particle/spacecraft in the figure is represented by a uniquely colored line representing the out-of-plane component relative to the baseline Lissajous trajectory as a function of time, where the specified plane of interest for the formation is the $yz$–plane. The motion is plotted for approximately 355 days, which is equivalent to two revolutions along the baseline Lissajous trajectory in the $xy$–plane. In this first example, four maneuvers per revolution in the $xy$–plane (nearly equally spaced in time) are executed where all six spacecraft implement their respective maneuvers simultaneously. The size of the maneuvers ranges from $4.3e-2$ m/s to $0.12$ m/s for a total cost (all six spacecraft included) of $2.93$ m/s for the specified duration. Recall that these maneuvers are necessary to define a nominal path for each of the spacecraft; additional stationkeeping maneuvers will also be required to accommodate errors and uncertainties. Even for the baseline motion, however, out-of-plane excursions between the maneuvers reach a maximum value at any one time of approximately 20 km in this example. This is a rather significant deviation given that the radius of the formation is designed to be only 100 km. In fact, other planes can be selected that result in excursions that may approach 45 km. The only means of reducing this deviation is to increase the frequency of the maneuvers. This effect can be demonstrated in a case where four times as many deterministic maneuvers are allowed for the same formation as that appearing in Figure 4. In this case, with the time between maneuvers approximately 11 days (as opposed to 44 days), the out-of-plane deviations never exceed 1.8 km. With considerably more maneuvers, the magnitudes of the individual maneuvers is reduced and now ranges between $9e-3$ m/s to $2.5e-2$ m/s with a total cost for all six spacecraft of $2.77$ m/s over the one 355 day duration. This is actually smaller than the $2.93$ m/s required for the case in Figure 4. However, as mentioned previously, fixed planes can be specified where the total cost increases with the increased number of maneuvers.

Another issue of interest regards the allowable size of the formation. Within the context of the current examples, it is appropriate to consider the effect of a larger value for the radius of the formation. Consider again the previous formation with six spacecraft evenly distributed on a circle that lies in the $yz$–plane, and deterministic maneuvers are executed at 11-day intervals. In this example, the radius is selected to be 1000 km. The magnitudes of maneuvers now range in value from $9.2e-2$ m/s to $0.245$ m/s with a total of $27.7$ m/s over the same 355 day duration, with a maximum out-of-plane excursion of $17.2$ km. The result reflects a
remarkably linear correlation between the radius of the circle and the resulting costs. This suggests that the size of the circle could likely be larger and that linear control methods may be effective in maintaining the formation.

In spite of the instability in this region of space, the sensitivities can be advantageous as seen in the relatively low cost of maintaining the configuration. However, this also underscores the dichotomy that while more maneuvers may be required, the magnitude of the individual maneuvers may decrease. From a practical perspective, however, smaller maneuvers tend not to be delivered as accurately as larger ones, thus introducing a larger percentage of uncertainty into the system. The effects of this reality will be considered in the next section.

**STATIONKEEPING**

Methods of controlling spacecraft in a libration point trajectory vary in development and application. In the late 1960's, Farquhar suggested a number of different strategies for controlling spacecraft in these types of orbits. More modern techniques include those developed by Howell and Pernicka as well as Simó et al. Howell and Pernicka suggest a method for discrete control that utilizes some number of target points – where two points are usually sufficient – along the nominal trajectory, points that are downstream from the current location of the vehicle. A quadratic cost function is defined that is dependent upon the projected error in position (and possibly velocity) relative to the target points at the associated future times. This cost function is then employed to minimize the magnitude of a stationkeeping maneuver ($\Delta V$) to be delivered at some specified time; the maneuver may be applied at the current time or later. (Note that this approach is conceptually similar to the quadratic function used by Breakwell, Kamel, and Ratner for a continuous controller).

Another approach is presented by Simó et al. and is based on Floquet theory. Fundamentally this method assumes that the entire trajectory is periodic, thus permitting the computation of stable and unstable Floquet modes corresponding to fixed points along the libration point trajectory. The maneuvers are then computed so that the unstable component of the spacecraft state vector relative to the nominal trajectory is annihilated. In doing so, the spacecraft remains in the vicinity of the nominal trajectory. Fundamentally, both of these methods are based on a certain premise, that is, the expectation that the natural dynamics in the vicinity of the nominal trajectory can be incorporated to enhance the control strategy. (This explicit dependence on the dynamical structure contrasts with the “loose” control employed in some previous missions where the singular objective is to simply keep the spacecraft from escaping the region near the libration point.) Between the two methods, Howell and Pernicka seek a strategy to guide the spacecraft back toward the nominal trajectory whereas Gómez et al. strive to maintain the spacecraft in the center manifold; the spacecraft is not necessarily targeted back to the nominal.

Both of these modern approaches have proven successful as well as robust in numerous trials and comparisons and, thus, appear to be a good starting point for a procedure to maintain a formation. Unfortunately, due to the assumptions in the development of these methods, both are unusable in their current form. The focus in the Howell and Pernicka strategy is reduction of the deviation between the actual state and the nominal trajectory (a solution to the differential equations) at each subsequent target point. But, it is apparent from the results that appear in Figure x, that the deviations from the specified formation do not decrease uniformly. More importantly, the solution that minimizes the cost function is derived with the use of the particular STM that corresponds to the nominal trajectory, with the assumption that the desired deviation is zero. (It may be possible to alter this algorithm to accommodate the constraints of formation flying; and, this type of modification may earn consideration in future investigations.) Similarly, the approach offered by Gómez et al. (right name?) is not effective either. The fundamental element in this second strategy is the annihilation of the unstable component. However, as mentioned previously, any generic non-natural formation will always possess an unstable component. Thus, annihilating the unstable component will likely contradict the specifications for the formation. It is noteworthy, however, that both methods can be successfully applied for control of the natural formation in the presence of errors and uncertainties.

Having excluded the modern techniques, and recognizing that the “loose” control from previous missions also would not be effective on a formation of spacecraft, other methods must be evaluated. There are two approaches considered here. The first strategy is comparable to a simplified version of the Howell and Pernicka algorithm, while the second method is an
iterative approach centered on a differential corrections scheme. The development of the first strategy proceeds as follows. Let \( t_0 \) be defined as the time at which a maneuver is to be executed, and let \( t_1 \) be some specified time downstream. The state transition matrix (STM) associated with the nominal libration point trajectory between times \( t_0 \) and \( t_1 \) can be expressed in the form,

\[
\Phi(t_1, t_0) = \begin{bmatrix} A & B \\ C & D \end{bmatrix},
\]

(1)

where \( A, B, C, \) and \( D \) are 3×3 submatrices. Thus, using the STM, projected deviations at time \( t_1 \) can be expressed as a function of the deviation at time \( t_0 \), i.e.,

\[
\begin{bmatrix} \delta r_1 \\ \delta v_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \delta r_0 \\ \delta v_0 + \Delta \vec{v}_0 \end{bmatrix},
\]

(2)

where \( \delta r_1 \) and \( \delta v_1 \) are deviations between the actual position and velocity, respectively, and the nominal libration point trajectory. The vector \( \Delta \vec{v}_0 \) represents the maneuver necessary to achieve some state relative to the nominal trajectory at time \( t_1 \). The vector \( \Delta \vec{v}_0 \) can then be expressed as,

\[
\Delta \vec{v}_0 = B^{-1}(\delta r_1 - A \delta v_0) - \delta v_0.
\]

(3)

The deviations at time \( t_0 \), \( \delta r_0 \) and \( \delta v_0 \), can be computed directly from the difference between the state on the nominal trajectory and the actual spacecraft state, or, at least, the best approximation to the state. The vector \( \delta r_1 \) provides the means for enforcing the geometrical constraints associated with the desired formation for one of the spacecraft. This process is a one-time calculation for each maneuver using the STM corresponding to the nominal trajectory. By definition, this computation is a linear approximation to the actual maneuver that is truly required to achieve the specified position \( \delta r_1 \) at time \( t_1 \).

The second strategy involves a straightforward differential corrections scheme where the maneuver \( \Delta \vec{v}_0 \) is computed through an iterative process, one that precisely targets the position \( \delta r_1 \) at time \( t_1 \) through the STM evaluated along the spacecraft trajectory between \( t_0 \) and \( t_1 \). By definition, this approach offers more precise targeting than the previous strategy. In most cases, both methods produce the same qualitative and quantitative results. However, for this study, equation 3 is used in the sample cases; results are verified by confirmation with the targeting scheme based on differential corrections.

**SOME RESULTS**

In evaluation of these stationkeeping strategies, the simulation environment is structured to incorporate some aspects of the important issues unique to a real mission. This is accomplished by including uncertainties and errors, and then Monte Carlo simulations are performed for a specified set of error levels. The sources of uncertainty for this study include orbit determination (OD) errors and errors in the execution of any maneuver. The OD errors are established in terms of RLP coordinates with one-sigma values of 0.5 km, 0.5 km, and 1 km for \( x, y, \) and \( z \) positions, respectively, as well as 1 mm/s, 1 mm/s, and 2 mm/s for the velocities \( x, y, \) and \( z \), respectively. These values are somewhat smaller than is usually assumed for libration point missions due to an assumption that information regarding the relative locations of the spacecraft will reduce the OD errors for a formation flying mission. It is anticipated that the OD errors will, in fact, be even smaller, thus the values here represent conservative estimates. Note that OD errors of this magnitude do not significantly affect the cost of stationkeeping or the robustness of the stationkeeping process. For any effects to be apparent, error levels that are approximately one order of magnitude larger would be required. Therefore, the values specified above are used as input for each set of simulations.

The execution errors are modeled with two components: magnitude errors in the along-track and cross-track directions. The along-track errors are simply a percentage-in-magnitude error in the direction of the computed \( \Delta \vec{v}_0 \) vector, and the cross-track errors are percentage-in-magnitude errors in the plane perpendicular to the \( \Delta \vec{v}_0 \) vector. The cross-track error is essentially a pointing or attitude error that can be related to the percentage errors as,

\[
\tan \alpha = \frac{q}{1 + p},
\]

(4)

where \( q \) is the percentage error for cross-track, \( p \) is the percentage error along-track, and the angle \( \alpha \) is the
The overall cost should not change significantly. Within the same specified time interval, it is required that no two spacecraft implement a maneuver roughly at the same time. It would be equally effective if all spacecraft perform their respective maneuvers as much as a year in advance. In this study, it is assumed that multiple spacecraft are involved, the issue of timing becomes more critical. In cases where deterministic maneuvers are incorporated into the libration point trajectory, it may be appropriate to coordinate a stationkeeping maneuver with a deterministic maneuver. Operationally, this is likely the most desirable approach. However, when multiple spacecraft are involved, the issue of timing becomes more critical. In this study, it is assumed that all spacecraft perform their respective maneuvers roughly at the same time. It would be equally effective to require that no two spacecraft implement a maneuver within the same specified time interval. In either case, the overall cost should not change significantly.

The timing and placement of the maneuvers must also be established to complete the simulation scenario. Many possibilities are available. For one option, consistent with some previously successful libration point missions, stationkeeping maneuvers are implemented only when necessary, i.e., at some time when a pre-determined set of criteria is satisfied. In such a case, there is no specified time to perform the maneuvers. However, current missions are, in some circumstances, forced to alter this approach and identify the opportunities for executing stationkeeping maneuvers as much as a year in advance. Additionally, in a situation where deterministic maneuvers are incorporated into the libration point trajectory, it may be appropriate to coordinate a stationkeeping maneuver with a deterministic maneuver. Operationally, this is likely the most desirable approach. However, when multiple spacecraft are involved, the issue of timing becomes more critical. In this study, it is assumed that all spacecraft perform their respective maneuvers roughly at the same time. It would be equally effective to require that no two spacecraft implement a maneuver within the same specified time interval. In either case, the overall cost should not change significantly.

For the simulations completed in this analysis, three different sets of execution error levels are included: 1) a magnitude error of 5% and a pointing error of 1 degree; 2) a magnitude error of 20% and a pointing error of 2 degrees; 3) a magnitude error of 20% and a pointing error of 5 degrees. This set represents a considerable range of potential errors. The first example, using the scenario just described, includes stationkeeping maneuvers coinciding with the deterministic maneuvers specified to be at 11 day intervals. The results, as presented in Table 1, include the total cost in terms of average, minimum, and maximum values for all six of the spacecraft combined, over the duration of the mission. As the error levels increase, the costs do increase, but not significantly. Additionally, the range in costs for each set of input errors remains relatively small. These results are not particularly surprising given the frequency of the maneuvers. Thus, it may be insightful to consider an example where the maneuvers are spaced further apart. The results of such a set of simulations appears in Table 2 where the maneuvers are specified to be 22 days apart. For the first set of errors, the costs actually decrease (consistent with the result presented earlier). However, the second and third sets of error levels, clearly indicating a decrease in the average value from the 11 day case, also demonstrate an increasing value of the maximum cost. Thus, the range is increasing. As the time between maneuvers increases, the ability to maintain the formation becomes increasingly difficult and the costs more uncertain; this trend is certainly not surprising.

Finally, the issue of the formation size is revisited in terms of stationkeeping costs. Recall the earlier result that the increase in the cost of the deterministic maneuvers associated with an increasingly large formation was relatively linear, i.e., for a formation with a radius of 1000 km, the cost was ten times more than that for a formation with a radius of 100 km. The results that appear in Table 3 further confirm that this trend continues when uncertainties are included. The costs in Table 3 are nearly ten times the values that appeared in Table 1.

It is also of interest to compare the stationkeeping costs obtained in the examples with the cost that is associated with maintaining the natural formation. Table 4 lists the results from such simulations for a natural formation of a size that is similar (at least, initially) to one considered in Table 1. The most apparent aspect, in comparing the results in Tables 1 and 4, is that, although the natural formation certainly requires an increase in maneuver costs with increasing error levels, the rate at which the costs increase is certainly not as steep at that for the non-natural formations. This simply punctuates an issue that was discussed earlier: the non-natural formations, in general, possess an unstable component that can magnify the effects of uncertainties.

**CONCLUSIONS**

The goal of this investigation is evaluation of the feasibility of controlling a formation of spacecraft near libration point trajectories. As part of this study, some of the important issues that must be considered are highlighted. This includes the frequency of the maneuvers (which will be further affected by other mission constraints such as hardware limitations and tracking availability), acceptable levels of uncertainty,
and choice of formation. These results are representative of other planar configurations that can be considered. It is unlikely that a mission will actually seek to maintain the same formation over an interval of four years, for example. However, this study marks a preliminary step. It is, in fact, demonstrated that configurations can be controlled or enforced at certain times without great cost, and, depending on the frequency of maneuvers, the required accuracy of the maneuvers falls within current hardware capabilities. Essentially, each of the spacecraft can be controlled individually. The next step is to consider continuous control as well as the formulation of a control law for the formation as a unit as opposed to the individual spacecraft.

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<th>Table 1. $yz$–plane Configuration with Maneuvers at 11 day Intervals</th>
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