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Abstract: Research in math education on mathematical creativity relies on the idea that creativity is potentially within all students and it can be fostered by properly structured activities. The tasks most commonly used for its assessment are problem solving and problem posing. In our approach we use problem posing tasks to get insight into students' creativity. Based on a qualitative analysis of the participants' answers to the questionnaire that followed the task, we define *algorithmic, combined* and *innovative creativity* as constructs that can be put in correspondence with the types and level of knowledge involved in the problem posing task. We propose criteria to identify these types of creativity and discuss aspects related to the quality of the resulting problems. A second set of criteria is defined in order to assess the novelty of the posed problems.

Keywords: assessment criteria for creativity, mathematical knowledge.

Introduction

The first accounts of mathematical creativity emerged in the context of the work of professional mathematicians (Poincare, 1948; Hadamard, 1954). These accounts were subjective and often associated with a "genius" view of creativity (Weisberg, 1988). However, over the past decades, the approach to creativity in the mathematics education research community has shifted and now creativity is seen as an ability that can be enhanced in students by properly selected mathematical activities. In this view, creativity is closely connected to deep knowledge of a domain; it is associated with long periods of work and reflection and might be influenced by previous experience and instruction (Holyoak & Thagard, 1995; Sternberg, 1988; Silver, 1997). Since creativity became a subject of research in mathematics education, several research issues and paths have emerged. One of which,, its assessment, will be discussed in this article. Two main approaches to assessment of creativity can be identified. The first one relies on an interpretation of the main components of creativity as they were defined by Torrence (1974). Fluency, flexibility and novelty are interpreted as number of identifiable changes in the approach to the problem, number of generated solutions and the level of their conventionality (Silver, 1997; Ervynck, 1991; Leikin, 2007). Another approach is represented by researchers who look at the relation between the traits, abilities and certain behaviours during task resolution and creativity. Balka (1974) in his article synthesized a set of criteria for measuring mathematical creative ability based on the works of Guilford; Torrance; and Meeker. He listed both convergent thinking, characterized by finding patterns and breaking from established frames of mind, and divergent thought defined as formulating mathematical hypotheses, evaluating unusual mathematical ideas, and splitting general problems into specific sub-problems. Haylock (1997) mentions two of these as being key-aspects for creativity: the ability to overcome fixations in mathematical problem-solving (like, for example, breaking away from stereotyped solutions), and the ability for divergent production within mathematical situations. Meanwhile, the two approaches are not independent; they focus on different aspects. In the first one, we have quantitative measures that allow the comparison between students performing the same task; the second approach gives us ways for fostering creative behaviour in problem solving.

As settings for the assessment, there are two major approaches: problem solving and problem posing tasks. Both have been recognized as being appropriate for this purpose. Namely, Ervynck (1991), Silver (1997) and much earlier, Polya (1973) among others, argued that solving problems in multiple ways is an expression of creative thought. In fact, Silver (1997) in his article stressed that inquiry-oriented mathematics instruction which includes problem-solving and problem-posing tasks and activities can assist students to develop more creative approaches to mathematics. Jensen (1973) said that for students to be creative in mathematics, they should be able to pose mathematical questions that allow exploration of the original problem as well as solve the problems in multiple ways.

We focus on the relation between problem posing and mathematical creativity; in particular, on the issue of defining criteria for creativity assessment through problem posing tasks in classroom settings. Our interest is to connect between mathematical knowledge and creativity. From this point of view, our approach is more related to the one of Haylock (1997), in terms that this would eventually lead to insight on stages of creative behavior and suggest ways for fostering students' mathematical creativity.

We shall start by describing the adopted working definitions for mathematical creativity, on one hand, and for classroom problem posing, on the other. Next, we present our methodology. In section three, we present arguments for the potentially creative nature of the problem posing process. In the next two sections we describe and give examples for the criteria derived from the experiments. We finish with conclusions and an outline of future research paths.

Definitions

Mathematical creativity

In the literature, we can find many definitions of mathematical creativity, but none is a commonly accepted one (Mann, 2006). Treffinger, Young, Selby and Shepardson (2002) identified over 100 contemporary definitions. Runco (1993) defines creativity as a construct involving both "divergent and convergent thinking, problem finding and problem solving, self-expression, intrinsic motivation, a questioning attitude, and self-confidence" (p. ix). Krutetskii (1976) characterized mathematical creativity in the context of problem formation (problem finding), invention, independence, and originality. Ervynck (1991) defines creativity in a framework of mathematical knowledge: "mathematical creativity is the ability to solve problems or to develop thinking in structures, taking into account of the peculiar logical-deductive nature of the discipline, and of the fitness of the generated concepts to integrate into the core of what is important in mathematics." (p. 47)

At the same time, researchers stressed the need to have workable definitions that can be applied at classroom level (Pehkonen, 1997; Freiman & Sriraman, 2007). A good, commonly agreed definition would help, on one hand, to identify students with creative mathematical thinking and, on the other hand, design meaningful tasks for them. In our paper, we shall adopt the definition given by Sriraman (2005) and also accepted by other authors (Liljedahl & Sriraman, 2006; Freiman & Sriraman, 2007). Mathematical creativity at classroom settings is defined as a) the process that results in novel and / or insightful solutions and b) the formulation of new questions and/or possibilities that allow an old problem to be regarded from a new point of view.

Problem posing in classroom setting

For mathematicians, problem posing refers to the process by which they formulate a problem that has not been solved by anyone before. In most empirical studies, though, problem posing means the formulation of novel problems with the solution unknown at least for its creator (Van den Heuval-Panhuizen et al. 1995). In other contexts it is understood as reformulation of an existing problem (Cohen & Stover, 1981), mostly ill-defined one. Silver's (1994) synthesizes these aspects in his definition in accordance with which „problem posing refers to both the generation of new problems and the re-formulation, of given problems". (p. 19)

We shall adopt the definition given by Van den Heuval-Panhuizen et al. (1995). Therefore, in this study we define problem posing in a specific topic as the process of formulating questions about 1) the existence of a mathematical object; 2) the relation between different mathematical objects; 3) new properties of a given object deduced or related to a set of specified properties. The classroom setting means that the problem posing happens "inside of a class", in a context shaped by school curriculum. We mean the "inside of a class" as opposite to the work of mathematicians; therefore all students and teachers are included here, no matter their experience in mathematics. This also implies that the problem posing process is initiated by teachers as purposeful, goal-oriented learning activity performed with the students in the mind (even if physically not present during the experiment). Teachers want to illustrate, through these problems, mathematical methods or concepts, rather than considering problem posing an end itself.

Methodology

Subjects

In the experiments participated high school and first year university students from Romania along with secondary / high school teachers, all from Romania, and Olympiad participants from Mexico. University students were of 18-20 years old and entered to university after completing an admission exam. None of the students has been involved in training on problem posing. High school students were 16-17 years old and they just have studied sequences as part of the school curriculum. Olympiad participants were 15-18 years old and had no previous contact with sequences (as topic in introductory calculus). The teachers who participated in the experiment had varied experience in teaching and, at the time of the experiments, they were participating at an in-teacher education program. Overall, in the experiments participated 44 high school students; 25 university students; 22 Olympiad participants; 41 middle school teachers and 22 high school teachers.

Task

Participants received the following instructions: *Consider three consecutive elements of a sequence, a_{n-1}, a_n and a_{n+1}, and the usual algebraic operations (inequality included). With these elements pose three problems such that to have an easy, one of average difficulty and a difficult problem. At the end, you need to handle in the drafts of your work.* At the moment of handling their problems in, they received a questionnaire about the following aspects of the problem posing process: the existence of an initial idea (for each problem of different difficulty), change of the idea during generation, problem types from which to start the generation process, a theorem or generalization as from where to trigger the problem posing process and difficulty criteria they used.

A remark needs to be made: no further clarifications were made about the difficulty of problems. Each participant could establish his own criteria for difficulty based on his experience. We plan to analyze our data from this point of view in the future.

Data analysis

In the first step of our analysis we looked at the problem posing process from the point of view of overall dynamics. The purpose was is identify recurrent actions that could, eventually, be grouped and considered as phases of the posing process. Further, by analyzing these phases we were hoping to have elements that would situate classroom problem posing as an instance of mathematical creativity.

What are the processes or phases that characterize creativity? Silver (1997, p.76) asserts "…It is in this interplay of formulating; attempting to solve, and eventually solving a problem that one sees creative activity. Both the process and the products of this activity can be evaluated in order to determine the extent to which creativity is evident."

In the analysis of our data, we hypothesized that, during the problem posing process, the knowledge available to the student is under a continuous reordering as the relevance of a piece of knowledge is under change. The aspects proposed by Silver (1997), like shifts in direction or reformulations or explored paths, relate to the change between on-focus and off-focus state of a particular mathematical object and property of the object. In one phase, there is a broad field which is briefly explored such to focus, immediately after, on a particular aspect of the mathematical object or property. Such a "reordering" allows cognitive change to occur and it is the base for the "shift from association-based to causation-based thinking, which facilitates the fine-tuning and manifestation of the creative work" (Gabora, 2002). Therefore, in the analysis of our data we paid special attention to the cases when participants reported changes in their approach or when that change was identifiable from the scratch work (even if not reported in the questionnaire). We conclude that problem posing is creative because involves the same mechanisms that are present during a creative endeavor. We shall give two examples to illustrate these ideas. The first one is presented in figure 1 and was given by a teacher. The teacher reported in the questionnaire: *The idea was to combine the theorems* (Fig1a.) *and I tried several expressions* (Fig. 1b) *until I get to the final form.*(Fig. 1c)

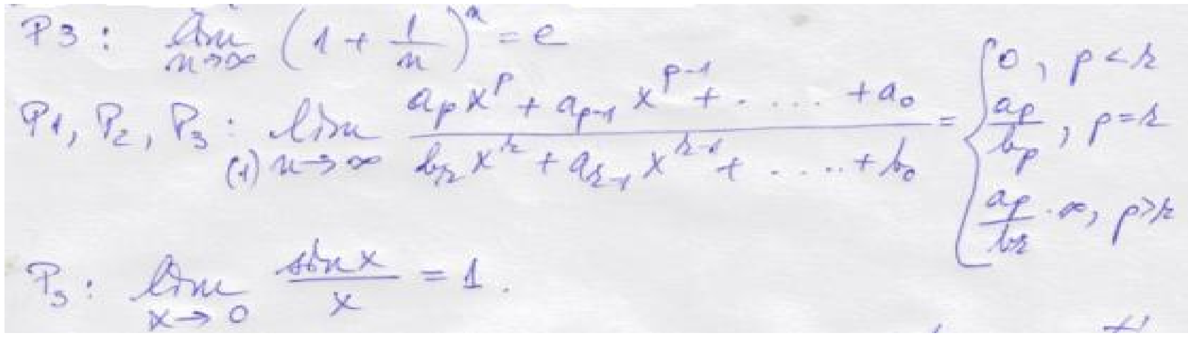
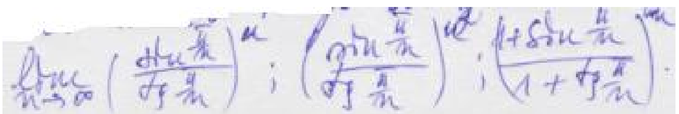
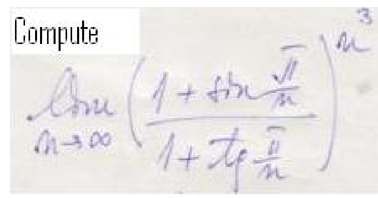


Figure 1. a. Theorems reported by the teacher



b. The expressions tried by the teacher



c. final expression of the problem

In the reformulation of an expression one draws on experience, searches for analogies or for new associations, meanwhile during the evaluation of the newly formed expression needs to search for causal relations, assess general characteristics of the problem and the aptness of the problem with the initial constraints or goals.

As second example we give the answer of an Olympiad participant to the question *Did you have from the very first moment what sort of problem will you generate at each level of difficulty? If you answer Yes, please specify it.* The answer was: *Neither yes, neither a no. I had an initial sketch of what I wanted to do, but the final product was not what I thought of initially.* The next question of the questionnaire referred to the change in ideas: *If you answered yes to the previous question, did the idea change during the process? If case of a yes answer, please specify*. The student's answer reveals that one switches from broad to focused look and continuously monitors the problem in formation: *Probably because the original ideas were not in concordance with the level of difficulty of the problem I was just creating and, also, because I was trying to create something new (especially for the difficult problem)*.

We see creativity in the problem posing task due to this cyclic alternation between the two types of thinking: an association based one during which ideas flow and a causal type of thinking that allows assessing the creation done so far and setting a new context for the next cycle.

Once we identify problem posing as a creative act, we concentrate in the next section on defining criteria to assess it. The assessment can be seen at process and results level. We shall focus on mathematical knowledge as a key factor in such an enterprise.

Criteria for creativity assessment through problem posing

In this section we define criteria for assessing creativity at process and result level. As we shall illustrate, a separation into these two aspects was necessary given that, in repeated situations, the quality of the generation process was not matching the quality of final results. First, we shall focus on the process of problem posing and, then, on the resulted problems.

Assessment of the problem posing process

In order to formulate the criteria, we analyzed the drafts handled in by the participants. The details from the drafts were interpreted, where possible, in terms of actions (steps taken towards the accomplishment of the task). At the same time, the actions (like for example, replacement of a constant with a variable) rely on knowledge and, therefore, we considered that the definition of criteria should relate to knowledge. A problem posing task always has a context given by the topic of the posed problems. As such, and especially at classroom level, we can identify a cluster of knowledge that typically is used in problems related to that topic. We shall refer to this as domain or topic specific knowledge.

In school mathematics, we consider the concepts, theorems, corollaries presented at a topic as the domain specific knowledge of that topic or domain. The clustering of knowledge based on its relevance to a particular task is a common practice between researchers. For example, Leikin (2007) introduces, between others, the concept of expert spaces as being the space of solutions to a problem given by an expert in the domain. After we delimited the domain and not-domain specific knowledge for the topic / domain of sequences by analyzing several textbooks, we categorized the steps, actions, taken by the participants during the posing process based on the belonging of the involved knowledge to domain specific or not clusters. After a systematical classification of the processes seen in the drafts, we identified three main ways for posing a sequence problem. Our criteria for the creativity of the process are based on these three categories.

We define as first level of creativity (*algorithmic)* one that it is characterized solely by the employment of domain-specific algorithm. Typical examples are the cases where problem generation is based on a rule, on problem types or specific techniques. For a rule based generation, consider the example presented in figure 2. The elements of the rule would be instantiated by known cases that are known from class or individual study. The problem was posed by a high-school student and refers to the rule: the sequence obtained as product between a sequence having the limit zero and one that is bounded, is convergent to zero. As it can be seen in the figure, the student defines a bounded sequence (a typical example for bounded sequences in Romanian textbooks) and one that converges to zero, and then asks for the limit of the product.

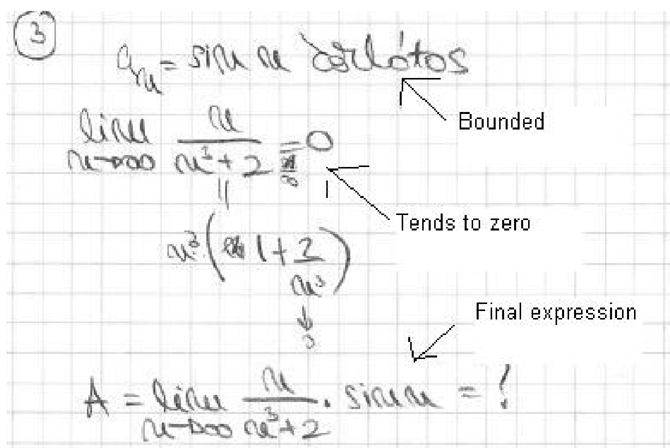
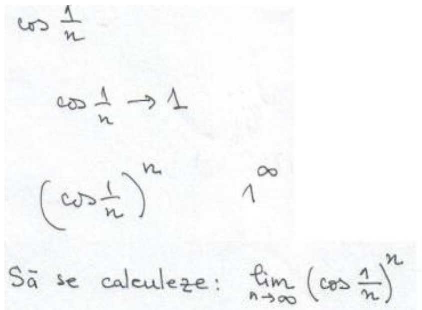


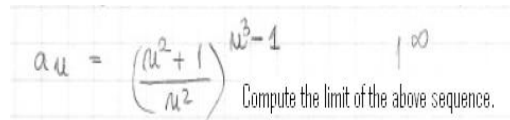
Figure 2. Problem posing by using a domain specific rule

However, it has to be said that the rule is not always profoundly understood (the relations between elements); situation that often leads to erroneous problems. Since at this moment we look at the process itself, it has to be underlined that high school students rely mostly on memory when trying to instantiate the rule elements. Knowledge is too rigid and not interconnected, leading to many unsolvable problems or, when solvable, they lack interest. The expertise in instantiating elements of a rule or of some technique will impact the quality of the result. We give three examples for the use of the same technique as base of the generation process with different results.

The first one is the one presented in Figure 1. Two others, one made by teacher and one posed by a high school student are shown in figure 3a and 3b.



a. Example of a teacher´s problem



b. Example of a high school student´s problem for algorithmic creativity

Figure 3. The use of a known limit as start point in the generation process

It can be seen, in an attempt to solve, that problem at point b, quickly leads to infinite as result, since the exponents of n are chosen so. In comparison with this, the problems posed by the teachers, need to be worked until the end in order to have a result and, also, require having knowledge about trigonometrically functions. In conclusion, even if the approach to problem posing is fundamentally the same, the quality of the resulting problems can vary significantly.

A second level of creativity is defined as the application of some domain-specific rule along with some other type of knowledge. We shall use the term *combined creativity* for this case. The "other knowledge" would be from another domain and its application not straightforward for the most. However, this not-topic specific knowledge plays a central role in defining the problem; the problem is structured around this knowledge and connected to the topic through the formulation of the problem. Example:

$$\textit{Consider}\,(a_n)_{n\in N}\ \textit{such that}\ a_0 = 1\ \textit{and}\ a_n = \frac{na_{n-1}}{a_{n-2}}.\ \textit{Prove that}\ \frac{(2n+1)!}{a_n a_{n+1}} \geq \frac{2^{2n+1}}{2n+1}.$$

It is interesting to see the procedure followed by this Olympiad participant to generate the problem. His answer in the questionnaire was: *Getting to n! is trivial and then I tried to "out inside" the combinatorial identity*. We give in Figure 4, the fragment with the most important step (from creativity point of view).

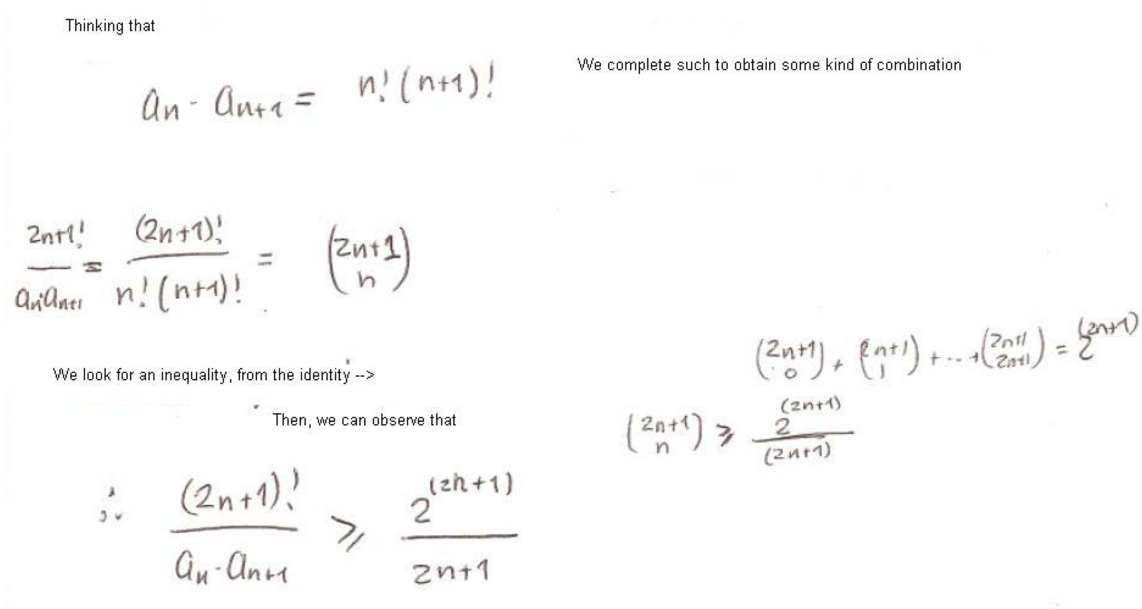


Figure 4. Example of problem generation

In this case, the question of the problem is not one typical for sequences. Indeed, the problem is about combinatorial, but it is formulated as one of sequences. The combination of knowledge from different topics can lead to a situation that is considered as worth for exploration. A second example comes from a first year University student and it was posed for the average difficulty problem:

Consider a sequence $a_{n+1} = (a_n + a_{n-1}) \bmod 100$ with $a_0 = 0, a_1 = 1$. *Prove that the sequence is periodical.*

In the questionnaire, the student reported that he wanted to build a periodical sequence, so he thought of the pigeonhole principle and then tried to define something to fit this idea. Once again, the problem is structured around this not-topic specific knowledge that also becomes essential for solving the problem. As a remark on the "quality" of the problem, it has to be said that under the current formulation the problem is straightforward, an aspect that seems to be ignored by the student (since he specifies the problem as average difficulty). Small changes in the initial values, and maybe other question could have turned the problem into a challenging one. In conclusion, the quality of the problem is not always in direct relation with the creativity shown during the generation process.

A third level of creativity was tagged as *innovative creativity* and it is defined as the process of using solely knowledge from outside of the topic for which the problem is generated. Example: *Consider the following sequence:* $a_1 = 3$, $a_{n+1} = a_n^2 - a_n$. *Decide whether 396,138,794,300,000 is term of the sequence.*

In the above case, the rule of divisibility with 3 was applied (as the start point) and generated a question. The result is an extremely simple problem, yet unusual at first. The main point we highlight is that they used knowledge and techniques from a completely different domain and, then, reformulated the problem in terms of the requested domain.

A second example comes from a University student: *Consider* $f:(0,\infty) \to R, f(x) = \frac{x+1}{2x+3}$. *Note with* $f_n(x) = \underbrace{(f \circ f \circ ... \circ f)(x)}_{n}$. *Prove that* $f_n(x) = \frac{a_n x + b_n}{c_n x + d_n}$ *where* $a_n, b_n, c_n, d_n \in N^*$.

The problem is built around function composition and uses no knowledge from sequences (as seen in introductory calculus). With regard to the problem, we observe that it is not a difficult one to solve, however – as a homographic function - it leads to an interesting exploration and far-reaching results.

As we underlined, it is not necessary that certain creativity in the process to lead to interesting or challenging problems and vice versa. Therefore, it is important that when judging the creativity of a student we pay attention also to the process by which he arrived to the results and not only to the final problem.

Assessment of the result

Plucker and Beghetto (2004), in their review on creativity, stressed that there are two key elements of creativity, specifically novelty and usefulness. We observe that this definition allows evaluating the results of the creative process, especially as usefulness is concerned. At this point we focus on the novelty of the posed problems, considering that their usefulness is given by the fact that we situate ourselves in a classroom setting, therefore the problems are useful because they carry a potential pedagogical value.

The novelty of a problem is judged in comparison with already existing problems, therefore we need to define the elements of the problems that should be compared at this phase. In the particular case of classroom setting, the core set of problems supposed to be known are those from the textbooks and some problem books. Generally speaking, we treat a problem as having a given part, requested part, form of the question, restrictions (when asking to apply some particular method, for example) and solutions. In some particular domain (sequences, for example), we can speak about problem types as determined by the expressions involved in the given part. Based on these specifications we define the following levels of novelty.

At the lowest level we define the *algebraic novelty* which consists of differences in the expressions in the given or requested part, meanwhile all the rest remains unchanged (the problem structure, type, and possible solution method). A very common way is to change the values of a constant thus obtaining something new (in terms of the expression involved in the problem), but in the same time having the same problem from structural point of view. High school students tend to generate problems with algebraic novelty only, especially if they experience a failure before.

The second level of novelty consists of a significant change in the given or requested or "form of the question" part, but the structure remains identical to the initially known problem. Such change it is reflected at the level of the nature of the used expression, therefore we shall use the term of *conceptual novelty*. The simplest example consists of *parameterization*, the process by which a constant is changed into a parameter. The new problem, though structurally identical with the initial one, is novel since it opens up a space for discussion based on the parameters values. This interpretation of novelty refers to comparing an initial (retrieved) problem and a new one, but can be easily extended to define the novelty of a problem in relation with a set of problems.

A third level of novelty is the *methodological* one. Let's analyze the following example given by a secondary teacher:

Consider the sequence 1,2, 2, 3, 3, 3,4,4,4, 4, … Answer the followings:

1. Which are the next three terms of the sequence?

2. *Is the sequence monotone*?

3. *Prove that the last digit of the index of the last elements from the part of equal numbers is not divisible with 4.*

The question 3 can be considered as one bringing a methodological novelty in play, since the question that can't be answered by the same method as the previous ones. In this case, we have a modification that turns the problem into a new one, and this novelty can be identified at the level of the applicable solution methods. It might seem that novelty is easy to be achieved, but often even a small change in the value of a constant can turn a problem previously easy to solve into a very difficult one. Therefore, one needs a good understanding of the problem's structure in order to maintain the problem solvable and well defined.

Conclusions

In our paper, we defined criteria for the assessment of mathematical creativity in classroom settings through problem posing tasks. The criteria were identified as result of a qualitative analysis of a series of problem posing experiments ran with high school, university students, teachers and Olympiad participants. The structuring element of the analysis was the topic-specificity of the knowledge involved in the process. Based on this, we introduced and illustrated the constructs of *algorithmic*, *combined* and *innovative* creativity. In each case, we outlined the possible links between the quality of the result and the creativity involved in the problem posing process. In the last part, we introduced criteria for the assessment of the results' novelty. Three constructs were given and exemplified: *algebraic*, *conceptual* and *methodological* novelty.

As future line of research, we envision the study of the co-growth of the body of mathematical knowledge and understanding along the creativity exhibited during a problem posing task. A second line of research concerns the development of activities that could foster creativity of students. As a third line, we want to study the constraints teacher consider during the posing process whether those are tacit or not by nature.

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