Integrated Curriculum Reform and its Impact on Science Education

—— Why is the West Falling behind East Asia in PISA and TIMSS?

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Abstract: *This paper investigates why western nations underperform in PISA and TIMSS compared to East Asia and explores the root causes of the decline in science education. By analyzing TIMSS data and comparing the science curricula and teacher qualifications in North America and East Asia, the article reveals how the integrated curriculum reform, promoted by UNESCO, has led to a severe and protracted declination, particularly in physics and chemistry.*

The excessive amount of non-basic contents and the interdisciplinary approach, of the integrated curricula, have diluted the focus on physics and chemistry, which are the foundation stone of science. Moreover, science teachers with general science degree other than subject-specific credentials lack knowledge in physical science, leaving students with poor mastery of the fundamental knowledge and skills; and underprepared for advanced scientific study and STEM careers. Consequently the U.S. and some other western nations are facing a crisis in cultivation of STEM talents and qualified labor force.

It is critical for the West to take bold steps immediately and rebuild the foundation of their science education. Some suggestions are provided.

Key words: K-12 *science education, integrated curriculum, teacher qualifications, TIMSS, PISA, STEM crisis*

1. A Shocking Gap

PISA and TIMSS are the two major international K-12 educational assessment programs. TIMSS runs every four years, testing mathematics and science for 4th and 8th graders. And PISA, examines 15-year-old students' literacy in three areas: mathematics, science and reading, every three years.

Since the end of last century, assessment results have consistently shown a striking trend: East Asian countries perform significantly better than Western nations.

Figure 1 shows the math and science scores of eight countries or regions in TIMSS 2019 and PISA 2022. Singapore has always topped the list. The scores descend one by one; and there is a clear gap between East Asia and the West. Compared with Singapore, in both PISA and TIMSS, the U.S. falls behind by more than 100 points in mathematics; and in science, Singapore surpasses U.S. by 60 points and 80 points respectively.[1][2]

Figure 1. TIMSS 2019 & PISA 2022 Math & Science Scores

The huge gap is shocking. It presents a major and serious question to the international community: How did it happen? What is East Asia doing right and where has the West gone wrong?

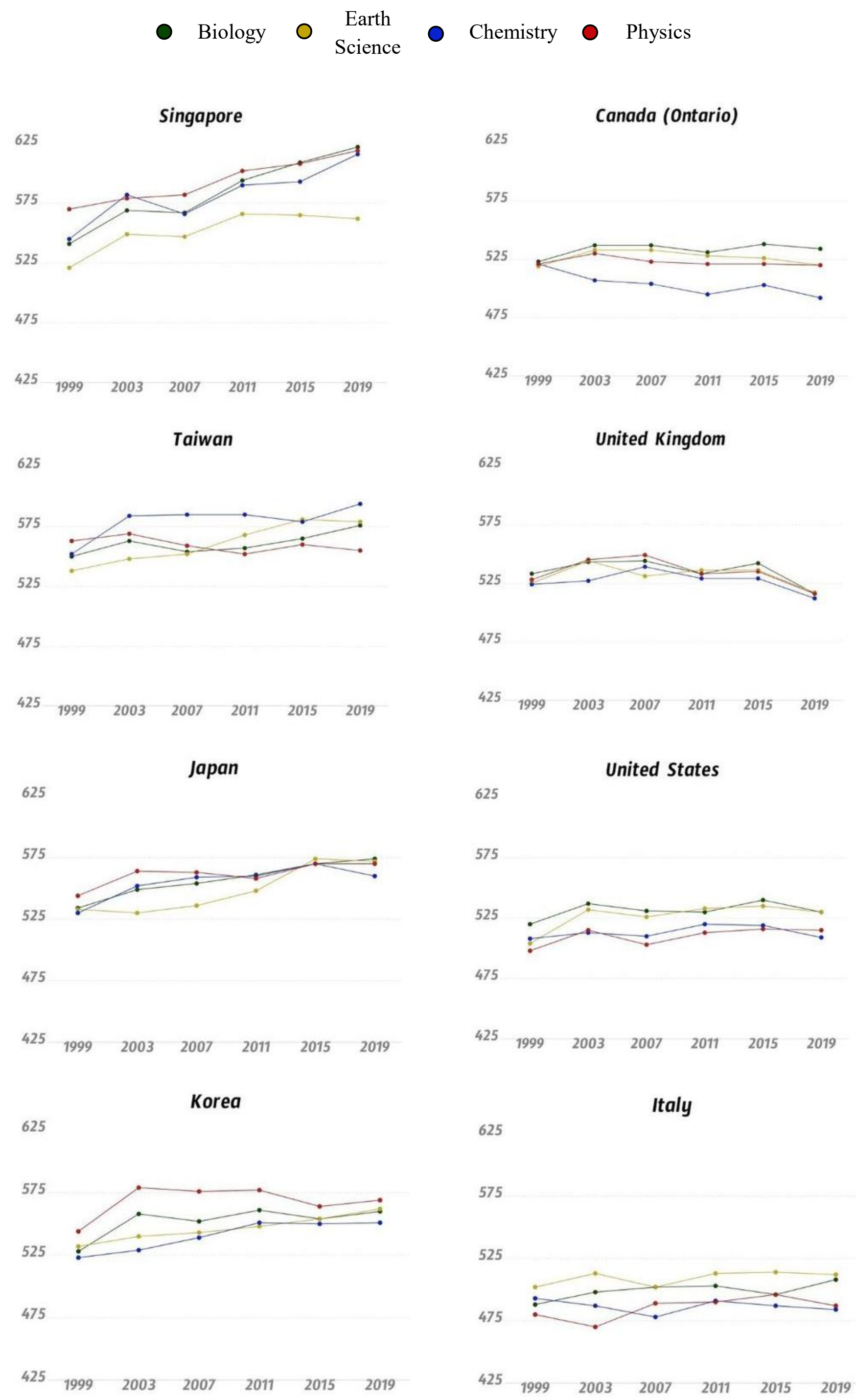
2. Physics and Chemistry —— Weak Disciplines of Western Science Education

Today's K-12 science education covers three content domains: life science, earth and space science, and physical science (including physics and chemistry). Which domain is the weakest and more difficult to the students in the West? To find it out, the author made Figure 2 based on TIMSS data over 20 years. The scores of biology, earth science, chemistry and physics are shown in green, yellow, blue and red colors respectively.[3][4][5]

It can be seen from Figure 2:

a. In all the four subject areas, East Asia achieved much higher than western nations in the recent two decades.

Figure 2. TIMSS 1999-2019: Grade 8 Science Subject-Specific Achievement Trend Comparison of Western and East Asian Countries



b. East Asian countries have been either rising, with Singapore the most significant; or stable. But the West has barely shown any rise. Therefore, the gap between them has widened rapidly as time goes by.

c. In East Asia, scores in physics and chemistry are usually higher or comparable to those in biology and earth sciences. In contrast, western countries, with the exception of the U.K., typically score lower in physics and chemistry. Most clearly in U.S., biology scores have been the highest and physics the lowest in almost every test; with a difference of 20 to 30 points.

Mathematics and science education, or STEM, is the weak area of K-12 education in the West today. The above data further reveals that, physics and chemistry are the weakest disciplines in science education where western students struggle the most.

One would ask, how could American and western students receive such low scores in physical science? The author took 16 physics questions from TIMSS 2019 8th grade science test, to examine the students' mastery. The numbers in Table 1 are the percentages of students who answered the question correctly in the country.[6][7]

These questions check the basic knowledge of physics, at a level up to grade 8. Usually two-thirds or at least half of the students should be able to answer them, and that is roughly the performance of the East Asian students.

But in western countries, only question 2 was answered correctly by more than two-thirds of the students, questions 7, 13, and 14 saw just over half of the students responding correctly. However, for the remaining 10 questions — covering topics like state change, buoyancy, and heat transfer — less than 40%, and in some cases as few as 10%, of students demonstrated adequate knowledge.

These results show that, physics is not being taught with the necessary depth in the West, and the students lack an understanding of fundamental concepts of physics.

Actually, not only the West. Performance of students in East Asian countries other than Singapore is not that satisfactory, there are many loopholes too.

3. What has Happened in Science Education?

The above three sets of data illustrate the severe decline of basic science education in the West over decades, which can be traced back to the integrated curriculum reform that began in the late 1960s.

Previously, secondary schools in most countries provided separate courses in physics, chemistry, and biology; with a strong emphasis on physics and chemistry. In six years, they

Table 1. TIMSS 2019 Grade 8 Physics Item Percent Correct Statistics

Number	Physics Test Items	Singapore	Japan	Korea	Taiwan	Canada	U.K.	U.S.	Italy
	Average Scores	619	570	569	555	520	516	515	487
1	S14_12: Identify the glass of ice cubes that melt faster based on size	57	37	23	52	17	12	11	5
2	S03_09: Recognize the energy change as a child slides down a slide	91	73	92	90	70	77	81	72
3	S02_13: Can a ringing cell phone in a vacuum chamber be heard from outside?	59	56	53	78	23	35	37	22
4	S01_09A：State one reason why a bulb in a circuit does not light	74	52	37	60	33	40	28	37
5	S05_06: Which substance will float on water using a table of densities	72	61	73	57	45	40	47	37
6	S10_11: Explain how a parachute slows a skydiver's fall	70	79	50	29	60	41	56	29
7	S11_14: Recognize the energy transformation when a toy car powered by battery begins to move from rest	86	63	63	44	53	61	57	53
8	S13_07: Whether a red object will absorb or reflect different colors of light	68	48	55	49	48	51	50	47
9	S08_11：State the two measurements needed to calculate average speed	80	37	62	66	19	49	44	12
10	S10_14： Recognize the position in a diagram where a thrown stone has the greatest kinetic energy	50	22	56	18	23	20	26	21
11	S04_10： Interpret a graph to identify how heat is transferred between a substance and its surroundings	50	41	37	48	31	34	31	25
12	S10_13：Recognize 5 materials as conductors or insulators based on a graph showing the electric current in circuits containing the materials	72	91	69	86	45	52	49	60
13	S06_07: Recognize which graph represents a musical note with given volume and pitch	66	77	71	74	62	59	59	48
14	S06_08: Recognize a free-body diagram of a box pulled by three forces that has a net force to the right	65	84	70	75	52	55	54	56
15	S06_06: Uses a diagram to explain one way to increase the strength of an electromagnet	88	40	45	20	6	37	15	8
16	S02_14: Why does a balloon get bigger as it rises?	45	68	63	63	37	42	40	45

were offered for four or five years, but time for biology was shorter. A solid foundation for students was laid this way, and generations of STEM talents and labour forces were cultivated.

However, a subversive reform in science education, characterized by integrated curriculum, has swept the world since the end of 1960s.

The biology course was expanded to life science, with its topics greatly increased; physics and chemistry are collectively referred to as physical science; and earth and space sciences introduced. They then became the three content domains in K-12 science education.

In terms of curriculum structure, the single-subject courses in middle schools were removed. Their topics were broken apart and reorganized, so that a science course in each grade covers materials in all three domains. These are the so-called integrated courses.

How did the reform happen? What challenges did the traditional method encounter?

On one hand, the development of life science and space technology; issues like environment, energy and population that global society was facing; and the emergence of interdisciplinary subjects; etc., required that new knowledge and disciplines be introduced into science education.

On the other hand, a transfer from elite to mass education was underway. Subjects like physics and chemistry were considered too advanced and taught over an extended period; thus unsuitable for ordinary students. And some remote areas or developing countries lacked teachers to provide many single-subject courses.

The integrated science curriculum was initiated in U.S., and advocated and implemented by UNESCO. In 1968, UNESCO released the program plan. Up to1990, six volumes of reports entitled "New Trends in Integrated Science Teaching" were published, to promote the reform.[8]

By 1986 the traditional subjects had been replaced by integrated courses, in most countries and regions including East Asia. Only China and Laos continued on the old track. In fact, the Ministry of Education in China also attempted to promote the integrated curriculum; but encountered strong resistance; so the program was only adopted in one province.

Since the introduction of the integrated curriculum in middle schools, science education began to collapse. The author taught high school physics in 1990’s and 2000’s in British Columbia, Canada, where many grade 11 students even could not handle problems of “d = v t”.

The consequences of the decline extend beyond academic performance. Without the foundational knowledge in physics and chemistry, it is hard for students to proceed to advanced scientific study, and underprepared for STEM careers.[9]

The U.S. and some other western nations have been facing a crisis in cultivating STEM talents and qualified labor force for long. In particular, a growing shortage of qualified science teachers is troubling the U.S.; e.g., about 100,000 and 150,000 senior and junior secondary school science teacher vacancies could not be filled in 2017-2018;[10] and a large percentage of high schools do not have teachers to offer physics course.

As a matter of fact, U.S. and the West have realized and acknowledged the crisis for a long time. Since the famous report "The State is in crisis, education reform is imperative" released in 1983,[11] U. S. has been implementing reform plans one after another, in order to change the situation and improve STEM education.

In Canada, the discussions have repeatedly drawn attention. In 2022, the C.D.Howe Institute published a commentary entitled "Knowledge gap: Canada Faces a Shortage in Digital and STEM Skills", emphasizing that the situation requires a fundamental change of secondary science education.[12][13]

However, without finding and removing the root causes of the crisis; no matter how much effort is devoted, the decline can't be reversed.

4. Overview of Science Education in North America and East Asia

People would wonder, is it really the integrated curriculum reform that has caused the declination? Now that East Asia and the West have both carried out the reform, why are their PISA and TIMSS results so different? To discover the secret, the author examined the science education in U.S., Canada, Singapore and Taiwan.

In **Singapore**, science education starts from grade 3 in primary schools. Teachers have bachelor's degree in science-and-education. Integrated courses are adopted in the 7^{th} and 8^{th} grades. Although named integrated science; physics, chemistry, biology and geography are actually taught separately by different teachers with bachelor's degrees in the subject areas.[14][15]

In grade 9 and 10, physics, chemistry and biology are set up as single-subject courses; e.g. in physics, topics of force, heat, sound, light, electricity and magnetism, radioactivity, etc., are proceeded one by one.

Singapore students begin to divert at this stage. Weak students take easy and mixed courses like physics/chemistry, biology/physics, and chemistry/biology; some students are even allowed to skip science.

After grade 10, the students are divided across schools. About 30% enroll in junior colleges and prepare to enter universities. 50% in the middle enroll three-year polytechnic to learn technical skill and some scientific knowledge. And the lower 20% will enter Institute of Technical Education (ITE) for one or two years and to receive vocational training.

Junior colleges offer courses of physics, chemistry and biology; each subject has three levels marked as H1, H2 and H3, covering different amount and depth of materials, to meet students' needs. Science students usually take 3 science or math courses, and 1 liberal art; e.g., mathematics, physics, chemistry, plus economics.

In **Taiwan**, science education also starts from grade 3. Biology is offered at grade 7; and grade 8 and 9 science are integrated with physics and chemistry, and some earth science; but taught by different teachers.

Grade 8 science introduces measurement, matter, wave and sound, light in physics part; chemistry part includes structure of matter, chemical reaction, oxidation and reduction, and organic matter. Grade 9 science covers basic mechanics and electricity; and water, rocks, minerals, earth structure and celestial bodies and climate.

After nine-year compulsory education, some students enroll ordinary high schools, and others enter vocational schools, or five-year higher technical and vocational schools.

In ordinary high schools, physics and chemistry are separated at grade 10, biology and earth sciences offered too; with all the disciplines mandatory.

In grade 11 and 12, single-subject courses continue, with different levels in terms of amount and depth. Mechanics is taught in physics 11, a course either one academic year or one semester. Physics 12 covers other topics.[16]

Science education in **British Columbia, Canada** starts from the 1st grade, with integrated curriculum till grade 10.[17] Most teachers hold 'general science and education' double-major degree.

In grade 8 and 9 science, there is not much physics covered, particularly no basic mechanics; only light is taught in grade 8, and DC circuit in grade 9. Physics part in grade 10 focuses on energy and its conservation. However, the students can not understand the concepts well, since they lack knowledge of kinematics and dynamics.

Single-subject courses start from grade 11. Chemistry, physics, biology, environmental science, earth science, and anatomy, physiology, etc., are offered in grade 11 and 12. Life science weighs more than physical science. Requirements for graduation is quite low, even a student with only one grade 11, and no grade 12 science course can be awarded a high school diploma.

All topics of physics are left for the last two years. For example, grade 11 physics covers kinematics, dynamics, heat, sound, light, and electricity, etc.; roughly the materials of grade 8 to 10. Then physics 12 must include all the advanced topics like circular motion, universal gravitation, momentum and electromagnetism, etc. When knowledge learned in 4 or 5 years before is now squeezed into two years, how could a good result be possible?

In Canada, all students enroll comprehensive secondary schools, where some elective courses like computer programming, woodwork, fashion, food studies, etc. are provided. But formal technical and vocational training start after secondary education.

In the **United States**, there are six (or five), two (or three), and four years in elementary, middle and high schools respectively. Like in Canada, basically there is no formal technical or vocational training in secondary level either.

Science education begins early in kindergarten. Middle schools have adopted integrated curriculum for decades, contents from all the three domains are covered.

High schools usually offer single-subject courses of physics, chemistry and biology, plus many electives, and Advanced Placement courses as well. Core subjects have three levels: regular, honors and AP. Some high schools first continue with integrated science for one year or one semester; and transfer to single-subject setting afterward.

In U.S. high schools, the way to set single-subject courses are different from other countries in that, only one subject is offered each year.[18] Subjects in the first one or two years are in fact mandatory; but the one left over more likely become optional. Thus the subject sequence has been a big concern. Although physicists led by Nobel prize winner Leon Lederman advocated "physics first", the biology-chemistry-physics sequence has dominated for long, in most public schools. Consequently, biology has become a mandatory subject, and physics abandoned by many students. But near half of the private schools implement physics first program.

AP courses and examinations are the step stones to top universities favored by high-achieving students. Being able to offer AP courses is also an indicator of a good high school. Years ago, students submitted at most three or four AP scores for university admission. But nowadays, since Chinese and Indian students have joined the competition, it is not surprising to submit as many as 10 AP scores.

Therefore in the U.S., with integrated courses in middle schools, and AP courses and examinations in grade 11 and 12, time to learn science subjects in a structured and sequential manner is far from enough. With a heavy load on shoulders, some good students often sleep four or five hours a night. Student suicide is not surprising. These problems and tragedies could be avoided if the curriculum is set more reasonably.

As to teacher qualifications, according to the National Committee on Teacher Quality (NCTQ), in 2010, 40 states have general science programs for training of secondary science teachers. Many of these teachers not only teach integrated science, but also single-subject courses.[19]

However, 11 states stick to tradition, such as Massachusetts, Minnesota and New Hampshire, and only issue teaching certificates in single disciplines. Consequently, Massachusetts scored 567 at TIMSS 2011 grade 8 science, and white students 587; second only to Singapore at 590. Remember the national average was as low as 525 that year.[20] Minnesota's scores are at the same level as Taiwan, Japan and South Korea.

As a matter of fact, K-12 education in U.S. is largely polarized.

5. What was Wrong with the Integrated Science Reform?

From the information above, it is clear that the differences of science education between North America and East Asia, and the problems of the integrated science reform, include the following:

The first is the selection and weight of the subject and their contents. In U.S. and Canada, physics and chemistry are compressed and downplayed compared to life science. But in East Asia, although life and earth/space sciences are also introduced, physics and chemistry weigh more and remain the focus.

Science is only one of the areas that students learn in secondary schools; class hours used for science are limited. Although it is good to include some new knowledge, but not everything. It is unrealistic that the students acquire the knowledge of all the disciplines in a few years of their secondary education.

Physics and chemistry, especially physics, are the cornerstone of all disciplines in natural science. Without knowledge of physics, one have no basis to understand in-depth concepts of chemistry, life science, and earth/space science. Physics develops essential cognitive skills related to problem-solving, analytical reasoning, and mathematical computation. It is also the basis of many types of engineering and technology: mechanical, electric and electronic, aeronautical and astronautical, and computer, etc.

However, without a structured and cumulative approach, plus an adequate level of mathematics, it is hard to comprehend the concepts of physics both qualitatively and quantitatively. Secondary education is the golden stage to develop intelligence. If a solid foundation in mathematics and physics is not laid, it will be extremely hard to make up in the rest of one's lifetime.

In contrast, life science is inherently descriptive and less demanding in terms of abstract thinking and mathematical skills. It doesn't make big difference to study earlier or later. University students majoring in life science can do well and achieve high, without learning much relevant knowledge in secondary schools.

The great progress of life science in the 20th and 21st century would be impossible without the knowledge of physical science. Scientific knowledge and subjects emerged and developed at different points of the timeline, it is unreasonable to learn everything at the same stage either.

In short, integrated science reform has brought excessive amount of non-basic contents into science curriculum, and diluted the time and attention devoted to the core subjects— physics and chemistry; thus has shaken the foundation of science education.

Another factor contributing to the decline is the qualification of teachers. With the advent of integrated curricula, the role of a science teacher has transformed into that of a generalist. Many teachers in the U.S. and Canada are trained in general science programs, that cover multiple disciplines but fail to provide the depth of subject-specific knowledge in physical science.

Although East Asian countries have to adopt the integrated curriculum, but they only issue single-subject certificates, and assign teachers with disciplines they are specialized in, to ensure students receive a high-quality and in-depth instruction.

Natural science includes a big amount of subjects and disciplines, and hardly anyone can master the knowledge of all of them. Hence a generalist of science is merely a joke.

A Texas survey released in 2010 with 93 grade 8 science teachers revealed that, their average semester credit hours (SCH) of biology, chemistry, physics and earth science were 19.9, 11.7, 3.9 and 7.1, respectively; and accordingly, their average scores in the diagnostic examinations were 2.57, 1.98, 1.49 and 1.86 (out of 4.0).[21] Obviously most of these teachers are biased to biology, and under-qualified with physics. In fact, to the author's knowledge, many good students learned physics from parents or after-school tutorials, not from their school teachers.

It is clear that shortage of science teachers in secondary schools can not be fixed by combining different subjects together. Under-qualified teachers as generalists have left their students with poor knowledge and skills in physical science.

6. The Path Forward: Rebuilding Science Education in the West

Western countries can learn valuable lessons from East Asia. They must address the root causes of the decline immediately, and take bold steps to rebuild the foundation of their science education. The following are proposed:

1. the integrated science curriculum as a core component of secondary science education has been proven inadequate, should be removed; and single-subject courses restored starting from middle school.

But some integrated courses can be kept for students who are not strong or not interested in academic courses.

2. policymakers must recognize the importance of physics and chemistry as foundational subjects that are critical to the development of STEM talent. Sufficient instructional time and resources must be devoted to them, to ensure that students master the fundamentals before moving on to more advanced topics.

To this end, some non-essential contents of life science and earth/space science have to be compressed, postponed, or offered as electives; some even canceled from secondary curriculum.

3. the general science training model for teachers must be changed. Secondary school science teachers should specialize in specific subjects, not being generalists; to ensure that students receive instruction from educators who have deep knowledge and expertise in the subjects.

4. to address the shortage of qualified science teachers, among other measures, it is suggested that any individual with adequate knowledge in physics or chemistry: immigrants, international students, retired teachers, etc. be recruited to teach the courses. A short training in teaching methods can be provided.

The time to act is now. With the right strategies, the U.S. and western countries could stop the declination, close the performance gap with their East Asian counterparts, and revive their K-12 science education.

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