How Does the Level of Field-Specific Knowledge Help Apply It in Other Contexts?

The first results of the comparative analysis between TIMSS-2011 and PISA-2012

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Summary. The research was aimed to measure how the level of field-specific knowledge and skills affects the ability to transfer this knowledge to a non-academic context. Analysis of TIMSS and PISA results in Russia was used as a foundation for research. TIMSS tasks are rather associated with formal knowledge, while PISA tasks deal with the ability to apply formal knowledge in a broad real life context. The sample consisted of 4,241 Russian students who participated in both the TIMSS-2011 and the PISA-2012. Based on average performance of each student in TIMSS mathematic tasks (PV), all students were divided into six groups. 10 and 20 most difficult tasks were selected using the Partial Credit Model. We also calculated proportions of the most difficult PISA tasks solved in each TIMSS group. This indicator provided a way to assess the ability to transfer field-specific knowledge to new contexts and to apply it to solve real life problems. As a result, we revealed a positive relation between the level of field-specific knowledge and the ability to transfer it to real life situations: the better performance in mathematics, the more likely a student is going to apply their knowledge to solve problems in a nonacademic context. However, this connection is not linear: a significant facilitation of transfer only comes from the highest level of performance. Medium levels of field-specific knowledge are hardly differentiated in terms of performance in solving context-based problems.

Keywords: school education, mathematics, transfer, context-based tasks, PISA, TIMSS.

Received in July 2013

The paper uses the results of the project "A Profound Analysis of International Research on Educational Quality and the USE in Terms of Economic Indicators of Education" implemented in 2013 under the NRU HSE Basic Research Programme.

1. Transfer of formal field-specific knowledge to out-of-field contexts

The key question in any learning is, will a student be able to use field-specific knowledge to solve problems outside that field? For instance, if an innovative course or a new learning approach is implemented in teaching, it is always suggested, more or less expressly, that benefits of learning will not be restricted to that specific course or approach.

The issue of using field-specific knowledge in out-of-field contexts has long been studied by both cognitive sciences and educational psychology. The problem of transfer has been persistently investigated since the early oeuvres by Thorndike [Thorndike, Woodworth, 1901], but there is still very little consonance about the nature, the mechanism and the prerequisites of such transfer. Interpretation variations are rather caused by the multifacedness of the issue as such than by the inconsistency of approaches due to differences between the academic fields of study (cognitive psychology, artificial intelligence, or building effective teaching methods [Reed et al., 1974; Gravemeijer, Doorman, 1999; Engle, 2006]). As this paper does not aim to go deep into history and current state of knowledge transfer research, we chose to refer to Barnett and Ceci's taxonomy [Barnett, Ceci, 2002], which suggests a number of dimensions to classify the key studies in this area. This taxonomy is first of all useful for us because it will let us locate our research on the map of existing studies right away and to explain the interpretation pattern for our results.

The first dimension of the transfer research classification is the subject of transfer. It may be content (what exactly is transferred) and/or context (when and where the knowledge is transferred). Content may include different types of knowledge acquired, from knowing a fact or an arithmetic operation to understanding the underlying mechanisms. Context also has several subdimensions that describe both learning conditions and the transfer test task: 1) field of knowledge (e. g. knowledge is acquired during a botany course; transfer to chemistry is tested); 2) physical context (e. g. knowledge is acquired in a class; transfer to an outlet or home environment is tested); 3) time context (how much time has passed between learning and the transfer test); 4) functional context (what the acquired skill or knowledge is used for, and what patterns of thought are involved, e. g. academic context or the practical purpose of tax calculation); 5) social context (individual or team work); 6) modality (e. g. visual perception or written language). All of these define the framework for transfer research projects.

Practically speaking, it would be perfect for schools and, on a larger scale, for any educational system, if students could transfer acquired knowledge to various fields out of school (physical context), if acquired skills were preserved for several years after graduation (time context) and were used to solve different problems (functional context). The concept of this intention may be described as a far

transfer. The more learning environment differs from test conditions, the farther the transfer. It is suggested that each transfer research may be distributed among these dimensional axes to see which axes are associated with a far transfer and which rather have to do with a near transfer.

Experimental studies that can be classified as far transfers on these axes all come to a common conclusion. Transfer only takes place in specific conditions. Students are more successful in transferring their acquired knowledge (making a far transfer) if they have a deep, fundamental understanding of the subject matter [Brown, Kane, Long, 1989]. Barnett and Ceci point out that the factor of having or not having this deep understanding of relationship in a subject matter or in a field may often be the reason for inconsistency of transfer research results [Barnett, Ceci, 2002].

A whole family of oeuvres is focused on exploring the methods of achieving such deep understanding (e. g. teaching certain algorithms, metacognitive skills, critical thinking) and the triggers of establishing relationship between formal knowledge, mostly mathematics, and real life situations where this knowledge can be applied. Oeuvres of this type often do not involve experimental control of many transfer-related variables, unlike in cognitively oriented research [Lobato, 2006]. Nevertheless, these works prove in some ways that teaching deep understanding in a complex learning environment through contextualized, metacognitive monitoring and critical thinking tasks ensures transfer of acquired knowledge to new environments [Halpern, Hansen, Riefer, 1990; Needham, Begg, 1991; Gentner, Loewenstein, Thompson, 2003; Thompson, Senk, Yu, 2012]. We are not going into detail about the methods of teaching deep understanding here. This is only to recognize the common statement expressed by many far transfer researchers.

We have only found few authors who touch to at least some extent upon interdependence between the level of field-specific knowledge and the possibility of knowledge transfer. Thus, Lehman, Lempert, and Nisbett showed that graduate training in law, psychology and medicine had a positive effect on statistical reasoning, methodological reasoning, and reasoning about real life problems [Lehman, Lempert, Nisbett, 1988]. Van der Stoep and Shaughnessy also found that psychology students who specialized in research methods performed better on real-life statistical and methodological reasoning tests than those who specialized in developmental psychology [Van der Stoep, Shaughnessy, 1997]. However, at least two particular aspects of this research prevent us from interpreting its results as a strong evidence of the effect that areas of learning have on knowledge transfer. First, there is little difference between the transfer test tasks cited by the authors and typical tasks of the Research Methods Course. Second, the authors did not measure students' levels of knowledge in any way. Similar limitations can be found in [Fong, Krantz, Nisbett, 1986].

Surprisingly enough, despite the great number of studies on the problem of knowledge transfer and application in new or real life situations, very few of them associate the level of knowledge with chances of using this knowledge in an out-of-field context. Ample research of transfer prerequisites does not explain the role of formal field-specific knowledge. Meanwhile, this type of learning prevails largely over laboratory or experimental training in a lot of countries, which makes assessing effects of formal field-specific knowledge on solving non-academic problems critically important.

2. TIMSS-2011 and PISA-2012 on the same sample as transfer tasks

Large-scale international education quality assessment programs TIMSS and PISA study results of general school education in different perspectives: TIMSS is designed to test field-specific knowledge and skills, while PISA uses its testing tools to assess the ability to apply knowledge to solve problems set in real-world contexts.

Technically, TIMSS and PISA have some overlapping areas of assessment. For example, TIMSS provides tasks to discover knowledge applying skills, and PISA evaluates academic performance. [Dossey, McCrone, O'Sullivan, 2006; Wu, 2009a, 2009b; Wu, 2010] contain a detailed comparative analysis of TIMSS and PISA task specifications.

However, despite overlapping areas and the fact that developers of both programs define the focus of some tasks almost identically[1], PISA and TIMSS tests can be regarded as *different* if judged by what is assessed: TIMSS tasks require a high level of formal knowledge, while PISA tests the ability to apply this formal knowledge in a broad real life context. This conceptual contrast deserves dwelling on.

PISA's idea of context-based tasks consists in "plunging" the mathematical component of a task into a non-mathematical, real everyday life context. To solve a task like this, we should first identify the possibility of using mathematics and then isolate the mathematical structure contextualized in the task. The situation described in everyday life terms is transferred to mathematics and the real life problem assumes a mathematical structure. Applying mathematical knowledge as such is only required at the next stage to solve the mathematically formulated problem. In the end, we perform a "backward transfer" of the mathematically formulated solution to the original problem context, thus assigning contextual, customized meaning to the results [OECD, 2013].

[1] Content domain "Quantity" of PISA-2003 mathematics shares a number of common features with content domain "Number" of TIMSS-2003, and cognitive domain "Reproduction" of PISA-2003 shares features with domain "Knowing facts and procedures" of TIMSS-2003 [Wu, 2010].

TIMSS offers a similar solution procedure, but only for "applying tasks" [Mullis et al., 2012]. However, most TIMSS tasks are field-oriented and designed to assess understanding of mathematical algorithms, knowledge, procedures, and using them in mathematical problems of varying difficulty. These problems are rather decontextualized: students are asked to solve a task of a purely mathematical structure. What's more, even TIMSS "applying tasks" with PISA-like solution procedures include no redundant, detracting information: students are only given information that should be translated into mathematical expression and used to solve the problem. As each "real-life" element corresponds to one element of the mathematical model, rather simple parallels may be used to translate a problem into mathematics. Unlike PISA, TIMSS doesn't include information in different forms—as texts, charts, or diagrams—into one task, which would require participants to correlate heterogeneous data first, at the same time keeping the problem question in their minds. Besides, although it doesn't play a big role, TIMSS field-specific tasks can be easily deciphered due to their typical forms and recognizable mathematical content. PISA tasks, in their turn, are set in out-of-field contexts and need to be recognized as "mathematical". All abovementioned specific features of the two types of tasks, contextualized (PISA) and decontextualized, field-oriented (TIMSS), can be found in the samples given in the Appendix.

Judging by the above said, we believe that TIMSS and PISA tests may be treated as "transfer tasks": they have a common mathematical content (specifically, division with remainders), explicit in TIMSS (only indispensable information uniformly represented in text form, having an academic format, and isomorphic to the one required to solve the mathematical model) and implicit in PISA (redundant information provided in various formats, nonequivalent to the required mathematical model and having a nonacademic context).

Using a common sample for these two tests could shed light on connection between the level of knowledge and skills, on the one hand, and their transfer to another context (in this case, real life), on the other hand. A joint analysis like that became possible when most 9th graders were examined in PISA-2012 after participating in TIMSS-2011 as 8th graders. The common mathematical basis has made the starting point of our research[2].

Our study should be qualified as a far transfer research, as it complies with at least two dimensions of the abovementioned taxonomy [Barnett, Ceci, 2002]. First, we are going to focus on transferring field-specific knowledge and skills (school mathematics) to other, nonacademic functional contexts similar to real life problems. Sec-

[2] For brevity sake, when we hereinafter mention TIMSS and PISA tasks we only refer to the area of mathematics assessed by both tests.

ond, transfer of field-specific knowledge to real-life situations was assessed about one year after measuring the level of this knowledge, which fits the time aspect of a far transfer.

The fundamental distinction of this research from all of the works mentioned above is that neither learning process nor teaching practices or educational approaches are in the spotlight of our attention. What we focus on is assessment of the level of field-specific knowledge, which we regard as an index of TIMSS performance [Hutchison, Schagen, 2007]. We are staying at this general operational level without pointing to specific skills or knowledge in school mathematics. We are going to use the term "field-specific knowledge in mathematics" and its sub-fields—algebra, geometry, etc.—without saying exactly what rules or mathematical operations students know, what algebra or geometry topics they understand. The TIMSS test is not designed to represent each subfield of mathematics to the full. Yet, all TIMSS tasks in a complex, as well as subfield-oriented tasks (e. g. on algebra or geometry), represent all the key topics of general school mathematics. That is to say, we can only make generalized conclusions about field-specific knowledge and skills in mathematics. There is little we can say about the content of transfer, i. e. whether (and to what extent) students apply standard problem solving algorithms or they rather transfer and use some fundamental principles, structures, and procedures embedded deep in their minds. Our paramount goal is to establish relationship between the level of field-specific knowledge and the possibility of applying it in other contexts.

3. The method

3.1. Sample

The joint TIMSS-2011 (8th grade) and PISA-2012 sample includes 4,241 Russian students from 229 schools, with 49.8% girls and 50.2% boys. All students were aged between 14 and 18 in 2012 (M=15.9; SD=0.50).

3.2. Test tools

Mathematic knowledge was assessed through 219 TIMSS tasks in mathematics and its subfields: algebra (71 tasks), data and chance (43 tasks), number (61 tasks), and geometry (44 tasks). Mathematical tasks were distributed among the cognitive domains as follows: 80 tasks for knowing, 87 tasks for applying, and 52 tasks for reasoning. PISA's cognitive skills assessment test consisting of 85 mathematical tasks was used to assess the ability to transfer field-specific knowledge to real life contexts.

3.3. Analysis strategy

The analysis aimed to compare student performance in TIMSS and PISA[3].

[3] A constraining condition was that we didn't have individual PISA-2012 results expressed in plausible values (PV) instead of test values when we were working on this paper. Thus, we couldn't possibly make the most obviously need-

At the first stage, we divided students into groups based on their TIMSS performance; as a result, we got six groups, from most successful to least successful. In this case, TIMSS plausible value (PV) served to measure the level of mathematical knowledge, i. e. allowed to assess its depth.

Next, we identified 10 and 20 most difficult PISA tasks.

We also calculated proportions of the most difficult PISA tasks solved in each TIMSS group. This indicator provides a way to assess the ability to transfer field-specific knowledge to new contexts and to apply it to solve real life problems.

Finally, we compared performance in transferring field-specific knowledge with the level of this knowledge in student groups determined based on the TIMSS results.

4. Results

4.1. Descriptive statistics

TIMSS points of Russian 8th grade students in mathematics vary between 309.85 and 804.03. The average points across Russia equaled 543.81, against the average international value of 500.

As our joint TIMSS-PISA sample could differ from the TIMSS representative sample, we performed a normal distribution test that revealed distribution that differed significantly from the normal one and was skewed to the left (skewness = −0.17; excess = −0.33; Kolmogorov—Smirnov test: stat. = 0.03; $p \leqslant 0.00$). However, an additional test revealed a distribution of points in the original TIMSS-2011 sample (8^{th} grade) very similar to ours. This is obviously how knowledge and skills measured by TIMSS are generally distributed in Russia, with a certain amount of extremely low points despite the overall high test performance.

4.2. Grouping TIMSS participants by performance rates

Average TIMSS points in mathematics were calculated for each student, which made it possible to identify the most talented 815 students (16.7%, group 1), 816 students slightly less gifted in mathematics (16.7%, group 2), and so on down to group 6. Table 1 describes the distribution of students among these six groups.

4.3. Identifying difficult PISA tasks

Item Response Theory (IRT), more specifically the Partial Credit Model, was used as a tool to measure difficulty of PISA tasks [Masters, 1982]. The results were expressed in the logit scale for each task. 10 and 20 most difficult tasks (with difficulty ranging from 1.25 to 3.96 on the logit scale) were selected for this analysis.

ed comparison between “performance in TIMSS” and “performance in PISA”. Neither can we conduct a correlation analysis of performance in TIMSS and PISA for the same reason. That is why we had to scale the PISA results and further identify the most difficult tasks with our own efforts. The next chapter describes the procedure in detail.

Table 1. **Distribution of students among groups based on their TIMSS-2012 performance**

Group	1	2	3	4	5	6
Number of students in the group	815	816	816	816	815	815
Proportion of the group in the total number of students,%	16.7	16.7	16.7	16.7	16.7	16.7

Table 2. **Performance in 10 most difficult PISA tasks among students with different TIMSS points in content domains of mathematics**,%

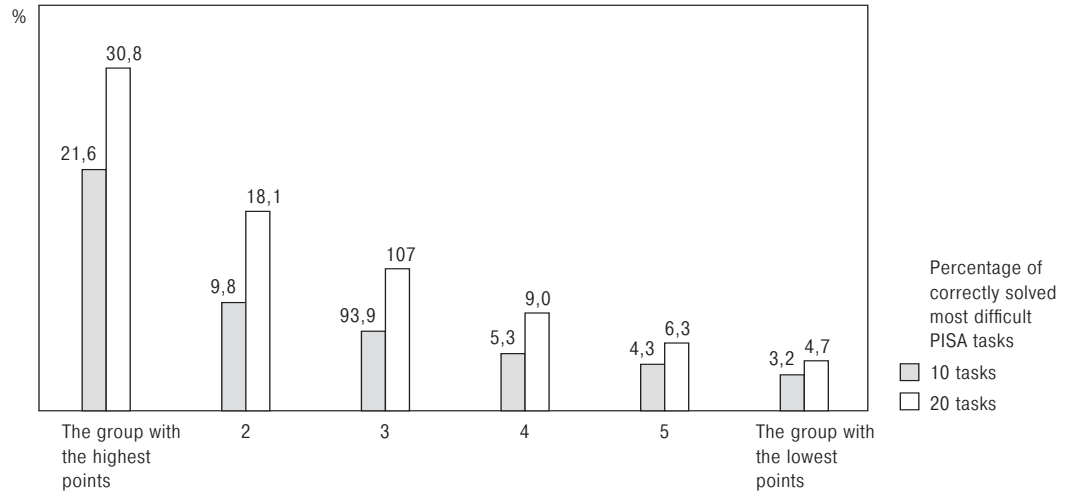
Group	Algebra	Data and chance	Number	Geometry
The group of students with the highest points in the content domain	20.5	20.7	20.2	20.0
2	10.1	10.7	11.4	11.1
3	7.5	6.9	7.1	7.5
4	5.7	5.4	5.5	5.5
5	4.6	4.6	4.0	4.8
The group of students with the lowest points in the content domain	3.2	3.6	3.5	2.7

Table 3. **Performance in 10 most difficult PISA tasks among students with different TIMSS points in cognitive domains of mathematics,%**

Group	Knowing	Applying	Reasoning
The group of students with the highest points in the cognitive domain	20.4	21.0	20.2
2	10.1	10.4	10.1
3	8.6	7.5	7.3
4	4.5	5.2	5.1
5	4.5	4.0	4.8
The group of students with the lowest points in the cognitive domain	3.5	3.5	4.1

A sample of a released PISA item is given in the Appendix. In difficult tasks, students are usually asked to find links between data expressed in different forms (e. g. a text and a chart), or to determine the relationship between variables so as to monitor it changing over time, or to translate relationship described in ordinary language to a mathematical model.

Figure 1. **Performance in difficult PISA tasks among students with different TIMSS points in mathematics**,%



4.4. Assessing difficult task performance in TIMSS groups

As all students didn't have the same number of difficult PISA tasks, we assume that 100% is the total number of difficult tasks actually assigned to a group of students. Performance was measured not only in mathematics as a whole (Fig. 1) but also by content domains (algebra, data and chance, number, geometry) and cognitive domains (knowing, applying, and reasoning) (Tables 2 and 3).

As shown in Figure 1, there is a direct relationship between TIMSS results and PISA performance: the higher TIMSS points, the higher the number of difficult PISA tasks a student is able to solve. However, there is a remarkable gap in performance of the 1st and 2nd best TIMSS groups: the first, the most efficient one completes 12% more difficult tasks than the second one. The difference between all the subsequent TIMSS groups doesn't exceed 2.5%. The same pattern (leveled difference in performance of the second best group and all the subsequent groups as compared to the huge gap between the first two) is discovered in 20 most difficult PISA tasks, too.

As for the content domains of mathematics distinguished by TIMSS (algebra, data and chance, number, and geometry), apart from the direct proportion revealed between TIMSS and PISA performance, there is also a 9–10% gap in percentage of correctly solved PISA tasks between the best performing group and the group that follows. Further gaps between successive groups are relatively small, from 3 to 1% (Table 2).

The same pattern is found when TIMSS tasks are classified by cognitive domains: knowing, applying, and reasoning (Table 3). Each level of TIMSS performance adds 1–3% to performance in difficult PISA tasks, while transition to the 1st, best performing group provides a boost of 10–11%.

5. Discussion

This study had a goal to find out to what extent the level of field-specific knowledge affects the possibility of its transfer and application in another context. Although previous research has provided some proof of the positive impact that deep understanding of a subject matter (on the level of principles, structures and procedures) has on transfer of the acquired knowledge, no research has been conducted yet to determine relationship between the level of field-specific knowledge and the transfer of knowledge and skills from one context to another. We have managed to provide evidence for this relationship in the paper. The better performance in mathematics, the more likely a student is going to apply their knowledge to solve problems in another context. Besides, we have found out that this connection is not linear. A significant facilitation of transfer only comes from the highest level of performance, as compared to all the other levels. Medium and low levels of field-specific knowledge provide more or less the same transfer opportunities.

The same pattern has been revealed in content domains of TIMSS mathematics, i. e. algebra, number, data and chance, and geometry. Students only had essential advantages in solving most difficult PISA tasks if they showed the highest performance rate in the domain. All medium levels of knowledge were hardly differentiated in terms of applying in a new context and contributed little to performance in solving context-based problems.

At this point, we could suggest that the cognitive domain defined in TIMSS as "applying" should differentiate better between students by their ability to solve applying-oriented PISA tasks. We would expect a direct linear relationship between performance in TIMSS applying tasks and performance in difficult PISA tasks assessing the same skill. Indeed, this relationship turned out to be positive but it was not linear: obvious advantages in transfer and application of knowledge in other contexts were only provided by the highest level of applying in terms of TIMSS. What's more, this relationship had the same nature as the one between performance in TIMSS "knowing" or "reasoning" tasks and performance in PISA "applying". There is only one explanation possible: TIMSS cognitive domains (knowing, applying, and reasoning) are rather designed to assess a common broad construct than three different ones[4], and this common construct is equidistant to the one assessed in PISA. We would prefer to interpret the relationship "TIMSS vs. PISA constructs" as "knowing, applying, and reasoning within a specific field" vs. "applying field-specific knowledge in a nonacademic context".

We find it essential to point out that results obtained in this study are limited by the two terms: "level of field-specific knowledge" and

[4] This is also proved by a fairly strong dispersion between these cognitive domains—from 58 to 94%.

"transfer to another context". Using these terms was rather intuitive than strictly quantitative. We operationalized the "level of field-specific knowledge" through solving a specific number of TIMSS mathematical tasks: the more tasks solved, the higher the level of field-specific knowledge and skills. This assumption is logically reasonable though not undisputable. Besides, the TIMSS test pool is not just a set of tasks—it is specifically designed to measure mathematical knowledge and skills and to represent the mathematics syllabus in general school.

As for "transfer to another context", Barnett and Ceci indicate that context is described through the function performed by the skill and through the thinking pattern it (the context) generates. They provide an example when the same skill can be used either in academic settings or in solving real life problems, like calculating a tax. An important point here is that "a problem solving tool learned and encoded for one purpose may not be transferred to the same extent to be used for another purpose" [Barnet, Ceci, 2002. P. 623].

Let's get back to the two released sample tasks (see Appendix) to illustrate our assumption that TIMSS and PISA belong to different functional contexts. The first task (TIMSS-2011, mathematics, numbers, cognitive domain "applying") is to calculate the least number of boxes needed to pack a certain number of eggs. The second task, closely related to the first one (PISA-2012, "Memory Stick" related to "numbers") is about comparing and performing a series of mathematical operations in order to find the required value. Although these tasks appeal to the same mathematical skill (performing arithmetic operations, comparisons, and division with remainders), the PISA task clearly has a nonacademic, everyday context, serves personal, non-learning purposes, and requires recognizing mathematical content behind the real life problem description. This is where contexts of the two tasks come apart.

Ability to solve context-based problems (i. e. problems with formal solution rules embedded in the context and having to be recognized and then translated back to that original context) should undoubtedly be influenced by other factors, apart from the level of formal field-specific knowledge, though we have proved the great importance of the latter. At the moment of writing this paper, we don't have any individual PV for PISA results yet and thus have a rather limited possibility of measuring the exact role of field-specific knowledge in solving context-based problems. We intend to resume the research when all of the PISA results have been released. Besides, with regard to the relative nature of the effects field-specific knowledge has on its transfer to another context, we are going to assess experimentally the cognitive skills required to apply formal knowledge in other contexts.

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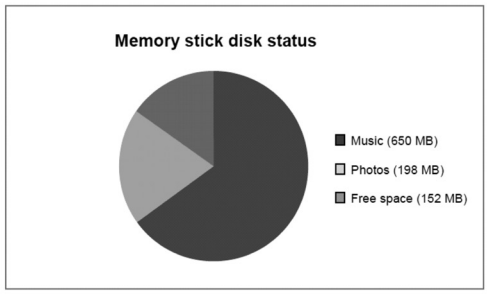
Appendix

MEMORY STICK

A memory stick is a small, portable computer storage device.

Ivan has a memory stick that stores music and photos. The memory stick has a capacity of 1 GB (1000 MB). The graph below shows the current disk status of his memory stick.



Question 1: MEMORY STICK *PM00AQ01 – 0 1 9*

Ivan wants to transfer a photo album of 350 MB onto his memory stick, but there is not enough free space on the memory stick. While he does not want to delete any existing photos, he is happy to delete up to two music albums.

Ivan's memory stick has the following size music albums stored on it.

Album	Size
Album 1	100 MB
Album 2	75 MB
Album 3	80 MB
Album 4	55 MB
Album 5	60 MB
Album 6	80 MB
Album 7	75 MB
Album 8	125 MB

By deleting at most two music albums is it possible for Ivan to have enough space on his memory stick to add the photo album? Circle "Yes" or "No" and show calculations to support your answer.

Answer: Yes / No

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