The ability of our students to think scientifically: probably not as great as we think

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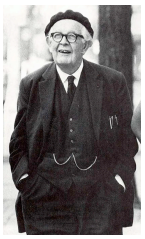
Outline

- About student cognitive abilities
  - Piagetian classifications
  - Testing for cognitive level: Lawson's Classroom Test of Scientific Reasoning (CTSR)
- Other diagnostic instruments
  - The Force Concept Inventory (FCI) and the Brief Electricity and Magnetism Assessment (BEMA)
- Some questions from the CTSR

About Student Cognitive Abilities

Piagetian Taxonomy



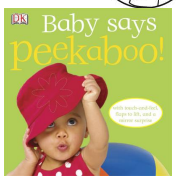
- Jean Piaget (1896 – 1980)
  - A developmental psychologist
- Developed a theory of cognitive development characterised by four stages
- A useful classification scheme in thinking about education

Piagetian Stages

1. Sensorimotor (birth – 24 months)

Learns that he/she is separate from the external world

Learns about object permanence



Piagetian Stages

1. Sensorimotor (birth – 24 months)
2. Pre-operational (2 – 7 years)

Can represent objects as symbols which can be thought of separately from the object ("make believe")

Wants the knowledge of knowing everything

Piagetian Stages

1. Sensorimotor (birth – 24 months)
2. Pre-operational (2 – 7 years)
3. Concrete Operational (7 – 11 years)

Can reason logically about concrete events or objects

Can reason inductively (i.e. generalising from observations), but not deductively (i.e. using a general principle to predict an outcome)

Piagetian Stages

1. Sensorimotor (birth – 24 months)
2. Pre-operational (2 – 7 years)
3. Concrete Operational (7 – 11 years)
4. Formal Operational (11 years – 17 years and onwards)

Similar to the history of science

As science educators, this is the most important one

Formal Operational Stage

- Can reason logically about abstract formal concepts
- Can reason with ratios
- Separation and control of variables
- Different points of view or reference frames
- Can think about thinking

"However, research has shown that not all persons in all cultures reach formal operations, and most people do not use formal operations in all aspects of their lives." – Arnett (2013)

Being Capable of Formal Operations

- Is not directly related to "intelligence" (whatever that is)
- Is related to age
- Can not be taught, at least not directly
  "Stage Promotion" from Concrete to Formal Operational is subtle

It is easy to sabotage

An Example of Formal Operational Thought

An algebra problem requiring Concrete Operations:

Solve for *a* and *b*

$b = a + 2$

$b + a = 8$

$(a + 2) + a = 8$

$2a + 2 = 8$

$2a = 8 - 2 = 6$

$a = \frac{6}{2} = 3$

$b = a + 2$

$= 3 + 2 = 5$

An algebra word problem requiring Formal Operations:

Bob is 2 years older than Alice. Taken together, the sum their ages is 8. What are their ages?

Some Years Ago, We Identified 1ST Year Physics Students in Trouble

- Organised a series of workshops and other interventions
  - Based on Piagetian ideas
- We didn't manage to actually help these students very much
- We did hear the following story in one form or another many times …

The Story We Heard

- "Johnny" is about 13 years old and a good student
  - about Grade 8
- In algebra, he encounters word problems for the first time
- Johnny can't do them, and the teacher tried to get him to work harder.
- Johnny still can't do them
- The teacher loses patience and says "Johnny, you're not smart enough to do this kind of work."

Johnny believes the teacher!

Test and Exam Questions Sometimes Are Not Asking What We Think

In Toronto we devised 2 versions of some test questions.

Both versions were testing the same Physics.

The wording of the questions were different: one version was more Concrete, the other more Formal Operational.

Example

- **Introduction for both versions**: Satellite 1 with mass m_1 is in orbit a distance r_1 from the centre of the Earth, which has a mass M. The force of gravity on it is $F_1 = G\,M\,m_1 / (r_1)^2$. Satellite 2 with mass m_2 is in orbit a distance r_2 from the centre of the Earth and has a force of gravity on it of $F_2 = G\,M\,m_2 / (r_2)^2$.
- **Concrete**: If $r_2 = 2 \times r_1$, then the force on Satellite 2, F_2, is: (A) 4 F_1 (B) 2 F_1 (C) F_1 (D) F_1 / 2 (E) F_1 / 4
- **Formal**: If $r_2 / r_1 = 2$, then F_2 / F_1 is: (A) 4 (B) 2 (C) 1 (D) ½ (E) ¼

Results

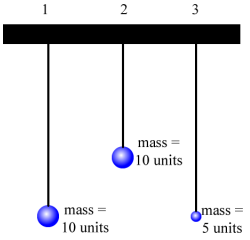
- For us, the difference in the 2 versions is trivial
- For the top 20% of the class, the difference in the 2 versions of the question was also trivial
- For the bottom 20% of the class, the Formal Operational version was much more difficult than the Concrete Operational one.

Testing for Formal Operational Ability

- Piaget devised many such tests
- Those tests and more have been incorporated into Lawson's *Classroom Test of Scientific Reasoning* (CTSR, 1978 revised 2000)
  - Lawson is a biologist at Arizona State University

An Example from the CTSR

You wish to determine whether the length of the string has an effect on the time it takes the ball to swing back and forth. Which strings would you use to find out?



~20% of 1st year University students cannot do this

Other Diagnostic Instruments

Physics Teachers Have Long Known That Many Students Have Fundamental Misconceptions About the Physical World

- Beginning ~1990, diagnostic instruments to identify those misconceptions were developed

Best Known: *Force Concept Inventory* (*FCI*, Hestenes, Wells, and Swackhammer, 1992, revised 1995). Tests conceptual understanding of Newtonian dynamics.

The *FCI* has been given to hundreds of thousands of students around the world

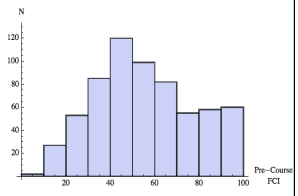
About the Diagnostic Instruments (such as the *Force Concept Inventory*)

- Conceptual: typically no formulae or even numbers
- Formative: not used to generate grades for students
- Typically a small grade (~ ½ %) is given for answering all the questions, **regardless of what the student answers**

Results are taken to be a measure of the quality of previous instruction

Results of the FCI

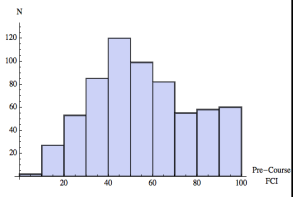
900 - student 1st Year U of T Introductory Physics (Calculus-Based, Mostly Life Science Students) Fall 2012, First Week of Classes)



U of T

Results of the FCI

Bao et al. tabulated the FCI results of beginning 1st year students at 4 U.S. and 3 mainland Chinese universities (Science **323**, 2009, pg. 586)



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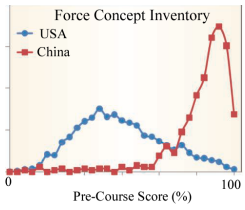
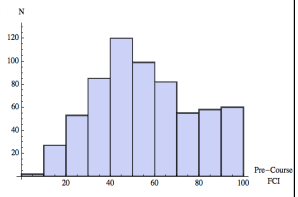
Results of the FCI



Bao et al.



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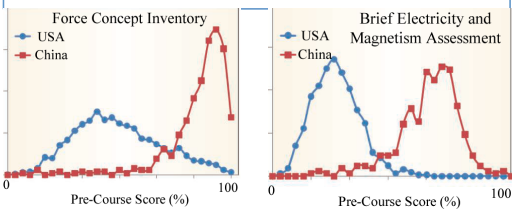
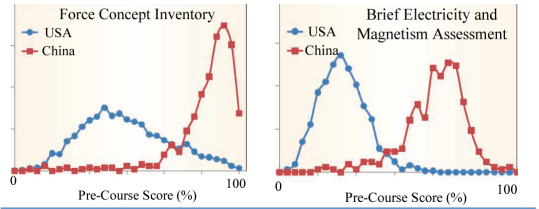
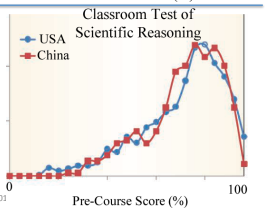
Another popular assessment tool is the *Brief Electricity and Magnetism Assessment* (BEMA). Here are some results from Bao et al.





Here are the results of testing for Formal Operational ability:



Some Questions from the Classroom Test of Scientific Reasoning

- For each question:
  - What is the correct answer?
  - What fraction of 1st year University students get the question wrong?

High school students are typically younger and will not do as well as University students

Lawson *CTSR* Question 1

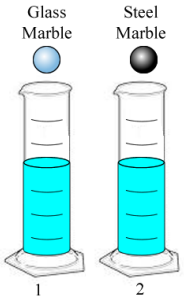
Suppose you are given two clay balls of equal size and shape. One ball is flattened into a pancake-shaped piece. Which of these statements is correct?

a. The pancake-shaped piece weighs more than the ball
b. The two pieces still weigh the same 5% wrong
c. The ball weighs more than the pancake-shaped piece

This is a classic test for Concrete Operational ability. Almost all children younger than about 6 miss this.

Lawson *CTSR* Question 3, Part 1

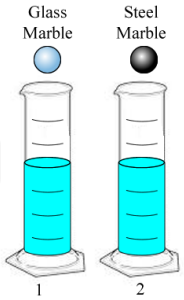
To the right are drawings of two cylinders filled to the same level with water. The cylinders are identical in size and shape. Also shown are two marbles, one glass and one steel. The marbles are the same size but the steel one is much heavier than the glass one.



Lawson *CTSR* Question 3, Part 2

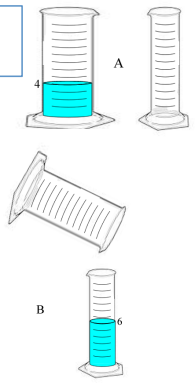
When the glass marble is put into Cylinder 1 it sinks to the bottom and the water level rises to the 5th mark. If we put the steel marble into Cylinder 2, the water will rise

a. To the same level as it did in Cylinder 1 30% wrong
b. To a higher level than it did in Cylinder 1
c. To a lower level than it did in Cylinder 1



Lawson *CTSR* Question 5 Part 1

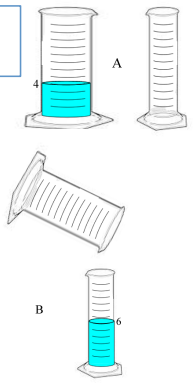
To the right are drawings of a wide and a narrow cylinder. The cylinders have equally spaced marks on them. Water is poured into the wide cylinder up to the 4th mark (see A). The water rises to the 6th mark when poured into the narrow cylinder (see B).



Lawson *CTSR* Question 5 Part 2

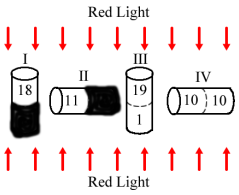
Both cylinders are emptied (not shown) and water is poured into the wide cylinder up to the 6th mark. How high would this water rise if it were poured into the empty narrow cylinder?

a. To about 8
b. To about 9 50% wrong
c. To about 10
d. To about 12
e. None of these answers is correct



Lawson *CTSR* Question 11 Part 1

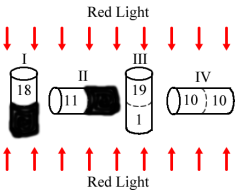
Twenty fruit flies are placed in each of four glass tubes. The tubes are sealed. Tubes I and II are partially covered with black paper; Tubes III and IV are not covered. The tubes are placed as shown. Then the are exposed to red light for five minutes. The number of flies in the uncovered part of each tube is shown in the drawing.



Lawson *CTSR* Question 11 Part 2

The experiment shows that flies respond to (respond means move to or away from):

a. Red light but not gravity
b. Gravity but not red light
50% wrong
c. Both red light and gravity
d. Neither red light nor gravity

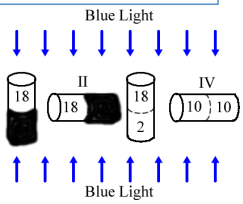


Lawson *CTSR* Question 13

In a second experiment, a different kind of fly and blue light was used. The results are shown in the drawing.

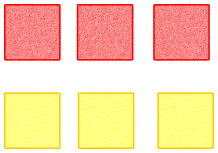
These data show that these flies respond to (respond means to move to or away from):

a. Blue light but not gravity
b. Gravity but not blue light
c. Both blue light and gravity 30% wrong
d. Neither blue light nor gravity



Lawson *CTSR* Question 15

Six square pieces of wood are put into a cloth bag and mixed about. The six pieces are identical in size and shape, however three pieces are red and three are yellow. Suppose someone reaches into the bag (without looking) and pulls out one piece. What are the chances that the piece is red?



a. 1 chance out of 6
b. 1 chance out of 3
c. 1 chance out of 2
d. 1 chance out of 1
e. Cannot be determined
10% wrong

Summary

- Cognitive ability is an often neglected but crucial factor in a student's ability to "do" science
- It is difficult to improve a student's cognitive ability
- We need to be sensitive to the issue

Thank you for your attention!