On a Making-&-Tinkering Approach to Learning Mathematics in Formal Education: Knowledge Gains, Attitudes, and 21st-Century Skills

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Abstract: Making and tinkering, as learning practices, have gained a lot of attention during the last decade, especially in STEAM education. Despite the significant interest in making-&-tinkering activities, most of the research has focused on implementations in non-formal and informal educational settings, with learners of older age (i.e., students in secondary school). The present study sought to investigate young students' knowledge gains, attitudes towards a making-&-tinkering approach to learning mathematics in formal education and the development of 21st-century skills as they engaged in a collaborative making-&-tinkering project using a variety of arts, crafts, and technological tools such as a physical robot. The making-&-tinkering approach involved making, tinkering, programming, and play in a group project integrated into the formal mathematics curriculum. Findings from the study suggest that young students can greatly benefit from such an approach. The study has demonstrated the applicability and value of such methods for young learners in formal educational contexts, with implications for future research and practice in the field.

Introduction and theoretical background

There is a lot of recent discourse on learning in STEAM (Science, Technology, Engineering, Arts, and Mathematics) and how it is promoted through making, tinkering, programming, and play activities in various contexts and settings, including CSCL ones. STEAM education has been given a lot of attention during the last decade, and it has become an emphasis in many curriculums around the world (Vossoughi & Bevan, 2014). Increased pressure has been placed on teachers to improve performance in the above disciplines (Vossoughi & Bevan, 2014). This improvement can be achieved through new ways of teaching. Students who have been taught through traditional methods may have limited critical thinking ability as these methods emphasize only on the right answer to the problem through a determined process (Rode et al., 2015). In contrast to traditional methods, newer ones that support making, tinkering and play, set the significance of the process (and not only the end-result) and provide better ways to attract students with diverse thinking styles (Rode et al., 2015). In the present investigation, we adopt a making-&-tinkering approach to learning Mathematics (M), together with Science (S), Technology (T), Arts (A) and Engineering (E), in formal education with young students in elementary school, aged 8 to 9 years old.

Making is a process of creating something (Hsu, Baldwin, & Ching, 2017), and specifically, it is "the act of creating tangible artifacts" (Rode et al., 2015, p. 8). The movement of making, called "the maker movement", as an active process of building, designing, and innovating with tools and materials to produce shareable artifacts, has gained enormous momentum during the last years (Papavlasopoulou, Giannakos & Jaccheri, 2017). Making is a learner-driven educative practice that supports learning, participation, and understanding (Vossoughi & Bevan, 2014). Tinkering as a part of making (Vossoughi & Bevan, 2014), is a problem-solving technique and learning strategy, which promotes a practice of improvement, and it is associated with experimentation and "trial and error" methods (Krieger, Allen, & Rawn, 2015). As Martinez and Stager (2013) indicate, making and tinkering involve a playful approach to solving problems through direct experience, experimentation, and discovery. Programming and physical computing are very often making and tinkering activities (Hsu et al., 2017), as students can build and rebuild their robot, make the program design, code and debug. Both in programming and in making and tinkering activities, the play is diffused. Play in this work is defined as a dynamic, active and constructive behaviour, and it's contiguous with the gamification of learning (Deterding, 2011; Ioannou, 2018). The connection between all the above concepts and learning in CSCL, including students' attitudes, are examined in this paper.

Both making and tinkering in education are not new ideas. They have their theoretical roots in Papert's constructionism, which is built upon Piaget's constructivism (Papavlasopoulou et al., 2017). Making is also noted by educators such as Froebel, Montessori and Dewey when they advanced practical, physical and playful learning

(Vossoughi & Bevan, 2014). As Vossoughi and Bevan (2014) indicated, the theories of Vygotsky, Lave and Wenger are related to making, too, in the notion that making can support learning and development.

The benefits of making in the learning process have been identified for many decades, thus during the last years a growing interest has been shown on making or "maker culture" as a philosophy or phenomenon (Papavlasopoulou et al., 2017), which should be examined more thoroughly through more empirical studies (Hsu et al., 2017). Making can change learners' role from passive recipients to active ones, taking control over their own knowledge (Papavlasopoulou et al., 2017), which it is a vital characteristic of learner-driven pedagogies that are compounded in curriculums. Learning by doing gives learners the opportunity to engage in problem-solving, self-directed and collaborative work (Hsu et al., 2017) through the development of interests, identity and knowledge, as it may involve the use of physical materials in traditional crafts or hobby techniques (such as woodworking, cooking, etc.) or the use of technology. During making, learners are engaged in tinkering, which also builds on inquiry-based pedagogy and exploits learner-centered learning (Papavlasopoulou et al., 2017). According to Sheridan et al. (2014), tinkering supports learning and promotes 21st-century skills. As programming involves tinkering, educational robotics as learning tool can also benefits teaching and learning in STEAM education. Making, tinkering and programming are closely related to playful and gameful learning, as experimental and hands-on activities are involved. Robots can be used as a game in students' hands and alongside with gameful design (Deterding, 2011; Ioannou, 2018), the learning outcomes can be beneficial.

Although a few researchers focus on the value of making, tinkering, programming, and play in learning (Krieger et al., 2015; Hsu et al., 2017; Martinez & Stager, 2013), studies which document the child's learning experience in making-based activities are currently lacking. A growing number of efforts in making-enhanced activities is observed in non-formal or informal learning environments, such as workshops, libraries, museums, summer-school and after-school programs rather than in formal education. Yet, most of these efforts are practice-oriented in contrast to only few research-oriented studies (Chu, Angello, Saenz, & Quek, 2017). Moreover, typically such activities are done with students of older age e.g., secondary education, 12-18 years old (Papavlasopoulou et al., 2017).

In the present investigation, we adopted a making-&-tinkering approach to learning Mathematics (M), together with Arts (A) and Engineering (E), in formal education with young learners. The study sought to investigate young learners' knowledge, attitudes towards a tinkering-&-making approach to learning mathematic and their development of 21st-century skills, as they engaged in a group project using a variety of arts, crafts, and technological tools. The study sought to answer the following research questions:

RQ1: What kinds of learning gains do young students experience during making-&-tinkering activities?

RQ2: What are their attitudes towards this approach of learning in formal (math) education?

RQ3: How this approach seems to enact the development of 21st-century skills?

Methodology

The study adopted a mixed methods research design, relying on both quantitative and qualitative data collection and analysis to answer the research questions under investigation.

Participants

The sample was composed of 18, 3rd-grade students (aged 8 to 9 years old), 12 girls and 6 boys. The students came from a small public primary school in a rural area in northeastern Mediterranean. The majority of the students came from families of middle socioeconomic status and education. The school was selected by convenience sampling, as the researcher was teaching at the school.

Procedures

The research work took place in the participants' regular classroom. The desks were set in a way so as students could work in six groups of three. The group formation constituted children from different cognitive, emotional and social behavior levels. Two groups used the classroom's computers and four groups used tablets. On each group's table, there were pencils, rubbers, rulers, variety of reused materials and an Edison robot. The 5-sessions intervention lasted four weeks as summarized in Table 1 (see also pictures in Figures 1, 2).

Table 1: The 5-sessions intervention

Sessions	Activity	Description
1st	craft	-the problem is given -brainstorming about how they could make their craft and materials they could use

		-students in groups create their craft
2nd	math goals	-small exhibition in the classroom of their "monster robot vacuum cleaners' -students write a four-digit price for their monster -they are taught about rounding to the nearest hundred -they choose six of their monsters' prices (the number six was given to limit the task) and try to round them to the nearest hundred
3rd	finish the artefacts and program the robot	-students work in three-members' group -they choose which monster is suitable to be set on the robot -they find a way to put the monster on the robot -they program their artefacts to move continuously
4th	improve the programming	-groups look for ways to improve their programming, by making their robot moving continuously without getting out of the borders
5th	prepare posters	- groups prepare their poster and organize their presentation

Data collection and analysis

Data collection included knowledge pre- and post- tests, questionnaire on students' attitudes, video data and focus groups data.

Knowledge test

A knowledge test was used pre and post intervention to measure students' acquisition of mathematical knowledge. The test included two exercises on the content of the math lesson. The same test was given a month later (i.e., as delayed-test) to measure the retention of knowledge. The tests were examined for face validity by an experienced teacher-colleague at the school. Another teacher-colleague examined and ensured that the lesson was relevant and in-line with the National Curriculum.

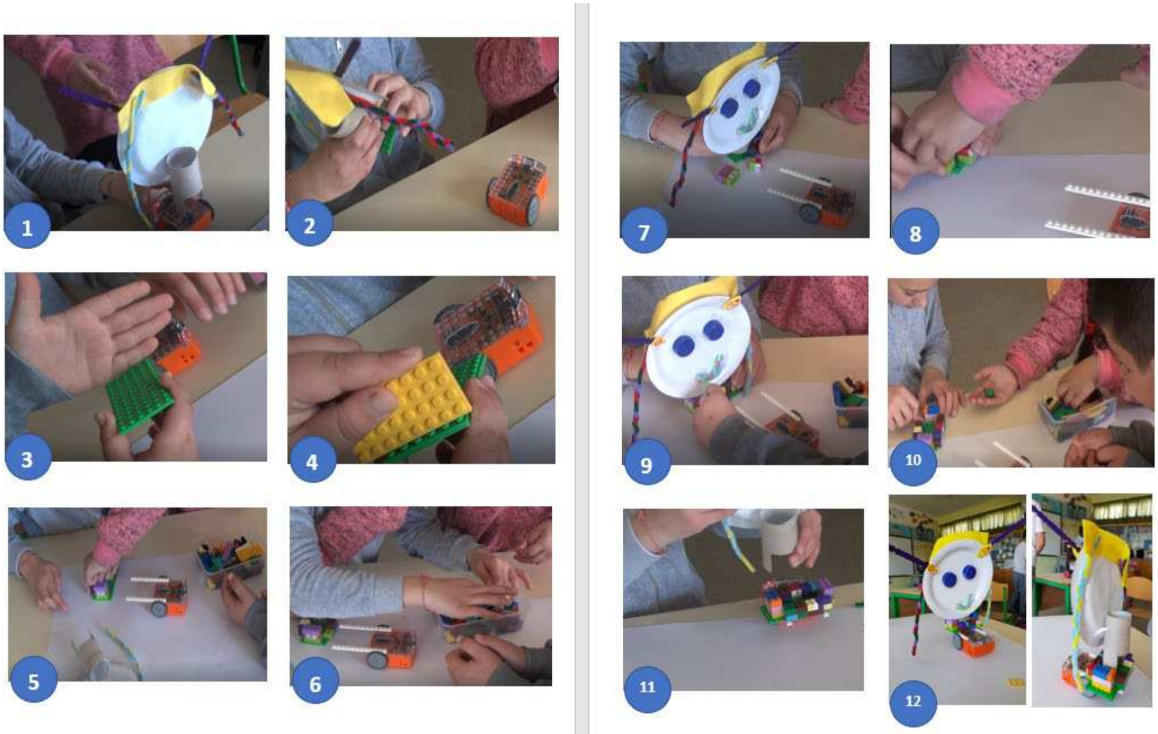

Figure 1. Making-&-tinkering activities to set the craft onto the robot.

Attitudes questionnaire

The questionnaire used is known as the My Class Activities (MCA), an instrument developed by Gentry and Gable (2001) to measure students' attitudes toward their class activities, specifically their level of: (a) interest e.g., "What I do in my class fits my interests", "I have an opportunity to work on things in my class that interest me", (b) challenge e.g., "The activities I do in my class are challenging", "I have to think to solve problems in my class", (c) choice e.g., "I can choose to work in a group", "I can choose materials to work with in class", and (d) enjoyment e.g., "I look forward to my class", "I have fun in my class". The questionnaire has previously reported good psychometric properties (Gentry & Gable, 2001). The questionnaire was translated from its English version to Greek, following the standard test adaptation guidelines (Chapman & Carter, 1979). Initially the MCA items were translated by the researcher, who is a native speaker of Greek and then the items were translated back to English by an English teacher, and finally they were compared. Two more experts reviewed the translated MCA items, to ensure the content validity of the items. Then it was piloted with four students of the same school age, coming from another school of the same district. The MCA questionnaire was administered at the end of the 5th session of the intervention.

Video data and analysis

Observational data were collected via video analysis, which was held in two rounds. In the first round, which was based on the Critical Incident Technique (Flanagan, 1954), general but important episodes and themes were noted (e.g. "Making and tinkering was detected during the phase of the craft's construction", "Tinkering helped students to improve their craft and their programming, to remember the result, and to feel satisfaction about their achievement", "Collaboration during the making and tinkering activities helped them to improve their artifact and to find the best programming solution"). These themes helped in the organization of the focus groups' protocol. The second round of video-analysis was conducted using the Manifest Content Approach (FitzGerald, 2012) on the episodes identified during the first round; the episodes were coded based on the Tinkering Dimensions Framework (Bevan et al., 2015) which was used as per Table 2. Both, the first and second video-analysis rounds were conducted separately by the researcher and another expert and inter-rater reliability (present agreement) was assessed to 87% and 89% respectively. Upon percent agreement computation, the raters discussed and resolved all disagreements.

Table 2: Learning Dimensions Framework developed by the Tinkering Studio (Bevan et al., 2015)

Learning Dimension	Indicators
Engagement	• Spending time in tinkering activities • Displaying motivation or investment through effect or behavior
Initiative & Intentionality	• Setting one's own goals • Seeking and responding to feedback • Persisting to achieve goals in the problem space • Taking intellectual risks or showing intellectual courage
Social Scaffolding	• Requesting or offering help in solving problems • Inspiring new ideas or approaches • Physically connecting to others' works
Development of understanding	• Expressing a realization through effect or utterances • Offering explanations for a strategy, tool or outcome • Applying knowledge • Striving to understand

Focus groups

Semi-structured focus-group interviews with students (3 focus groups with 6 students each, 40 minutes each) were conducted at the end of the experience. The focus-group interviews were organized based on the framing of the study, the themes derived from the video analysis, and the research questions of the study (e.g.," What did you learn from the experience?", "How do you feel about this approach to learning mathematic at school?"). The focus-group interview data were video-recorded and transcribed for subsequent data analysis. Data were transcribed and qualitatively analyzed using a thematic analysis approach (Attride-Stirling, 2001).

Findings

Knowledge gains

A Wilcoxon Signed Rank Test demonstrated statistically significant gains in students' knowledge from pre- to post- testing ($W_{(18)} = 2$, $z = -2.18$, $p < .05$). Also, a Wilcoxon Signed Rank Test was used to examine knowledge retention (i.e., delayed test data); results showed that knowledge gains were preserved since there was no statistically significant difference from post to delayed testing ($W_{(18)} = 1$, $z = -1.34$, $p > .05$).

Consistent with the quantitative data, during the focus group discussions, almost all the children (n=15 out of 18) mentioned that they could explain how to round a four-digit number to the nearest hundred. Specifically, a girl noted:

> *I really liked the session where we gave four-digit prices to our monster-hoovers and organized a small shop. And it was nice when we walked around the classroom -to the shop-desks- to choose 6 prices and try to round them to the nearest hundred…We didn't know how to round the numbers and we were trying […] Only John was right and when he explained to us, I understood and now I know!* [#12, Girl]

Attitudes towards the tinkering-&-making approach

Descriptive statistics on the attitude subscale mean-scores showed that the students appreciated and enjoyed the tinkering-&-making approach to formal (math) learning, particularly the opportunity to choose the way they could work in the project and to face challenges during the project, which triggered their interest (Table 3).

Table 3: Subscale mean-scores for attitudes

Subscale	Mean	SD
Interest	3.30	0.61
Challenge	2.88	0.66
Choice	1.90	0.77
Enjoyment	3.50	0.61

Findings from the video-analysis supported the results from questionnaire data on attitudes, as 27% of the incidents concerned the presence of the dimension of "Engagement" (see Figure 2), based in the framework by (Bevan et al., 2015).

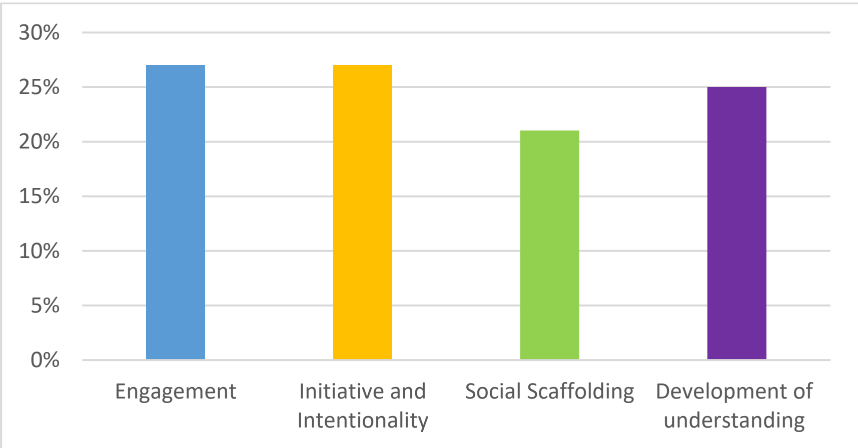

Figure 2. Results according to the "Learning Dimension Framework".

The focus-group interviews provided additional evidence of students' attitudes, in fact, demonstrating a positive shift in attitudes over time, e.g.

> *At the beginning, we couldn't work […] by the end, I liked it!*
> *When you gave us the programming challenge, we thought it was something difficult, but after we tried it was easier[…] I liked the project because we programmed the robots through the computers!* [#1, Girl]

> *I was enthusiastic! Basically, we felt happiness![…] All the sadness we felt at the beginning had gone away by the end as we were happy about our achievements! […] That time I felt I was a scientist who invented something very great. And we learned a thousand of things we didn't know before! And using all those materials you gave us, we managed to do something we never did before[…] Will we make again a lesson with robots?* [#4, Girl]

21st-century skills

Most of the results derived from the focus-group interview data referred to the 21st-century skills. The data were grouped into three categories -- Learning & Innovation Skills, Information Media & Technology Skills, and Life & Career Skills – per framework by the Partnership for the 21st Century Learning (P21, 2015). Findings concerning the "Learning & Innovation Skills" are organized below in categories.

Creativity and innovation

The focus-group data revealed that creativity and innovation skills were worked throughout the project. The students used their imagination to construct their craft and design and to prepare their poster. During the project, the students improved their crafts and their programming, invented new ideas, improved or changed their initial ideas and found ways to fasten their craft onto the robot, e.g.

> *At the beginning, I had an idea, later I got another idea, and finally, I got another idea…*
> *We put our imagination to make our monsters and posters!*
> *I mostly liked the craft part and when I used my imagination!*
> *[…] and we managed to fasten our monster on the robot without any lego or anything else! We just set it on the robot and it wouldn't fall.*
> *My team found another way […] we set the monster onto the robot, but when we realized that there was no space to put our fingers to press the robot's buttons, we used the small wood chips that were set on the monster to press the buttons. So, we turned the monster in a way that the yellow wood chip could press the circular button, the green wood chip could press the square button, and the other wood chip could press the triangle!!!* [#13, Girl]

In most groups, the students worked creatively with others and they implemented or suggested innovations, e.g.

> *I liked the moment we invented new things.*
> *That time I felt I was a scientist who invented something very important!*
> *When you are engaged in such a kind of activities you feel like you are Einstein!*
> *Instead of the monster-hoover robot, we could have made the caveman robot related to our history […]*
> *Yes! Or to use the idea in Gymnastic where the robots could be our bodies!"*
> *And invent more outdoor activities, not only indoor activities.*
> *[…] the teacher could use more puzzle challenges leading us to a treasure, for more mystery and fun!*
> *Oh! We could also write the programming commands on a paper and later when we find the treasure, we could test them on the tablet.* [#18, Girl]

Critical thinking and problem-solving

In students' reporting we could easily identify strategies related to critical thinking and problem solving e.g.

> *We learned how to describe step by step the process we followed from the beginning to the end*
> *[…] we planned with all the steps until we could solve the problem and reached our goal!*
> *[…] we made questions to find other solutions […]*
> *We should be careful, and we should observe what we were doing to avoid making mistakes…*
> *We knew why we made each step, and we were able to explain it…*
> *At the beginning, we couldn't find the right programming solution, but later we understood how to do it! I know how to do it!" (talking about rounding to the nearest hundred)*
> *I realized that we must finish something before we review and make judgments […] it may not be so difficult […]*
> *why the other group found the programming and we did not?*
> *[…] I saw the other posters full of colours and I felt nervous.* [#12, Boy]

Communication and collaboration

It became apparent in the focus-group interview data that the students communicated clearly with others via a variety of communicative ways, ranging from body movements and discussions to the usage of descriptions, posters and narrative stories. They also learned to collaborate with others especially their groupmates, e.g.

At the beginning, when one child told us to do it like this, the other one disagreed and we started to quarrel each other, but later, we managed to collaborate […]
I would like to have more group works and collaborate with more kids.
We learned to work in groups without loud voices and quarrels.
We learned to respect each other in our group, especially we learned to help, and give advice […]
When my groupmate resigned and didn't want to try again in finding the right programming, I was telling her to continue and that we could make it! [#8, Boy]

Even though most data were categorized as "Learning & Innovation Skills", students also reported ideas related to "Information Media & Technology Skills", e.g.

We learned how to use the technology […] our robot, the computer, the tablet, and we first saw and touched an iPod and a camera! [#3, Boy]

We managed to program our robot…We learned to use the computer or the tablet, and to program the robot…I learned robotics and programming! [#6, Boy]

Furthermore, students also reported learning gains related to "Life & Career Skills", e.g.

The project taught me that I must have patience and persistence, because I had to finish something. [#2, Girl]

We were so happy, because we tried again and again, to make it […] to what we wanted to… we never stopped trying. [#12, Girl]

We've been taught to respect others […] and help each other […] We've been taught to be hard-workers […] to reach our goals! [#1, Girl]

Discussion and implications

The present study sought to investigate students' knowledge gains, attitudes towards a making-&-tinkering approach to learning mathematics and development of 21st-century skills as they engaged in a making-&-tinkering project using a variety of arts, crafts, and technological tools such as a physical robot. The approach involved making, tinkering, programming, and play in a multidisciplinary project integrated into the mathematics curriculum. Findings from the study suggest that young students can greatly benefit from such an approach. While making-&-tinkering activities are typically enacted in informal learning settings with learners of older age e.g., secondary education, 12-18 years old (Papavlasopoulou et al., 2017), the present study demonstrated the applicability and value of such methods, in formal educational context with young students.

RQ1: What kinds of learning gains do young students experience during making-&-tinkering activities? Findings demonstrated that students' mathematical ***knowledge*** was improved by the end of the project and that the knowledge gained was retained, consistent with previous work reporting that making is in favour of knowledge acquisition (Chu et al., 2017). Indeed, previous work has also reported that making activities helped young children develop knowledge whilst the nature of these activities helped them share the new knowledge with others (Sheridan et al., 2014).

RQ2: What are their attitudes towards the tinkering-&-making approach in formal (math) education? Findings from the present investigation suggest positive shifts in students' ***attitudes*** towards the making-&-tinkering approach. Interestingly, while at the beginning students exhibited negative behaviours, the implementation of the interdisciplinary project allowed shifts towards more positive attitudes; the shifts seemed to be related to students' opportunity to choose the way they could work and to overcome challenges throughout the project. The "engaging" nature of the project was demonstrated in the video data (27% of the observed incidents concerned this dimension) as well as students' statements in the focus-group interview data. Relevant findings, that is, making-&-tinkering activities influencing students' attitudes towards STEAM, have been reported in recent studies (Chu et al., 2017; Harnett et al., 2015).

RQ3: How this approach seems to enact the development of 21st-century skills? The study further supports that making-&-tinkering projects can support the development of students' ***21st-century skills***, particularly in all the three categories of the framework by the Partnership for 21st Century Learning (P21, 2015). Throughout this experience we documented multiple episodes of critical thinking, problem solving, creativity and innovation, communication and collaboration. Similar results were found in previous works (Bevan, Gutwill, Petrich & Wilkinson, 2015; Harnett, Tretter, & Philipp, 2015).

Although the study, confirms to a large extent, findings already reported in previous works, the field is still in maturing and therefore replicability helps to enhance the validity of such methods and practices in education. The present study is one of very few with young children of this age (8 to 9 years old), engaging in making-&-tinkering activities in the context of formal mathematics curriculum and therefore, has a unique merit in the research literature with implications for researchers and practitioners in the area. The small (N=18) sample of convenience in the present investigation does not allow for generalizability of findings, yet the rich description of our methods and procedures should enable other researchers and practitioners to transfer these findings into similar contexts and settings. Overall, a better understanding of how making-&-tinkering occurs in formal settings with young learners will enable researchers and practitioners to nourish learning environments which can serve the development of the 21st-century skills.

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