Student Understanding of the Primitive Spring Concept: Effects of Prior Classroom Instruction and Gender

by

Mark J. Lattery
University of Wisconsin-Oshkosh

Introduction

During the last thirty or so years, education researchers and cognitive scientists have been working together to study students' alternative conceptions in science (Wandersee, Mintzes, & Novak, 1994). These conceptions are often context dependent; i.e., students tend to respond inconsistently to tasks related to the very same scientific concepts (Clough & Driver, 1986; diSessa, 1993; Steinberg & Sabella, 1997). To explain this phenomenon, cognitive scientists (diSessa, 1983; Stavy & Tirosh, 1996) express student cognition in terms of a heterarchical collection of intuitive rules or phenomological primitives (p-prims). The word 'primitive' reflects the axiomatic character of these rules in scientific explanations. Example p-prims include: rigidity, springiness, bouncing, and Ohm's (diSessa, 1983, 1993; Wittman, 2002). The subject of this article is the springiness p-prim.

The springiness p-prim (diSessa, 1983) is summarized by the causality (deformation$\rightarrow$ restoring force $\rightarrow$ rebound). Due to its wide range of applicability in the physical world, and its apparent familiarity among even physics-naïve students, the springiness p-prim represents a potentially important entry point or 'anchor' for the development of higher-order physics concepts (Clement, Brown, & Zietsman, 1989). Applications include Newton's third law, normal force, and friction (Minstrell, 1982;

Clement; 1998; Thijs & Bosch, 1995). An entire physics course based on the spring concept was developed (Camp & Clement, 1994).

Research Objectives

The purpose of this study is to examine the prevalence of the springiness p-prim among students with little or no physics background. We extend diSessa's general notion of springiness to include a *qualitative* relationship between force and compression distance of a spring; i.e., more deformation → more force. This primitive concept implies an increasing monotonic relationship, but should not be equated with Hooke's law for an ideal spring.

In this study, we set out to answer the following questions: What fraction of college students understand basic spring phenomena? What alternative conceptions do students hold? Do differences exist by either science background or gender? No previous studies are known that address these questions. The importance and relevance of these questions follow from the fundamental nature of p-prims in construction of scientific knowledge.

Study Design

Participants and Context

This study was conducted at the University of Wisconsin Oshkosh during the 1999-2000 and 2000-2001 school years. The student sample (N=558) consists of introductory astronomy students and physical-science students seeking to fulfill a general education requirement. Students with a high school physics background (64%) are studied separately. The sample contains approximately the same number of males and females.

Data Collection and Instrument

All data collection took place at the beginning of the semester, prior to instruction. Using a pencil-and-paper assessment, students compare forces felt by a hand compressing a spring under various conditions (Figure 1). The assessment contains two parts. In Part I, a hand presses vertically downward on a spring resting on the floor. In Part II, a hand presses horizontally (from left to right) on a spring against a wall. These parts provide an important measure of context dependence; we expect students with a good understanding of spring phenomena to provide responses that are stable under a change in spring orientation.

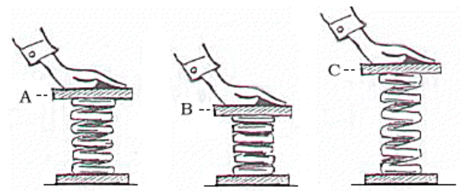
In this article, the term *understanding* is used broadly. It may refer to either instinctive knowing (i.e., without the use rational processes), appropriate to a primitive concept; or, to explicit knowledge developed through formal or informal experience.

Each of the above parts contains two items. The first item asks the student to compare the force on the hand by a spring (in static equilibrium) with another in a more compressed state. The second reverses the order of the comparison, and asks the student to compare the later state with one in a less compressed state. This line of questioning helps to identify student confusion about the terms *less* and *more*, and the correspondence of these terms with the figure. For each item pair, students provide a written explanation.

Face validity of the assessment was established through review by numerous content experts (university physics faculty). The content experts agreed on the 'right' answer. Items were further validated through twelve (12) student interviews, including five men and seven women. Interviews lasted between 20-30 minutes. Students were asked to explain the meaning of each item in their own words and evaluate the test for clarity. Student responses to the items corresponded well to student thinking.

Part I: Use the following statement and figure to answer Questions 1-2.

Bob pushes down on a spring three (3) times. First, Bob pushes the spring down to A and holds it there. Then, he lets up on the spring. Then, Bob pushes the spring down to B and holds it there. Again, he lets up on the spring. Then, Bob pushes the spring down to C and holds it there.



1. Bob feels ________ force on his hand at A than at B. (Complete the sentence.)

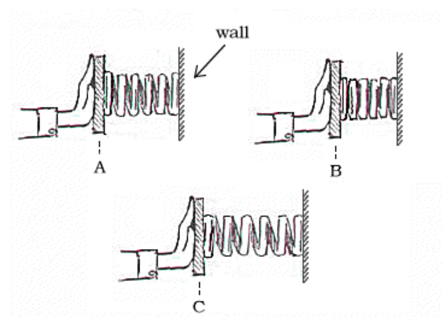
   a) more
   b) less
   c) None of the above. Bob feels the same amount of force at A and B.
   d) None of the above. Bob does not feel a force at A or B.

2. Bob feels ________ force on his hand at B than at C. (Complete the sentence.)

   a) more
   b) less
   c) None of the above. Bob feels the same amount of force at B and C.
   d) None of the above. Bob does not feel a force at B or C.

Part II: Use the following statement and figure to answer Questions 3-4.

Bob pushes a spring on a wall three (3) times. First, Bob pushes the spring across to A and holds it there. Then, he lets up on the spring. Then, Bob pushes the spring across to B and holds it there. Again, he lets up on the spring. Then, Bob pushes the spring across to C and holds it there.



3. Bob feels ________ force on his hand at A than at B. (Complete the sentence.)…

4. Bob feels ________ force on his hand at B than at C. (Complete the sentence.)…

Figure 1. Spring assessment.

Student Interviews

To illustrate the nature and quality of the interview data, excerpts for four (4) student interviews are presented below.

Student 1

Interviewer: How would you answer *Question 1*?

Student 1: Less. Bob is applying less force to A than B and will in turn feel less force with A… Like trampolines—the greater force in meeting the trampoline will make you jump higher.

Interviewer: How do you know the hand at A is applying less force?

Student 1: I guess that they could be applying the same amount of force, just that B is applying it for a greater amount of time

Interviewer: Hmm… The time between when and when?

Student 1: If they are pushing with the same amount of force, A could be the result of pushing for, say, 4 seconds, and B could be the result of 5 seconds worth of pushing. The amount of time from the onset of the pushing until it stopped was greater.

Interviewer: I get it. So, does the force that Bob feels while ‘holding it there’ at point A, for example, depend on what happens during the pushing down?

Student 1: Yes.

Interviewer: What if the hand is replaced by a book? That is, one book pushes the spring down to A, and another different book down to B.

Student 1: If both books are placed on the spring (in the same way), the heavier book will cause the spring to be pushed to B.

Interviewer: So, is this situation like the hand…

Student 1: I don’t know that they would be pushing with the same force. (The one that is) heavier than the other would ‘feel’ more force. There would be more of a force…waiting to be released in B. Say if the book were removed, we would see more action in releasing spring B than in A.

Interviewer: Okay. How would you answer *Question 2*?

Student 1: Bob feels more force on his hand at B than at C, because B has more energy waiting to be released.

Interviewer: Is it possible that Bob is pushing with the same force at B and C, ‘holding it there’ in either case?

Student 1: No, I think that Bob would have to be holding B down with more of a force than in C.

Interviewer: How would you answer *Question 3* (spring against wall)?

Student 1: Bob is feeling less force on his hand at A than at B. Even with the spring on the wall at 90 degrees, the same principles, which I have been attempting to explain, hold true.

Student 1 draws upon experiences with a trampoline to answer the questions. The student’s initial response is consistent with responses to Items 2 and 3 on the paper-and-pencil assessment (all correct answers). During questioning, the interviewee entertains the possibility that the *same* amount of force is required to hold the spring at position A and B, stating that only the time required to prepare the spring in this position is different. However, when the book example is used, the primitive spring concept is recovered.

<u>Student 2</u>

Interviewer: Why don’t you tell me a little about *Item 1* and what you did?

Student 2: *Item 1*? I dunno. I chose “None of the above”. Bob feels the same pressure on A and B. I just didn’t see a difference in amount of force or pressure he applied to each spring…everything was just the same so…I just thought all the reactions would just be the same.

Interviewer: Okay…So this hand [pointing to position A] feels the same amount of force as this hand [pointing to position B]?

Student 2: I think so…

Interviewer: Tell me about *Item 2* and why you answered the way you did.

Student 2: It was the same…I thought he was pushing down with the same…I mean he wasn't pushing down any faster…or slower…that's the way I thought about it…

Interviewer: Okay, he's not pushing down any faster?…

Student 2: Or, he is not using more force.

For Student 2, the compression distance of the spring is irrelevant. The student proposes that the process of compressing the spring (faster or slower) *could* affect the force felt by the hand. However, since "he was pushing down…the same," the process is irrelevant as well. So, the student selects alternative (c) ("Bob feels the same amount of force at A and B") for all four items. The student seems to lack a physical intuition for spring phenomena.

Student 3

Interviewer: Can you tell me a little about *Question 1* and why you answered alternative (b) ("Bob feels less force on his hand at A than at B")?

Student 3: It is like your pushing down on a pump…like in soccer…(I'm from Ghana and we play a lot of soccer)…When you're going all the way down, you're exerting a lot of force to let out a lot of air. When you press midway you exert a middle force…when you have a middle amount of air pumped, you just exert a lesser force, and that's why…that is how I came to this conclusion.

Interviewer: What if the hand didn't need to do the work of pushing down the spring? Suppose someone else pushed down on the spring for this person….And the only role of this person was to slip their hand over the top. Which hand would feel more force?

Student 3: (After a long pause) I still go with position B.

Interviewer: Why?

Student 3: I still feel that…the lower the level of the spring, the more force that is exerted. There is more input on the spring, so…(long pause)

Interviewer: Why is it that a more compressed spring would make the hand feel more force?

Student 3: Its like, you're doing more work…your putting more energy in the work…

Interviewer: But in the case where somebody else does the compression for the person…and this person just slips a hand up top… why would the person at B feel any more feel any different than A?

Student 3: The person at B will feel different than A because someone else…already exerted…already put the force in…so I don't think…he just there…he's not using energy…not gaining force or anything…he is just kind of stationary…

Interviewer: …Somebody else already did the work…yet this person (pointing to position B) would feel more force even though they didn't do any work prior…?

Student 3: Yes.

Student 3 draws upon experiences with a soccer-ball pump to answer the questions. Interviewee responses are consistent with responses to Items 2 and 3 on the paper-and-pencil assessment (all correct answers). The student conflates 'mechanical work' with force. However, further questioning reveals an understanding of the primitive spring concept.

Student 4

Interviewer: How would you answer *Question 1*?

Student 4: I wrote [pointing to the pencil-and-paper assessment] "his hand was used to it"…Do you want me to explain?…

Interviewer: Yes. Tell me what that means.

Student 4: After he pushes on A…Bob doesn't know how much force its going to be until he pushes A…by the time he has to push B…he already knows that there's going to be force…so he expects it…so I don't think there is going to be as much force…there…than at A.

Interviewer: As you look at A and B…in which case does the hand feel more force?

Student 4: Position B.

Interviewer: …that is because he is used to it?

Student 4: Oh no!…[interviewee pauses]

Interviewer: Would he feel the same amount of force acting…at position B…if he hadn't done A first?

Student 4: No.

Interviewer: Why?

Student 4: I dunno. I think that…after he pushes A…you already know how much force there is going to be…when you push B, you're going to expect that much force…your [voice fades] not have to push as hard…but here it shows that he is pushing harder (pointing to position B)…or there is more force…no there'd be more force at A…because he is unsure of how much to push down…

Student 4 indicates that the person compressing the spring is *de-sensitized* to the force sensation with each, successive compression (i.e., more force at A than B, and more force at B than C). In this case, the compression distance of the spring is irrelevant. The psychology of the "pusher" plays an important role: [mine]

> …you already know how much force there is going to be…when you push B…his hand was used to it [after pushing at A]…you're going to expect…force…[so you do] not have to push as hard…"

Yet, at points during the interview, Student 4 seems to accept the primitive spring concept. Answers to the pencil-and-paper assessment were similarly inconsistent.

Summary Remarks

Eight (8) of 12 students interviewed provided: (1) the "correct" answers to all four items on the pencil-and-paper assessment and (2) demonstrated an understanding of the primitive spring concept during interviews. One student suggests that force is proportional to the physical size of the spring, reminiscent of student difficulties with mass-volume discrimination (Driver, Guesne, & Tiberghien, 1985). Three students consider the compression distance to be irrelevant: one suggests the speed of compression determines the perceived force (cf. Student 2); and two offer a "psychological" model (cf. Student 4). To obtain a broader understanding of student conceptions, a quantitative study was performed.

Quantitative Analysis

To quantify student responses, we use three measures, or *error rates*: the fraction of students failing to answer:

(1) both items of Part I correctly,

(2) both items of Part II correctly, and

(3) all four (4) items correctly.

Responses were studied according to the physics background and gender of the subjects. Special care was taken to study gender effects, since such effects have been reported and discussed in the recent literature (McCullough, 2004; AAUW, 1999; Becker, 1989). For this purpose, we define the *gender ratio* (R) as

$$R = \frac{e_f}{e_m} \quad ,$$

where e_f (e_m) is the error rate for the female(male) sample. The statistical significance of the results is determined using a κ-test for two dichotomous distributions (α=0.90). The test statistic κ is given by

$$\kappa = \frac{\left(e_f - e_m\right)}{\sigma} \quad ,$$

where σ is the standard deviation of the numerator (calculated from the binomial distribution).

Quantitative results

The results of this study (Tables 1 and 2) indicate that about 10% of college males and 30% of college females, enrolled in physical science and astronomy, lack a strong understanding of the spring concept. The gender effect size (κ) is 3σ. No significant difference is observed between the physics and non-physics samples.

Table 1
Non-physics sample

		Error Rate (e)			
Measure	Part(s)	Male (N=108)	Female (N=168)	Gender Ratio	Effect Size (κ)*
1	I	0.07	0.18	2.6 ± 1.0	2.8
2	II	0.10	0.21	2.1 ± 0.7	2.6
3	I-II	0.11	0.27	2.5 ± 0.8	3.6

*For all measures, $p < 0.001$.

Table 2
Physics sample

		Error Rate (e)			
Measure	Part(s)	Male (N=150)	Female (N=132)	Gender Ratio	Effect Size (κ)*
1	I	0.07	0.16	2.3 ± 0.8	2.4
2	II	0.11	0.21	1.9 ± 0.5	2.3
3	I-II	0.12	0.27	2.3 ± 0.6	3.2

*For all measures, $p < 0.001$.

Table 3

Results of the factor analysis

Item	Descriptor	Factor 1	Factor 2	Factor 3	Factor 4
1	FLOOR (A⇔B)	0.80	0.42	0.40	-
2	FLOOR (B⇔C)	0.80	0.43	-	-
3	WALL (A⇔B)	0.83	0.44	-	-
4	WALL (B⇔C)	0.86	-	-	-

Note: Only loadings higher than or equal to 0.40 have been printed.

Factor analysis

A principal component analysis is performed to determine the extent to which a 'test score' on this assessment is associated with a single mental construct: spring understanding. Methodologically, this approach follows other recent studies (e.g. Kuiper, 1994). For this purpose, items 1-4 (Figure 1) are dichotomously scored (right or wrong). Table 3 provides the results of an analysis based on a matrix of non-parametric correlation coefficients. The data shows a very clear grouping of the items around a single factor; i.e., students with a good understanding of spring phenomena tend to answer all four items correctly.

Student Written Responses

Student written responses are not elaborate. Responses such as, "It just seems like that is the way is should be, but I can't tell you why," are not uncommon. One interpretation is that knowledge of the primitive spring concept is tacit (Reber, 1995). Nevertheless, student written responses reveal a number of interesting, and alternative, spring models. Below are a few examples.

Spring on floor

> Spring A has more force because it's a larger spring.

In this response, force is proportional to the physical size of the spring (also observed in student interviews.)

> There is more pressure on his hand (for spring A) because he hasn't broken the resistance point yet, then breaks past (like for spring B)… His resistance barrier has not been broken yet at spring A.

Here, the spring exhibits a threshold behavior. Beyond a point, the spring becomes easier to deform with effort.

> At B the spring is almost completely down, so it will not try to expand as much.

Similar to the previous response, the spring 'submits' to the external agent—weakens under the control of the hand.

> No matter how hard Bob pushes on the spring, it is going to react the same way. Bob isn't pushing any harder on the spring, he is just pushing further.

In this case, the force response of the spring is constant. The student clarifies his answer by drawing a distinction between 'further' and 'harder'. The response suggests that one should not be 'fooled' by the physical size of the spring.

Spring against wall

Difficulties of a different nature arise in the wall items. Examples are:

> Bob feels about equal forces because the gravitation isn't causing the spring to vary its resistance.

Gravity takes priority over other features of the system, acting as a 'valve' for other applied forces.

> Bob feels the same pressure because gravity is the same when the spring is on the wall. There is no downward pull on the spring, so no matter how hard Bob pushes, he will feel the same force.

Similar to the previous response, the rule 'same gravity—same spring force' seems to be operative.

> Spring A and B have the same force… there is no longer the pressure… on the spring. Instead there is a force pulling down on the spring, so I think that Bob feels the same amount of force at both positions.

Again, the presence of gravity seems to confound the student's reasoning. This type of difficulty is discussed in detail elsewhere (Author, 2005).

The 3-σ gender effect is of particular interest, and relevant to general discussions about gender and science education (e.g. Cole, 1997). Researchers vary in their interpretations of data on gender gaps. On one extreme, feminist philosophers of science (e.g. Bleier, 1986; Keller, 1985) argue that traditional science is inherently masculine and therefore biased against females. In this view, persistent gender gaps in science education are avoided only by a dramatic shift in scientific epistemology. Perhaps the most radical example of this is the position that analytic behavior is "masculine" (Bell, 1988).

Less radical researchers trace gender differences to specific and unnecessary masculine elements in traditional science instruction (Wilder & Powell, 1989). In this view, gender gaps are mended, within traditional science instruction, by replacing male-oriented examples with female-oriented or gender-neutral ones. However, a recent study concludes such changes can "affect(s) student performance…in ways that are hard to predict in terms of gender bias" and that "women may be accustomed to male-oriented examples" (McCullough, 2004). Some researchers explain gender differences in technical areas in terms of innate differences (e.g. Benbow & Stanley, 1980; Lawton & Morrin, 1999).

Which is the best interpretation here? First, we consider the possibility of gender bias in our research instrument (Figure 1). The instrument contains one masculine reference (*Bob*) and many other terms difficult to classify by gender (e.g. *down*, *hold*, *pushes*, and *force*). The figure shows a hand pushing down on a large spring. The spring resembles a shock absorber for a truck, and *could be* perceived as masculine by some students.

To explain the gender effect in terms of contextual bias, the masculine reference (*Bob*) and the image of the spring must confuse or distract enough female students in the sample *who truly hold the primitive spring concept* to produce a 3σ gender gap. We find this hypothesis untenable.

Another possibility is that females have less contact with spring phenomena than males. Indeed, it is plausible that females have less contact with mechanical devices (e.g. springs, levers, gears, and wheels) *generally*. This hypothesis is supported by the common perception that mechanical tasks are masculine (Signorella & Vegega, 1984; Huston, 1983.) Consider, children's building sets (e.g. Lego®, Tinker Toys®, ImagiNext©, K'nex©) are primarily marketed to and purchased by boys; and, careers such as engineering and auto mechanics (which involve plenty of springs!) are male-dominated. For a more complete discussion, see Ritter (2004).

In author's experience, helping students (male and female) acquire a primitive spring concept is easily accomplished through hands-on activities with loose coils and bungy chords. An intricate scheme for intervention is not necessary (unlike for many student difficulties in mechanics.) The issue here is merely one of awareness. Student unfamiliarity with simple spring phenomena can be a blind spot for instructors and curriculum developers.

Classroom Implications

The value of the spring concept as a conceptual resource for physics learning is demonstrated well by Camp and Clement's *Preconceptions in Mechanics* (1994). In this popular and effective workbook, the spring model is used extensively. For example, students explore Newton's third law by studying the collision of bumper carts. A bumper cart is a standard rolling cart with a large visible spring mounted to the front end. During the activity, students are asked to compare the compression distances of the springs for a variety of situations, such as a moving cart collides with a cart at rest, and a heavy cart collides with a light cart. The concrete model of a spring replaces the abstract notion of a 'force'. A series of bridging analogies (Clement, Brown, & Zietsman, 1989) is used to develop a formal understanding of the necessary concepts. The use of mechanical models to explicate invisible or subtle forces in a physical system, as a teaching strategy, is an important research area (Author, 2005). However, the teaching strategy just described is predicated on a good understanding of spring phenomena. As this study shows, an appreciable fraction of students do not possess this understanding. It is important to address this issue first through hands-on activities.

Conclusions

This research leads to three conclusions: (1) the primitive spring concept is not understood by all students; (2) females have more difficulty with the spring concept than males; and (3) student understanding of the spring concept is not strongly linked to prior physics instruction. These results are surprising considering the simplicity of spring phenomena.

Like other p-prims, the *springiness* p-prim is a sort of 'fundamental particle' of physics learning. More basic research is needed to study the nature and prevalence of other p-prims (diSessa, 1983; diSessa, 1993). Such studies will lead to better understanding of learning and teaching in physics education.

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About the author…

Mark J. Lattery is an Associate Professor of Physics in the *Department of Physics/Astronony at the University of Wisconsin-Oshkosh, Oshkosh, Wisconsin.*

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