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Scientific Reasoning Abilities of Undergraduate Science and Engineering Students at King Faisal University*

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Science is a discipline that uses experimentation and thought to study various aspects of nature. A major prerequisite for training young students to be future scientists is to hone their scientific reasoning abilities. In addition, students enrolled in engineering studies should be acquainted with scientific reasoning abilities in order to form creative solutions and applications. The present study was conducted at KFU to assess scientific reasoning abilities among first-year engineering and science undergraduate students. A Scientific Reasoning Test was administered, then the students were categorized into three levels of scientific reasoning: Empirical Inductive (low-level), Transitional (average), and Hypothetico Deductive (high-level). As a result, most of the students fell into the Empirical Inductive level and no significant difference was depicted between science and engineering students. Furthermore, in the Test, items regarding 'Conservation of weight' have the highest percentage of right answers (95.12%), followed by items about 'Conservation of displaced volume' (63.4%). On the other hand, the lowest percentages of right answers correspond to items of 'Identification and control of variables' (20.7%) and items of 'Hypothetico-deductive thinking' (19.5%).

Keywords: education; research projects; thinking; deductive thinking; inductive reasoning

1. Introduction

Thinking can be perceived as an active confirmation between an individual and data. When students are exposed to sets of data from a certain discipline such as science or engineering, they classify the data and then assimilate it into conceptual systems, compare the data with other data, and come up with generalizations and inferences. Scientific reasoning is a pattern of thinking; it refers to the intellectual manipulations that occur when confronting scientific learning situations, including the cognitive processes required for theory generation, experiment design, hypothesis testing, data interpretation and scientific discovery [1]. Congruently, in engineering scientific reasoning is necessary to form creative solutions and applications for designing and developing structures, machines, apparatuses, or manufacturing processes.

In addition, science is a fertile and rich area that encompasses knowledge and skills. This paper proposes a shift from looking at science as a knowledge-based discipline to a more operative and procedural approach. This means that students should go beyond learning objectives that stress subject matter and related facts and concepts and get acquainted with the essence of the ability to think. For this reason, a major prerequisite for training young students to be future scientists is to hone their scientific reasoning abilities.

This paper is an attempt to articulate the levels of Scientific Reasoning Abilities of Undergraduate Science and Engineering Students at King Faisal University. The findings of this study are deemed most important for curriculum development and decision making with regards to the level of cognitive readiness of high school students admitted to the Schools of Science and Engineering. Further, this study corresponds to the current project that the Ministry of Education in Saudi Arabia has implemented to develop math and science through focusing on activities geared to epistemology and reasoning abilities.

2. Research objectives

The objectives of this study are:

1. To articulate the level of scientific reasoning abilities among first-year engineering and science undergraduate students
2. To determine if there is a significant difference in the scientific reasoning abilities between first-year science and engineering undergraduate students
3. To specify the scientific reasoning abilities that are perceived as the most and least difficult for first-year science and engineering undergraduate students
4. To determine if there is a significant correlation between students' achievement in the Scientific Reasoning Test and their high school average scores.

3. Theoretical background

Thinking skills have two connotations in the literature: internal skills and external skills. The external meaning refers to the attempts and processes of

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creating a sequence of interrelated transactions between components of the situation with which you are confronted and perceived information. The internal meaning is the manipulation of these means and processes in the confronted situation [2]. In addition, thinking skills are arranged in a hierarchy from basic to higher order skills. Also, there have been a number of attempts to develop a single classification system for thinking skills. Each model has some strengths and some weaknesses. One well-known model is Bloom's taxonomy of thinking skills, classifying them into: knowledge, comprehension, application, analysis, synthesis, and evaluation. Although many educators have used Bloom's taxonomy, others primarily use the classification system developed by Edys Quellmalz, which divides thinking skills into five categories: recall, analysis, comparison, inference, and evaluation. The latter four categories of analysis, comparison, inference, and evaluation are collectively called higher order thinking skills (HOTS) or critical thinking skills [3].

Inductive and deductive reasoning are the two primary methods of scientific thinking. Inductive reasoning is a process of reaching general conclusions based on observing patterns in specific events, although the findings are not necessarily true in nature [4]. On the other hand, deductive reasoning is a process of arriving at specific conclusions by beginning with general theories and gathering evidence to support them; the derived conclusions are valid in nature, confirming hypotheses [4].

The manifestation of scientific thinking skills across stages of cognitive development has been outlined by Piaget's Cognitive Theory. According to this theory, human cognitive development happens in four stages [5]:

1. Sensorimotor period (years 0–2)
2. Preoperational period (years 2–7)
3. Concrete operational period (years 7–11)
4. Formal operational period (years 12 and up).

The essence of Piaget's Cognitive Theory comprises two premises: (1) the prediction of what pupils can and cannot understand at different age levels; (2) the description of how pupils develop cognitive abilities. Learners construct mental structures/schemas at different age levels. To maximize the outcomes of a learning setting, learners must adapt to physical and mental stimuli. The adaptation process encompasses two principles: assimilation and accommodation. In assimilation, the learners possess mental structures that assimilate changing events and formulate them to fit their mental structures. In accommodation, mental structures adjust themselves to new aspects of the learning setting [6].

According to Piaget, the progression of students' thinking passes through discrete stages that will eventually lead to the development of the skills to perform scientific reasoning that broadly represents the thinking skills involved in inquiry, experimentation, evidence evaluation, inference, and argumentation, which support the formation and modification of concepts and theories about the natural and social world [7]. For example, at the concrete operational stage, students can classify objects and understand the concept of conservation, but they are not able to form hypotheses or understand abstract concepts. At the formal operational stage, they should become able to identify variables, construct relationships, and think abstractly.

Contrary to Piaget's theoretical notion, research has shown that many students have not reached the formal operational stage [8]. The variations in scientific ability exist across Piaget's stages as well as across individuals at the same age level. Consequently, the variations in the accomplishment of conceptual tasks in different student populations is caused by variations in the average scientific reasoning ability. To support this proposition, Coletta and Phillips studied the association between Lawson's test of scientific reasoning and the Force Concept Inventory (FCI), and found a highly significant positive correlation between the students' normalized FCI gains and their Lawson test scores [9].

In addition to Piaget's efforts to outline thinking stages across different age levels, Lawson identified reasoning patterns throughout the course of cognitive development in a Scientific Reasoning Taxonomy, which includes Empirical-Inductive (EI) and Hypothetico-Deductive (HD) thinking [11]. Empirical-Inductive (EI) thinking is a low level of scientific reasoning development, encompassing primary thinking skills. EI is a systematic process to form a result out of a finite number of discrete cases through observation of a pattern, conjecturing that this pattern applies generally, testing of the conjecture, and generalization of the conjecture [10].

On the other hand, Hypothetico-Deductive (HD) thinking is a high level of scientific reasoning development with advanced thinking skills, including: proportion, control of variables, combinatorial capacity, probability, and correlation. The primary element that distinguishes EI from HD is relative abstraction, which is the ability to reason logically and abstractly [11]. Flavell outlined that hypotheses are created and then the empirical states of affairs are presumed with corrected hypotheses [12]. As a result, the formal operation level comprises Hypothetico-deductive thinking rather than the empirical-inductive. Accordingly, cognitive skills at EI and HD levels are refined to correspond to Piaget's theory at the concrete and formal operation stages.

Piaget's seems to be very idealistic in his theory about human cognitive development and, consequently, research studies have found that the majority of middle and even secondary school students do not reach formal operation levels [13, 14]. For example, Piburn investigated the correlation between spatial reasoning and formal thought as related to achievement in science in New Zealand high school students. The results showed that 18% of the students were at the concrete operational stage (Empirical-Inductive), and 35% of the students were at the formal operational stage (Hypothetico-Deductive), while the others were at a transitional level [15].

For this reason, the scientific thinking of students has long been a challenge for educators, as focusing on content is a well-recognized teaching practice. A group of researchers investigated scientific understanding in astronomy in high achieving high school students in New York City [16]. The findings of this study pointed out that the students were struggling to offer scientific justifications and structure deliberate approaches. Moreover, the study concluded that teachers are prepared to teach science in high schools and colleges where content is well addressed and the nature of science is less recognized; consequently, those teachers propagate this teaching style to their students. On the other hand, inquiry training promotes students' intellectual ability and curiosity, subsequently enhancing their reasoning and answering skills [17]. Scientific reasoning skills can be transferred and escalated through training; therefore, instructional techniques should be coupled with potential activities that can leave an impact.

To support this proposition, a recent study showed that college freshmen in China have more knowledge of science than their US peers; nonetheless, both groups are equal in terms of scientific reasoning abilities [18]. Both of the groups averaged a score of 75, which indicates insufficient reasoning skills for students who are intending to major in science or engineering. The study stresses that educators should not only teach to target knowledge, but they must also integrate knowledge to boost the students' reasoning abilities [18].

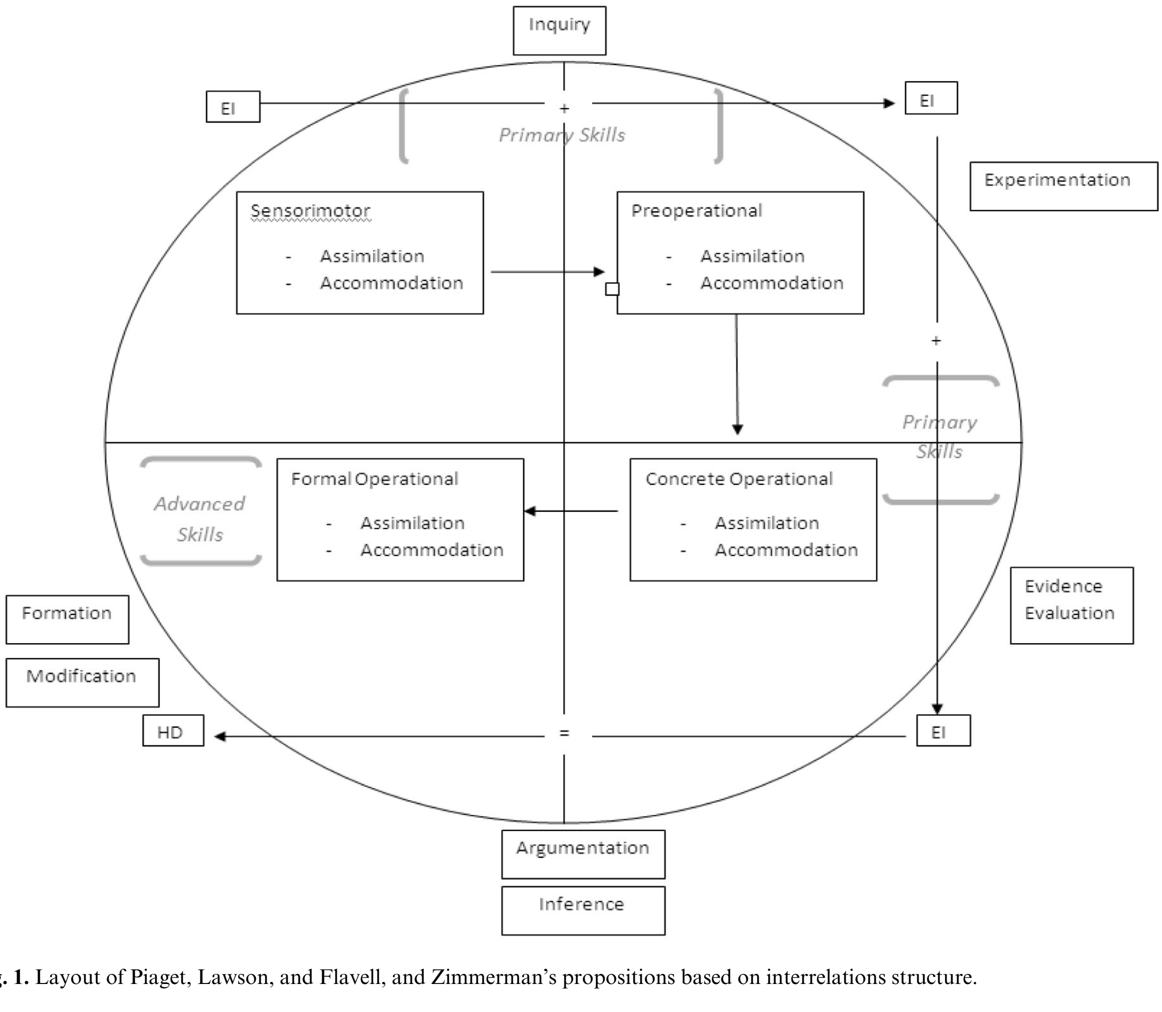


Fig. 1. Layout of Piaget, Lawson, and Flavell, and Zimmerman's propositions based on interrelations structure.

4. Research methodology

A sample of 82 students was chosen to represent the population of this study, which comprises freshmen students in the Colleges of Engineering and Science. The research instrument used in this study is a 'Scientific Reasoning Test,' constructed by the researcher and consisting of 24 items. The ideas embodied in the Test were derived from prior tests such as Lawson's Classroom Test and the Spatial IQ Test (Fig. 2).

Specifically, the instrument used in this research, the Lawson's Classroom Test of Scientific Reasoning, and the Spatial IQ Test assess students' abilities in six aspects that are vital to science and engineering through the presentation of an experiment or a problem: students were asked to select the best solution from a choice of three to five options. Every two items on the test addressed different reasoning patterns: Conservation of weight, Conservation of displaced volume, Proportional thinking, Advanced proportional thinking, Identification and control of variables, Identification and control of variables and probabilistic thinking, Probabilistic thinking, Advanced probabilistic thinking, Spatial transformations, Hypothetico-deductive thinking, Hypothetico-deductive reasoning.

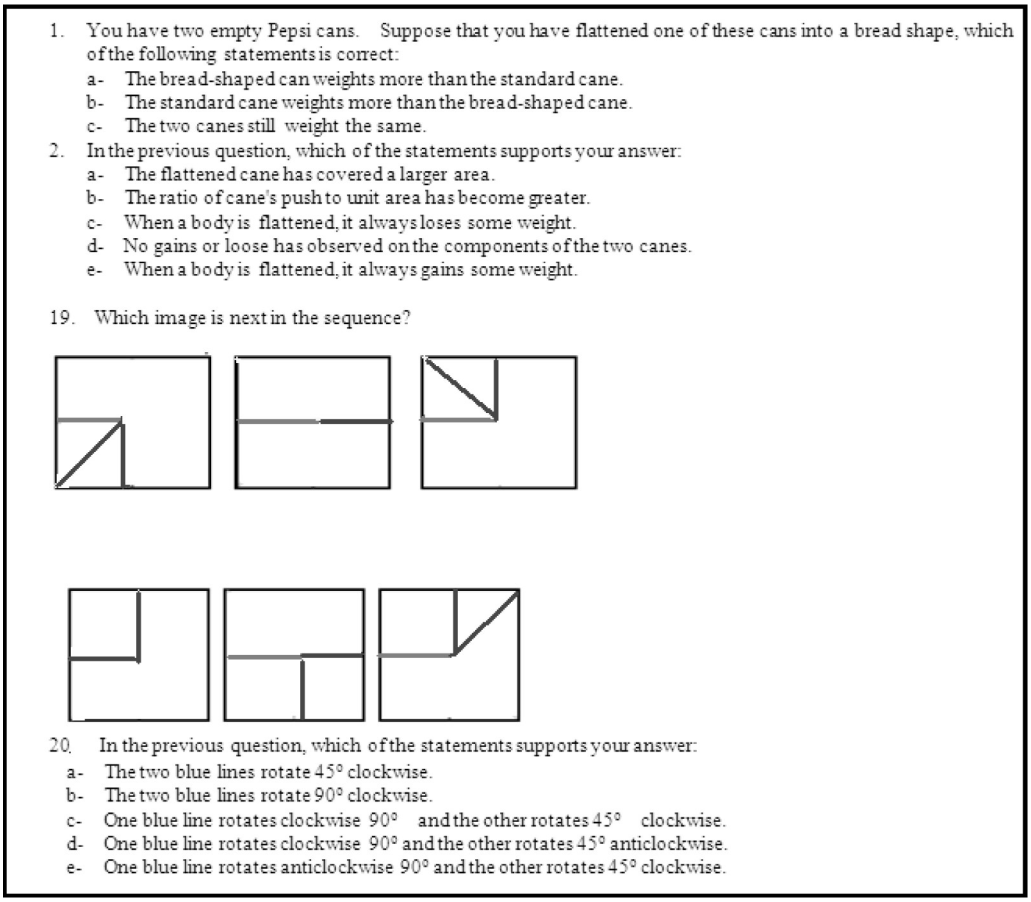
Students were allowed 90 minutes to complete or revise the ten items but there were no restrictions or indications as to the approximate time required for each item. The students' levels of reasoning were then categorized based on their total scores for all 24 items; each item is worth one point and requires the students to respond to a question as well as explain the chosen answer:

0–4 : EI (Empirical-Inductive)
5–8 : transitional
9–12 : HD (Hypothetico-Deductive)

A pilot study was carried out to measure the Cronbach Alpha reliability coefficient of the constructed test. The estimated reliability coefficient of this test is 0.77, which indicates that the test is sufficient to determine the students' reasoning abilities.

Table 1. Descriptive statistics for the students results on the scientific reasoning test

N	Mean	Std. deviation
82	4.6	2.01



1. You have two empty Pepsi cans. Suppose that you have flattened one of these cans into a bread shape, which of the following statements is correct:
   a- The bread-shaped can weights more than the standard cane.
   b- The standard cane weights more than the bread-shaped cane.
   c- The two canes still weight the same.
2. In the previous question, which of the statements supports your answer:
   a- The flattened cane has covered a larger area.
   b- The ratio of cane's push to unit area has become greater.
   c- When a body is flattened, it always loses some weight.
   d- No gains or loose has observed on the components of the two canes.
   e- When a body is flattened, it always gains some weight.

19. Which image is next in the sequence?

20. In the previous question, which of the statements supports your answer:
   a- The two blue lines rotate 45° clockwise.
   b- The two blue lines rotate 90° clockwise.
   c- One blue line rotates clockwise 90° and the other rotates 45° clockwise.
   d- One blue line rotates clockwise 90° and the other rotates 45° anticlockwise.
   e- One blue line rotates anticlockwise 90° and the other rotates 45° clockwise.

Fig. 2. Sample of questions presented at the scientific reasoning test.

5. The limitations of the study

The study was conducted in the second semester of the academic year 2008–2009 with a convenient sample of 82 students. However, with a small sample size caution must be applied, as the findings might not be transferable to the KFU population. The study is also the first use of spatial transformation items driven from the IQ test and presented by the Lawson test. Thus, the scientific reasoning abilities (SRA) are confined to these two tests and their overall structure. Another important limitation lies in the fact that the students were given no incentive to participate in completing the test and this might have limited the intellectual input to deal with it.

6. Findings and discussions

Of the 82 students, three students (3.65%) were found to be at the Hypothetico-Deductive level, 13 students (15.85%) were at the transitional level, and 66 students (80.4%) were at the Empirical-Inductive level. These measures show that 79 students (96.25%) are not functioning within the cognitive level that they presumably should attain. The findings fall into line with previous studies that proposed that a significant number of students operate below HD or Piaget's formal operation [19, 15, 20].

The mean score was 4.6, and the standard deviation of scores was 2.01 (Table 1). This result shows that some students' scores are far from the mean; consequently, scientific reasoning abilities vary strongly. In addition, these results support Wilson and Wilson's view that cognitive abilities can differ from one society to another and even differ among students who are in the same classes [21].

Levene's test of homogeneity shows that $F = 3.65$, with a significance of 0.059 (Table 2). These measures imply that the two variances of the two groups are not significantly different; that is, the two variances are approximately equal. Further, the t-score is 0.527, and the p value is 0.6 (Table 2); thus, there is no significant mean difference in the scientific reasoning abilities between first-year science and engineering undergraduate students. This result does not correspond with the fact that the nature of science yields itself to the development of Hypothetico-deductive reasoning. A possible explanation for the equal mean differences of the two groups could be that the essence of science and engineering entails parallel skills that participate equally in the construction of Hypothetico-deductive reasoning abilities.

The Pearson correlation coefficient is -0.083, with a significance of 0.457 (Table 3). These measures show that there is no significant correlation between the students' attainment in the Scientific Reasoning Test and their high school average scores. A previous study asserted that students who are at the upper cognitive levels have higher scores in science lessons [22]; however, Rifkin and Georgakakos, who studied the influence of an introductory chemistry course on students' reasoning abilities, found that the course had a negative impact on science reasoning [23]. Thus, the type of exposed content may have less impact on science reasoning than other factors associated with how this content is communicated to students. Accordingly, relationships between formal reasoning abilities and instructional methods have been addressed in previous research studies, concluding that inquiry based instruction enhances students' acquisition of reasoning skills [13, 24, 25].

In the present study, high school performance is measured as the average score over all classes taken by the students, including: science, mathematics, literature studies, religion studies, and social studies. Consequently, a high school performance might not reveal the students' scientific reasoning abilities.

The percentage of correct answers that reflect each pattern has varied consistently. Table 4 shows that items regarding 'Conservation of weight' have the highest percentage of correct answers (95.12%), followed by items on 'Conservation of displaced volume' (63.4%). On the other hand, the lowest percentage of right answers, as shown by Table 5,

Table 2. Independent samples t-test for the results of the scientific reasoning test by group

	Leven's test for quality of variance		t-test for equality of means						
	F	Sig.	t	df	Sig. (2- tailed)	Mean difference	Std. error difference	95% confidence interval of the mean	
								Lower	Upper
Equal variance assumed	3.65	0.059	5.27	80	0.600	0.3923	0.7450	–1.09	1.87
Equal variance not assumed			5.17	68.84	0.607	0.39	0.759	–1.12	1.9

Table 3. Pearson's correlation coefficient between the results of the scientific reasoning test and high school GPA

		Students' attainment	Students' attainment
Pearson	Students' attainment	1	–0.038
Correlation	High school GPA	–0.038	1
Sig.	Students' attainment		0.457
(2-tailed)	High school GPA	0.457	
N	Students' attainment	82	82
	High school GPA	82	82

Table 4. Highest percentage of attainable pattern on the scientific reasoning test

Scientific reasoning pattern	N	%
Conservation of weight	78	95.12
Conservation of displaced volume	52	63.4

Table 5. Lowest percentage of attainable pattern on the scientific reasoning test

Scientific reasoning pattern	N	%
Identification and control of variables	17	20.7
Hypothetico-deductive thinking	16	19.5

correspond to items on 'Identification and control of variables' (20.7%) and items on 'Hypothetico-deductive thinking' (19.5%).

The interdependencies between 'conservation of weight' and 'conservation of displaced volume' may explain why correct answers associated with these two patterns were so depicted. The lower scores with items related to 'Identification and control of variables' are somewhat surprising; however, the lower scores with items related to 'Hypothetico-deductive thinking' are expected, due to the lack of competency at this level.

7. Conclusions and recommendations

The present study shows that 3.6% of the students tested are at the Hypothetico-Deductive level of scientific reasoning ability; 15.8% of the students are at the transitional level; and 80.4% of the students are at the Empirical-Inductive level of scientific reasoning ability. The impact of deductive reasoning on the students' future education should be a focus for further research. One possible study could be conducted to gauge the correlation between students' attainment in the Scientific Reasoning Test and their grade point average in university science courses. In the event of a significant result, the failure to move from the Empirical-Inductive level to the Hypothetico-Deductive level should be analyzed in depth.

This study also shows that there is no significant correlation between the students' achievement in the Scientific Reasoning Test and their high school performance. Looking at primary education as a metaphor and higher education as a symbol supports calls to form efficient ties between higher education and primary education to effect an efficient transition. The failure of the majority of students to attain the formal operation stage could be the result of their preparation in primary education. Thus, further research could be undertaken to analyze high school curricula in mathematics and science to determine whether the current implemented courses promote scientific reasoning abilities.

In addition, a long-term study could be implemented to assess the role of enhancement materials and curricula that stimulate discovery/inquiry learning and problem-solving to accelerate reasoning abilities. Thus, it is important to set strategies to look at the major factors that contribute to the manifestation of these reasoning abilities in different science and engineering fields. In the long run, by considering all the factors that help students to acquire reasoning abilities we can shape how we educate our future engineers and scientists.

The overall results of this study raise questions about the legitimacy of the admission process adopted by King Faisal University (KFU) that, at the Colleges of Science and Engineering, places great weight on applicants' scores in the aptitude exam, QEYAS (an exam that emphasizes students' reasoning abilities). KFU has always demanded a higher score on QEYAS for admission to the College of Engineering than to the College of Science.

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