Visualizing Groundwater Dispersion: Laboratory Exercise on Dispersivity with Hands-on and Online Students

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Abstract—Longitudinal groundwater dispersion is measured by calculating the spreading of a solute in the direction of groundwater flow as a function of time. Two-dimensional physical groundwater flow models were used in a laboratory exercise to illustrate groundwater dispersion to hands-on and online students. Learning assessment of the pedagogical value of the laboratory exercise was based on a student survey and an independent laboratory assignment graded by the course instructor. Both tools indicated that student learning was effectively enhanced by the dispersivity laboratory exercise; however, it was more effective for the hands-on students.

Keywords—dispersivity laboratory, hands-on learning, hands-on students, online students, physical groundwater flow models

1 Introduction

Many educators agree that student learning is enhanced by incorporating laboratory experiments [1, and reference therein] and hands-on activities [2–4]. Herein a laboratory exercise on dispersivity is described that uses physical groundwater flow models for engineering and geoscience university students – both hands-on and online students. My hypothesis was that visualizing dispersivity in a lab experiment would help students understand the concept of dispersivity more than reading about it and/or attending a lecture on it. Therefore, the objective of the laboratory assignment was to demonstrate the hydrogeologic process of dispersion to enhance student learning compared to reading the course textbook on dispersion and/or attending a class lecture on dispersion.

The manuscript text continues below with the following sections: Background, Methods, Results and Discussion, and Conclusions.

2 Background

Below I review the use of physical groundwater flow models as pedagogical tools. Then I describe how aquifer dispersivity is measured in the field and how it may be estimated in two-dimensional physical groundwater flow models.

2.1 Physical groundwater flow models

Physical "Ground-Water Flow Models" (GFMs) consisting of porous media sandwiched between two clear plates were described by Lehr [5] in 1963. He used them to simulate groundwater movement toward a pumping well, flow toward a groundwater gaining stream, groundwater recharge from an infiltration pit, groundwater flow through beds of varying permeability, refraction of water flow across strata of varying permeability, and flownet displacement caused by wells being pumped in the vicinity of strata of varying permeability [5]. Since then, similar GFMs, or "physical models" of groundwater processes, have been used for students as early as sixth grade [6]; however, the laboratory exercise on dispersivity described herein was designed for engineering and geoscience university students in my hydrogeology course. Other laboratory exercises for university students using similar GFMs include the following, in chronological order: Parkinson and Reid [7] used a "two dimensional sand-tank model" to illustrate the influence of ground slope on agricultural tile drain discharge and associated groundwater movement; Merritts and Shane [2] used physical plexiglass models (two-dimensional) coupled with mathematical models as a hands-on activity for an introductory environmental geology course; Gates et al. [8] used a thicker "ground-water-simulation apparatus" (three-dimensional) with layers of sand and clay to investigate the movement of a pollutant slug and to model the potentiometric surface in the groundwater simulator and with modeling software; Passey et al. [9] used an "ant farm tank" (two-dimensional) to simulate the cross-section of an earthen dam to teach basic concepts of hydrology and sedimentary geology; Singha and Loheide [10] linked "2-D ant farm sand tanks" and numerical modeling to help students associate processes that they visualized in the tanks with the results of numerical modeling; Rodhe [11] used "simple physical models" (two-dimensional) for various demonstrations, including quantitative determinations of hydraulic properties such as the storage coefficient and saturated hydraulic conductivity; Marques et al. [12] used an acrylic tank and interactive video to demonstrate two-dimensional flow lines associated with seepage in embankment dams, under sheet piles, or into cofferdams to soil mechanics students; and, Lehr et al. [13] built a three-dimensional physical model of the water cycle in a landscape comprised of postglacial sediments. In these studies, only [10] discussed dispersion; students could visualize it in the sand tank and model it numerically with instructor-provided dispersivity values, but dispersivity was not measured in GFMs based on visual experiments.

2.2 Aquifer dispersivity

A large-scale natural gradient experiment for three-dimensional solute transport was done in Borden, Ontario, using over 5,000 sampling points in the zone traversed by the solutes [14]. Freyberg [15] analyzed the movement of "nonreactive" groundwater tracers at the Borden experiment to determine, among other parameters, the dispersion of the plume. The ijk −th moment of the solute concentration distribution in space is [15].

$$M_{ijk}(t) = \iiint_{-\infty}^{\infty} nC(x,y,z,t)x^i\, y^j z^k dx\, dy\, dz \tag{1}$$

Where $C(x,y,z,t)$ is the concentration field above background, n is the porosity, x, y, z are the spatial coordinates for time, t, and integer indices $i+j+k = 0$, 1, or 2, respectively [15]. The plume center of mass has the coordinates [15], [16]:

$$x_c = {}^{M_{100}}/_{M_{000}} \qquad y_c = {}^{M_{010}}/_{M_{000}} \qquad z_c = {}^{M_{001}}/_{M_{000}} \tag{2}$$

Where M_{000} = tracer mass in solution. For $i+j+k \geq 2$ the moments about the plume center of mass, $\bar{M}_{ijk}$ are [16]:

$$\bar{M}_{ijk}(t) = \iiint_{-\infty}^{\infty} nC(x,y,z,t)(x-x_c)^i\, (y-y_c)^j (z-z_c)^k dxdydz \tag{3}$$

The variances of plume spreading in the three principle directions are [16]:

$$\sigma_{xx}^2 = \bar{M}_{200} / M_{000} \qquad \sigma_{yy}^2 = \bar{M}_{020} / M_{000} \qquad \sigma_{zz}^2 = \bar{M}_{002} / M_{000} \tag{4}$$

Equation (4) assumes plume spreading is Gaussian [17], which is why Freyberg [18] called the resulting parameters "apparent dispersivities." For negligible effective molecular diffusion and constant plume velocity, the dispersion coefficient in the principle ("longitudinal") direction of groundwater flow, $D_{xx} = D_L$, is [19]:

$$D_L = \frac{1}{2}\frac{d}{dt}\sigma_L^2(t) = a_L V_L = \frac{1}{2}\frac{d\sigma_L^2}{dL}\frac{dL}{dt} \tag{5}$$

Where a_L is the longitudinal dispersivity and velocity $V_L = \frac{dL}{dt}$. Therefore:

$$a_L = \frac{1}{2}\frac{d\sigma_L^2}{dL} \tag{6}$$

Equation (6) indicates that aL may be approximated in two-dimensional physical GFMs by visually estimating the rate of spreading of the plume in the longitudinal direction as it moves downgradient across the clear plate of the model. Equations (5) and (6) assume that molecular diffusion is negligible, which may be verified in physical GFMs. Effective molecular diffusion ~10^{-9} m^2/sec [20], or less if particle tortuosity is considered [19], and it will be shown that it is negligible compared to $a_L V_L$ (see (5)) in the laboratory exercise on dispersivity described below.

3 Methods

The methods used are described below. The first set of methods describe the laboratory exercise on dispersivity. The second set of methods explain how learning assessment for the lab experiment was accomplished.

3.1 Laboratory exercise on dispersivity

Our GFMs were purchased from the College of Natural Resources, University of Wisconsin-Stevens Point (https://www.uwsp.edu/cnr/gmp/Pages/default.aspx); however, similar models are available elsewhere (for example, http://www.envisionenviroed.net/, https://engineering.unl.edu/groundwater-flow-models/, https://www.wardsci.com/store/product/8876260/ward-s-groundwater-simulation-system). Figure 1 shows a cross section of the models; their approximate dimensions are 61 cm × 30 cm × 4 cm.

To prepare the lab for the students, set up enough GFMs so that there are preferably five or fewer students at each GFM. I used a head box that allowed me to string tubing and direct water to the inlet reservoir (shown on left side of GFM in Figure 1), so that a constant head was maintained near the sand interface of the water table aquifer and the inlet reservoir for each GFM (see Figure 2). Plug any wells that interfere with lateral flow in the water table aquifer; in our GFMs I put a light-blue syringe tip in the "Lake or Artesian" well and closed the outlet in the "Lake or River" (see Figure 2). Choose the dye color that is least retarded (adsorbed onto the sediment) with respect to groundwater flow. I used red food coloring for the dispersion lab. (Green food coloring, which is a mixture of blue and yellow dyes affords a striking chromatographic demonstration that may be used with the GFMs where the primary colors separate with flow distance, with the yellow dye moving faster than the blue.) Dilute the food coloring with water at a ratio of ~1:10 and make it available for student use.

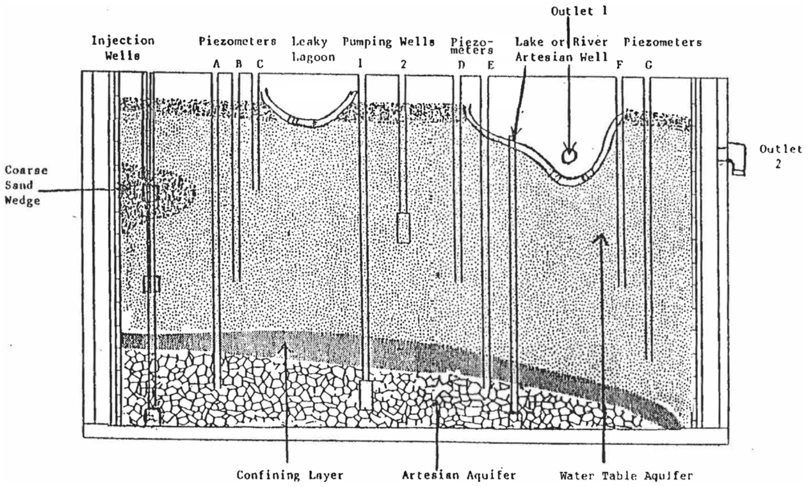


Fig. 1. Cross sectional drawing of groundwater flow model

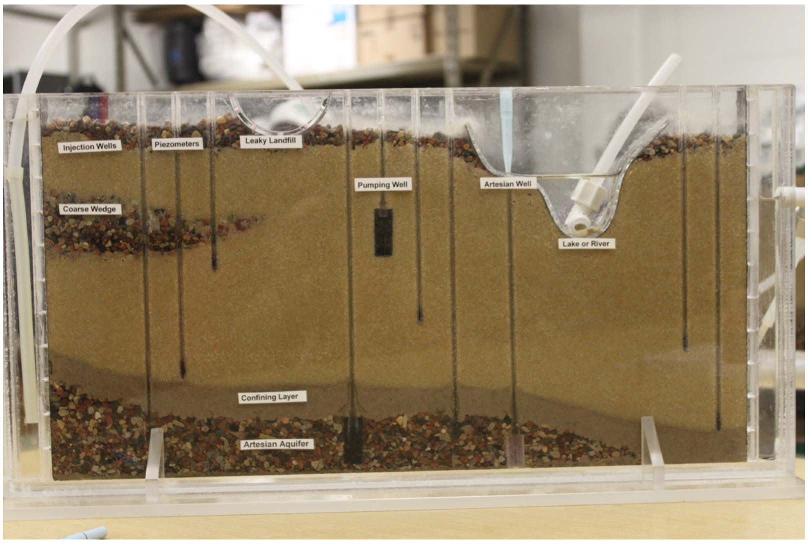


Fig. 2. Groundwater flow model prepared for dispersivity lab

The hands-on students were instructed to begin the lab by using a syringe to slowly add 7 to 8 cm^3 of red-colored water in the blue injection well (see Figure 2), which is screened in the water table aquifer near the upgradient side of the GFM between the "Coarse Wedge" and the "Confining Layer" (see Figures 1 and 2). The students were directed to continue, as follows:

- With a water-soluble ink pen mark on the back of the model (where no vertical piezometers are visible) the plume center and draw a circle around the outline of the diameter of the plume; note that the initial time is t_0.
- Continue to outline the plume and mark the approximate plume center of mass about every five minutes until at least five plume outlines are drawn (t_i., $i = \{0, 1, 2, 3, 4\}$) (see Figure 3).
- Add measurements to Table 1. The total distance traveled is the distance between the initial plume center of mass at t_0 and that for the current time internal. The longitudinal length is the length of the plume in the direction of groundwater flow; at t_0 the longitudinal length is the diameter of the circle of red dye injected into the model. The change in longitudinal length (Δ longitudinal length) is the increase in plume length from that measured at t_0.
- Plot (Δ longitudinal length$)^2$ (see Table 1, column 6) as a function of total distance traveled (see Table 1, column 3) with and without point $(0, 0)$. For the former graph, note if the data have upward concavity; if so, some retardation of the red dye on the sediment occurred. For the later graph, the slope of the linear regression is an estimate of the longitudinal dispersivity (see (6)); include the coefficient of determination (R^2) for the relationship.
- Compare your dispersivity results to those in Neuman's equation using L = the total distance in meters traveled by the plume center of mass [22]:

$$a_L = 0.0175L^{1.46} \tag{7}$$

Equation (7) is a linear regression through data with 10^{-1} m < L < 10^{5} m. With the value for longitudinal dispersivity calculated for the GFM and an estimate of V_L (total distance traveled divided by travel time), determine D_L (see (5)) and verify the assumption that molecular diffusion is negligible.

Table 1. Calculations for dispersivity lab

	Time	**Total travel distance**	**Plume longitudinal length**	**Δ longitudinal length**	**(Δ longitudinal length**
$t_0 =$					
$t_1 =$					
$t_2 =$					
$t_3 =$					
$t_4 =$					
$t_5 =$					

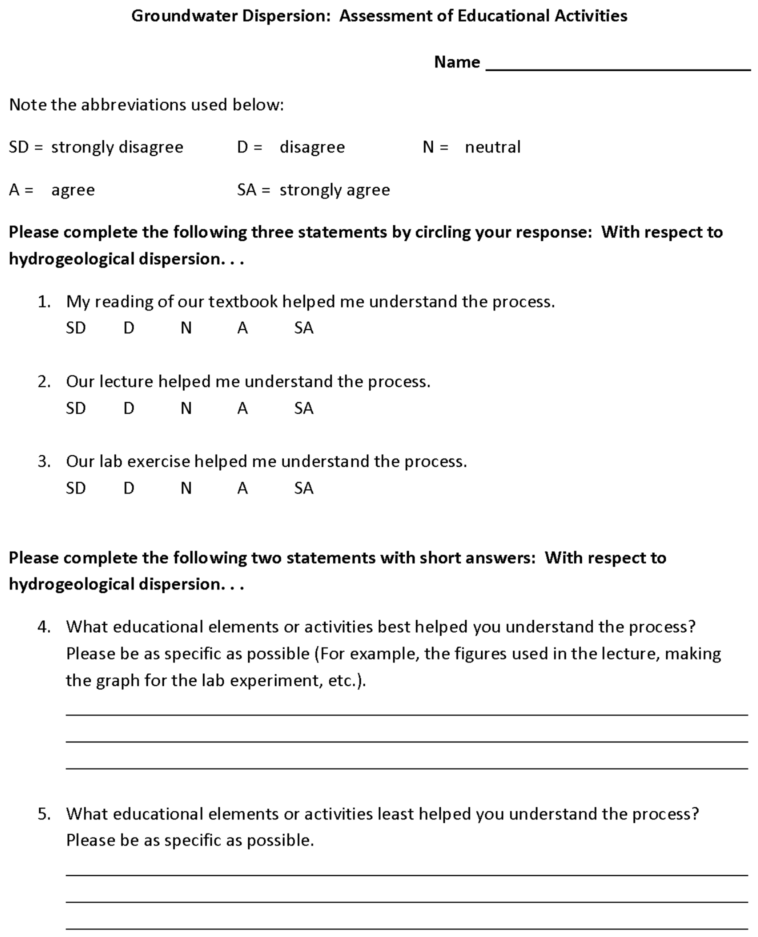
Fig. 3. Plume spreading with travel distance

Online students were given video clips and photographs of the lab done by the hands-on students. Online students worked independently on the lab assignment.

3.2 Learning assessment

The objective of the laboratory assignment was to demonstrate the hydrogeologic process of dispersion to enhance student learning compared to reading the class textbook on dispersion and/or attending a class lecture on dispersion. Before the lab exercise, students were assigned reading from the course textbook [23], particularly sections 10.6.4 and 10.6.5 on mechanical dispersion and hydrodynamic dispersion, respectively. In addition, a lecture on this material was presented.

After the lab, students were given the five student assessment questions shown in Figure 4. Questions 1−3, each of which incorporated a five-point Likert scale, comprised the quantitative portion of the assessment. The responses to these questions were compared statistically using the nonparametric Mann-Whitney test [24]. Hands-on and online student performances on the laboratory exercise were compared to student performances on the mean of other homework assignments using hypothesis testing [25]. Questions 4 and 5 were qualitative questions to understand the student experience with the dispersivity lab. 22 hands-on students, including five graduate students, completed the lab exercise and the student assessment questionnaire; whereas, eight online students, including two graduate students, completed these same assignments. In addition, student performance, as graded by the course instructor (and manuscript author), on the dispersivity lab was compared to student homework scores on 18 other assignments.



Groundwater Dispersion: Assessment of Educational Activities

Name ______________________________

Note the abbreviations used below:

SD = strongly disagree D = disagree N = neutral

A = agree SA = strongly agree

Please complete the following three statements by circling your response: With respect to hydrogeological dispersion. . .

1. My reading of our textbook helped me understand the process.
   SD D N A SA

2. Our lecture helped me understand the process.
   SD D N A SA

3. Our lab exercise helped me understand the process.
   SD D N A SA

Please complete the following two statements with short answers: With respect to hydrogeological dispersion. . .

4. What educational elements or activities best helped you understand the process? Please be as specific as possible (For example, the figures used in the lecture, making the graph for the lab experiment, etc.).
   ____
   ____
   ____

5. What educational elements or activities least helped you understand the process? Please be as specific as possible.
   ____
   ____
   ____

Fig. 4. Student assessment questions

4 Results and discussion

This section has two subsections and includes results with discussion for the laboratory exercise and learning assessment.

4.1 Laboratory exercise on dispersivity

Students noted some slight retardation of the red dye because of the upward concavity in the first graph including point (0,0). However, linear regression coefficients for the second graph, without point (0,0) (and with correct calculations), were good ($R^2 > 0.87$). GFM estimates for longitudinal dispersivity were mostly $0.02 \text{ m} < a_L < 0.05 \text{ m}$, depending on the model used. $L \sim 10^{-1}$ m, which in Equation (7) gives $a_L \sim 10^{-3}$ m. However, data provided in [22, Figure 1] show for $L \sim 10^{-1}$ m that $a_L = 0.01$ to 0.03 m;

values closer to those measured in the GFMs. Estimates for the longitudinal dispersion coefficient, D_L (see (5)), were ~10^{-6} m^2/s, which verifies that the contribution of the effective molecular diffusion (~10^{-9} m^2/s, or less) was insignificant.

4.2 Learning assessment

For the three questions in Figure 4, students only used N, A, and SA, effectively reducing the five-point Likert scale to a three-point Likert scale. Table 2 shows the statistical comparisons of the student responses. Hands-on and online students ranked the lab exercise (Q3 = question 3) higher than reading the textbook (Q1) and attending the lecture (Q2) for understanding dispersivity; however, the hands-on student responses about the lab exercise involving Q3 were statistically more rigorous (lower p value) than the online student responses by about an order of magnitude.

Table 2. Statistical comparisons for questions 1−3 on Figure 3

Student Type	Q1 vs Q3	Q1 vs Q2	Q2 vs Q3
Hands-on (n =22)	Q3 ($p < 0.001$)	Q2 ($p < 0.02$)	Q3 ($p < 0.01$)
Online (n = 8)	Q3 ($p < 0.01$)	Q2 ($p < 0.06$)	Q3 ($p < 0.1$)

p is the probability of obtaining test results at least as extreme as the results observed, under the assumption that the null hypothesis is correct; the null hypotheses were that the rankings for the two compared questions were equal.

That the hands-on students regarded the lab exercise as more helpful to their learning is also evident in their responses to Q4 in the Student Assessment Questions (see Figure 4). Representative responses include the following:

"The figures used in the lecture were helpful, but actually ding (sic) the experiment itself made it very clear to me what I was doing."

"The step-by-step lab procedure and results comparison post-lab with the graphing and calculations best helped me."

"Just the visual experience of tracing out the dispersion over time during lab."

"Measuring the length and distance traveled by the plume. Using excell (sic) to find the line of best fit."

"The lab experiment because I'm a hands on (sic) learner."

"Watching the dye travel and analysing (sic) the results helped me understand groundwater dispersion."

"In the lab, the concept of dispersion can be grasped much more easily. Dispersion is a time-dependent phenomenon, and you can't get that dimension explained well without a visual-aided lab experience."

Only two out of 22 hands-on students responded to Q5 (see Figure 4) that that lab was the least helpful for them to understand dispersion.

The responses to Q4 and Q5 (see Figure 4) by the online students were mixed. Some online students found the lab exercise helpful, and wrote the following for Q4:

"Just doing the experiment, and analyzing experimental vs. expected values."

"Actually watching the process occur in the lab really helped to illustrate the math and theory that we had discussed in lecture."

"watching (sic) the videos of the lab occurring was very helpful in understanding the process."

However, some students found the lab exercise less helpful and had the following responses to Q5:

"making (sic) the graph of the experiment did not really help me understand the process."

"The videos and pictures were too vague. I would have liked to see a full video. . ."

"The recording of injection movies makes it a little difficult to follow through. Also as a distance student, watching the lab experiment instead of actually doing it may not give the complete feeling of the whole process."

Table 3 records the mean lab scores for the hands-on and online students, based on a 30-point assignment, as well as the mean for the other (not for dispersivity) homework scores, based on 18 assignments of 509 total points. Both sets of scores were converted to percentages. Neither the lab scores for both student types, nor the other homework scores for both student types, were statistically different from each other ($\alpha < 0.1$). However, the mean lab score for the hands-on students was higher than the mean of the other homework scores ($p < 0.0005$); for the online students, this comparison was less impressive ($p < 0.28$).

Table 3. Statistical comparisons for lab and other homework scores

Student Type	**Mean Lab Score*** (± 1 stand. dev.)	**Mean Other Homework Scores**** (± 1 stand. dev.)	**Lab Score vs Other Homework Score**
Hands-on (n =22)	94.5 ± 3.5	85.0 ± 10.6	Lab Score ($p < 0.0005$)
Online (n = 8)	88.8 ± 11.4	84.6 ± 13.2	Lab Score ($p < 0.28$)

*Mean lab scores for both student types were not statistically different ($\alpha < 0.1$).

**Mean other homework scores for both student types were not statistically different ($\alpha < 0.1$).

Most of the previous publications on physical groundwater flow models [2, 5, 7−9, 11−13], if learning assessment was provided, was qualitative; authors relied on their experience to validate that the physical models enhanced student learning. Singha and Loheide [10] provided the only quantitative results. They [11] linked physical GFMs and numerical models in exercises. Using a histogram they [11] showed that post-exercise students could better approximate groundwater flow velocities than pre-exercise students.

More generally, as noted in the introduction, educators agree that student learning is enhanced by incorporating lab experiments [1, and reference therein] and hands-on activities [2–4]. Therefore, it is not surprising that hands-on student responses to a Likert scale, their qualitative opinions, and their performance on the lab assignment, the latter graded by the instructor, documented that the objective of the laboratory assignment was achieved, which was to demonstrate, using a dispersivity laboratory, that student learning was enhanced over merely reading about dispersion or attending a lecture about it. While this lab also had pedagogical value for the online students, their results were less compelling. Online student opinions on the dispersivity lab were mixed, as were online student performances on the lab assignment. Overall, this lab assignment was effective for enhancing student learning for both types of students, but more so for the hands-on students. Future work should focus on improving the dispersivity lab for online students, perhaps by using interactive videos as proposed by [12] and [13]. Enhancing this lab for online students is important for sustainable hybrid learning [26], i.e., the mixing of distance and face-to-face students.

Student learning on dispersivity may be further enhanced by using the "reverse teaching" methodology proposed by Jacques and Lequeu [27]; whereby students are given the dispersivity lab assignment before a dispersivity lecture that provides time for questions and student discussion.

5 Conclusions

A laboratory experiment using two-dimensional physical groundwater flow models was designed to allow students to visualize groundwater dispersion; the lab objective was to demonstrate the hydrogeologic process of dispersion to enhance student learning. Two types of students completed the lab assignments, 22 were hands-on students (including 5 graduate students) and 8 were online students (including two graduate students), the latter of which completed the lab using video clips and photographs taken during the lab session for the hands-on students. The hands-on student opinions and their performance on the lab assignment, the latter graded by the instructor, documented that the objective of the laboratory assignment was achieved. However, the online student opinions on the dispersivity lab were mixed, as were online student performances on the lab assignment. The dispersivity lab described herein was effective for enhancing student learning for both types of students, but it was more effective for the hands-on students.

6 Acknowledgments

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