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Understanding the Siphon: An Example of the Development of Pedagogical Content Knowledge Using Textbooks and the Writings of Early Scientists

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Understanding the siphon: An example of the development of pedagogical content knowledge using textbooks and the writings of early scientists

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Abstract

In this paper a general explanatory principle for determining whether fluid will flow or will not flow from a siphon is developed and discussed after a consideration of the explanations provided by textbooks and the writings of Blaise Pascal. It is demonstrated how this explanatory principle, based on a consideration of pressures on either side of a fluid disc of negligible thickness, can apply to other fluid-flow devices such as the syringe. The wide applicability and stable structure of the explanatory principle makes it a useful pedagogical device for nurse and science education and highlights the importance of pedagogical content knowledge in the teaching process.

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The siphon is an important fluid-flow device in nursing, industry and agriculture which enables fluid to flow from one container to another through the action of pressure differences without any of the containers being disturbed. It is featured in education settings ranging from experiments at elementary school level to courses in fluid dynamics at university level. Our interest in the siphon was catalysed by our experience in teaching fluid flow in a biophysical science course for nurses where the students typically used their own intuitive ideas rather than any scientific principles to decide whether fluid would flow or not in devices such as syringes, siphons, intravenous giving sets (gravity devices for intravenous feeding), and drainage bottles (Greive & de Berg, 1994, 1996). Intuitive ideas are not always unproductive, but in the case of providing an explanation for the operation of fluid-flow devices it was found that they led to inconsistent explanations by students and were often in disagreement with basic scientific concepts. For the nursing devices listed above fluid flow was discussed by students in terms of "suction" and the source of "suction" was often considered to be at high pressure rather than low pressure. The heavy reliance on the "suction" principle meant that students rarely referred to atmospheric pressure or air pressure in their explanations. In the case of the siphon, students recognised the fluid flow as being due to "siphoning action" but could not explain what caused the "siphoning action." However, how important is it for a nurse to understand fluid flow in scientific terms? This question was addressed in our 1996 study and it was found that the competent operation of fluid-flow devices in the professional setting did not depend upon a scientific understanding of the devices, but a scientific understanding did promote confidence and positive attitudes for nurses in relation to their professional ability. For this reason we believe it was important to persevere in seeking consistent scientific explanations for fluid flow in nursing devices rather than relying only on an adequate procedural knowledge.

In the process of teaching fluid flow we discovered that a scientific explanatory principle for fluid flow which could apply across a range of devices was not easy to find and this article summarises our attempt to find or develop such an explanatory principle from textbooks and from an investigation of an historical work on the siphon. We viewed this as a critical exercise because of the fundamental importance to science education at all levels of providing for "understanding" through the fabric of science, even given the recognised limitations within science for establishing ultimate meaning and understanding. Scientific concepts are valuable because of their capacity to apply consistently across a range of situations and hence, in comparison to intuitive concepts, should facilitate learning. The product of transforming subject matter into a form that will facilitate student learning has been termed, "pedagogical content knowledge" (PCK), by van Driel, Verloop, and de Vos (1998). The origin of the concept of PCK has been attributed to Shulman (1986) in his reorientation of the role of subject matter knowledge in teaching but the concept has not received the full endorsement of the science education community. Lederman, Gess-Newsome, and Latz (1994), for example, consider the concept somewhat of an enigma. We believe, with van Driel et al (1998), that the concept has validity particularly when applied to specific content. This article focuses on "explanation" as an important component of PCK and shows how an explanation is generated for siphon action using textbooks and historical writing from a teacher's point of view.

Richard White (1988) views "explanation" as the key to "understanding" despite the fact that "understanding is a complex, multifactor notion which cannot be described simply" (p. 72) and "the nature of explanation itself is not easy to describe" (p. 55). For the purposes of this article, therefore, we need to highlight what it is about the siphon that needs to be understood and also on what concept(s) an explanatory principle might be based. We will be guided by the needs of undergraduate nursing students in establishing these criteria although we suspect these needs will match the needs of other students as well. Starting with a siphon in equilibrium (no fluid flowing) we need to understand why fluid flows in the direction it does or doesn't flow at all when the liquid is allowed to move freely. This is what needs to be understood for our purposes here. Confining ourselves only to this task initially makes it easier to arrive eventually at a satisfactory understanding of the whole phenomenon of siphon action. In this paper, then, we confine ourselves to considering a siphon at the instant barriers such as stoppers are removed from the static fluid and it is allowed to flow freely. The explanatory principle for such a situation advantageously would be based on the concept of pressure as this is the key concept associated with fluid properties such as fluid flow. The concept of pressure itself will not be the focus of this article, but rather our focus will be on how the pressure concept can be used to formulate an explanatory principle for the action of a siphon and other fluid-flow devices. We will assume that the concept of pressure as the magnitude of normal force per unit area (how concentrated the force is on a surface) or energy per unit volume (how concentrated the energy is in space) is not at issue here. An appropriate explanatory principle will be characterised, according to Gilbert, Boulter and Rutherford (1998), by four features: plausibility, parsimony, generalisability, and fruitfulness. In a sense these features are related because an explanation that is based on a minimum number of well-established scientific concepts (parsimony and plausibility) will tend to apply to a range of contexts (generalisability) and hence be fruitful. We now examine the principles outlined in a selection of textbooks for fluid flow from a siphon.

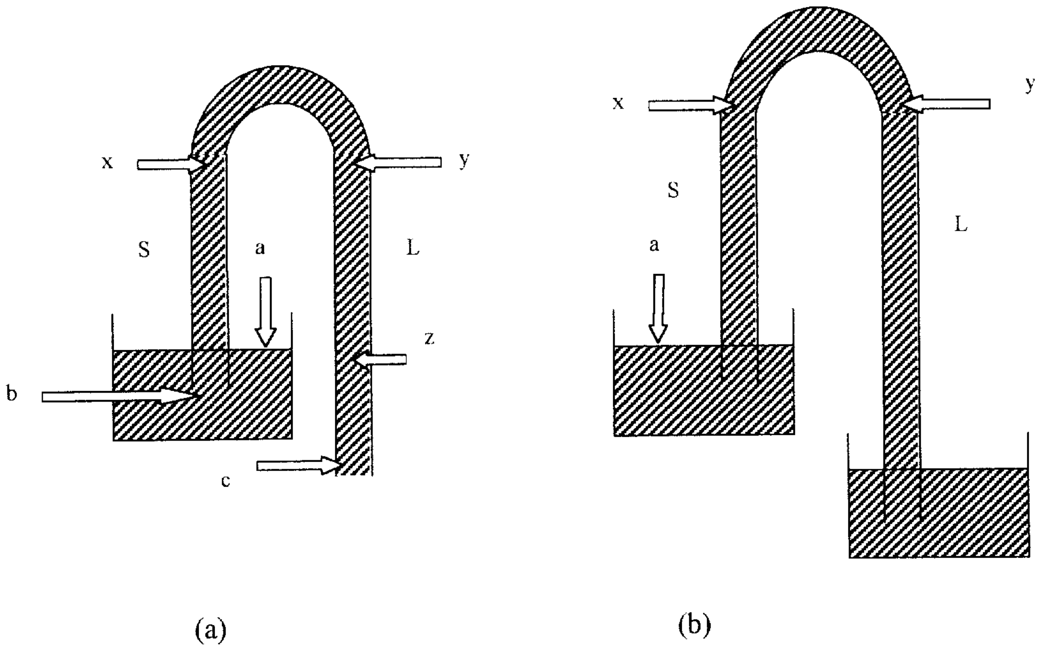
Textbooks

Eight physics textbooks and five physical science nursing textbooks were examined for their treatment of the siphon and the results are summarised in Table 1. The textbooks deal with a siphon either in the form shown in Figure 1(a) or that shown in Figure 1(b) in the text itself or in the form of a question at the conclusion of the chapter. Four of the eight physics textbooks and two of the five nursing physical science textbooks focus on siphon action once fluid is already flowing rather than on what causes the fluid to flow in the first place, which is our emphasis here. The explanation for siphon action once the fluid is flowing involves a reduction in pressure below atmospheric pressure inside the tube when fluid is flowing which enables the outside atmospheric pressure to keep fluid moving through the tube. These textbooks usually indicate that the bottom end (c) of the leg (L) outside the container of liquid in Figure 1(a) must be below the surface of the liquid, "a," in the container for fluid to flow but they do not explain why this should be the case. Cree and Rischmiller (1991), in relation to Figure 1(a), actually suggest that the outside leg (L) must be below the leg (S) opening inside the container of liquid, "b," rather than below the surface of the liquid, "a," for siphon action. More liquid will siphon in this case but siphon action still occurs, albeit to a lesser extent, when the outside leg is below the surface of liquid in the container but above the leg opening in the container.

The other four physics textbooks and three nursing textbooks focus on why fluid commences to flow. Of these, Giancoli (1988) asks for an explanatory principle for understanding the flow characteristics of a siphon but does not provide clues in the text for such an explanation.

Table 1. Principles of explanation for siphon action found in textbooks

Textbook	Siphon Type	Text	Questions	Focus
Physics				
Duncan & Starling (1954)	Figure 1(a)	+	+	Describes the action when fluid is flowing and before it flows
Bluh (1955)	Figure 1(a)	+	-	Liquid runs out of longer leg because liquid column is heavier than for the short leg
Morgan (1963)	Figure 1(b)	-	+	Liquid flows if the pressure at 'x' is greater than that at 'y'
Reimann (1971)	Figure 1(a)	+	-	Describes the action when fluid is flowing
Kinsky (1982)	Figure 1(a)	+	+	Describes the action when fluid is flowing including the speed of flow
Giancoli (1988)	Figure 1(b)	-	+	Asks for explanation as to why fluid flows from 'x' to 'y'
Resnick et al. (1992)	Figure 1(a)	-	+	Describes the action when fluid is flowing including speed of flow
Serway (1996)	Figure 1(a)	-	+	Describes the action when fluid is flowing including speed of flow
Physical Science (Nursing)				
Elhart et al. (1978)	Figure 1(b)	+	-	Fluid in the long arm weighs more than fluid in the short arm
Nave & Nave (1980)	Figure 1(a)	+	+	Describes the action when fluid is flowing
Chapple & Drew (1981)	Figure 1(a)	+	-	Fluid in the long arm weighs more than fluid in the short arm
Cree & Rischmiller (1991)	Figure 1(a)	+	-	Describes the action when fluid is flowing
Hickman & Caon (1995)	Figure 1(a)	+	-	Fluid flows if the arm out of the container is longer than the arm in the container



(a) (b)

Figure 1. Two textbook representations of the siphon. S = short leg, L = long leg

Duncan and Starling (1954) consider the pressure at "z" at that instant before flow to be atmospheric pressure and acting downwards and the liquid column from "z" to "c" to have a weight acting downwards thus overbalancing the atmospheric pressure acting upwards at "c" and leading to the discharge of liquid at "c." Whilst this explanation has some merit it suggests vector characteristics for pressure and uses two concepts, pressure and weight, rather than just the concept of pressure itself, to determine the direction of fluid flow. Duncan and Starling (1954) are effectively comparing the pressures at the upper surface and under surface of the liquid at "c," although they don't state this as such and it is not clear at what point in the apparatus they consider there to be a net downward tendency. Elhart, Firsich, Gragg and Rees (1978) suggest that liquid will always run out of the longer leg because its liquid column is heavier. Bluh (1955), Chapple and Drew (1981), and Hall (1976) use the same argument and conclude that the cohesion of water molecules then leads to water being "pulled over" from the short side to the long side. One could argue, without recourse to the concept of cohesion, that the water follows itself from the short leg to the long leg because if it didn't the resulting vacuum space would lead to a pressure difference which would collapse the vacuum space leading to a continuous flow. Hickman and Caon (1995) also describe siphon action as fluid always flowing from the short leg, S, with height measured from the surface "a," to the long leg, L, but they mention that this arises from a higher pressure at "b" than at "c" with fluid flowing from high pressure to low pressure. However, they only consider the case where the inlet tube opening "b" and the outlet tube opening "c" are at the same horizontal level and describe the pressure at "b" as being due to atmospheric pressure plus the height of liquid and the pressure at "c" as being only atmospheric pressure thus giving the pressure difference leading to fluid flow. Morgan (1963) also considers fluid flow in terms of pressure differences by comparing the pressures at the same horizontal level except that he compares the pressures at "x" and "y" at the top of the siphon. No indication is given by Morgan about how to determine these pressures because this was not a part of the text but was part of a question at the conclusion of the chapter. Some textbooks consider the operation of the siphon in a vacuum but this is a special case and will not concern us in this article.

Two explanatory principles thus clearly emerge from this brief textbook analysis. One, based on comparing the weight of liquid columns in the two legs, and the other, based on comparing the pressures at the same horizontal level in the siphon. A third explanatory principle can be inferred from the work of Duncan and Starling (1954) and involves comparing the pressures acting at the upper and under surface of liquid at some section in the siphon for the static condition immediately prior to flow. However, explanations which are predictive and which can apply to a range of fluid-flow devices are not a common feature of recent textbooks and one might assume, therefore, not commonly taught in physics curricula. This is consistent with the observations of Gilbert, Boulter, and Rutherford (1998) that predictive explanations are not commonly featured in science classrooms. It is, therefore, interesting to ponder how the scientists of the early modern scientific period understood the action of the siphon and it is with this thought in mind that we next consider the work of Blaise Pascal on the siphon.

Blaise Pascal

In 1663 Pascal's treatise on the equilibrium of liquids and the weight of the mass of the air was published and included a section on the siphon entitled, "That the weight of the mass of the air makes water rise in siphons." The siphon referred to by Pascal is shown in Figure 2. This set-up was used to show that mercury rose in the siphon, not because of its "horror" of a vacuum, but because of the weight of the mass of water. The fact that the siphon tube was open to the atmosphere proved conclusively that the mercury rose in the tube for reasons other than that of a vacuum.

The explanatory principle given by Pascal (1663) for the operation of the siphon in Figure 2 reads, "whence the quicksilver in each leg being pushed up by the weight of the water, they contend at the top of the siphon, pushing each other, so that the one having the greater force must prevail" (p. 413). Thus the flow of fluid in a siphon is the result, according to Pascal, of two competing forces at the top of the siphon. These two forces are calculated using the following reasoning (Pascal, 1663).

> Now that will be easy to calculate; for it is clear that since the water has greater depth above the vessel which is an inch lower, it pushes up the quicksilver in the longer leg more forcibly than that in the other leg by the force which an inch of depth gives it; whence it seems at first the result should be that the quicksilver should be pushed from the longer leg into the shorter; but we must consider that the weight of the quicksilver in each leg resists the effort made by the water to push it up, but they do not resist equally, for since the quicksilver of the long leg has an inch more of height, it resists more forcibly by the force given it by the height of one inch; therefore the mercury in the longer leg is more pushed up by the weight of the water by the force of an inch of water, but it is more pushed down by its own weight by the force of an inch of quicksilver; but an inch of quicksilver weighs more than an inch of water; therefore the quicksilver in the shorter leg is pushed up with more force, and consequently it must rise and to continue to rise as long as there is any quicksilver in the vessel in which it dips. (p. 413)

Thus in each leg of the siphon the weight of water acting on the surface of the mercury is opposed by the weight of mercury in the leg and this determines if there is any imbalance of forces at the top of the siphon.

The principle that fluid flows from the shorter leg to the

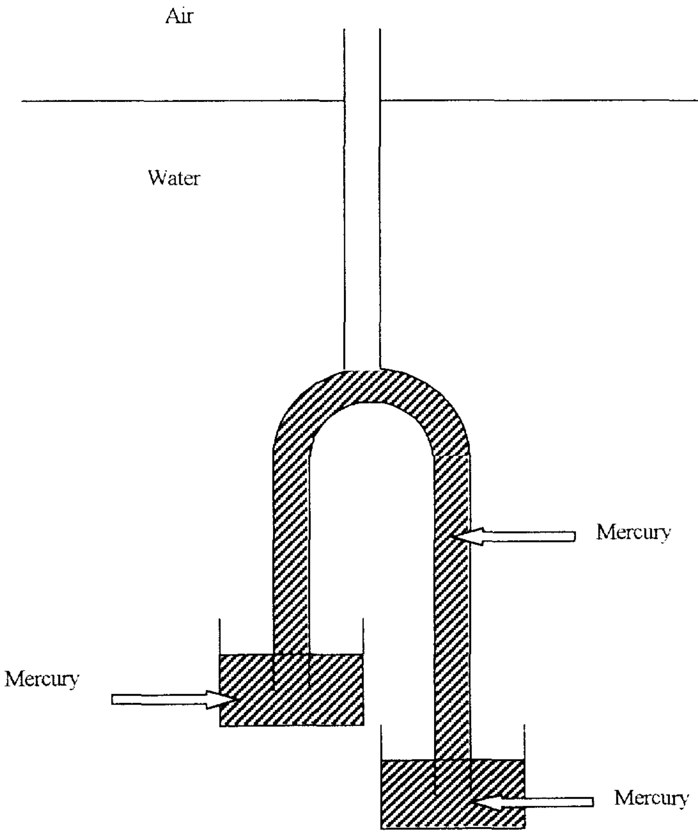


Figure 2. The siphon system discussed by Pascal (1663)

longer leg only works if the fluid in the siphon is more dense than the fluid pressing on the liquid surface in the containers. Pascal (1663) illustrates, in the hypothetical argument below, what would happen if the liquid densities were reversed.

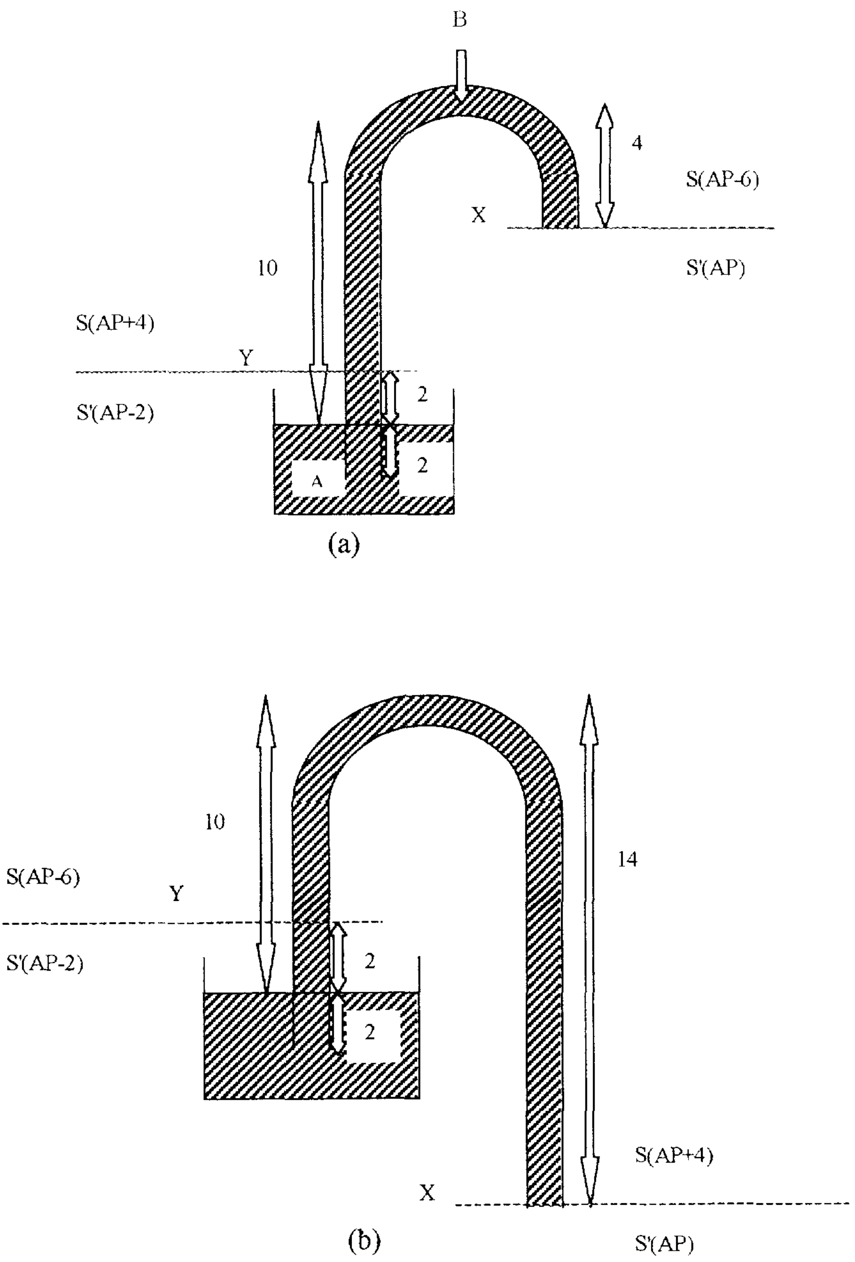
> Whence it is apparent that the reason why the higher vessel empties into the lower is that quicksilver is a heavier liquid than water. The opposite would happen if the siphon were filled with oil and the whole were in the same tank of water, for then the oil in the lower vessel would rise and flow through the top of the siphon into the higher vessel for the same reasons just given; for the water still pushing the oil in the lower vessel with more force because it has an inch more of depth and the oil in the long leg resisting and weighing more by its extra inch of height, since an inch of oil weighs less than an inch of water, the oil in the long leg would be pushed up with more force than the oil in the other leg, and consequently it would flow and would pass from the lower vessel to the higher vessel. (p. 413)

In the case of a siphon of water sitting in air one only needs to compare the height of water in each leg since the air pressure for both legs is approximately the same. So, if the fluid in the siphon is more dense than air, fluid will pass from the shorter leg to the longer leg since the pressure of the fluid at the base of the longer leg (the press of the weight of fluid in the longer leg) exceeds that in the shorter leg and pressure differences will maintain a continuous flow of fluid. This is the explanatory principle used by Bluh in his text although he attributes the continuous flow to cohesion of the fluid.

Conclusion

The explanatory principle based on comparing the weights of fluid in both legs of a siphon occurs, in some shape or form, in the textbook analysis and in the work of Pascal. The advantage of this principle is that it is relatively simple and easy to recognise and would apply to siphons as commonly employed in nursing. Its disadvantages are that it is context-specific, that is, applies only to siphons and not other fluid-flow devices such as syringes, intravenous giving sets, and drainage bottles; applies only in cases where the siphon fluid is more dense than the external fluid; and doesn't always use the concept of pressure which is central to an understanding of fluid flow. The explanatory principle based on comparing the pressures at the same horizontal level (featured in the textbook analysis) overcomes some of the difficulties mentioned above but is unsuitable as a general principle for explaining fluid flow in other devices such as intravenous giving sets.

The notions of contending weights or forces used by Pascal (1663), or pressures used by Duncan and Starling



(a)

(b)

Figure 3. Two siphon systems showing heights in arbitrary units for the calculation of pressures on either side, S and S', of fluid discs at X and Y of negligible thickness

(1954) at a particular position in the siphon (Pascal chose the top of the siphon; Duncan and Starling effectively chose the exit point of the siphon) are useful ones to explore for a general principle. We have recently extended this idea to form an explanatory principle which overcomes all the disadvantages previously mentioned. Consider the siphon in Figure 3(a) and a fluid disc of negligible thickness anywhere in the siphon tube but characteristically at the opening, say X, and consider the contending pressures either side, S and S′, of this disc at the moment the stopper is removed from X. The pressure on side S′ is atmospheric pressure. To locate the pressure on side S of the disc, one needs to follow the pressure changes on the other side of the siphon starting at the surface of the fluid in the container where the pressure is atmospheric pressure (AP), then to A where it is (AP + 2), to B where it is (AP + 2 - 12), to X where it is (AP + 2 - 12 + 4) which gives (AP - 6). So the pressure on side S′ exceeds that on side S so the liquid will not siphon from the tube but move back into the longer leg and into the container. In Figure 3(b) at X, the pressure on side S′ is again AP. On side S, following the same principles as for Figure 3(a), the pressure is (AP + 2 - 12 + 14) which gives (AP + 4). So the pressure on side S exceeds that on side S′ and so fluid siphons from the beaker out of the longer leg of the siphon. The same explanatory principle holds for any other position in the siphon. Consider, for example, a fluid disc of negligible thickness at Y in Figures 3(a) and (3b). The contending pressures either side of this disc in Figure 3(a) are (AP-4+8) for S and (AP+2-4) for S′. Thus the pressure on side S exceeds that on side S′ leading to the same conclusion as above for X that fluid flows from the short leg to the long leg. The contending pressures either side of the disc at Y in Figure 3(b) are (AP-14+8) for S and (AP+2-4) for S′ thus giving a higher pressure on side S′ compared to S leading to fluid flow into the longer tube as predicted previously for X. The concept of the fluid disc of negligible thickness is important to the explanatory principle because, being infinitely thin, it makes no contribution to the pressure. The idea is to calculate the pressures either side of the disc using both ends of the fluid-flow device. One, in effect, calculates the pressures by approaching the disc from two different directions. This general approach can then apply to a whole range of fluid-flow devices.

The explanatory principle, then, has the big advantage that it is not context-specific and can be used to explain the operation of the syringe and other fluid-flow devices. Consider the syringe in Figure 4 and the pressures on either side of a fluid disc of negligible thickness at the opening of the needle after the plunger has been moved back but before fluid has begun to flow. On side S the pressure is less than AP because a small sample of air at AP was expanded into a larger volume. On side S′ the pressure is (AP + h). So the pressure on side S′ exceeds that on side S and fluid moves into the syringe from high pressure to low pressure. After having dealt with this general explanatory principle which applies across a variety of devices as mentioned it is instructive to point out to nurses that, in the case of a water siphon in air, water will always siphon from the short leg into the longer leg as mentioned earlier. This latter principle, however, serves best as an observational principle rather than a general explanatory principle because it is context-specific.

The general explanatory principle outlined here, based on comparing the pressures either side of a fluid disc of negligible thickness, has been used with undergraduate nurses in their first semester of study. Whilst the students initially are inclined to explain the operation of fluid-flow devices using the "suction" principle and "ad-hoc principles" (Greive & de Berg, 1994, 1996), they eventually begin to adopt a more scientific approach once they have reviewed the concept of pressure again and see that the operation of a large number of devices can be explained using the same general principle. The approach described here has been favourably received by nursing students under these conditions. This paper highlights the fact that explanations suitable for a teaching-learning context in science often do not appear "ready-made" in textbooks and historical sources and are even less likely to appear in student responses. As illustrated in this paper, strands of ideas taken from textbooks and history may have to be woven together

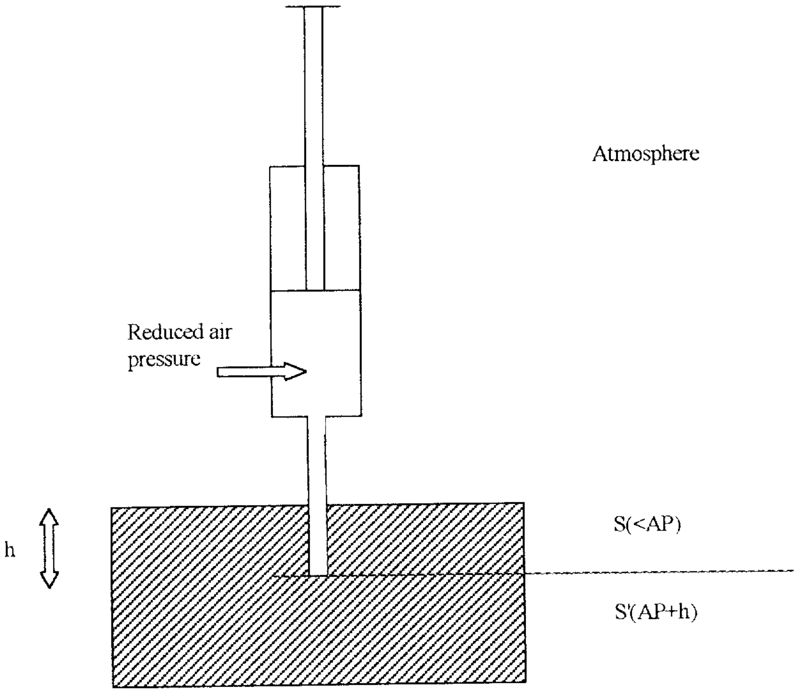


Figure 4. Pressures on either side of a fluid disc at the end of a needle of a syringe immersed to a height 'h' in a liquid

to produce an explanation that is plausible, generalisable, parsimonious, and fruitful. We have illustrated how this can be done in the case of the siphon but much more research is needed into how this can be done for many other situations encountered in science classrooms. In the case of the siphon and other fluid-flow devices there is a sense in which PCK feeds back into the subject matter and enriches it since we now view these devices somewhat more wholistically from their embodiment in PCK. The potential for PCK to enrich subject matter invites further needed research in other content areas. Explanation, as a significant component of pedagogical content knowledge, remains a much neglected area of research in science education.

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The Case of the Tammar Wallabies

Recently, conservation geneticists employed their innovative techniques to solve the strange case of the missing tammar wallabies, which is reported on the Australian Academy of Science's *Nova: Science in the News* web site (www.science.org.au/nova).

When colonial administrator Sir George Grey released a handful of tammar wallabies onto New Zealand's Kawau Island in 1870, he may have inadvertently performed a great service for conservation. The species was once widespread in South Australia, but by the early 1900s the population on mainland Australia was extinct, a victim of habitat destruction, fox predation and shooting.

Fortunately, the species itself wasn't extinct. It still persisted on some islands, including Kangaroo Island. But these populations had been separated from the mainland population for around 10, 000 years and were therefore likely to be quite different genetically. When the mainland population became extinct, the species lost a significant part of its genetic diversity.

Research by biologists at the Cooperative Research Centre for Marsupial Conservation and Management showed that the Kawau Island colony had been established with animals from the mainland population. Land managers in South Australia are now considering plans to re-introduce the animals to their original range.

For further information about
Nova: Science in the News contact Nancy Lane
02 6247 5777 or nancy.lane@science.org.au