Interactive lecture demonstration in thermodynamics

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Abstract

Physics demonstrations are often used to convey physics concepts but most students do not gain sufficient understanding when passively observing the demonstrations. This paper presents an interactive lecture demonstration (ILD) on teaching thermodynamics by using an exotic but everyday example, called pee-pee boys. This ILD was used in teaching thermodynamics at two universities in Thailand and Australia. A total of 319 student prediction sheets were analyzed and student reasoning were categorized. The results of student preference when using this ILD to teach the first law of thermodynamics are reported.

Keywords: Interactive lecture demonstrations, thermodynamics, isobaric process.

Resumen

Demostraciones de Física se utilizan a menudo para comunicar conceptos de Física, pero la mayoría de los estudiantes no obtienen suficiente comprensión cuando pasivamente observan las manifestaciones. En este trabajo se presenta una demostración de charla interactiva (ILD) en la termodinámica de enseñanza por medio de un ejemplo exótico cada día, llamado pi-pi chicos. Este LDI fue utilizado en la enseñanza de la termodinámica de dos universidades de Tailandia y Australia. Un total de 319 fichas de predicción de estudiantes fueron analizadas y el razonamiento del estudiante fue categorizado. Los resultados de la preferencia de los estudiantes al utilizar este ILD para enseñar la primera ley de la termodinámica son reportados.

Palabras clave: Demostraciones interactivas de lectura, termodinámica, proceso isobárico.

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I. INTRODUCTION

Physics demonstrations are often used in lectures to exhibit physics phenomena, to stimulate student interests and to make connection between physics principle and real experiments [1]. However, many studies provide strong evidence that students passively observing physics demonstrations gained conceptual understanding no different than those being taught with direct instruction [1, 2]. During "the traditional approach to demonstrations" [1, 3], most students often do not understand underlining concepts and incorrectly recalled what happened during the demonstrations [4].

Can student learn from demonstrations? [4]. Many studies found that an active learning [5, 6] approach to demonstrations helped student gain conceptual understanding [1, 2, 4, 7, 8, 9, 10] and promote long-term retention of knowledge [11].Instead of note taking or passively observing, students have an opportunity to actively engage with the demonstrations by predicting and discussing possible outcomes of the demonstrations before observing it. By devoting 3-5 minutes of class time to students' predictions and discussions, an instructor provides meaningful learning opportunity for improving student learning [5].

However the active learning approach to demonstrations has a limited effectiveness depending on the demonstration structure and the instructor's experience. The demonstrations which are designed based on student difficulties and misconceptions are more effective in improving student learning gain [1]. The active learning approach is not quite effective if the instructors do not have enough experience and sufficient understanding of how to implement active learning approach in teaching [12]. Therefore, we have reviewed literature and conducted studies on topics of thermodynamics, to gather enough student difficulties and misconceptions in basic laws of thermodynamics. Our main goal is to develop a demonstration that can be implemented actively, captures student interest and helps students to construct correct thermodynamic concepts. Thus in this paper, we aim (1) to show a demonstration of isobaric process using an exotic but everyday example, called pee-pee boys; (2) to identify types of reasoning that students gave in this example in Australia and Thailand; and (3) to display student preference when using the pee-pee boys in Interactive Lecture Demonstration (ILD) for the first law of thermodynamics.

II. INTERACTIVE LECTURE DEMONSTRATIONS

Interactive Lecture Demonstrations (ILDs) was developed by David Sokoloff and Ronald Thornton (1997). The ILD is an active learning approach in a lecture based model of teaching [6]. Other approaches include Peer Instruction [13] and Just in Time Teaching (JITT) [14]. The instructor spends most class time giving a lecture but asks challenging questions in between. These questions are derived from research findings to help students recognize their conflicted beliefs and misconceptions while discussing and exchanging ideas with their neighbors. However, the ILD requirs simple but thought-provoking experiments, so the instructors have to prepare equipment beforehand and that usually requires at least two instructors for team-teaching, demonstrating, posting challenging questions and keeping students actively engaged in learning. The ILDs consist of eight steps in order to give a structure underpinning active learning in lectures, as shown in Fig. 1.

Cummings *et al*., (1999) suggested reducing the eight steps, so inexperienced instructors could more easily adopt this technique. They found that the additional prediction time (step 5 in Fig. 1) was inefficient because several students lost interest and did not pay much attention. Also in some smaller class, students already interacted with their peers and an instructor, so going through the 8-steps "made discussion of common misconception awkward" [7]. They also found that a class taught with incomplete ILDs had conceptual learning gains no different to a class taught with full ILDs. Therefore, implementing interactive lecture demonstrations requires three important steps—(1) predict, (2) observe and (3) discuss [1].

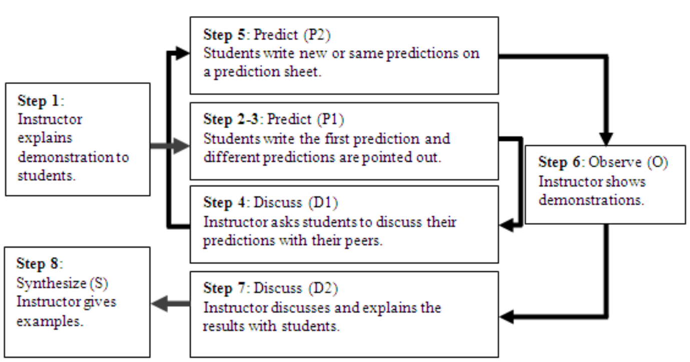

FIGURE 1. Interactive Lecture Demonstration Learning Cycle [10].

In Thailand, ILDs have been used to teach several physics topics in both high school and college levels including mechanics [15], heat and temperature [8], and thermodynamics [10]. These research studies found that student learning with ILDs significantly increased students conceptual learning gains which were assessed using measures such as the Force and Motion Conceptual Evaluation or FMCE [16], the Heat and Temperature Conceptual Evaluation or HTCE [17] and the Thermodynamic Conceptual Survey or TCS [18].

III. PHYSICS OF PEE-PEE BOYS

A clay ceramic doll, called a pee-pee boy can be found in most Chinese tea shops and used for testing if water is hot enough for making tea. Fig. 2 shows a picture of a pee-pee boy and when hot water is poured over it. To fill the doll with water, we have to submerge the doll in hot water. Air inside the doll will expand and air bubbles emerge from a hole in front of it. Then the pee-pee boy is placed in a container filled with room-temperature water. The air pressure inside the doll is much less than atmospheric pressure, so the water will be pushed into the doll. If the doll has been filled with enough water, then about 80% of the doll will be submerged under water. The doll will partly float in the room temperature water because there is some air trapped inside the doll. The doll is then ready to use as a rough thermometer for checking whether water is hot enough for making tea. There are two way to explain how the pee-pee boy works.

1) Volume expansion

When hot water is poured on the doll, heat transfers into the doll. The doll consists of clay materials, air trapped inside and water at room temperature. All of these expand when heated, but air expands more because it has the highest coefficient of volume expansion (the clay is 10^{-6} K^{-1}, the water (at 20ºC) is 0.207×10^{-3} K^{-1} and air is 3.67×10^{-3} K^{-1}). Also, air is trapped at the top of the doll, so when pouring hot water, most heat transfers to air which expands. Air pushes water out of the hole as it is expanding, so we see water shooting out of the hole in front of the doll. Based on the thermal expansion relationship, volume expansion is $\Delta V = \beta V_0 \Delta T$, where β is the coefficient of volume expansion, V_0 is an initial volume and ΔT is the temperature difference [19]. If there is a larger temperature difference (ΔT), then air expands even more or ΔV is larger. Thus the volume of water shooting out will be greater as a result.

2) The first law of thermodynamics

When pouring hot water onto the doll, heat transfers to it. If we consider the air as a thermodynamic system, then the heat transfers into the system or the heat transfer (Q) is positive. The system also does work by pushing water which is inside the doll to come out of the hole, so the work done by the system (W) is positive. A change in internal energy (ΔU) is positive because the system will reach thermal equilibrium at a higher temperature. This process is considered to be isobaric because the system is under constant atmospheric pressure.

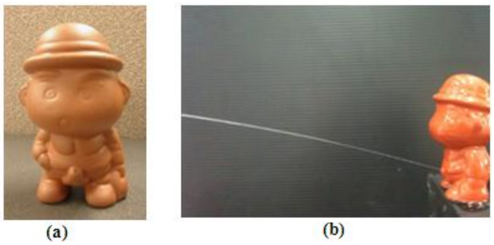

FIGURE 2. (a) a pee-pee boy or a clay doll (b) a doll after pouring hot water on it.

IV. METHODOLOGY

This pee-pee boy ILD was implemented in both Thailand and Australia. Fig. 3 shows the apparatus which includes four filled pee-pee boys, hot water with red color, cold water with blue color, and ice-cold water to submerge two pee-pee boys in. The prediction sheet is included in the appendix. In second semester of 2009, we used thermodynamic ILDs when teaching Physics I at Chiang Mai University, Thailand. We had developed four ILDs including pee-pee boys, isobaric process, isothermal process and adiabatic process. In 2011, three ILDs had been translated and implemented in teaching a thermodynamic module for Regular physics at the University of Sydney, Australia. Data were collected from two sources:

- **Prediction sheet:** There were a total of 224 Thai student responses and 95 Australian student responses. The sheets were analyzed in terms of student reasoning on the first law of thermodynamics. The students' reasoning on the prediction sheets were analyzed and categorized by one of the researchers. Then another researcher performed the analysis based on the first researcher's categories. Then both researchers compared their analysis and discussed the discrepancies of their analysis resulting in common categories.
- **Student survey:** The survey consisted of two parts. The first part consisted of 18 Likert-scale statements and the second part consisted of 4 open-response questions. The survey aimed to capture data on student experiences of the ILDs. The results from the Likert-scale items are provided below in Fig. 4 and Table III, regular gradations apply with 1 as strongly disagree, 5 as strongly agree and 3 as neutral. The results are separated into Thai and Australian data.

FIGURE 3. Apparatus for the pee-pee boys ILD.

V. RESULTS AND DISCUSSIONS

The results are presented and discussed in two parts. Student predictions were analyzed and are discussed in section 5.1. Student opinions on using the pee-pee boys as one of the ILDs presented is compared with other ILDs in section 5.2.

Student predictions

In this part, the completed prediction sheets were analyzed in two dimensions—student predictions and their reasoning, as shown in Table I. Students were asked to make their predictions and provide their reasoning before observing Demonstration 1 and Demonstration 2 as follows:

Demonstration 1. Ceramic dolls A and B contain room temperature water. When pouring hot water on ceramic doll A and room temperature water on ceramic doll B, which ceramic doll will have water shooting out from the hole in front? Please explain your reasoning.

Demonstration 2. Ceramic dolls C and D containing water were submerged in ice-cold water until they were are at thermal equilibrium with the cold water. When pouring hot water on ceramic doll C and room temperature water on ceramic doll D, which ceramic doll will have water shooting out from the hole in front? Please explain your reasoning.

TABLE I. Student predictions and reasoning on Demonstration 1 and 2. There were 224 responses from Thailand and 95 responses from Australia. (* indicates correct answers).

Reasoning		*Student predictions*			
		Demonstration 1		*Demonstration 2*	
		*Only A**	*Both A and B*	*Only C*	*Both C and D**
Correct explanation	Thai	30%	0%	15%	3%
	Aus.	39%	0%	7%	25%
Incorrect explanations					
pressure	Thai	26%	0%	4%	26%

depends on temperature	Aus.	41%	0%	11%	30%
large temperature differences	Thai	29%	0%	2%	13%
	Aus.	15%	0%	8%	17%
Other reasoning	Thai	15%	0%	23%	14%
	Aus.	5%	0%	4%	0%

In the first part of this ILD, student reasoning were analyzed and categorized into two types, as shown in Table I. We describe these incorrect explanations in detail in the following section.

Pressure depends on temperature

For both demonstrations, most students made correct predictions but provided incorrect reasoning. Most reasoning of Australian students indicated that pressure depends on temperature, for example:

> "Temperature of the air inside the doll increases. This increases the pressure of the air, ejecting water".
>
> "When hot water is poured over it, the air heats up increasing air pressure in the doll, forcing the water out of the doll".

Student making their predictions based on this type of reasoning clearly relating pressure with temperature has been documented in previous literatures [20, 21]. When using this reasoning, students often visualize the system consisting of gas molecules. When the system is heated up, gas molecules move faster and hit a container wall more often, so gas pressure increases [21] and they strongly relate pressure with temperature so that they forget to consider a change in gas volumen [20]. The instructor aware of this mental image that most students have with pressure and temperature is advised to point out to students that there are actually three variables in these demonstrations—temperature, volume and pressure. Also the system pressure is considered to be constant because the hole in front makes the system pressure at equilibrium with the atmospheric pressure.

Large temperature differences

Another reasoning categorized as "large temperature differences" was considered to be unclear because students did not provide enough wording to justify their reasoning. Most Thai students provided reasoning in terms of large temperature difference causing water to shoot out. It might be that they based their predictions on volume expansion but they did not explain it well by writing. However, we cannot categorize this reasoning as correct because many students who answered "the large temperature difference between dolls and environment", also answered incorrectly that only doll C had water shooting out. This indicate that they might have some misunderstanding that only a really large temperature difference will make the water come out. However in case of doll D, the temperature difference is about 20ºC and the water is still shooting out slightly.

TABLE II. Student responses to questions 3-5 in terms of work, heat transfer and change in internal energy. (* indicates correct answers).

Reasoning		*Answers*			
		*positive**	*negative*	*No answers*	*zero*
Work done by the system (*W*)					
correct or partially correct explanation	Thai	55%			
	Aus.	67%			
incorrect explanation Increasing pressure pushes the water out	Thai	1%	5%		1%
	Aus.				1%
Other reasoning	Thai	12%			
	Aus.	4%			
No explanation	Thai			26%	
	Aus.	4%		24%	

TABLE III. Student responses to questions 3-5 in terms of work, heat transfer and change in internal energy. (* indicates correct answers).

Reasoning		*Answers*			
		*positive**	*negative*	*No answers*	*zero*
Heat transfer (*Q*)					
correct or partially correct explanation	Thai	66%			
	Aus.	23%			
incorrect explanation					
heat causes temperature to rise	Thai		12%		
	Aus.	8%			
Other reasoning	Thai		16%		
	Aus.	3%	2%		
No explanation	Thai		2%		4%
	Aus.	52%	3%	9%	
Reasoning		*Answers*			
		*positive**	*negative*	*No answers*	*zero*
Change in internal energy (ΔU)					
correct or partially correct explanation					
Temperature increases	Thai	20%			
	Aus.	7%			
Using the first law equation	Thai	22%			
	Aus.	10%			4%
incorrect explanation					
Increasing pressure causes an internal energy to	Thai	15%			
	Aus.				

increase					
Other reasoning	Thai		14%	9%	2%
	Aus.				
No explanation	Thai	12%			6%
	Aus.	10%	10%	23%	36%

For the second part of the prediction sheet, students had to justify three thermodynamic quantities of the system—work, heat transfer and a change in internal energy after students observed the demonstrations. Student reasoning were analyzed, as shown in Table II and III. In general students answered correctly that all three quantities are positive and provided correct explanations. However, several students provided incorrect reasoning as follows:

Increasing pressure pushes water out

A few students overlooked a change in volume causing the work done by the system to be positive. They thought that the pressure increased so that air pushed water to shoot out. This is similar to "pressure depending on temperature" reasoning that we found in students' explanation in the first part.

Heat transfer causes temperature to rise

Most students answered and explained heat transfer of the system correctly. They reasoned that heat transfers from an environment to the system because the system is at lower temperature than the environment. This type of reasoning agrees with a definition of heat that "heat is energy that is transferred from one system to another because of a difference in temperature" [19]. However, several students thought that heat transfer caused temperature to rise as follows: "Air temperature goes up, so the heat transfer is positive".

A few students also used an equation $Q = mc\Delta T$ as part of their reasoning. This indicates that a few students might still think of "heat and temperature as the same thing" [22], "temperature is the amount of heat" [23] or "Heat is a quantity consisting of a change in temperature" [24].

Increasing pressure causes an internal energy to increase

When asking about the change in internal energy of the system, many Thai students answered correctly that the change in internal energy was positive but they provided incorrect explanation. They related pressure with an internal energy. These were students who also used "pressure depends on temperature" reasoning in the first part of the prediction sheet. They related pressure with temperature, and then they connected pressure with an internal energy.

Therefore an instructor needs to clearly explain that an increase in temperature does not necessarily imply an increase in pressure because it depends on external conditions. The instructor can use a constant pressure situation, as shown in Fig. 4, to work out and confirm his/her point. Pressure of a gas inside the system relates with a force exerted on a piston. It is easier to understand why pressure stays constant even when temperature increases. Also it is easier for an instructor to explain the situation of constant pressure in term of a free body diagram, as shown in the figure. The forces acting on the piston are the same, so the force from air pressure has to be the same.

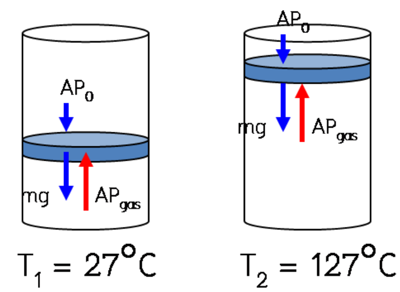

FIGURE 4. A situation of constant pressure with an increase in temperature.

Student surveys

Student surveys were administered at the end of the thermodynamic module and included 4 items asking students to rate ILDs as the most favorite, the least favorite, understand the most and understand the least. The student responses were analyzed and plotted comparatively, as shown in Table IV. Majority of Thai and Australian students thought that the pee-pee boy ILD were their most favorite and they understood it the most. They also provided some responses that

"Interesting to see practical application of physics".

"It was fun and easy to understand the 1st law".

"Very well explained after attempting to hypothesize the reason. Made a lot of sense about the expansion of air".

These results from both parts of the survey indicated that students found the pee-pee boys ILD to be exceptionally interesting and they learned about the first law of thermodynamics as well. Therefore, the pee-pee boys ILD is a stimulating and engaging teaching materials for the first law of thermodynamics.

TABLE IV. Thai and Australian (Aus.) student opinions on four interactive lecture demonstrations (ILD).

ILDs		*Student opinion*			
		most favorite ILD	*least favorite ILD*	*understand the most*	*understand the least*
Pee-pee boy (isobaric)	Thai	70%	6%	48%	4%
	Aus.	68%	4%	47%	2%
Movable syringe (isobaric)	Thai	3%	12%	11%	16%
	Aus.	12%	7%	16%	12%
Fog in a bottle (adiabatic)	Thai	6%	19%	8%	19%
	Aus.	16%	15%	3%	26%
Simple heat	Thai	6%	22%	8%	20%

engine (cyclic)	Aus.	12%	38%	10%	39%

VI. CONCLUSIONS

In this paper, we present a way to implement pee-pee boys as an interactive lecture demonstration. Using the pee-pee boys ILD gives an opportunity for students to explicitly present their reasoning. Our analysis on data from two universities indicated that students often used several dominate misconceptions as their reasoning such as pressure depends on temperature and heat causes temperature to rise. When these misconceptions are identified, an instructor needs to discuss with students making them realize the limitations of their misconceptions. From the questionnaire, students found the pee-pee boys ILD to be interesting and exhibiting the first law of thermodynamic quite well. This ILD can be also employed at either college or high school physics in order to present an exotic example of the first law of thermodynamics.

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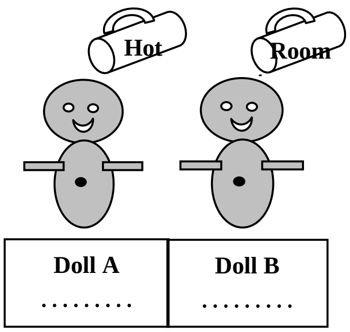
APPENDIX

Demonstration 1. Ceramic dolls A and B contain room temperature water. When pouring hot water on ceramic doll A and room temperature water on ceramic doll B, which ceramic doll will have water shooting out from the hole in front? Please explain your reasoning.



Reasoning
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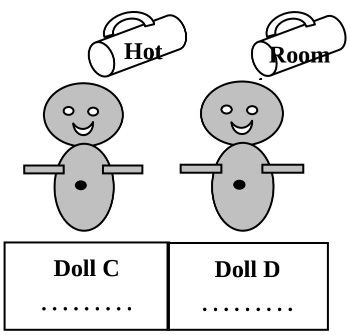
Demonstration 2. Ceramic dolls C and D containing water were submerged in ice-cold water until they are at thermal equilibrium with the cold water. When pouring hot water on ceramic doll C and room temperature water on ceramic doll D, which ceramic doll will have water shooting out from the hole in front? Please explain your reasoning.



Reasoning
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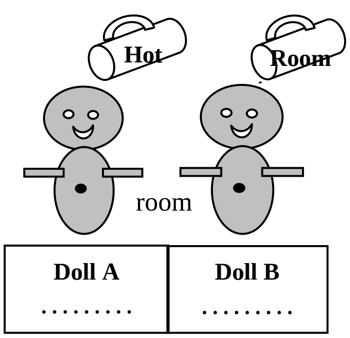
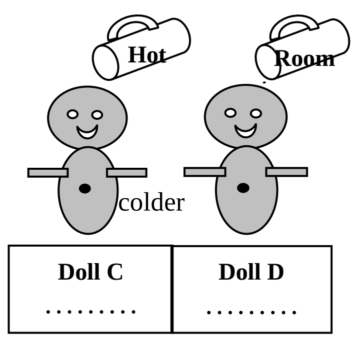
2. Write down the results of demonstrations for ceramic dolls A, B, C and D. Please explain your reasoning.





3. When the water is shooting out of the doll, is work done by the system (ΔW) (positive, negative or zero)? Please explain your reasoning.

4. When the water is shooting out of the doll, is heat transfer between the system and the environment (ΔQ) (positive, negative or zero)? Please explain your reasoning.

5. When the water is shooting out of the doll, is the changed in internal energy of the system (ΔU) (positive, negative or zero)? Please explain your reasoning.

6. This process is called