Interactive Computer Simulation and Animation (CSA) to Improve Student Learning of Projectile Motion in an Undergraduate Engineering Dynamics Course

Yongqing Guo and Ning Fang

Department of Engineering Education, Utah State University, Logan, UT, U.S.A.

Keywords: Computer Simulation and Animation (CSA), Interactive Learning Modules, Projectile Motion, Engineering Dynamics, Quasi-experimental Research Design.

Abstract: Computer simulation and animation (CSA) has been receiving growing attention and application in recent years in the international engineering education community. In the present study, an innovative set of CSA learning modules was developed to improve student learning of projectile motion in engineering dynamics, an important yet difficult undergraduate engineering course. The new CSA learning modules integrate visualization with mathematical modeling to help students directly connect engineering dynamics with mathematics. Quasi-experimental research involving an intervention group and a comparison group was performed to investigate the extent to which the new CSA learning modules improved student learning of projectile motion. The results show that as compared to the comparison group, students in the intervention group increased their learning gains by 30.3% to 43.6% on average, depending on the specific CSA learning modules. The difference in learning gains between the two groups is found to be statistically significant. From the present study, it is concluded that properly-designed computer simulation and animation not only provides students with a visualization tool for them to better understand engineering phenomena, but can also improve their procedural skills for finally solving problems in engineering dynamics.

1 INTRODUCTION

Engineering dynamics is a fundamental core course in many undergraduate engineering curricula, e.g., mechanical, aerospace, civil, biological, and biomedical engineering. Students in these programs are typically required to take engineering dynamics before they are allowed to take subsequent advanced courses such as advanced dynamics, structural mechanics, system dynamics and control, and machine and structural designs (Bedford and Fowler, 2009; Hibbeler, 2012).

Nevertheless, dynamics is widely regarded as one of the most difficult engineering courses to succeed in (Cornwell, 2000). When asked for their perspectives on dynamics, many students used phrases such as “much harder than statics,” “extremely difficult,” “very challenging,” and “I am afraid of it.” It was reported that on the standard Fundamentals of Engineering examination in the U.S. in 2009, the national average score on the dynamics portion was only 53% (Barrett et al., 2010).

A variety of instructional strategies, such as hands-on experimentation, multimedia games, and computer simulations and animations (CSAs), have been developed to improve student learning (Bates and Poole, 2003; Bernadin et al., 2008; Budhu, 2009; Calderón and Ruiz, 2014). Among these instructional strategies, CSA has been receiving increasing attention and application in recent years in the international engineering education community (Clark and DiBiasio, 2007; Donnelly et al., 2004; Philpot and Hall, 2006). CSA does not require expensive hardware, so it can be readily implemented in teaching and learning. All the hardware needed for running a CSA software program is a computer. Most importantly, as many students are visual learners, CSA provides them with a visualization tool to better understand various engineering problems (Dunn and Griggs, 2000; Kolmos and Holgaard, 2010).

We have performed an extensive literature review using a variety of popular databases, such as

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the Education Resources Information Center, Science Citation Index, Social Science Citation Index, Engineering Citation Index, Academic Search Premier, and the American Society of Engineering Education (ASEE) annual conference proceedings (1995-2014). The recent Proceedings of the International Conference on Computer Supported Education were also examined.

The results of our extensive literature review show that the vast majority of existing CSA software programs developed for engineering dynamics (e.g., Flori et al., 1996; Gu and Tan; 2009; Kumar and Plummer, 1997; Manjit and Selvanathan, 2005; Stanley, 2009; Stanley, 2008) use graphs, charts, and curves to show what happens in science or engineering phenomena, but fail to show or explain the mathematical equations used to generate those graphs, charts, and curves. Students clearly see "what" happens but may not understand or be able to explain "why" or "how" it happens. For example, Stanley (2008, 2009) developed a CSA program to help student learn projectile motion. The CSA program used graphs and charts to show the variation of velocity while a particle undergoes projectile motion. However, no mathematical equations were provided to illustrate why velocity changes. The assessment of student learning outcomes relied heavily on questionnaire surveys.

The present study makes two contributions. First, an innovative set of interactive CSA learning modules was developed for engineering dynamics, focusing on projectile motion, an essential learning topic in engineering dynamics. In our CSA learning modules, mathematical modeling was incorporated into CSA to help students not only see "what" happens but also understand "why" and "how;" or in other words, to help students connect dynamics phenomena with the mathematics behind them.

Second, a quantitative, quasi-experimental research study involving an intervention group and a comparison group was performed to investigate the extent to which our CSA learning modules improved student learning of projectile motion. The existing relevant research (Flori et al., 1996; Gu and Tan; 2009; Kumar and Plummer, 1997; Manjit and Selvanathan, 2005; Stanley, 2009; Stanley, 2008) heavily depends on student surveys and interviews to assess student learning outcomes associated with CSA. Compared to the quantitative, quasi-experimental study performed in the present study, student surveys and interviews are subjective and may not provide an objective assessment.

In the remaining sections of the paper, we first describe how our CSA learning modules were developed, focusing on a description of their unique features. Then, the research question and the research method are presented, followed by a detailed description of the results and analysis. Some discussions about the research findings are provided. Conclusions are made at the end of this paper.

2 DEVELOPMENT OF INTERACTIVE COMPUTER SIMULATION AND ANIMATION (CSA) LEANRING MODULES

2.1 Design of Real-World Technical Problems

In the present study, three real-world technical problems were designed, as shown in Figures 1-3. These three problems all involve hitting a golf ball to a target. In the first problem, the ball is initially on the ground and finally lands at another position on the ground. In the second problem, the ball is initially on a hill and finally lands on the ground. In the third problem, the ball is initially on the ground and finally lands on a hill.

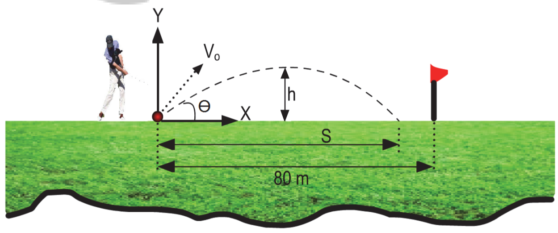

Figure 1: Technical Problem 1.

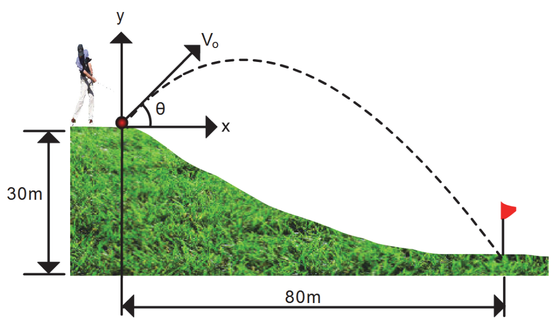

Figure 2: Technical Problem 2.

Each of the above three problems requires a different mathematical treatment involving proper

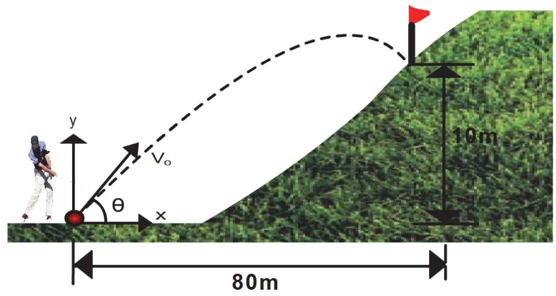

Figure 3: Technical Problem 3.

selection of the origin and the coordinate system based on which the position of the ball can be determined.

2.2 Development of Interactive CSA Learning Modules and Their Unique Features

From a variety of computer programming tools such as ADAMS, Maple, Matlab, Working Model 2D, and Adobe Flash, we chose Adobe Flash to develop our CSA learning modules because once these modules are developed, they can be directly uploaded to the Internet for students to run. If a software program is developed using ADAMS, Maple, Matlab, or Working Model 2D, students must use these particular programming tools, which typically require payment of license fees to run the software program.

Our CSA learning modules share the following two learning objectives: a) apply kinematical equations to determine displacement and velocity in a projectile motion; and b) learn how velocity and acceleration vary in a projectile motion. They have the following primary features, among others:

1) Each CSA learning module integrates visualization with the mathematical modeling of projectile motion to help students directly connect engineering dynamics with mathematics.

2) Each CSA learning module has an interactive computer graphical user interface that allows students to vary inputs and see how the numbers in mathematical equations change, simultaneously and dynamically, as the golf ball moves in a space.

3) Each CSA learning module is a web-based and stand-alone computer software program, so anyone who has access to the Internet can use it anytime, anywhere, and at his or her own pace.

Figures 4 and 5 are two representative examples showing the computer graphical user interfaces of the first CSA module. Students learn how to perform vector analyses of velocity (Figure 4) and acceleration (Figure 5). Students can change the initial velocity V_o and the initial angle θ, and then run computer animation to study how the horizontal and vertical components of velocity (Figure 4) and acceleration (Figure 5) vary both graphically (via the varying length of a line) and numerically (via the varying values of outputs of relevant mathematical equations).

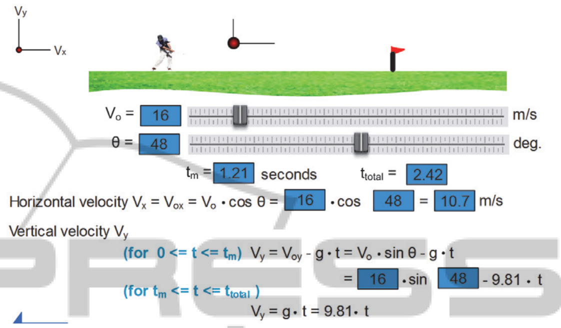

Figure 4: Example 1: velocity analysis.

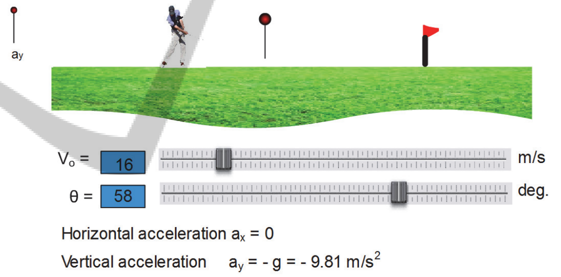

Figure 5: Example 2: acceleration analysis.

For example, in Figure 4, as the ball moves, students can see that the horizontal component (V_x) of the velocity keeps constant; whilst the vertical component (V_y) of the velocity gradually decreases before the ball reaches the highest point, and then gradually increases after the ball reaches the highest point. In Figure 5, as the ball moves, students can see that the horizontal component (a_x) of acceleration is always zero; whilst the vertical component (a_y) of acceleration keeps a constant value of 9.81 m/s^2.

3 RESEARCH QUESTION AND RESEARCH METHOD

3.1 Research Question

The research question of this study is: To what extent did the CSA learning modules developed in the present study improve student learning of projectile motion in engineering dynamics?

3.2 Research Method

3.2.1 Quasi-experimental Research Design

A quantitative, quasi-experimental research design, as shown in Table 1, was employed to answer the research question above. The undergraduate students who took an engineering dynamics course in either of two recent semesters participated in the present study. Students in Semester A were employed as a comparison group, and they received classroom lectures only but no CSA learning modules. Students in Semester B were employed as an intervention group, and they received classroom lectures as well as the CSA learning modules. The same instructor taught in both semesters. Pretests and posttests were administrated in both groups to compare student learning gains.

Table 1: Quasi-experimental research design.

Group	Pretest	Intervention	Posttest
Comparison	O		O
Intervention	O	×	O

3.2.2 Student Participants

Prior to the present study, all student participants in the comparison and intervention groups signed a Letter of Informed Consent approved by an Institutional Review Board. Table 2 shows the number of students who participated in pretests and posttests that were built upon each of the three technical problems described in Section 2.1. Note that not every student participated in each pretest or each posttest. Therefore, the number of students varied slightly for different pretests and posttests.

Five assessment questions were built upon Technical Problem 1. Another five assessment questions were built upon Technical Problem 2. Four assessment questions were built upon Technical Problem 3. Students in both comparison and intervention groups were asked to answer these assessment questions. All assessment questions are quantitative, multiple-choice questions.

Table 2: Number of student participants.

Group	Number of student participants who participated in pretests and posttests that were built upon		
	Technical Problem 1	Technical Problem 2	Technical Problem 3
Comparison (not using CSA modules)	59	60	63
Intervention (using CSA modules)	83	84	85

Student participants included approximately 90% males and 10% females. The small percentage of female students is very common in engineering schools in the United States. Student participants were primarily from three departments: mechanical and aerospace engineering, civil and environmental engineering, and biological engineering. The majority of student participants were from either the mechanical and aerospace department or the civil and environmental engineering department.

3.2.3 Calculation of Normalized Learning Gains

The normalized learning gain was calculated for each student and each assessment question using the following equation proposed by Hake (1998):

$$\text{Normalized learning gain} = \frac{\text{Posttest score in \% - pretest score in \%}}{\text{100 \% - pretest score in \%}} \quad (1)$$

Statistical analysis was conducted to compare learning gains between the two groups.

4 RESULTS AND ANALYSIS

In this section, the effects of the three CSA learning modules 1, 2, and 3, which correspond to the three technical problems described in Section 2.1, are described and analyzed.

4.1 Effect of CSA Learning Module 1

Figures 6 and 7 show the percentages of students who chose correct answers for assessment questions that were built upon Technical Problem 1 in the comparison group and in the intervention group, respectively.

From Figures 6 and 7, the percentages of students who chose correct answers in pretests are close between the two groups. However, the percentage of students who chose correct answers in posttests is significantly higher in the intervention group than in the comparison group.

Figure 8 shows a comparison of normalized,

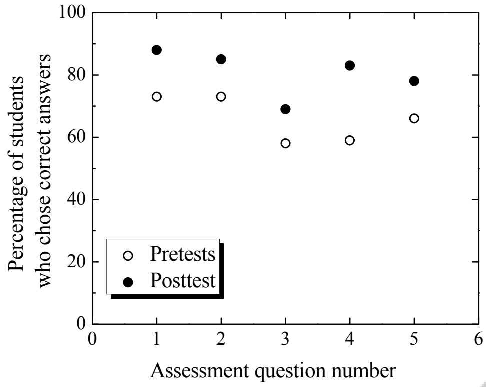

Figure 6: Comparison of pretests and posttests for Technical Problem 1 for the comparison group.

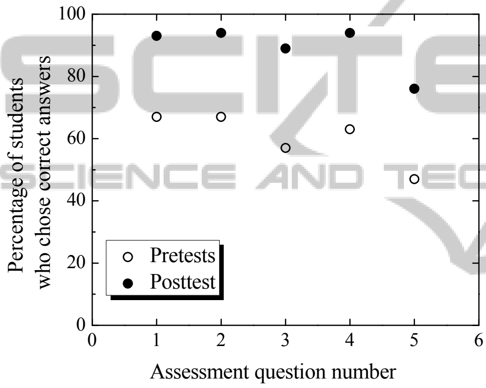

Figure 7: Comparison of pretests and posttests for Technical Problem 1 for the intervention group.

class-average learning gains between the two groups for Technical Problem 1. As seen from Figure 8, the intervention group has higher, or significantly higher in some cases, learning gains for each assessment question than does the comparison group.

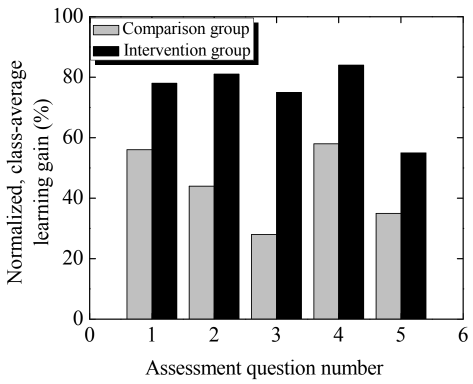

Figure 8: Comparison of normalized, class-average learning gains for Technical Problem 1 between comparison and intervention groups.

4.2 Effect of CSA Learning Module 2

Figures 9 and 10 show the percentages of students who chose correct answers for assessment questions built upon Technical Problem 2 in the comparison group and in the intervention group, respectively. A

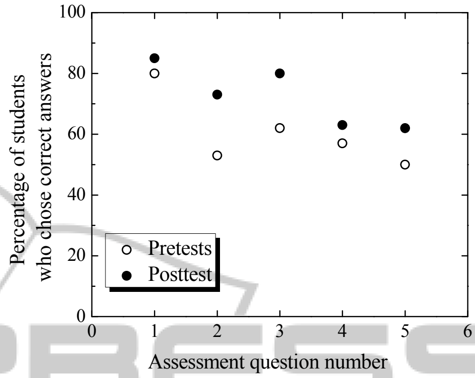

Figure 9: Comparison of pretests and posttests for Technical Problem 2 for the comparison group.

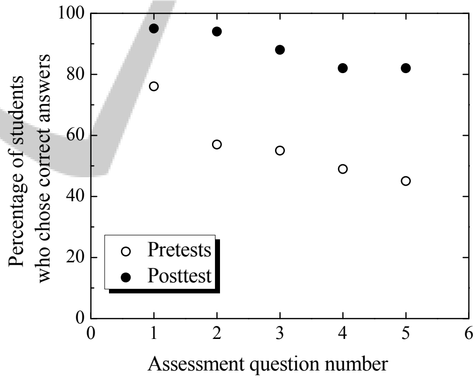

Figure 10: Comparison of pretests and posttests for Technical Problem 2 for the intervention group.

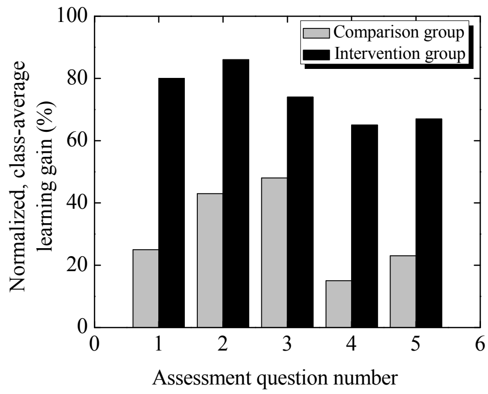

Figure 11: Comparison of normalized, class-average learning gains for Technical Problem 2 between comparison and intervention groups.

comparison of normalized, class-average learning gains between the two groups is shown in Figure 11.

Observations similar to those described in Section 4.1 can be made for Figures 8-11. The intervention group has higher, or significantly higher in some cases, learning gains for each assessment question than does the comparison group.

4.3 Effect of CSA Learning Module 3

Figures 12 and 13 show the percentages of students who chose correct answers for assessment questions that were built upon Technical Problem 3 in the comparison group and in the intervention group, respectively. A comparison of normalized, class-average learning gains between the two groups is shown in Figure 14.

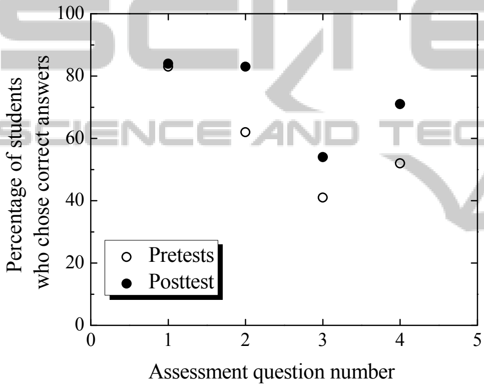

Figure 12: Comparison of pretests and posttests for the comparison group for Technical Problem 3.

The results in Figures 12-14 illustrate that the intervention group also has higher, or significantly higher in some cases, learning gains for each assessment question than the comparison group.

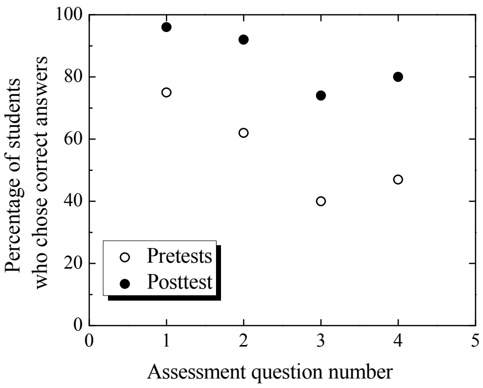

Figure 13: Comparison of pretests and posttests for Technical Problem 3 for the intervention group.

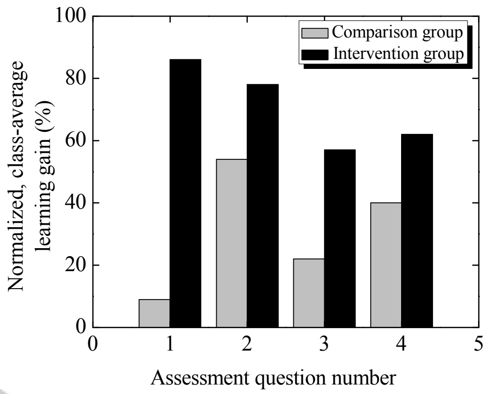

Figure 14: Comparison of normalized, class-average learning gains for Technical Problem 3 between comparison and intervention groups.

4.4 Overall Class-average Learning Gains

Table 3 summarizes the overall class-average learning gains for all three CSA modules. The overall class-average learning gain for a particular CSA learning module was calculated by taking the average of normalized, class-average learning gains for each assessment question associated with that particular CSA module. The data shown in Figures 8, 11, and 14 were employed. For example, in Figure 8, which corresponds to CSA learning module 1, the normalized, class-average learning gains for the intervention group are 78%, 81%, 75%, 84%, and 55% for five assessment questions, respectively. The overall class-average learning gain for CSA learning module 1 for the intervention group is (78% + 81% + 75% + 84% + 55%)/5 = 74.5%.

Table 3: Overall class-average learning gains.

Group	Overall class-average learning gains measured through pretests and posttests that were built upon		
	Technical Problem 1	Technical Problem 2	Technical Problem 3
Comparison (not using CSA modules)	44.3%	30.9%	31.2%
Intervention (using CSA modules)	74.5%	74.5%	70.7%

Based on Table 3, as compared to the comparison group, students in the intervention group increased their learning gains by 30.3%, 43.6%, and 39.5% on average for CSA learning module 1, 2, and 3, respectively.

To further study whether there exists a statistically significant difference in the overall class-average learning gains between the two groups, non-parametric statistical Mann-Whitney U tests were conducted, and the results are shown in Table 4. The reason we chose non-parametric statistical tests (rather than t-tests) in the present study is that the distribution of raw datasets collected (i.e., pretest and posttest scores) was found to be not perfectly normal. Based on the values of asymptotic significance shown in Table 4, the difference in the overall class-average learning gains between the two groups is statistically significant.

Table 4: Results of statistical Mann-Whitney U tests.

	CSA module 1	CSA module 2	CSA module 3
Z value	-2.481	-4.080	-3.422
Asymptotic significance (2-tailed)	0.013	0.000	0.001

5 DISCUSSIONS

Much existing literature asserts that computer simulation and animation has a major limitation: It can improve students' conceptual understanding only because CSA is primarily a visualization tool; and CSA cannot improve students' procedural skills. Procedural skills are generally defined as skills to get a numerical solution to, other than a qualitative understanding of, a technical problem (Case and Marshall, 2004; Hiebert and Lefevre, 1986; Rittle-Johnson and Star, 2007; Taraban et al., 2007).

However, the research findings from the present study reveal that *if properly designed*, CSA can also simultaneously improve students' procedural skills to finally solve problems in engineering dynamics. Our assertion is well supported by quantitative evidence summarized in Table 3. The key is to incorporate mathematical equations and procedures into the design of CSA. Therefore, when students run a CSA software program, they not only see "what" happens via computer animation, but also understand "why" and "how" via mathematical equations and procedures. Interactive computer graphical user interfaces are also important to actively engage students in the learning process. So students can learn by active doing, rather than by passive watching.

6 CONCLUSIONS

With the advancement of modern computer technology, computer simulation and animation has been receiving growing attention and applications in the international engineering education community. In this paper, we have described the development and assessment of an innovative set of CSA learning modules to improve student learning of projectile motion in engineering dynamics, a fundamental undergraduate engineering course. We have employed a quasi-experimental approach to quantitatively measure student learning gains. Students' attitude towards and experiences with our CSA learning modules, via student surveys and interviews, will be reported in a separate paper as they address a different research question, "What were students' attitudes toward and experiences with the developed CSA learning modules?"

The present study makes two primary scientific contributions. First, our new CSA learning modules integrate visualization with mathematical modeling, which greatly improves students' procedural skills for finally solving engineering dynamics problems. Second, based on the results of quasi-experimental research, it is found that as compared to the comparison group, students in the intervention group increased their learning gains by 30.3% to 43.6% on average. The difference in learning gains between the two groups is found to be statistically significant. Finally, we suggest that mathematical equations and procedures be incorporated into the design of computer simulation and animation.

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