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A visual, intuitive and engaging approach for explaining the concept of feedback in control systems

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Abstract

One of the main challenges in teaching a basic level Control Systems class is that many students consider it to be "just another math course", without comprehending the connection to engineering. Part of the reason is textbooks' lack of basic experience-based intuitive explanations, resulting in a disconnect to real-life physical examples. Students may get good grades in the Control Systems class but at the same time may miss some basic essential concepts, such as modeling, stability, and the true meaning of feedback.

In this paper we explain the concept of feedback using visual, intuitive, and engaging daily experience-based examples. The paper is an effort to help students understand the true meaning of feedback beyond the "line" in the block diagram. In addition, the paper tries to explain the physical meaning of the "subtraction unit" in the closed-loop block diagram and how the difference between the output and the input that results in an error signal looks like in real systems. We address cases in which there is no specific sensor, and the error is obtained directly without an "official" subtraction, as well as real-life cases where the desired reference point is not known, and where the sensing element is not clearly visible.

We present an approach that may help students reach the physics/engineering "aha" moment prior to delving into the math. The examples are focused on visual intuitive, and experience-based feedback systems where sometimes the connection to traditional textbook block diagrams is not obvious.

The examples are grouped into three categories:

1. Mechanical examples, including (a) Balancing bird, where gravity-based feedback keeps the bird balanced at a specific orientation, (b) Roly-Poly toy, where gravity-based feedback leads to a steady state equilibrium, and (c) Flush Toilet, self-contained feedback mechanism to achieve desired water level.

2. Electrical and Electromechanical examples, including (a) the use of Bi-metal to explain sensing, error and action in A/C, Car Blinker, and Kettle, (b) Buzzer, to explain feedback based on switching/oscillating between two positions, (c) Operational Amplifiers to explore the meaning of the feedback resistor, (d) DC Motor, where the sensing, feedback, desired value, and error value are all very clear.

3. Human-in-the-loop examples, including (a) Escalator, using visual feedback to compensate for the escalator motion, when attempting to move up an escalator while the escalator is moving down, (b) Autonomous Driving, to explain sensing, error, and action signals,

and (c) Broom stick, where the desired end position is not known a-priori, but the feedback error signal is automatically generated.

The paper also suggests a set of exercises for students. The goal is to help students to further capture the essence of sensing, feedback, and error signals in real systems.

The contents of this work have been shared and assessed with students in “Control Systems 1”. The presentation was assessed following the lecture using an anonymous questionnaire. Initial results from 28 responses indicate that the students preferred being introduced to the topic in a visual and intuitive manner, and they highly commended the approach.

The examples and activities as shown in this paper are intended to be supplemental to traditional presentations, and by no means to replace existing textbook or other pedagogical methodologies.

Keywords

Control Systems, Control loop, Feedback, Error signal

Introduction

After many years of teaching "Control Systems 1" course at Florida Atlantic University my colleagues and I have observed conceptual misunderstanding of some topics. We noticed that some students, while doing very well in assignments, quizzes, and tests, are missing understanding of basic key concepts. Apparently, material that we think is very well presented in class, based on well-known textbooks, is not clear to students. This is undoubtedly a shift from two or more decades ago. Information is too conceptually abstract for some, making the class "just another math class", with little relevance to engineering. Simple concepts such as feedback is "just another line" in the block diagram, and the subtraction element is not clearly connected to real systems. In addition, many students have turned away from textbook-based learning, relying more on visual and intuitive methods, such as short videos from multiple internet sources. Based on our observations in engineering classes, many instructors have not modified their teaching to adapt to students' new learning preferences. Instead, they stick to textbook-style presentation of the material.

This paper focuses on addressing some of the most fundamental elements and signals in feedback control systems using basic visual and intuitive examples. The emphasis is on better explanations of the concept of feedback, the subtraction element, and the error signal of basic feedback systems. Based on our experience, it appears that simple, experience-based examples are needed prior to digging into the math, i.e., examples that are meant to enhance students' comprehension, development of intuition, and increase their interest in learning the idea of feedback.

In this paper we share examples that we have used in our control classes. They are divided into three categories: Mechanical, Electrical/electromechanical, and human-in-the-loop. The visual examples are followed by a set of exercises intended for students to explore and analyze feedback systems. The exercises are meant to enhance students' comprehension of the big picture, system-level, understanding block diagram of processes, focusing on how feedback works, and how feedback can minimize the error over time. Students may notice cases where the subtraction is not obvious, the reference may not be known, the sensing is "invisible", as well as cases where identifying the controller and the plant is not obvious.

The material presented in this paper *is not meant to replace existing textbooks chapters*. It is just an attempt to better introduce and explain the concept of closed loop control system. We have tested the approach a few times and received very positive feedback. This work has been shared with students and its validity assessed using an anonymous questionnaire. Initial results based on 28 responses, detailed in the Appendix, show that this teaching method is effective in helping students understand basic concepts related to feedback control systems. Overall, students felt that understanding the concept of feedback was important, as seen in their responses to question 1. They also felt that learning feedback systems through visual examples (question 2 and 3), hands-on activities (question 4), and in-class exercises (question 5) were important, while general views on learning through techniques such as traditional presentations (question 6 and 7) and reading relevant textbook material (question 8) were more mixed. Soon, this work will be presented to a larger group of students learning feedback control systems, and their responses will be assessed through more rigorous assessments.

We would like to refer the reader to references that address different types of introductions to control systems. This is of course in addition to the very many well written control systems textbooks. A good collection of examples of feedback systems, many of which are very visual can be found in [1], and [5] is a good reference for introducing topics and concepts in feedback control systems. In fact, some illustrations in this paper have been borrowed from [5] with permission. [6] is a very well explained historical, mostly mechanical, set of examples of feedback control systems. The first Automatic Self-Regulatory Device is described well in [2], and [3] does very well in describing different control systems such as the 1958 Chrysler cruise control, centrifugal governors. Reference [7] describes teaching feedback control systems using visual gaming and programming. A highly relevant book to this paper is [8] in which there are several examples, including liquid weighing station, feeding station for chickens, spring based mechanical scale, pressure control, and water level control. The paper [9] can serve as a good reference for visually introducing the most basic concepts in control systems.

This paper focuses on some elements of feedback control systems as seen in figure 1. Specifically, it focuses on a) feedback element and feedback signal, where the output variable of the system is usually measured by a feedback element, fed back, and subtracted from the desired input, b) subtraction element that results in an error signal.

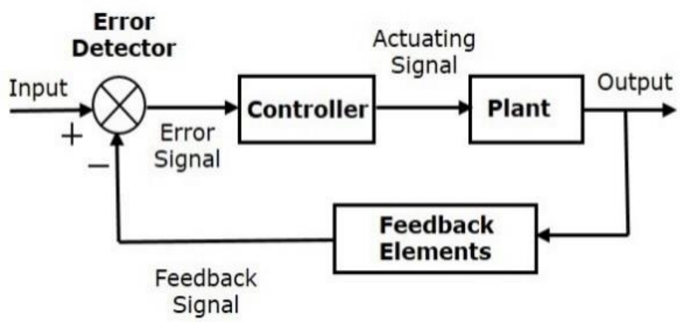


Figure 1: Close loop diagram of a control system

Examples

The following three groups of examples are divided into three categories: Mechanical, Electrical/electromechanical, and human-in-the-loop.

Group 1: Mechanical examples

<u>Example 1: Balancing bird</u>

Balancing bird is an example of a basic mechanical feedback control system designed to keep the bird balanced at a specific orientation (figure 2).

The center of gravity below the beak causes the bird to be stable/balanced at an equilibrium point. Any deviation from this point moves the center of gravity to a higher point (see orange arrow), leading to a non-zero moment that tends to bring the bird back to equilibrium. A basic block diagram that describes the balancing process is illustrated below (figure 3).

The orientation error is obtained naturally without knowing or measuring the actual bird orientation and without knowledge of the orientation at equilibrium. The orientation error causes moment error which in turn causes the bird to move towards equilibrium.

Figure 2: Balancing bird

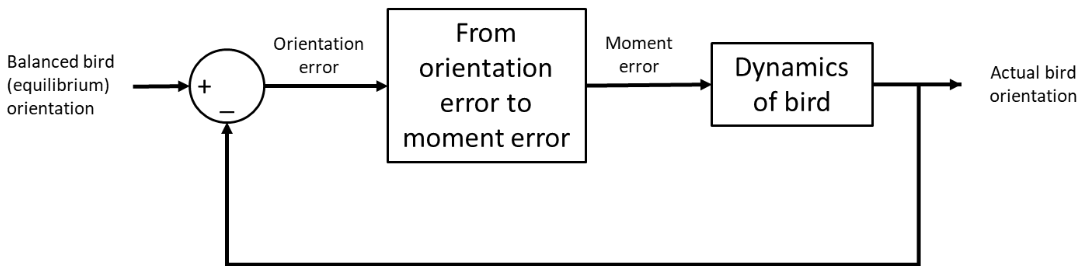


Figure 3: Block diagram of the balancing bird

<u>Example 2: Roly-Poly toy</u>

Refer to figure 4. The roly-poly toy is designed in such a way that its center of gravity is at its lowest in the upright position. Any deviation from this equilibrium orientation causes the center of gravity to move higher and away from the point of support due to its inclination away from the upright position. This shift creates a moment that tends to move the toy back towards the vertical orientation. It rolls back and forth until resting at the standing upright position.

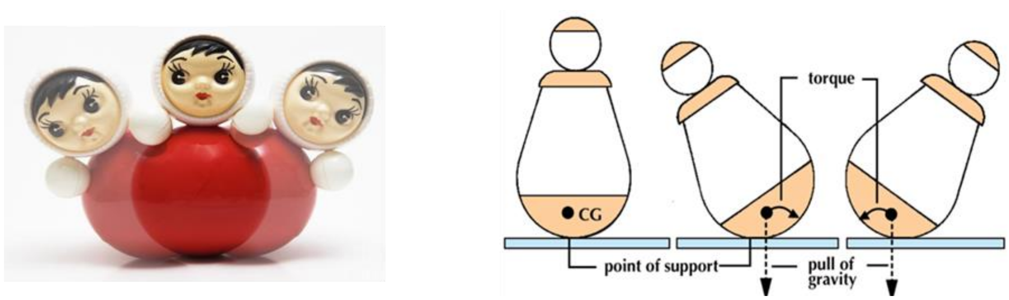


Figure 4: Roly-poly toy

Image sources: https://fineartamerica.com/featured/roly-poly-toy-giphotostock.html
https://kids.britannica.com/students/assembly/view/53661

Refer to figure 5. In terms of feedback control, the desired position (reference input) is upright. The actual angle due to an initial external disturbance may not be vertical. This difference causes the center of gravity to shift horizontally and vertically, leading to a horizontal shift "d" between the center of gravity (CG, which is the same as the center of mass CM) and the point where the doll touches the surface. This in turn generates a non-zero moment which is proportional to the distance "d" by a factor of "k" that tends to move the doll back toward its upright position. The non-zero moment changes the actual angle of the doll until it reaches an equilibrium. At this point the error angle becomes zero. In this example there is no "sensor" that measures the actual angle, and there is no "feedback line" in real life. The desired orientation, the actual orientation and the subtraction are all one natural "built in" unit. A note that can be shared with students: A different design, for example where the center of gravity is placed higher, may lead to an increasing error over time causing the doll to fall. This is the case of instability.

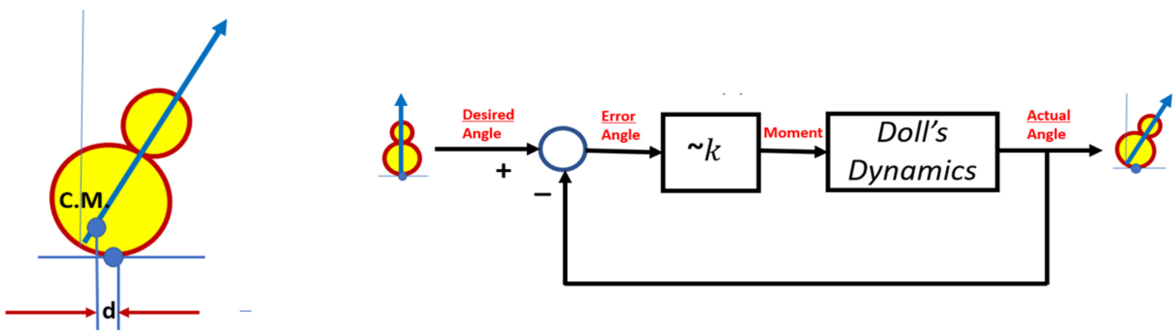


Figure 5: Roly-Poly system diagram

Example 3: Flush toilet mechanism

The Toilet: A mechanical closed loop system

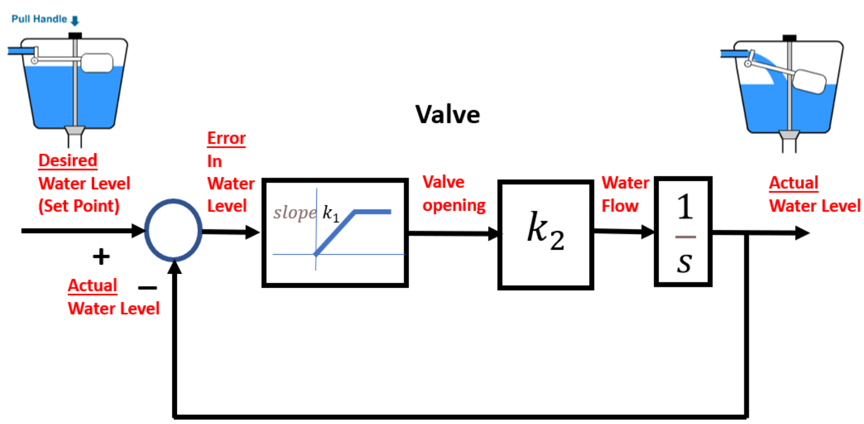


Figure 6: Flush toilet mechanism system diagram

Refer to figure 6. After flushing the toilet, the water level is lowered along with the float device, thereby opening the valve, allowing the water to flow into the tank. This process continues until the valve is shut off again. During this process, the float device is sensing the water level and provides mechanical feedback to the system through lifting the lever, thereby closing the valve.

Group 2: Electrical and electromechanical examples

<u>Example 1: Bimetal controller</u>

Air conditioning system.

Let's examine a cooling system that uses feedback. An air conditioning system has a thermostat: a component of a control system that senses the ambient temperature and compares it to a desired pre-set temperature. Based on the difference of the two temperatures, the thermostat switches the cooling device on or off, to regulate and maintain a certain temperature. An A/C system with a thermostat is a closed loop system, i.e., it utilizes feedback to achieve a desired temperature. An oversimplified version of an A/C system is shown in figure 7. Note the feedback and the subtraction of the two temperatures, that is usually done using a bimetal sensor.

Thermostats, kettles, and car blinkers share the same bimetal sensor (figure 8). It is a way to measure temperature. The sensor translates temperature to mechanical motion/bending then to a binary on/off decision. If it deflects above a certain threshold, it disconnects a circuit. Figure 9 illustrates a closed loop feedback system using a bimetal sensor.

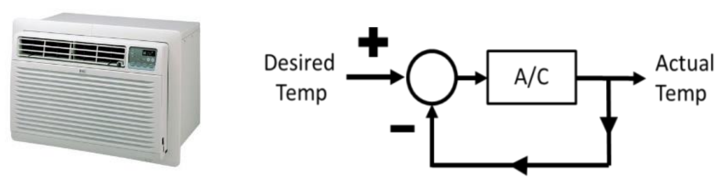


Figure 7: A/C system

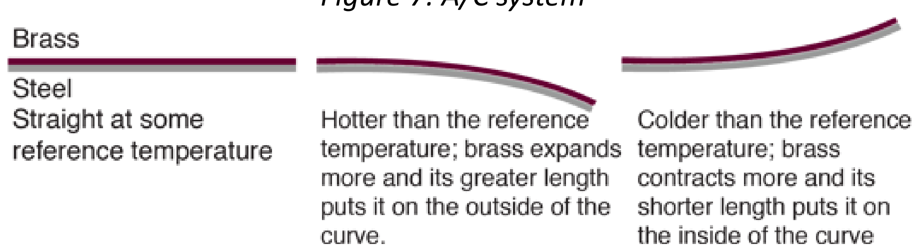


Figure 8: Bimetal principle of operation

Image source: http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/bimet.html

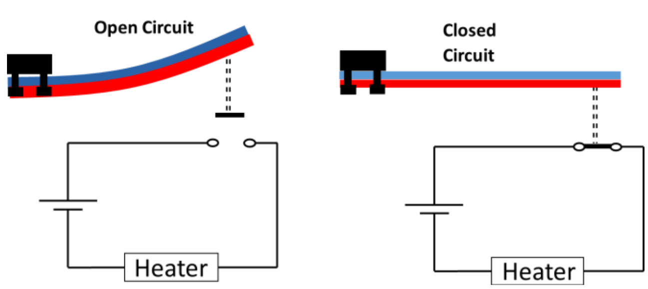


Figure 9: Heater system using bimetal

Example 2: Buzzer

In a buzzer, an electromagnet is used to electromechanically and repeatedly self-interrupt a circuit. In a way we can view it as a set of semi-binary operations ("binary pulses") that open and close an electric circuit repeatedly, leading to a series of buzzes that collectively cause the buzzing sound of the bell.

In the case where the battery is continuously connected to the circuit: if the circuit is closed (as in figure 10), the electromagnet pulls up the contact arm. This arm movement breaks the bell circuit (i.e., makes it "open circuit" as in the right of figure 10) which shuts off the electromagnet. This process repeat itself to become the familiar buzzer noise.

Figure 11 shows the feedback control system of the buzzer. Note the output, subtraction element and the binary error that controls the electromagnet.

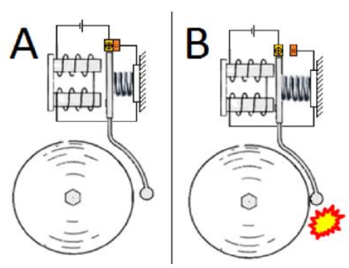


Figure 10: Buzzer

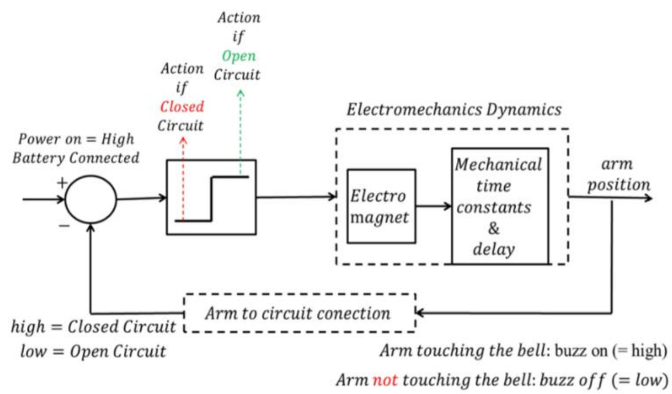


Figure 11: Buzzer system block diagram

Example 3: Operation amplifier

An operational amplifier is an integrated circuit with two inputs and one output. Basically, a voltage amplifying device designed to be used with electronic components, such as resistors and capacitors. Figure 12a is also known as inverting op-amp with the block diagram shown in figure 12b, which is one way to describe the close loop system [3]. We used superposition to obtain an expression for the error voltage. The feedback here is clear: for a positive input, this inverting op-amp multiplies the negative output by a scale factor.

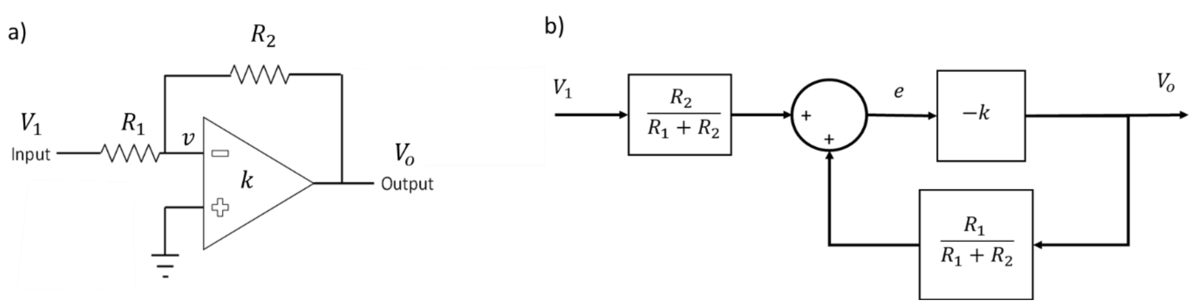


Figure 12: Operational amplifier

Example 4: DC motor

DC motors are used in countless devices where precision is required in the motion of mechanisms, for example in actuators to control the steering wheel of autonomous vehicles, when moving aircraft ailerons, or when positioning the nozzle in 3D printer.

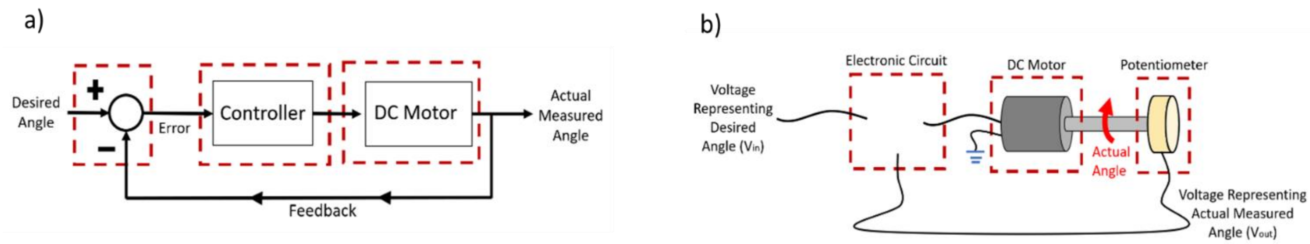


Figure 13: DC motor block diagram

Refer to figure 13. A DC motor is shown as part of a closed-loop control system. Ideally, we would like to subtract the output angle from the desired input angle (figure 13a). Practically, the angle is measured with a potentiometer that converts the output position angle to a voltage signal (figure 13b). Using feedback, this voltage signal is fed back and compared with the voltage signal corresponding to the desired angle position. The difference between the two voltages, i.e., the error signal, serves as the input to the motor. Eventually the error signal becomes zero.

Group 3: Human-in-the-loop examples

Example 1: Moving escalator

This example shows the use of visual feedback error to compensate for the escalator motion when attempting to move up an escalator while the escalator is moving down (figure 14).

A person is trying to move up the steps of an escalator while the escalator is moving down. The person's goal is to keep the desired distance $\boldsymbol{x_o}$ constant. The actual distance is $\boldsymbol{x}$ and the error is the difference between the two. At some point the person finds the right speed so the location $\boldsymbol{x}$ becomes very close to $\boldsymbol{x_o}$.

In figure 15 the actual location $\boldsymbol{x}$ is continuously subtracted from the desired location $\boldsymbol{x_o}$ to generate an error signal. This error signal is translated to the person's speed (by a scale factor $\boldsymbol{K}$). This speed is integrated to become the actual location $\boldsymbol{x}$.

This is an example that can helps students understand the concept of negative feedback.

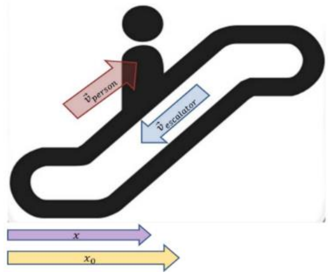


Figure 14: Moving escalator

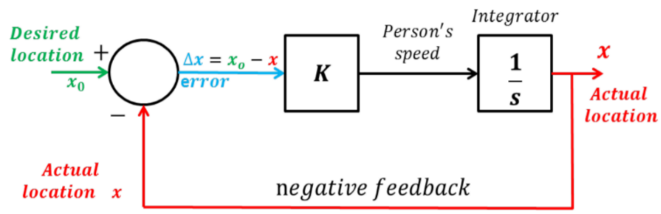


Figure 15: Diagram of the system for a person moving on an escalator

Example 2: Driving

As drivers, we sense, compare, decide, and act. A driver senses the environment using vision and compares the actual direction and speed of the car to the desired velocity, followed by decisions and actions.

The process of sensing and acting on the decisions can be represented using a block diagram. The driver controls the car's pedals (acceleration and braking) and the steering wheel, causing the car to change its speed and heading. In figure 16 only the speed control is shown. The error signal is the difference between the desired speed and the actual speed. This error is desired to be zero.

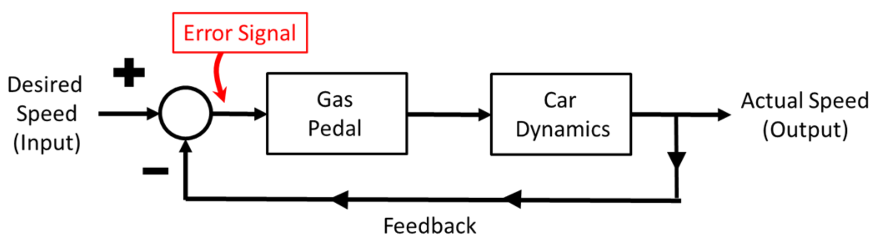


Figure 16: Speed control system

Example 3: Broom stick

The following engaging example is a great experiment to illustrate negative feedback.

Balance a broom on your outspread forefingers as shown in figure 17a. Now start to move your fingers towards each other until they come together. They will end up touching each other and the broom will balance (figure 17b).

Even if you change the initial position of your fingers, the result will always be the same. This is an example of negative feedback that happens naturally. The fingers alternate in motion until they touch each other. Note that during the experiment only one finger moves, it is the one that experiences less friction due to a lower vertical force. This action continues until the friction between the broom and the moving finger equals or slightly exceeds the friction of the other finger. At this point only the other finger moves. The process repeats itself until the fingers touch each other, in the vicinity of the center of gravity.

a) b)

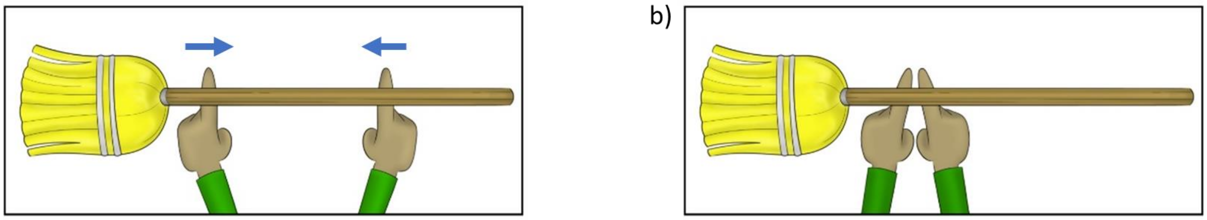


Figure 17: Broom experiment

Exercises for students

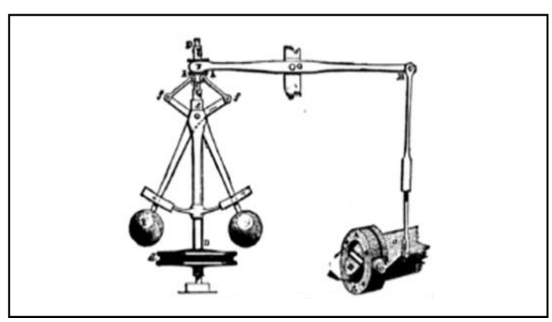
The purpose of this section is to provide students with multiple questions so that they explore mechanical processes that include feedback. We expect students to research each process and come up with solutions to several tasks.

For each one of the examples, the following are specific questions/tasks that students may be asked

- Describe the process
- Draw a qualitative system-level block diagram that explains the process
- What is the input?
- What is the output?
- What is the error signal?
- How is the error signal being measured?
- How does the system minimize errors over time?
- What is the error after a very long time?
- Explain how the feedback works

Vietnam water

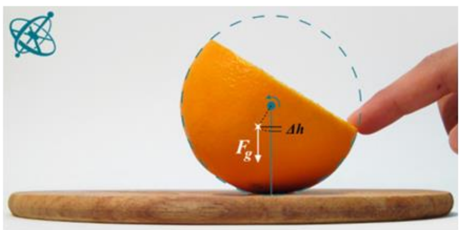
Universal governor



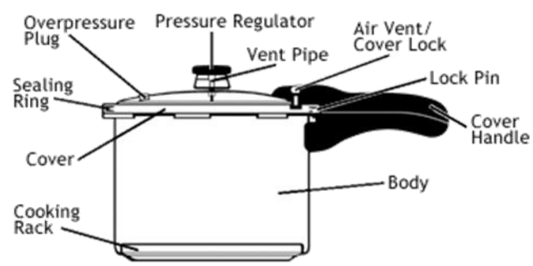
Windmill fantail

Windsock

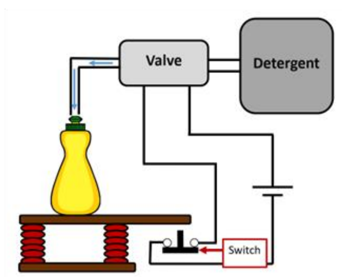
Swinging fruit



Pressure Cooker



Liquid weighting station



Rolleron

Conclusion and future work

In this paper we presented several mostly non-textbook examples attempting to introduce and explain the concept of feedback using a non-traditional approach. This set of visual and intuitive examples focuses on explaining the basic concept prior to delving into math formulas. They are meant to be supplementary in nature and by no means to replace textbook chapter examples. They are followed by a series of problems for students that can serve as homework assignments. It turned out that examples with mechanical elements are attractive and more engaging to students. Initial assessment is very encouraging. Students praised the approach and we decided to further develop and expand it. We hope that instructors may choose some of them while teaching the topic as necessary to enhance students' comprehension of the topic. The concept of feedback is part of a larger set of concepts in Control Systems that we have tried to teach differently over the past few years attempting to modify our teaching to better relate to students' learning preferences.

Acknowledgements

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References

[1] Lewis, F., *Applied Optimal Control & Estimation: Digital Design & Implementation*. Prentice Hall and Texas Instruments digital signal processing series. Prentice Hall. 1992.

[2] Normans, J., "*Ctesibius Builds the First Truly Automatic Self-Regulatory Device*". History of Information.com. https://www.historyofinformation.com/detail.php?entryid=2306.

[3] Åström, K. and Murray, R., *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton University Press. 2010.

[4] Wieringa, J., *Representativeness of Wind Observations at Airports*. Bulletin of the American Meteorological Society 61 (9), 962–971. 1980, September.

[5] Raviv, D., Roskovich, G. and Noguera, P., *Understood: A Visual and Intuitive Approach to Teaching and Learning Control Systems*. Understood Series. CreateSpace Independent Publishing Platform. 2014.

[6] Bennett, S., *A History of Control Engineering*, 1930-1955. United Kingdom: P. Peregrinus, 1993.

[7] Coller, B. D*., A video game for teaching dynamic systems and control to mechanical engineering undergraduates*. In Proceedings of the 2010 American Control Conference, pp. 390–395. IEEE. 2010.

[8] Karniel, B., Artzi, G. and Barak, M., *Introduction to Control (In Hebrew)*. The Centre for Educational Technology. The Open University. Ramat Aviv. Israel. 2009.

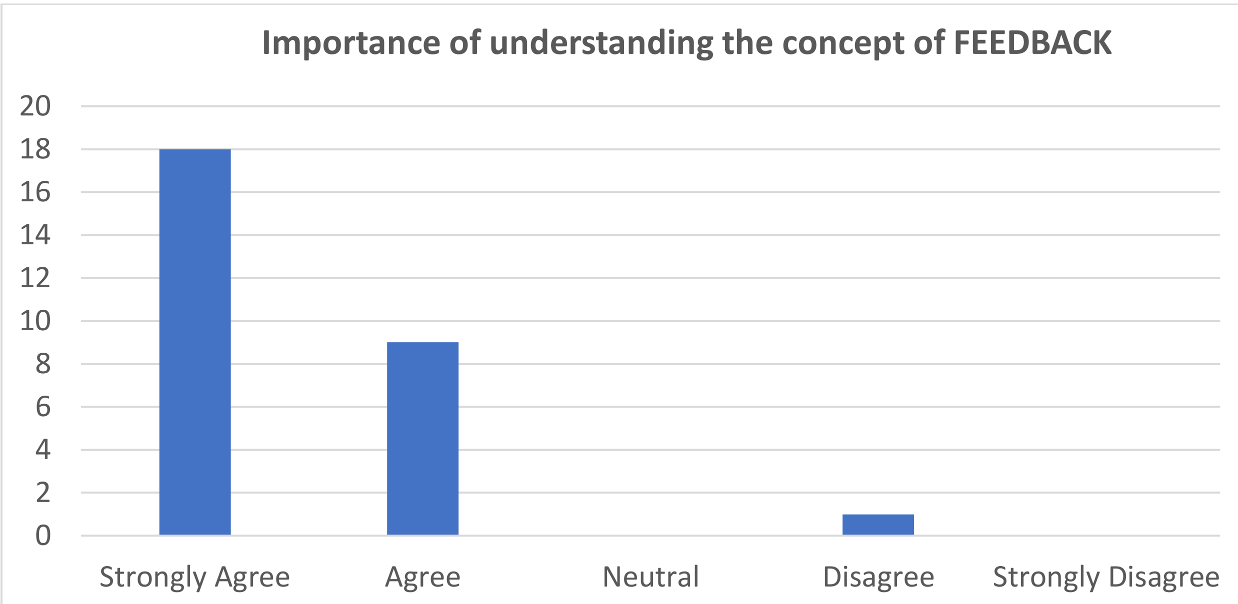
[9] Raviv, D. and Roskovich, G., *An intuitive approach to teaching key concepts in control systems*. In 2014 ASEE Annual Conference & Exposition, pp. 24–173. 2014.

[10] Perelman, Y., *Physics for Entertainment*. Number bk. 2. Hyperion Books. 2008.

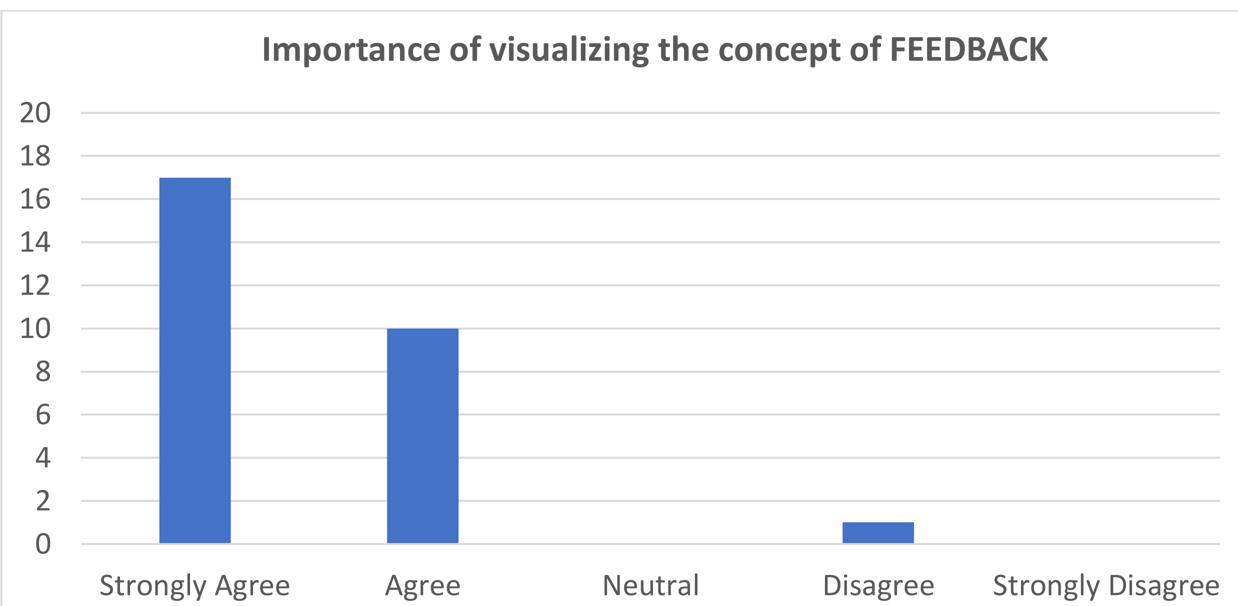
Appendix: Assessment

The vertical axes on the graphs refer to the number of students.

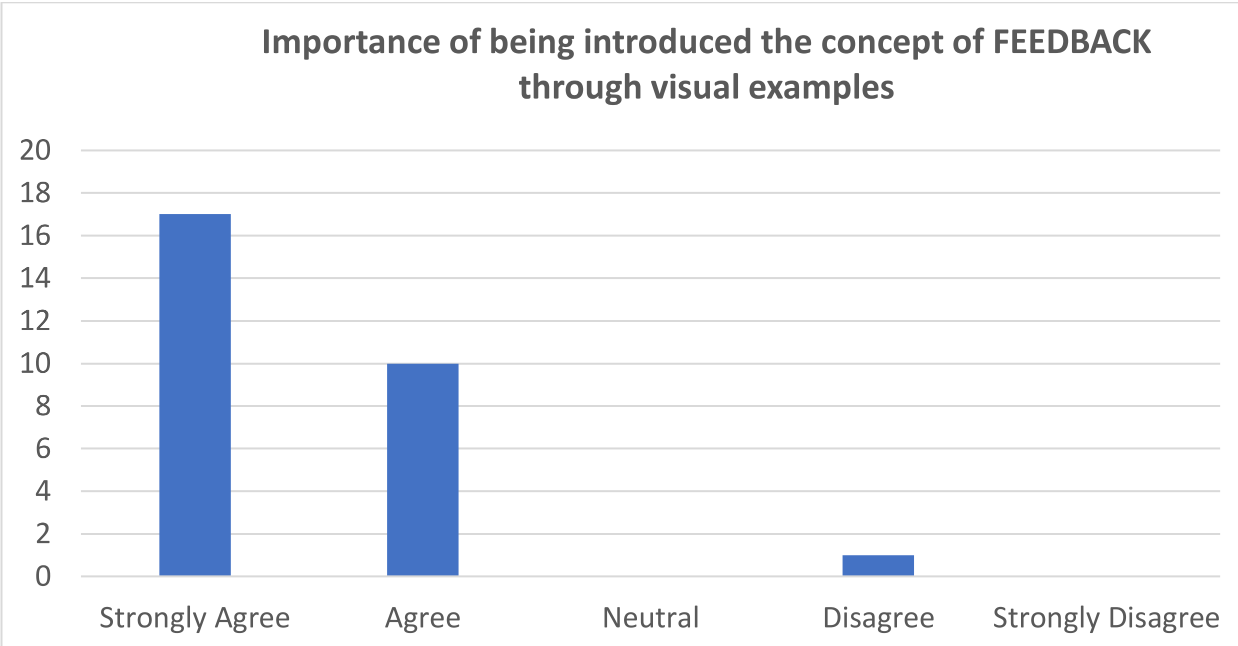
Question 1



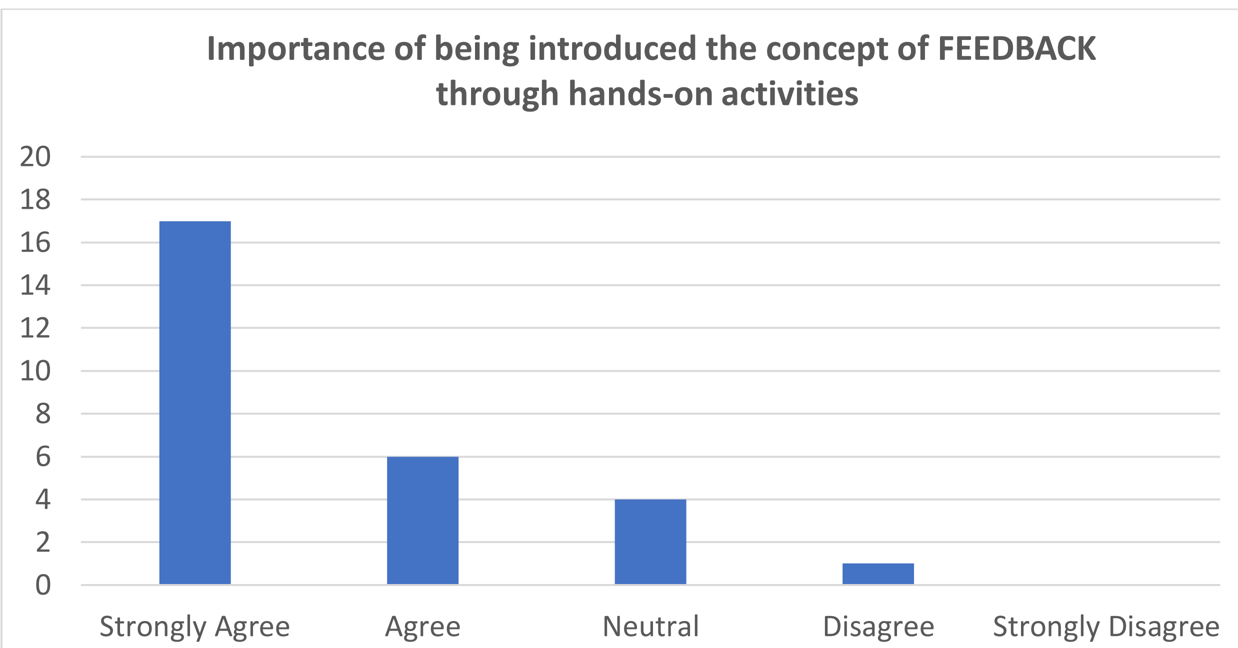
Question 2



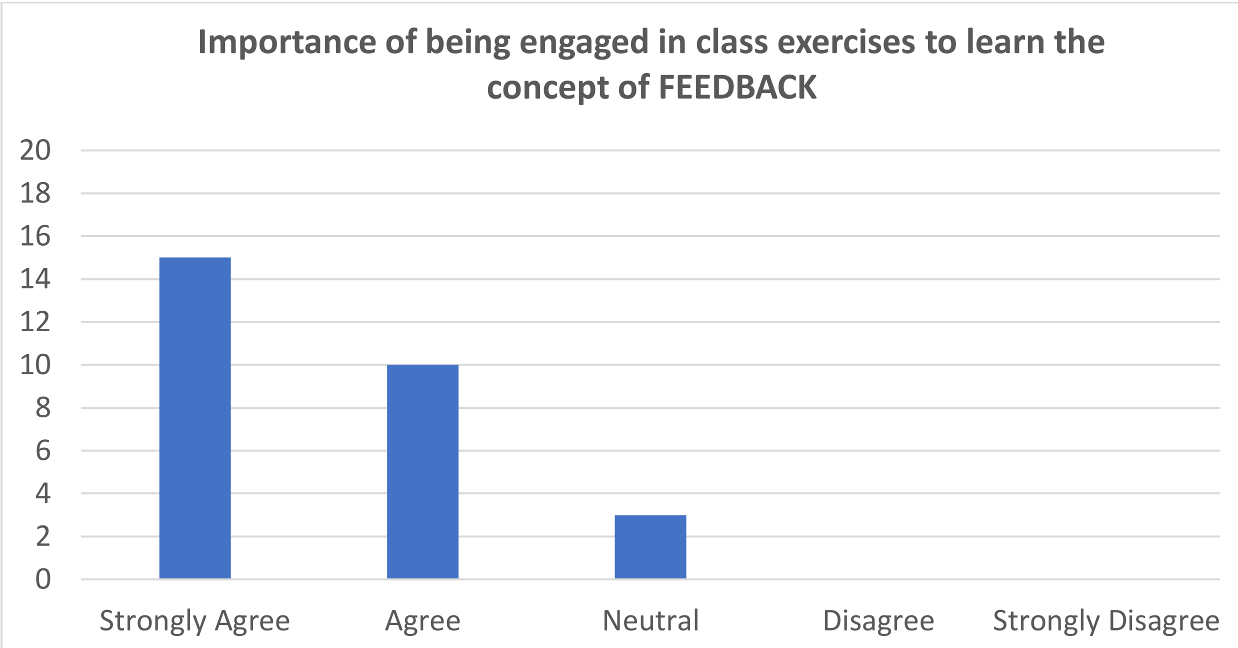
Question 3



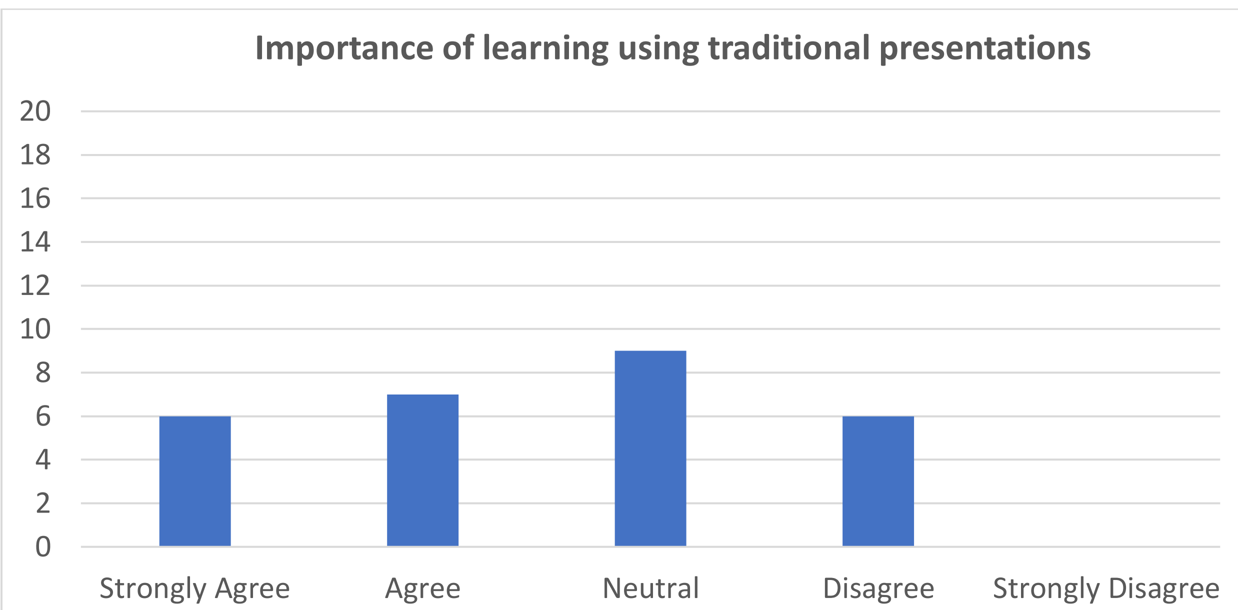
Question 4



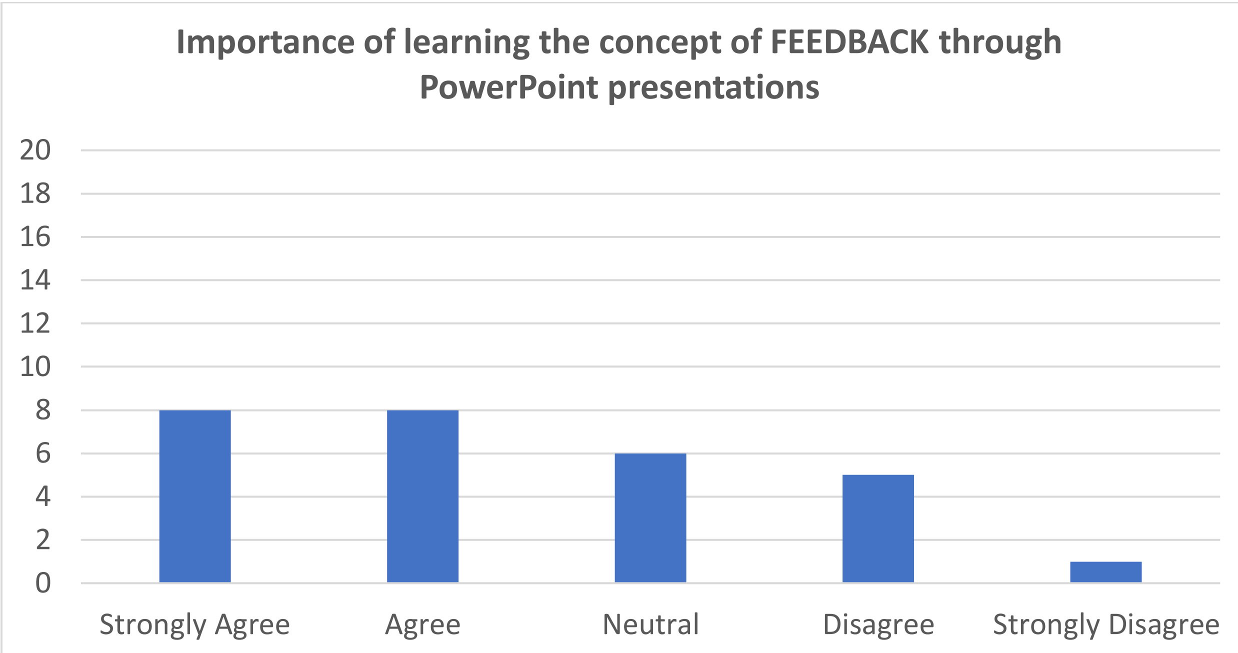
Question 5



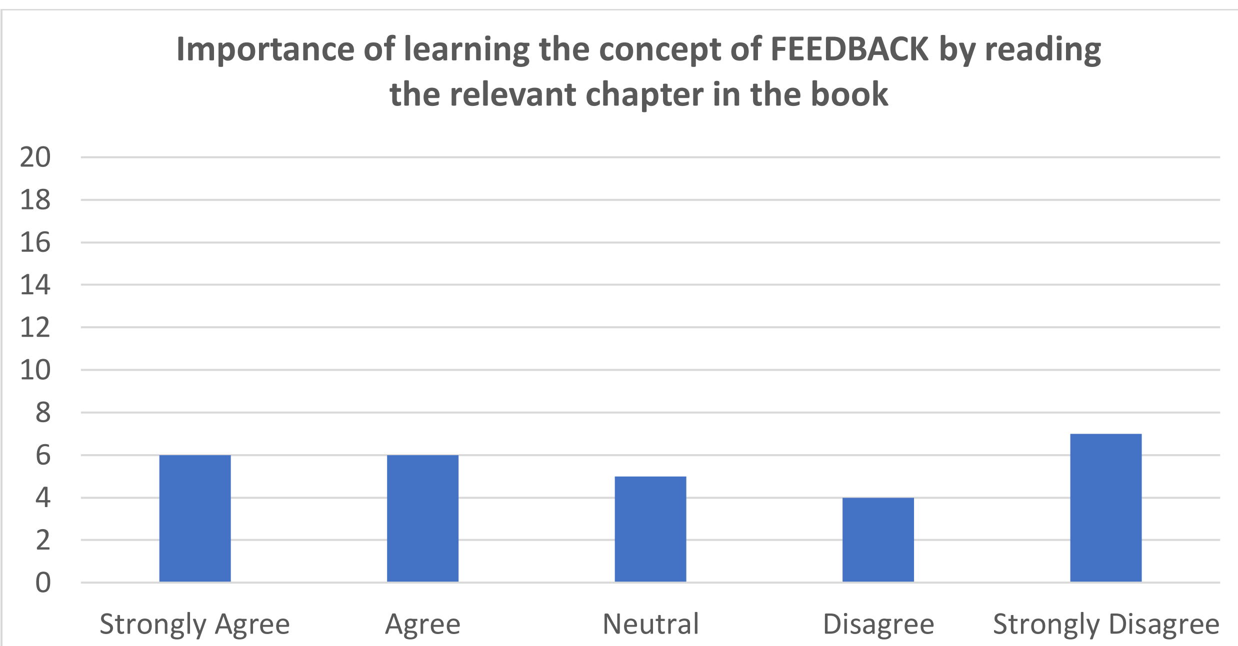
Question 6



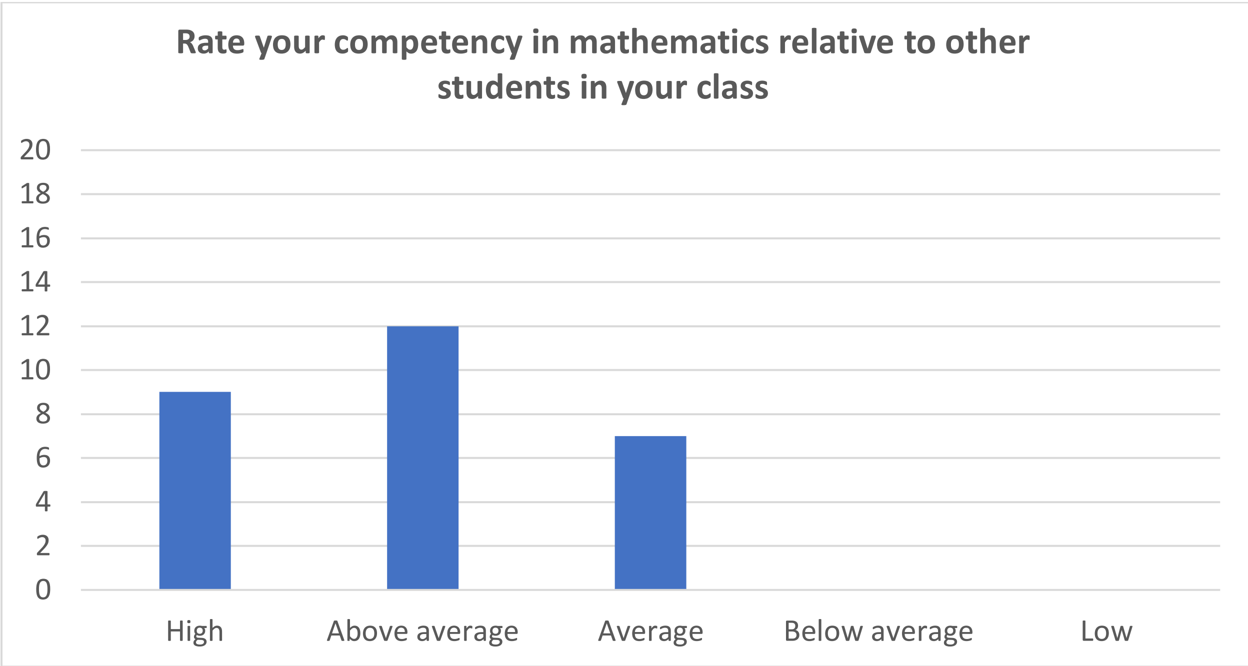
Question 7



Question 8



Question 9



Question 10