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Behavior and passage of silver-phase American eels, *Anguilla rostrata* (LeSueur), at a small hydroelectric facility

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Abstract
Downstream migrant eels were monitored near a small (51 MW) hydroelectric facility on the Connecticut River (Massachusetts, USA) for two seasons using acoustic and radio telemetry. Eels frequently made several attempts over periods of one to several days to pass the station. Diel activity of eels was variable, although most movements occurred at night. Eels occupied a variety of depths in the forebay area, but spent the greater proportion of time at or near the bottom (10 m), occasionally venturing to the surface. Horizontal movements usually spanned across the entire width of the forebay. There was no significant relationship between duration of forebay presence and either flow or light intensity. Although all telemetered eels passed via the turbines, some migrant eels did use a surface bypass.

Keywords: *Anguilla*, fish passage, telemetry, behavior, dam.

Introduction
Mortality of downstream migrant anguillid eels (silver-phase) passing through turbines at hydroelectric facilities can be significant (Desrochers 1995, EPRI 1999, Travade & Larinier 1992). Knowledge about downstream migratory behavior of silver eels and their responses to forebay hydraulics and structures is incomplete, and the effects of hydroelectric facilities on downstream migration of these eels are poorly understood.

Run timing of silver-phase eels has been related to high or low flow (Haraldstad *et al.* 1984, Winn *et al.* 1975), and lunar phase (Lowe 1952, Tesch 1977). Vøllestad *et al.* (1986) found that the start of the run of silver-phase European eels (*Anguilla anguilla*) was correlated with water temperature and flow, and timing of a portion of the run (5-25% cumulative passage) was correlated with temperature only. Downstream movement of eels can be highly variable temporally, as evidenced by long periods of low weir catches interspersed by large but short peaks in catch (Winn *et al.* 1975, Wippelhauser *et al.* 1998).

Telemetry studies conducted with yellow and silver-phase eels in estuarine environments have indicated that movements occur primarily at night, and at a variety of depths (Bozeman *et al.* 1985, Ford & Mercer 1986, Helfman *et al.* 1983, Parker 1995, Stasko & Rommel 1977). Several telemetry studies have focused on general migratory behavior and patterns of movement of downstream migrant silver eels in fresh water.

In the Shenandoah River (Virginia), radio-tagged silver eels required an average of 21 days to move from a release point to a hydroelectric dam 4.8 km downstream (RMC 1995). Three of six silver eels captured, tagged, and released in the Connecticut River, Massachusetts (Haro & Castro-Santos 1996) moved more than 5 km downstream within 5 days of release, primarily at night. Stresses induced by capture, handling, anesthesia, and tag attachment probably have significant, but as yet undetermined, inhibitory effects on downstream migratory behavior of eels.

Swimming behaviors of silver-phase European eels in an experimental flume (water velocities 0.5-1.0 $m \cdot s^{-1}$) included passive drift (absence of rheotactic behavior and swimming movements), controlled drift (positive rheotactic behavior and swimming at speeds less than the water velocity), and active, head-first downstream swimming (Adam *et al.* 1999). Eels swimming in the artificial channel often collided with objects and readily passed through conventional louver and bar rack arrays.

In order to develop effective technologies for mitigation of turbine entrainment mortality of eels, downstream migratory behaviors and responses to hydroelectric forebay hydraulics and structures need to be characterized. For example, effectiveness of surface vs. deep bypass entrances will be dependent on depth of swimming of actively migrating silver-phase eels (e.g., shallow vs. deep). Also, it is not known whether eels search for specific exit hydraulics in a forebay or are passively entrained through trashracks and into penstocks. The objective of this study was to characterize some of the downstream movements and behavior of telemetered, actively migrating silver-phase American eels (*Anguilla rostrata*) near a hydroelectric facility, specifically with respect to depths and routes of movements.

Methods

Study site

Telemetry experiments were performed at Cabot Station, a 51 MW hydroelectric facility operated by Northeast Utilities, Inc., located on the mainstem Connecticut River (Massachusetts, river km 198; Figures 1 & 2), from 3 October to 27 November, 1996, and from 30 September to 20 November, 1997. Although this facility has no upstream

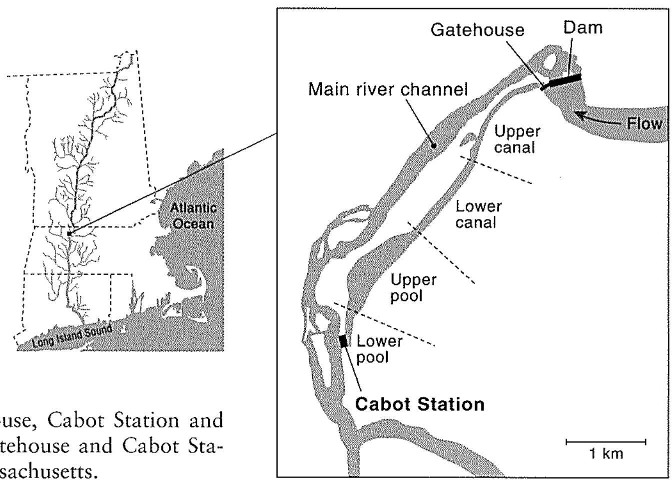

Figure 1. Location of gatehouse, Cabot Station and power canal (between the gatehouse and Cabot Station), Connecticut River, Massachusetts.

or downstream passage structures built specifically for eels, juvenile eels have been observed ascending a pool and weir fishway in the spring. Silver-phase eels have been collected in small numbers at a downstream migrant fish bypass sampler and in penstock nets during the fall months. These downstream migrant eels are typically large (>500 mm TL), and presumably mostly female, based on the latitude and distance inland of the site (Krueger & Olivera 1997).

Cabot Station passes an average of 354 $m^3 \cdot s^{-1}$ of flow at full generating capacity. Bypass flow is maintained at 6-8 $m^3 \cdot s^{-1}$ (1.6% minimum of station flow) from 1 September to 31 October for downstream passage of anadromous clupeids. Water velocities in the canal range from approximately 0.1 to 1.0 $m \cdot s^{-1}$, and average approximately 0.5 $m \cdot s^{-1}$ in the forebay area. For the purpose of coarse locations of telemetered fish within the canal, we divided the canal area into four zones: upper canal, lower canal, upper pool, and lower pool (Figure 1), and forebay and tailrace (Figure 2). Depth in the forebay area averages 10 m. The trashracks are bar racks spaced 3.2 cm apart from the surface to 3.5 m depth. Below 3.5 m the bar spacing is 10.2 cm. Approach velocities at the trashracks at full generation capacity are 0.3-1.2 $m^3 \cdot s^{-1}$, depending on depth. Canal and river flow data were obtained from Northeast Utilities and the USGS Water Resources database. Water temperature (nearest 0.1 °C) and ambient (in air) light intensities (0.1 lux) were recorded hourly for the duration of the study (LI-COR LI-1000 datalogger with LI-212SB spherical quantum sensor and t-type thermocouple probe) at the release site.

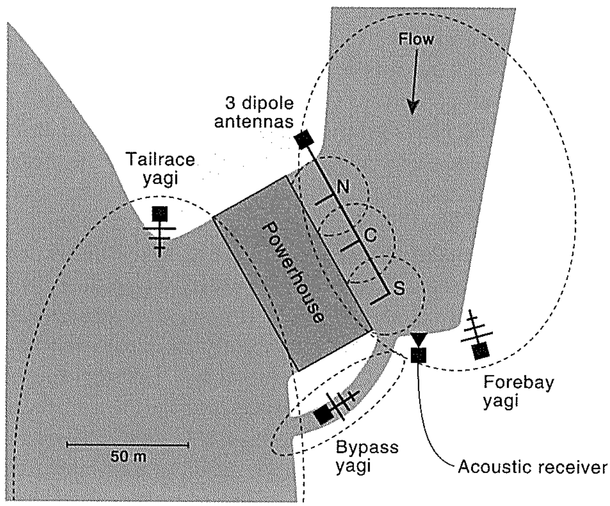

Figure 2. Plan view of Cabot Station and locations of datalogging radio telemetry receivers and antennas. Forebay dipole antennas (N, C, and S denote North, Center, and South, respectively) were interfaced to a single receiver. A datalogging acoustic receiver was installed at the downstream-most end of the forebay.

Telemetry

The study used datalogging radio receivers (Lotek SRX-400, W16 firmware) located at strategic points within the forebay, bypass sluice, and tailrace of Cabot Station (Figure 2). Three underwater dipole antennas (North, Center, and South) suspended from a rope spanning the forebay were used to detect radio-tagged eels approaching the trash racks at all depths (surface to bottom). The dipole antennas were connected in parallel to the receiver during the 1996 season, but were individually scanned with an antenna multiplexer (Lotek ASP-8) in 1997, allowing coarse resolution of horizontal fish position (i.e., closest dipole antenna). Tag detections were logged every 5 sec. We used Lotek CFRT-3B (1996; 149.76 MHz, 10.7 g, 14.5 mm diameter × 43.0 mm length, 440 mm whip antenna) and CFRT-3CM (1997; 149.76 MHz, 5.9 g, 10.6 mm diameter × 36 mm length, 420 mm antenna) digitally coded radio tags. Eels were also located by scanning the entire canal on foot with a radio receiver and handheld yagi antenna every 1-4 days during October and early November, and every 1-2 weeks during mid- to late November.

Larger eels were also tagged with acoustic depth transmitting tags (Vemco, V16-P-3H acoustic depth tags, 50-69 kHz, 14 g, 16 mm diameter × 74 mm length). Percent tag weight as a proportion of total body weight (calculated from total length using the equation: $3.2385 \log L - 3.17328 = \log W$; G. Zydlewski, pers. comm.) for tagged eels ranged from 0.01 to 1.72%. A directional hydrophone was installed near the entrance of the bypass and oriented upstream to reduce interfering turbine noise. A frequency-scanning acoustic receiver (Vemco VR-60) measured tag ping interval (a function of depth) and logged depth data at 1-5 sec intervals.

Fish capture, tagging, release, and monitoring

Silver-phase eels were captured at the downstream bypass sampler located at the bypass sluice of Cabot Station. Collections were made between 19:00 and 23:00 h EST on 3, 7, 10, and 21 October, 1996, and 29 September, 6 and 29 October, and 3 and 12 November, 1997. During tagging operations in 1996, eels were either restrained in a wooden foam-lined trough (no anesthetic used), or deeply anesthetized using buffered MS-222 (methane tricanesulfonate, 100 mg$\cdot$liter^{-1} in ambient river water), or a crushed-ice slurry, similar to the method used by Parker (1995). Eels were tagged in 1997 using only a crushed-ice slurry. During holding or anesthesia, eels were measured for TL (nearest cm) and horizontal eye diameter (nearest 0.1 mm).

In 1996, eleven eels were radio-tagged; three of these fish also carried an acoustic tag. In 1997, five of fourteen radio-tagged eels were acoustically tagged. In order to minimize stress from handling and surgery, we attached transmitters externally (rather than internally) using a method similar to that of Parker (1995). Transmitters were attached to eels using 2-0 polyamide suture material or 30 lb. test Dacron line and a size 12, 3⁄8-circle cutting needle. Each transmitter was attached with two sutures (one at each end of the transmitter) through the skin on the dorsal surface approximately 3-5 cm anterior to the origin of the dorsal fin. Tagging and measurement procedures took approximately 5-10 min. Unanesthetized fish were released immediately after tagging and measurement, while anesthetized eels were allowed to recover for approximately 30 min in a holding box containing ambient temperature river water. Tagged eels were then released within one hour of capture in the canal at either a site 0.4 km (1996) or 1.5 km (1997) upstream of the station.

Logging of receiver data was begun immediately upon release. Receiver data were downloaded every 1-2 days, and receiver clocks were synchronized to the nearest second. Fish that were not detected by the logging receivers were relocated within the canal from the shore with a portable radio receiver and yagi antenna every 1-3 days, and their approximate positions recorded. Canal monitoring and receiver datalogging was terminated when water temperatures were deemed too low for downstream migration (3.6 °C in 1996, 3.9 °C in 1997).

Data analysis

Radio telemetry data were entered into a database and records were filtered to remove spurious signals caused by noise interference. Acoustic data were similarly entered and filtered, and all erroneous depth records (>10.5 m, maximum forebay depth) were removed from the dataset. Radio and acoustic telemetry data were integrated to provide a record of individual eel movements in the vertical (depth) and horizontal (forebay dipole zone) dimensions, based on the number of 5-sec detections per presence logged in each depth or dipole zone.

We classified presences of tagged eels within the forebay area when both: a) multiple consecutive detections of radio tags were made on any forebay dipole antenna, and b) signal strengths (*SS*) of detections on dipole antennas were >70. A presence ended when detections did not meet these criteria for an interval greater than 15 min. Tests with single radio tags in the forebay defined the dipole antenna detection zone as extending from the trashracks to approximately 40 m upstream. Test tags were also detected on the dipole antennas throughout the full depth of the canal within this zone. In 1996, radio tags at depths greater than approximately 5 m produced a strong *SS* on the dipole antennas but weak *SS* on the forebay yagi antenna, except at points close to the yagi antenna, where *SS* was strong on both antennas. Thus a tag with a strong *SS* on the dipole antennas and weak *SS* on the yagi antenna could be assumed to be deep (> 5 m) within the forebay. However, we could not determine if 1996 tagged eels in the forebay were at shallow depths from *SS* data alone.

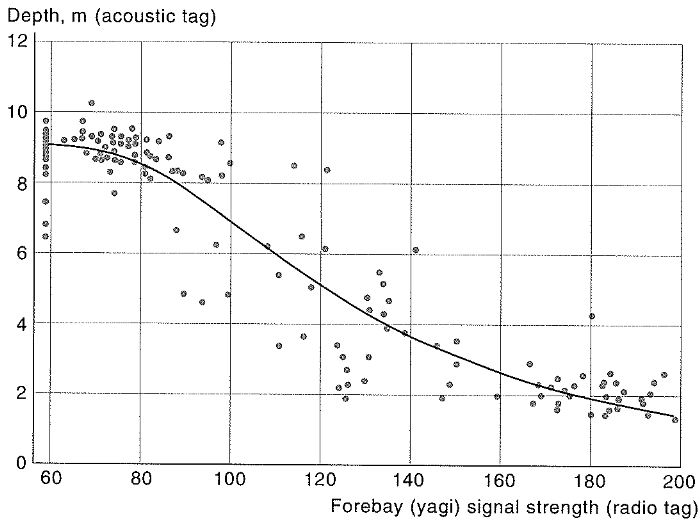

Figure 3. Relationship between radio-tag depth (as measured from acoustic tag) and signal strength from the forebay yagi antenna. Nonlinear regression (line) was used to infer depths of eels carrying only radio tags.

In 1997, we reduced the gain on the forebay yagi antenna such that depth of tags could be inferred by relative *SS* on the dipole and yagi antennas. Correlation between actual depth as recorded by the acoustic tag and inferred depth from *SS* data from eels carrying both tags was high ($r = 0.95$) and significant ($p < 0.01$) when regressed using nonlinear regression (Figure 3). Eels were classified as passed when radio tag signals ceased to be logged on the forebay dipole or yagi antennas and were subsequently detected on the tailrace antenna shortly thereafter.

Table 1. Summary of presence (detection of eels in the Cabot Station forebay area) data for 1996. Eel numbers with asterisks indicate fish carrying an acoustic depth tag; depth data from these fish are from acoustic tag data only. Depth data were apportioned into two bins, 0-5 and 5-10 m. Time to pass is calculated from time of release to time of detection in the tailrace. All eels were released 0.4 km upstream from the station forebay.

Eel number:	3	6	10	80	90	91*
Total length, cm	71	75	84	74	76	90
Release date	3 Oct.	3 Oct.	3 Oct.	7 Oct.	3 Oct.	21 Oct.
Release time	20:10	19:50	20:31	22:12	23:30	23:45
Number of presences	1	3	4	9	1	3
Mean presence duration, min	14.0	15.0	10.3	12.4	1.0	4.7
Time to pass, h	0.2	71.5	–	338.0	–	11.6
Exit route	Turbine	Turbine	Unknown	Turbine	Unknown	Turbine
Modal depth, m	5-10	5-10	5-10	5-10	5-10	5-10

Table 2. Summary of presence (detection of eels in the Cabot Station forebay area) data for 1997. Eel numbers with asterisks indicate fish carrying an acoustic depth tag; depth data from these fish are from acoustic tag data only. Time to pass is calculated from time of release to time of detection in the tailrace. All eels were released 1.5 km upstream from the station forebay. Percentages (depth and dipole rows) are calculated as percent of time spent in each depth or horizontal position bin for each presence, then averaged over all presences for each eel.

Eel number:	31	32	33*	34*	35	55	38*
Total length, cm	73	85	91	89	91	76	85
Release date	30 Sep.	30 Sep.	30 Sep.	30 Sep.	30 Sep.	29 Oct.	3 Nov.
Release time	21:30	21:30	21:30	21:30	21:30	23:30	21:45
Number of presences	14	2	6	14	15	4	1
Mean presence duration, min	77.0	89.5	35.8	84.9	43.1	1.5	24.6
Time to pass, h	282.5	2.9	8.5	–	76.5	1.5	86.0
Exit route	Turbine	Turbine	Turbine	Unknown	Turbine	Turbine	Turbine
Depth, % of time spent							
0-3.3 m	0.5	0.5	35.6	1.0	7.7	0.0	11.1
3.3-6.6 m	4.5	4.5	19.4	6.0	9.6	0.0	8.8
6.6-10 m	94.9	94.9	45.1	93.0	82.7	100.0	80.2
Dipole, % of time spent							
North	47.5	47.5	27.5	16.8	48.0	100.0	48.1
Center	39.3	39.3	37.9	59.7	32.4	0.0	32.5
South	13.2	13.2	34.6	23.6	19.6	0.0	19.4

Results

Of the 25 telemetered eels released into the canal, 50% or greater entered the forebay zone at least once (6 of 11 in 1996 and 7 of 14 in 1997, Tables 1 & 2). Other eels usually showed some activity (movement between canal zones) within the first day after release, but some tags remained relatively stationary thereafter. However, one of these eels (eel 90) resumed movements after a 13-day sedentary period within the upper pool and passed Cabot Station. Water temperatures between first day of release and last detection of an eel in the forebay area ranged from 16.9 °C (3 October) to 9.5 °C (22 October) in 1996 and from 17.7 °C (30 September) to 9.7 °C (4 November) in 1997.

Active eels usually moved into different canal zones within several days after release. Within 1 to 22 days they ventured downstream to the forebay area, and subsequently either swam back upstream or passed through the turbines. Of the 13 active eels entering the forebay, 10 passed via the turbines. The remaining three active eels were not detected within the canal after 1 to 14 forebay presences. No telemetered fish were recorded passing via the bypass sluice. Duration of presence of fish within the forebay zone ranged from <1 min to 8.3 h (mean 31.8 min). Presence duration was not significantly correlated to either forebay flow or light intensity ($p > 0.05$). As defined by the forebay presence criteria, active eels encountered the forebay from 1 to 15 times before passing. The interval between first forebay presence and passage through the turbines ranged from 0.2 to 338 h. Six of the thirteen active eels entered the forebay most frequently (percent of presences) between 18:00 and 21:00 h.

Although depth of 1996 radio-tagged eels could not be determined by relative *SS* when they were at shallow depths, most radio-tag detections had high *SS* on the forebay dipole antenna while *SS* was low on the forebay yagi. This indicated that tagged eels occupied depths greater than 5 m most frequently when in the forebay. 1997 radio-tagged eels reflected this depth distribution, with the majority of detections occurring at depths between 6.6 and 10 m. Data from acoustically tagged eels also indicated that eels frequented the deep portion of the forebay, but made regular excursions to the surface (Figure 4).

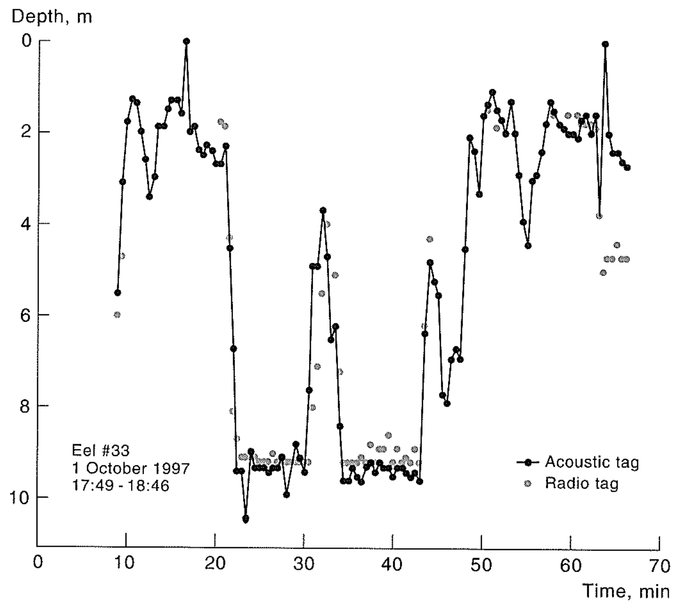

Figure 4. Time-depth track of single telemetered eel in Cabot Station forebay. Symbols depict raw data from acoustic tag and depths inferred from radio-tag signal strength ratio. Note variable movements throughout entire depth range.

From analysis of 1997 depth data, all of the seven telemetered eels entering the forebay occupied the deepest third of the forebay most frequently (χ^2, $p < 0.01$). Four of the seven eels were detected significantly more frequently at the north dipole, and one eel was detected more frequently at the center dipole (χ^2, $p < 0.01$). However, we were not confident that the reception area of each of the dipole antennas was equal, therefore, the horizontal distribution data may be biased.

Discussion

Behaviors of eels within the Cabot canal and forebay were variable with respect to movements and occupied depths. Eels moved very little during the day, and downstream movements to the forebay occurred primarily within several hours after sunset. This is consistent with diel counts of eels at the Cabot bypass (A. Haro, unpubl. data) and other studies of diel migratory movements of eels (Vøllestad *et al.* 1986). There was no relationship between forebay presence and either flow or light intensity. Eels occurred at all depths within the forebay zone, and several fish rose and sounded within the forebay. We observed eels at Cabot Station swimming at night near the surface in front of the trash racks, then sounding after several seconds. These observations and the fact that some eels use the surface bypass indicate that they occupy near-surface waters in the forebay at least for some period of time. The method of inferring fish depth from analysis of signal strength data from radio tags was shown to be accurate, as evidenced by the close fit to the corresponding acoustic tag data.

Because we were unable to assess the effect of handling and tagging, the migration delay caused by Cabot Station could not be estimated. Although we sought to minimize any deleterious effects on downstream migratory motivation by externally attaching tags, this method introduces problems of premature tag loss, irritation, and potential for entanglement of tags in vegetation or substrates. Many of the tags that had become stationary soon after release were probably shed. Subsequent studies (Baras & Jeandrain 1998, Haro & Boubée, unpubl. data) have indicated that surgical implantation of tags has minimal effect on downstream migration of eels, and we recommend surgical implantation of tags using methods similar to that of Baras & Jeandrain (1998) for future studies.

Nonetheless, behaviors of telemetered eels in the forebay area can be characterized from the results. Four eels (6, 10, 80, and 91) entered the forebay, then moved upstream several times in succession, indicating that eels may be reluctant to pass either through the racks or into the bypass on their first forebay encounter. Similar observations of other species of *Anguilla* have been made at other sites (J. Boubée, pers. obs.), and similar delays have been noted for Atlantic salmon smolts (Jepsen *et al.* 1998). Higher flows and approach velocities may make it more difficult for eels to swim back upstream or avoid being entrained through the trash racks. Ten of the 13 telemetered eels passed Cabot Station via the turbines, but it could not be determined at what depths eels passed through the trash racks.

It appears that eels are behaviorally unlike other downstream migrants such as Atlantic salmon (*Salmo salar*) smolts and juvenile anadromous clupeids, which are primarily surface-oriented species (Ferguson *et al.* 1998, Jepsen *et al.* 1998). Eels can move through the Cabot canal system at a variety of depths, and can quickly alter their depth of swimming. Although large, eels have been described as weak swimmers for their size (Blaxter & Dickson 1959, McCleave 1980) and may have difficulty avoiding racks or screens at high approach velocities. Migrant silver eels are also strongly photophobic, and station/forebay lighting may alter normal downstream migratory behavior. The response of eels to conventional behavioral barriers (lights, bubble curtains, louvers) has been variable (Hadderingh *et al.* 1988, 1992, U. Dumont & J. Boubée, pers. comm.). These factors will likely make the search for effective protection of downstream migrant eels at larger hydro stations a new and considerable challenge for the future.

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