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Insights Into Global Engineering Education After the Birth of Industry 5.0

Edited by Montaha Bouezzeddine

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Meet the editor

Montaha Bouezzeddine received a DiplEng in Networks and Communication Systems, a master's in Engineering Research (I-MARS) from INSA Rennes, France, in 2012, and a Ph.D. in Electrical Engineering from the University of Duisburg-Essen, Germany, in 2018. From 2012 to 2017, she worked as a research engineer at RheinMain University of Applied Sciences, Germany, on the design of multiport antenna systems for mobile communications. Between 2017 and 2019, she worked at Telit on the design of Bluetooth and BLE hardware, then at Kathrein Automotive (now, Continental) on the design of antennas for automotive applications and at Ford Company as a technical consultant. In October 2019, she joined Fraunhofer IZM where she is currently a research engineer. Her research interests include MIMO antennas, antenna arrays, millimeter-waves, tunable and reconfigurable antennas, characteristic modes theory, antennas for automotive applications, IoT, and adaptive tuning and digital control. Dr. Bouezzeddine was the recipient of the ESoA Best Student Paper Award at EUCAP 2016 and received honorary awards in the 2016 student Feko competition and RADIO conference 2016. She is also a reviewer for several international journals.

Contents

Preface

Insights Into Global Engineering Education After the Birth of Industry 5.0 presents a comprehensive overview of recent developments in the fields of engineering and technology education. It includes seven chapters complete in itself but directly related to the book's topics and objectives.

The book includes chapters dealing with the topics of engineering education 5.0, node-RED, teaching IIoT through hands-on activities, fusion skills and industry 5.0, communication protocols, digital skills, engineering education of holism, using ICT and energy technologies for improving global engineering education, autopoiesis, project-based learning, educational innovation, classroom humor, misconception, science assessment.

The target audience comprises scholars and specialists in the field.

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Chapter 1

The Multi-Tier Instrument in the Area of Chemistry and Science

Habiddin Habiddin and Septiana Ayuningrum Nofinadya

Abstract

Knowledge of students' unscientific understanding before learning a new topic known as students' preconception or prior knowledge is vital for helping the teacher design a proper teaching strategy. Meanwhile, knowledge of students' understanding after teaching will provide a way for a teacher to evaluate the effectiveness of his/her teaching. For these reasons, science educators should investigate students' understanding over time. Studying students' understanding requires a proper and powerful tool/instrument such as a multi-tier instrument. This paper describes the history of multi-tier instruments initiated by the two-tier and recently became a five-tier instrument, the procedure to develop the instrument, and how to utilize the instrument to identify students' unscientific understanding. Our recent study describing the development of a four-tier instrument of electrolyte and non-electrolyte solution (FTI-ENES) is presented.

Keywords: multi-tier instrument, four-tier instrument, three-tier instrument, two-tier instrument, five-tier instrument, unscientific understanding, misconception, science assessment

1. Introduction

Investigating students' in-depth understanding, mainly their unscientific knowledge, has been carried out for decades. Teachers' knowledge of students' understanding, including their prior knowledge or preconception and understanding after teaching, is valuable. Knowledge regarding students' preconceptions is essential in assisting educators in providing effective teaching and learning. Many studies have proved the contribution of students' prior knowledge to their teaching success [1, 2]. Several instruments have been used for uncovering students' conception in science, including concept mapping [3], interviews [4], and the multiple-choice test [5, 6]. A proper and effective instrument must be utilized to investigate students' understanding. A typical instrument such as a multiple-choice question (MCQ) cannot uncover a deep understanding [7] in science, particularly students' unscientific understanding/misconceptions. It has been revealed that the previous instruments have some disadvantages. Concept mapping relies on students' ability to master vocabulary [8], while the interview is time-consuming [9]. For multiple-choice questions, students' test-wiseness skills [10] could affect their reliability and validity indices, and the reason for students' answers cannot be fully uncovered [11]. Also, the role of guessing is often dominant in a multiple choice question [12].

Due to those previous instruments' disadvantages, the multi-tier format's diagnostic tool has recently been one of the most frequent instruments applied in science education studies. Our previous study [13] investigated the instrument used in the study involving students' understanding of chemistry and other science disciplines (biology and physics) covered in Indonesian journals. We revealed that multi-tier instruments, particularly four-tier instruments, have been the most accepted instrument and widely applied by Indonesian researchers in identifying students' unscientific understanding.

In this paper, several terminologies, including students' conception, students' understanding, students' scientific understanding, students' scientific knowledge, students' unscientific understanding, and misconceptions, are found. Students' conception reflects students' ideas and mental processes regarding natural phenomena. The ideas could be relevant or irrelevant to the concept accepted by the scientific community [14]. For this reason, the terminology of students' conception and students' understanding are interchangeable in this paper. The ideas which adhere to the concept accepted by the scientific community are called scientific knowledge. In contrast, those different from a view taken by the scientific community are called unscientific understanding.

The incorrect idea harbored by any particular person has been described in several different terminologies in the scientific literature, including wrong knowledge, misconception, erroneous ideas, unscientific understanding, alternative conception, misunderstanding, erroneous concepts, naïve idea, alternative frameworks, naïve concept, misinterpretation, and oversimplifications. Although these terms are interchangeable, the "unscientific understanding" is preferred in this paper because it reflects the nature of students' incorrect ideas or concepts.

2. The development of multi-tier instrument: the chronological perspective

2.1 Two-tier instrument: The milestone of multi-tier instruments

The use of multi-tier instruments in science education was initiated by Treagust [15], investigating students' unscientific understanding in particular. The example of the two-tier instrument applied in such an instrument's initial development is provided in **Figure 1**.

The first-tier at the initial format portrayed in **Figure 1** consists of a multiple-choice question (MCQ) with only two options (one correct answer and one incorrect answer). This MCQ with a two-options format is quite uncommonly applied in science assessment, common in at least four options. The second tier consists of four statements covering the reasons for students' answers to the first-tier. The four reasons consist of one valid or scientific reason and three wrong or unscientific reasons. The combination of students' incorrect answers and the incorrect reason is the basis for revealing students' unscientific understanding or misconception. All incorrect reasons in the reason tier are composed based on students' actual unscientific understanding obtained from preliminary tests, interviews, and literature. The next generation of the two-tier instrument has employed a more standard MCQ in the first-tier, as depicted in **Figure 2**.

This two-tier format has been applied to investigate students' conception in many science education research including Tan et al. [16] in inorganic chemistry, Tuysuz [17] in Separation of Matter, Griffard & Wandersee [18] in Photosynthesis, Chandrasegaran et al. [9] in Chemical reaction, Peterson et al. [5] in covalent bonding, Tyson et al. [19] in chemical equilibrium, Adadan & Savasci [20] in solution chemistry and many others.

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Water (H_2O) and hydrogen sulphide (H_2S) have similar chemical formulae and have V-shaped structures. At room temperature, water is a liquid and hydrogen sulphide a gas. The difference in state between water and hydrogen sulphide is due to the presence of strong intermolecular forces between

(1) H_2O molecules (2) H_2S molecules

Reason

(*a*) The difference in strength of the intermolecular forces is due to differences in the strength of the O–H and S–H covalent bonds.

(*b*) The bonds in H_2S are easily broken, whereas in H_2O they are not.

(*c*) The difference in strength of the intermolecular forces is due to the difference in polarity of the molecules.

(*d*) The difference in strength of the intermolecular forces is due to the fact that H_2O is a polar molecule, and H_2S is a non-polar molecule.

Figure 1.
Example of the two-tier instrument developed by Treagust [15].

When powdered zinc is added to blue aqueous copper(II) sulfate and the mixture shaken, the blue colour of the solution gradually fades and it becomes colourless. At the same time a reddish-brown deposit is produced.
The chemical equation for the reaction that occurs is,

$$Zn(s) + CuSO_4(aq) \rightarrow ZnSO_4(aq) + Cu(s),$$

while the ionic equation is, $Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)$.

Why did the solution finally become colourless?

A Copper has formed a precipitate.
B Zinc is more reactive than copper(II) sulfate.
C The copper(II) sulfate has completely reacted.
D Zinc has dissolved, just like sugar dissolves in water.

The reason for my answer is:

1 Zinc ions are soluble in water.
2 Zinc loses electrons more readily than copper.
3 Soluble, blue Cu^{2+} ions have formed insoluble, reddish-brown copper atoms.
4 In aqueous solution Cu^{2+} ions produce a blue solution, while Zn^{2+} ions produce a colourless solution.

Figure 2.
Example of the next generation of the two-tier instrument developed by Chandrasegaran et al. [9].

2.2 Three-tier instrument

After being applied in many studies, science education researchers realized that the two-tier instrument has deficiencies. Students selected the correct answer and correct reason randomly without holding a scientific reason to the relevant concept on certain occasions. The role of guessing and the actual unscientific understanding are difficult to be differentiated in a two-tier instrument [21, 22].

To overcome the two-tier instrument's drawback, a three-tier instrument was developed with the additional confidence rating tier, as shown in **Figure 3**. The third-tier requires students to state whether they are sure or unsure of their answer and reason. A correct answer and reason with a sure expression imply a scientific understanding. Meanwhile, an incorrect answer and reason with a sure expression imply an unscientific understanding or misconception. An incorrect answer and reason with an unsure expression imply that the incorrect answer is not a result of

The ozone layer,

a. Protects the Earth from acid rain.
b. Filters the ultraviolet (UV) rays of the sun.
c. Helps to keep the Earth's temperature stable to make it livable.

Which one of the following is the reason for your answer to the previous question?

a. The ozone layer absorbs the sun's ultraviolet (UV) rays which is potentially damaging to life on the Earth.
b. The ozone layer prevents sun rays to exit from the atmosphere, consequently keeps it warm enough to live.
c. The ozone layer works as a kind of shield, so it does not let acid rain to reach the Earth's surface.
d. ....

Are you sure about your answer given to the previous two questions?

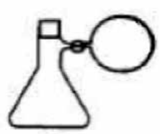
a. Yes.
b. No.

Figure 3.
Example of a three-tier instrument developed by Arslan et al. [23].

misconception or unscientific understanding; instead, it lacks knowledge or guessing. This aspect distinguishes the three-tier format and the previous format. The same pattern of the three-tier instrument portrayed in **Figure 3** has been used in the following studies [11, 24, 25].

The subsequent development of a three-tier instrument utilized a more flexible confidence rating with a broader range of confidence, as displayed in **Figure 4**. This pattern seems to have been influenced by the standard confidence rating scales applied in many four-tier instruments that had been published before this three-tier work was carried out.

1.1



The system shown on the left figure represents a closed flask connected with a balloon and filled with air at 40 ^{0}C. If the temperature of the system was decreased from 40 ^{0}C to 5 ^{0}C, how would the volume of the balloon change? (Atmospheric pressure is 1 atm for both temperatures.)

A) It would decrease.
B) It would not change.
C) It would increase.

1.2 Which one of the followings is the reason of your answer for the previous question?

A) If the temperature was decreased, air particles in the system would shrink.
B) If the temperature was decreased, the pressure in the system would decrease.
C) If the temperature was decreased, the pressure in the system would increase.
D) If the temperature was decreased, the distance between air particles would decrease.
E) Atmospheric pressure is constant.
F) ....

1.3 How sure you are about your answers for the previous two questions?

	Unconfident						Confident
Confidence Rating:	1	2	3	4	5	6	7

Figure 4.
Example of a three-tier instrument developed by Aydeniz et al. [26].

2.3 Four-tier instruments

The confidence rating index (CRI), which is only attached to the third tier of the three-tier instrument, leads to an unclear message whether students have the same or different confidence levels between their answer and their reason [23]. For this reason, many science education researchers developed and applied the four-tier instrument. The first-tier, called Answer-tier (A-tier), consists of MCQ with several options (commonly 4). The second tier is the confidence rating for the A-tier. The third-tier, which is called Reason-tier (R-tier), consists of several statements with one correct statement relevant to the selected answer and several unscientific statements. The fourth-tier is the confidence rating for the R-tier.

The confidence rating index (CRI) for A-tier and R-tier ranged from 1 (just guessing) to 6 (absolutely confident). This more comprehensive range was then adopted for some studies that utilize three-tier instruments, as shown in **Figure 4**. In our recent works [7], we prefer to apply five scales of confidence rating instead of 6 scales (**Figure 5**).

Using five scales of CRI provides better clarity in differentiating students' level of confidence ratings. For example, the difference between 'confident' [4], 'very confident' [5], and 'absolutely confident' [6] in a six scales CRI format is quite challenging to be recognized. However, 'quite confident' [4] and 'very confidents' [5] in 5 scales format is more comfortable to be understood. When a student is 100% sure of his/her answer, he/she will state very confident. Meanwhile, when he/she is not 100% sure of his/her answer, he/she will state quite confident. 'Average' [3] is used to express an equal portion of sure and unsure, which is not available in the six scales format. 'Very unconfident' [1] is used to express 100% unsure, including guessing or absolutely no knowledge regarding the concept. While 'not very confident' [2] is used to express an unsure reason with a small portion of feeling that his/her answer may be correct. For this reason, we suggest using five scales of CRI instead of 6 scales (**Figure 6**).

The current development of a multi-tier instrument is a five-tier instrument published by Anam et al. [28], with the additional fifth tier in which students are required to provide a draw/pictorial representation of his/her answer. This

Consider a real gas placed in a container. If intermolecular attractions were to disappear suddenly, which one of the following is likely to occur?

Answer

(a) the pressure decreases
(b) the pressure increases (*)
(c) the pressure remains the same
(d) the gas expands

Confidence Rating for Answer:

1	2	3	4	5	6
Just Guessing	Very Unconfident	Unconfident	Confident	Very Confident	Absolutely Confident

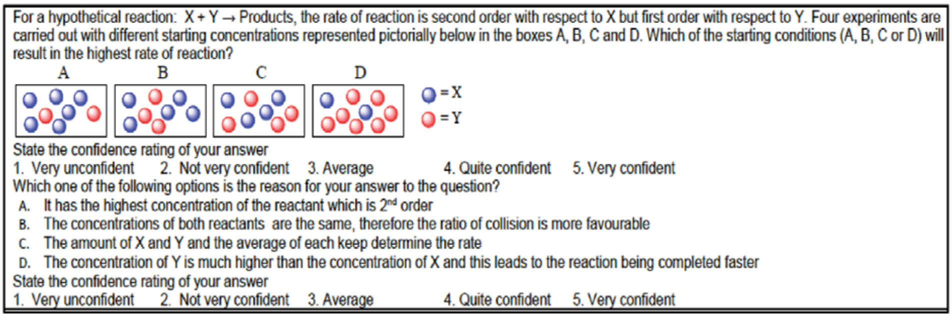
Reason

(a) the gas molecules are further away from each other
(b) the frequency of collisions of the molecules with the walls of the container increases (*)
(c) the gas molecules will have more freedom to move around
(d) It will behave more like an ideal gas,

Confidence Rating for Reason:

1	2	3	4	5	6
Just Guessing	Very Unconfident	Unconfident	Confident	Very Confident	Absolutely Confident

Figure 5.
Example of four-tier instrument with six confidence ratings [27].


For a hypothetical reaction: X + Y → Products, the rate of reaction is second order with respect to X but first order with respect to Y. Four experiments are carried out with different starting concentrations represented pictorially below in the boxes A, B, C and D. Which of the starting conditions (A, B, C or D) will result in the highest rate of reaction?

State the confidence rating of your answer

1. Very unconfident 2. Not very confident 3. Average 4. Quite confident 5. Very confident

Which one of the following options is the reason for your answer to the question?

A. It has the highest concentration of the reactant which is 2nd order
B. The concentrations of both reactants are the same, therefore the ratio of collision is more favourable
C. The amount of X and Y and the average of each keep determine the rate
D. The concentration of Y is much higher than the concentration of X and this leads to the reaction being completed faster

State the confidence rating of your answer

1. Very unconfident 2. Not very confident 3. Average 4. Quite confident 5. Very confident

Figure 6.
Example of four-tier instrument in chemical kinetics with five confidence ratings [7].

additional drawing will ensure the mental model of the students can be uncovered. Even though the work in a five-tier instrument is still limited, we believe that it offers a more powerful tool in this regard. A pictorial tool is supported by psychology cognitive theory that helps students solve a multistep task [29].

3. The procedure in developing a multi-tier instrument

Treagust [15] proposed the two-tier instrument development is the fundamental development of the next generations of multi-tier instruments, including three-tier and four-tier instruments. Treagust [15] employed ten steps with three board categories in developing a two-tier instrument. The first four steps are named *defining the content*. Steps 5, 6, and 7 are named *obtaining information about students' misconceptions*. The last three steps are named as *developing a diagnostic test*. The steps are:

1. Identifying proportional knowledge statements
2. Developing a concept map
3. Relating proportional knowledge to the concept map
4. Validating the content
5. Examining related literature
6. Conducting unstructured student interviews
7. Developing multiple-choice questions with free responses
8. Developing the two-tier diagnostic tests
9. Designing a specification grid
10. Continuing refinements

When we developed a four-tier instrument in the area of chemical kinetics named FTDICK [7], we simplified the procedure to be six steps as the following. This procedure is applicable to developing multi-tier instruments.

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3.1 Step 1: Mapping concept

In this step, several essential concepts in a particular topic are identified concerning the concept's scope in the relevant curriculum. For example, when we developed a four-tier instrument to identify secondary school students' understanding of thermochemistry, the competence mastery indicator document (Indikator Pencapaian Kompetensi, IPK) in the syllabus for Indonesian chemistry secondary school was considered. System and surrounding, enthalpy, exothermic reaction, and endothermic reaction are essential concepts in the Indonesian curriculum. When we developed a four-tier instrument of chemical kinetics for first-year chemistry students, university students' chemistry curriculum was considered. Rate law, the relation between reactant concentration and time, temperature and rate, activation energy, and reaction mechanisms are essential concepts for first-year university students.

3.2 Step 2: Developing the multiple-choice question with free responses (MCQ-FR)

Each essential concept should be represented by two or more questions to ensure that it reflects all the competence and knowledge that should be mastered at the concept. **Figure 7** below depicts an example of MCQ-FR in the concept of chemical kinetics, particularly rate law and the relation of concentration and rate.

3.3 Step 3: Validating the MCQ-FR

Before it is used to collect the preliminary data, the content of MCQ-FR, the relevance with curriculum, and language clarity are assessed to get feedback from some experts in the field. This feedback will be the basis to revise the MCQ-FR.

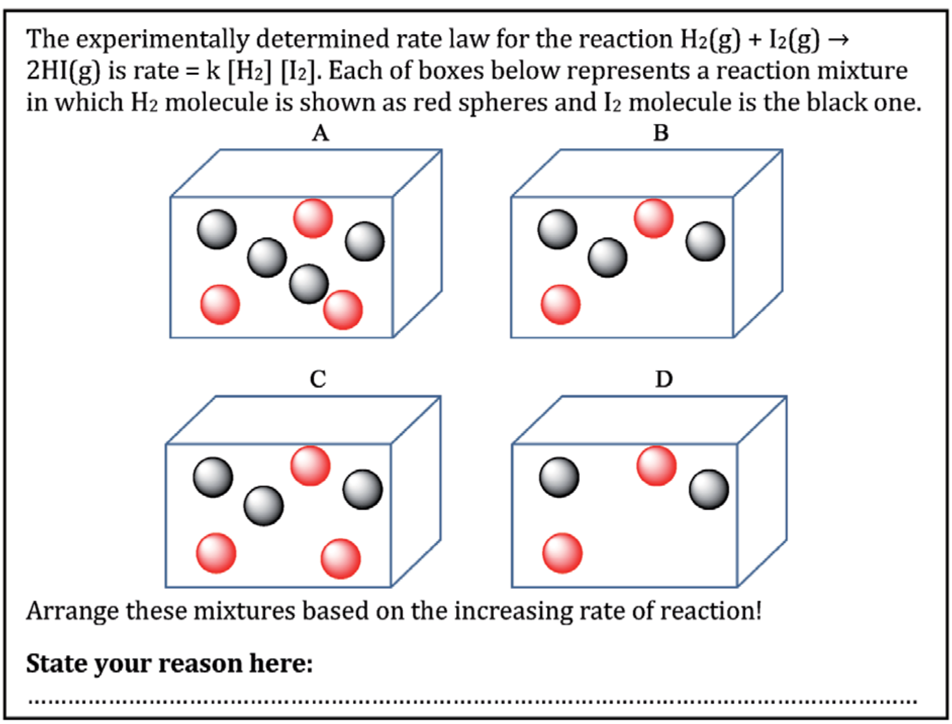

Figure 7.
Example of MCQ-FR in chemical kinetics.

3.4 Step 4: Testing and collecting students' unscientific understanding

The revised MCQ-FR is then used to collect preliminary data, which are students' unscientific understanding or illogical reasons. For example, in answering the question in **Figure 7**, some students believed that *option D would be the highest rate because the concentration of two reactants (H_2 and I_2) is the same*. These illogical reasons are then collected and employed as the basis to develop the prototype multi-tier instrument.

3.5 Step 5: Developing the prototype multi-tier instrument

A significant number of students should demonstrate students' unscientific understanding used as a reason option. Students' responses in this step are also used to measure the MCQ-FR quality in terms of validity, reliability, distractor effectiveness, discriminatory index, and difficulty level. The unscientific understanding above is utilized as the optional reason at the multi-tier instrument (**Figure 6**, Reason B).

3.6 Step 6: Validating the prototype and refining the final multi-tier instrument

The next step is testing the prototype multi-tier instruments to a group of students to measure its validity, reliability, distractor effectiveness, discriminatory index, and difficulty level (5 parameters). This step is also named empirical validity. Please refers to the educational evaluation and measurement references to find out the formulae to calculate these parameters. The analysis of the five parameters' values is the basis for revising the prototype and producing the final multi-tier instrument, which applies to the broader community.

4. Grading students' responses and how to determine students' unscientific understanding level

4.1 Treatment of data

Students' responses to the multi-tier questions provide four types of combinations of students' answers and reasons, namely: Correct Answer and Correct Reason (CACR) representing good scientific understanding; Correct Answer and Wrong Reason (CAWR) representing a false positive of students' unscientific understanding; Wrong Answer and Correct Reason (WACR) representing a false negative of students' unscientific understanding. These three categories are not discussed widely in this paper. Wrong Answer and Wrong Reason (WAWR) represents an actual student's unscientific understanding. This WAWR is the central aspect discussed in this regard and the prime category to be used in interpreting students' unscientific understanding.

4.2 Parameters to classify students' unscientific understanding

Students' unscientific understanding is determined based on students' WAWR combinations. Several parameters and terminologies have been used to determine the level of students' unscientific understanding based on the students' confidence ratings or confidence rating index (CRI) of WAWR. Caleon & Subramaniam [21] employed six scales of confidence ratings and classified unscientific understanding or misconception as to the following. A *genuine* unscientific understanding is an unscientific understanding expressed with a CRI ≥ 3.5. Meanwhile, a *spurious*

CRI	Category
≥ 3	*Genuine* unscientific understanding
	3–4: *Moderate* unscientific understanding
	≥ 4: *Strong* unscientific understanding
< 3	*Spurious* unscientific understanding

Table 1.
The parameter to classify unscientific understanding for 5 CRI scales.

unscientific understanding is an unscientific understanding expressed with a CRI < 3.5. *Genuine* unscientific understanding is further categorized into *moderate* unscientific understanding (those expressed with medium level CRI - between 3.5 and 4.0) and high level of unscientific understanding (those expressed with a high CRI of 4.0 and above). Literature using this scale [1–6] considers 3.5, i.e., the mid-point of unconfident and confidence as the limit of a *genuine* misconception.

The use of this parameter with a decimal number (3.5 as the limit) raises a critique considering that all the CRI scales are in whole numbers. Therefore, the rationale to use the decimal limit is questionable. For this reason, we suggest using the following parameter to classify students' unscientific understanding for a multi-tier instrument that employs five scales of CRI (**Table 1**).

The example of how to determine students' unscientific understanding is provided from our work in the area of thermochemistry, which is in the press for publication elsewhere. The question in **Figure 8** was intended to investigate students' understanding of the system and surroundings, particularly the difference between open, closed, and isolated systems.

In answering the question in **Figure 8** above, 34.43% of students demonstrated an unscientific understanding that the *drop of water in the bottle's outer wall comes from the bottle's melting ice*. This unscientific understanding was demonstrated by those provided WAWR combination and also CAWR combination. The WAWR combination was with answer A - Reason B, while the CAWR combination was mostly with Answer B - Reason B. To justify that the unscientific understanding is *genuine* or *spurious*, the CRI must be taken into account. If the CRI of whom provided WAWR and/or CAWR combinations is 4.0, it can be declared that the unscientific understanding is *genuine* and fall in the *moderate* category. If the CRI of those provided WAWR and/or CAWR combinations is 3.0, it can be declared that the unscientific understanding is *spurious* and is a result of a *lack of knowledge* rather than a misconception.

An ice cube is placed in a closed plastic bottle. After sometime, the ice melts and some drops of water are observed at the outer wall of the bottle. Referring to this phenomenon, it can be concluded that it is a/an….
A. open system B. closed system C. isolated system

Please state your confidence rating for the answer
1. very unconfident/guessing 2. unconfident 3. moderate 4. confident 5. very confident

State the reason for your answer
A. There is energy exchange between system and surrounding but not for the matter exchange
B. Drops of water confirm the matter exchange between system and surrounding
C. The is no exchange of matter and energy between system and surrounding

Please state your confidence rating for the answer
1. very unconfident/guessing 2. unconfident 3. moderate 4. confident 5. very confident

Figure 8.
Example of a four-tier instrument in thermochemistry [30].

5. Development of four-tier instrument in the topic of electrolyte and non-electrolyte solution (FTI-ENES): an empirical study

This section will present our current study in this area involving the development of a four-tier instrument in the topic of electrolyte and non-electrolyte solution. The instrument that was produced in this study is named the Four-Tier Instrument of Electrolyte and Non-Electrolyte Solution (FTI-ENES).

5.1 Method

This research employed the procedure proposed by Habiddin & Page [7] with six steps, as explained in Section 3 above. In the first step (mapping concept), it was found that differentiating electrolyte solution and non-electrolyte solution based on its electrical conductivity is the essential concept for a secondary school in Indonesia. The essential concept covers three indicators of competencies, including [1] identifying the electrical conductivity of the solution of an ionic compound, [2] identifying the electrical conductivity of the solution of covalent compound, [3] identifying the electrical conductivity of the solution of the polar covalent compound.

Next, several 22 MCQ-FR questions were constructed and intended to measure students' unscientific understanding regarding the three indicators. The example of a question in the MCQ-FR is presented in **Figure 9**. The questions were assessed in term of the scope of chemistry content and clarity in the language before being used for data collection by the chemistry lecturer and school teacher. The suggestions and feedbacks obtained were the basis for improving or revising the MCQ-FR.

In this study, the questions were focused on the conceptual type of question and avoided the algorithmic type. The initial data collection was carried out and involved five groups of students (153 in total) from two public secondary schools in Malang, East Java, Indonesia. Two groups from SMA Negeri 3 Malang (Public secondary school 3 in Malang) and three groups from SMA Negeri 8 Malang (Public secondary school 8) had taken the subject of electrolyte and non-electrolyte solutions.

Students' responses to the MCQ-FR of electrolyte and non-electrolyte solutions were categorized into scientific responses, unscientific responses and random responses. The unscientific responses were the basis to produce the FTI-ENES with 13 questions that experienced content validity afterwards. Next, the FTI-ENES was validated empirically involving two groups of students (62 in total) from SMAN 2 Ponorogo, East Java, Indonesia (Public secondary school 2 in Ponorogo). The parameters used in the empirical validation, including reliability, validity, difficulty level, discriminatory index and distractor effectiveness. Based on these parameters' values, improvements/revisions were made to refine the FTI-ENES and produce the final version of FTI-ENES.

At the same concentrations (1M), the following solutions having the strongest electrical conductivity is....
A. $HCl(aq)$ B. $KOH(aq)$ C. $H_2SO_4(aq)$ D. $NaOH(aq)$

State your reason:
....

Figure 9.
Example of a four-tier instrument in electrolyte and non-electrolyte solution.

5.2 Results and discussion

5.2.1 Revealing students' unscientific understanding in the topic of electrolyte and non-electrolyte solution

In the initial data collection, several students' unscientific understanding were uncovered using the MCQ-FR. Some examples of students' unscientific understanding that $C_{12}H_{22}O_{11}(aq)$ is electrically conductive, partially ionized in water, and contains hydrogen bonding. Those unscientific understanding then adopted as the reason tier in the FTI-ENES, as shown in **Figure 10**.

5.2.2 The empirical validity of the FTI-ENES

The quality of the FTI-ENES is primarily reflected based on the values of 2 parameters, including validity and reliability. The two parameters are the most valuable aspect in assessing the quality of a question [31]. The last three parameters, including difficulty level, discriminatory index, and distractor effectiveness, are also essential, particularly formative and summative tests.

5.2.2.1 Validity

All the questions of the FTI-ENES instrument are valid with high validity indices. The average validity index for A-tier, R-tier and B-tier are 0.46, 0.45 and 0.53, respectively. These values confirm that the FTI-ENES is powerful for identifying students' unscientific understanding in the area of electrolyte and non-electrolyte solutions. The detail values for each question and each tier are provided in **Table 2**.

First-tier Sucrose with molecular formula $C_{12}H_{22}O_{11}$ is dissolved in water. Based on its electrical conductivity, the solution can be categorized as … A. Strong electrolyte B. weak electrolyte C. Non-electrolyte
Second-tier State the confidence rating of your answer 1. very unconfident/guessing 2. Unconfident 3. Moderate 4. Confident 5. Absolutely confident
Third-tier What is the reason for your answer? A. $C_{12}H_{22}O_{11}(aq)$ is not an electrically conductive solution because it does not ionize in water. B. $C_{12}H_{22}O_{11}(aq)$ ionize partially in the water. C. $C_{12}H_{22}O_{11}(aq)$ produce the mobile ions in the solution. D. $C_{12}H_{22}O_{11}(aq)$ is an electrically conductive solution because it ionizes entirely in water.
Fourth-tier State the confidence rating of your reason 1. very unconfident/guessing 2. Unconfident 3. Moderate 4. Confident 5. Absolutely confident

Figure 10.
Example of a four-tier instrument in the FTI-ENES.

Question	Answer-tier (A-tier)		Reason-tier (R tier)		Both tier (B tier)	
	r	Category	r	Category	r	Category
1.	0.696	Valid	0.500	Valid	0.611	Valid
2.	0.495	Valid	0.372	Valid	0.564	Valid
3.	0.469	Valid	0.523	Valid	0.532	Valid
4.	0.524	Valid	0.404	Valid	0.644	Valid
5.	0.506	Valid	0.451	Valid	0.459	Valid
6.	0.455	Valid	0.485	Valid	0.515	Valid
7.	0.407	Valid	0.496	Valid	0.582	Valid
8.	0.339	Valid	0.357	Valid	0.455	Valid
9.	0.456	Valid	0.522	Valid	0.473	Valid
10.	0.592	Valid	0.583	Valid	0.697	Valid
11.	0.346	Valid	0.252	Valid	0.366	Valid
12.	0.265	Valid	0.513	Valid	0.514	Valid
13.	0.453	Valid	0.317	Valid	0.422	Valid

Table 2.
Validity indices of the FTI-ENES.

5.2.2.2 Reliability

The reliability index of the FTI-ENES was measured using the technic of Cronbach's Alpha. The reliability indices for A-tier, R-tier and B-tier are 0.69, 0.66 and 0.78, respectively. The values demonstrate that the instrument will produce a consistent result when it is employed over time.

5.2.2.3 Difficulty level

The difficulty level index (P) ranges from 0 to 1 and represent the number of students answering the question correctly. The higher the difficulty level value, the higher the number of students answering the question correctly, and vice versa. **Table 3** shows that the "moderate" category is the majority incident regarding the question's difficulty level. On average, the P values for A-tier, R-tier and B-tier are 0.58, 0.53 and 0.42, respectively and fall in the "moderate" category. These values imply that the level of the questions is relevant for secondary school students.

5.2.2.4 Discriminatory index

Discriminatory index (D) compares the number of students answering the questions correctly between high achievement students and low achievement ones. The higher the D indices, the higher the number of students answering the question correctly from high achievement students, and vice versa (**Table 4**).

On average, the D values for A-tier, R-tier and B-tier are 0.53, 0.52 and 0.62, respectively and fall in the "moderate" category. These values imply that the instrument can differentiate students with high achievement and those with low achievement.

Question	Answer-tier (A-tier)		Reason-tier (R-tier)		Both tier (B-tier)	
	P	Category	P	Category	P	Category
1.	0.726	Easy	0.790	Easy	0.613	Moderate
2.	0.742	Easy	0.565	Moderate	0.484	Moderate
3.	0.516	Moderate	0.484	Moderate	0.435	Moderate
4.	0.387	Moderate	0.435	Moderate	0.274	Difficult
5.	0.581	Moderate	0.452	Moderate	0.419	Moderate
6.	0.597	Moderate	0.339	Moderate	0.323	Moderate
7.	0.677	Moderate	0.677	Moderate	0.645	Moderate
8.	0.532	Moderate	0.419	Moderate	0.226	Difficult
9.	0.468	Moderate	0.452	Moderate	0.435	Moderate
10.	0.710	Easy	0.629	Moderate	0.548	Moderate
11.	0.355	Moderate	0.726	Easy	0.306	Difficult
12.	0.726	Easy	0.565	Moderate	0.484	Moderate
13.	0.565	Moderate	0.306	Moderate	0.274	Difficult

Table 3.
The difficulty level of questions of the FTI-ENES.

Question	A-tier		R-tier		B-tier	
	D	Category	D	Category	D	Category
1.	0.765	Excellent	0.588	Good	0.647	Good
2.	0.647	Good	0.529	Good	0.706	Good
3.	0.647	Good	0.706	Good	0.706	Good
4.	0.647	Good	0.412	Good	0.706	Good
5.	0.529	Good	0.529	Good	0.529	Good
6.	0.471	Good	0.471	Good	0.588	Good
7.	0.529	Good	0.588	Good	0.765	Excellent
8.	0.353	Good	0.471	Good	0.412	Good
9.	0.588	Good	0.647	Good	0.471	Good
10.	0.647	Good	0.765	Excellent	0.882	Excellent
11.	0.353	Good	0.176	Moderate	0.471	Good
12.	0.118	Moderate	0.647	Good	0.647	Good
13.	0.588	Good	0.176	Moderate	0.526	Good

Table 4.
Discriminatory indices of questions of the FTI-ENES.

5.2.2.5 Distractor effectiveness

The distractor effectiveness parameter represents whether each wrong option in the A and R tiers is functional. An option is considered functional when it is chosen by at least one student [32]. **Table 5** demonstrates that all the options are functional, implying the homogeneity of the options.

Question	*A* tier (%)				*R* tier (%)			
	A	B	C	D	A	B	C	D
1.	16.13	11.29	72.58		72.58	6.45	8.06	12.90
2.	11.29	74.19	14.52		12.90	22.58	8.06	56.45
3.	33.87	14.52	51.61		17.74	48.39	6.45	27.42
4.	38.71	45.16	16.13		32.26	19.35	41.94	6.45
5.	29.03	58.06	12.90		45.16	27.42	6.45	20.97
6.	59.68	17.74	22.58		20.97	19.35	25.81	33.87
7.	11.29	67.74	11.29	9.68	17.74	9.68	64.52	8.06
8.	30.65	6.45	52.23	9.68	33.87	41.94	17.74	6.45
9.	14.52	46.77	27.42	11.29	22.58	16.13	16.13	45.16
10.	11.29	12.90	6.45	69.35	12.90	14.52	62.90	9.68
11.	25.81	24.19	35.48	14.52	46.77	25.81	19.35	8.06
12.	70.97	29.03			19.35	56.45	8.06	16.13
13.	11.29	48.39	33.87	6.45	14.52	32.26	20.97	32.26

Table 5.
Distractor effectiveness for each option each question of the FTI-ENES.

6. Conclusions

A two-tier instrument that was initially developed by Treagust [15] is the pioneer of a multi-tier instrument. The next generation of multi-tier instruments, including three-tier, four-tier, and five-tier, responds to the drawbacks of the two-tier, which is the inability to distinguish an actual unscientific understanding and the role of guessing. We also believe that an additional drawing tier, as shown by the work of Anam et al. [28], is a rational exercise to be applied in future assessment purposes. By adopting the procedure of two-tier development, we suggest a more straightforward procedure to develop a multi-tier instrument including Mapping concept, Developing the multiple-choice question with free responses (MCQ-FR), Validating the MCQ-FR, Testing and Collecting Students' Unscientific Understanding, Developing the prototype multi-tier instrument, and Validating the Prototype and refining the final multi-tier instrument. A wrong answer-wrong reason (WAWR) combination accompanied by a high confidence rating index (CRI) is the parameter to justify students' unscientific understanding level. In this paper, we suggest employing a five scale CRI instead of 6 because it provides a better clarity of students to express his/her level of confidence. We also suggest that using a CRI of 3 as a limit between *genuine* and *spurious* unscientific understanding will ensure a robust justification regarding students' unscientific understanding and lack of knowledge.

The FTI-ENES instrument developed in this study consists of 13 questions covering the topic of electrolyte and non-electrolyte solutions. The instrument's validity and reliability revealed that it is applicable to be used in identifying students' understanding of electrolyte and non-electrolyte solution. Even though the scope of the concepts covered in this study is relevant for secondary chemistry school, it may also be transferable for fresh university students, particularly to identify their basic chemistry knowledge gained from their learning experiences in their secondary school chemistry. Other detailed examples of the application of this procedure in developing multi-tier instruments can be found in our previous works, including in chemical kinetics [7], acid–base properties of salt solution [33, 34], and thermochemistry [30].

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Conflict of interest

We can declare that there is no 'conflict of interest' in this paper.

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Chapter 2

Engineering Education 5.0: Strategies for a Successful Transformative Project-Based Learning

Andrés Díaz Lantada

Abstract

Project-based learning has importantly helped to transform engineering education over the last decades, as it has been increasingly applied worldwide, as a fundamental methodology for shifting to student-centered engineering programmes. To enlighten the transition from Industry 4.0 to Society 5.0, and from Engineering Education 4.0 to Engineering Education 5.0, project-based learning (PBL) methodologies should also evolve. In terms of focus and topics selected for the PBL experiences, it is necessary to put forward the relevance of global challenges and to nurture a compromise for sustainability and ethical behaviour, while bringing students as close as possible to real multifaceted engineering problems. As regards connections with other educational methodologies, PBL and service learning (SL) are bound to hybridization and may benefit from innovative approaches, like the use of flipped classrooms, the promotion of gamification or the support of online resources and e-/b-/m-learning tools and methods. Complete PBL experiences will also synergize with and contribute to open-source engineering movements, like the "makers" movement, and will benefit from open software and hardware tools for increased educational equity. This chapter analyses and discusses trends in PBL methodologies, in connection with these new industrial and educational paradigms.

Keywords: project-based learning, service-learning, Industry 4.0, Society 5.0, educational innovation, Engineering Education 5.0, PBL5.0

1. Introduction

Technology is advancing at an extremely rapid pace, transforming societies, and reformulating all areas of education in the majority of the world, especially in the engineering field. Around a decade ago, the concept of "Industry 4.0" was proposed to summarize a set of industrial technologies from the fourth industrial revolution, linked to interconnected smart technologies, and evolving from the third (or digital) industrial revolution [1, 2]. Almost in parallel, the concept of "Society 5.0", in short: *a human-centered society that balances economic advancement with the resolution of social problems by a system that highly integrates cyberspace and physical space*, was proposed in Japan [3]. "Industry 5.0," the current industrial revolution, has been also recently proposed [4, 5], and is a consequence of applying the technologies from Industry 4.0, and their diverse successors, to the Society 5.0 paradigm.

"Education 5.0" also benefits from these contemporary technological resources and aims at constructing Society 5.0, solving problems through value creation and quality education worldwide [6], in connection with the Sustainable Development Goals and the Agenda 2030 [7, 8]. Education 5.0 is bound to affect all educational levels and areas. In the engineering realm, the shift to innovative scenarios, which promote a continuously evolving engineering education, capable of adapting to these non-stop technological revolutions, is of special relevance.

Accordingly, the concept of "Engineering Education 5.0" has been also just proposed as an educational paradigm [9]. In short: *Engineering Education 5.0 transcends the development and application of technology and enters the realm of ethics and humanism, as key aspects of for a new generation of engineers. Ideally, engineers educated in this novel educational paradigm should be capable of leading and mentoring the approach to technological singularity, which has been defined as a future point in time at which technological growth becomes uncontrollable and irreversible leading to unpredictable impact on human civilization, while ensuring human rights and focusing on the construction of a more sustainable and equitable global society*.

Taking into consideration recent engineering education transformations with international impacts, like the Conceive, Design, Implement, Operate (CDIO) initiative [10], it is necessary to put forward the relevance of problem- and project-based learning methodologies (PBL), which recreate the real professional life of engineers and train students for solving real-world challenges. Indeed, project-based learning has helped to reformulate engineering education over the last decades, as it has been increasingly applied worldwide, as a fundamental methodology for shifting to student-centered engineering programmes.

To enlighten the transition from Industry 4.0 to Society 5.0, and from Engineering Education 4.0 to Engineering Education 5.0, project-based learning (PBL) methodologies should also evolve:

In terms of focus and topics selected for the PBL experiences, it is necessary to put forward the relevance of global challenges and to nurture a compromise for sustainability and ethical behaviour, while bringing students as close as possible to real multifaceted engineering problems. As regards connections with other educational methodologies, PBL and service learning (SL) are clearly bound to hybridization and may benefit from innovative approaches, like the use of flipped classroom, the promotion of gamification or the support of online resources and e-/b-/m-learning tools and methods. Complete PBL experiences will also synergize with and contribute to open-source engineering movements, like the "makers" movement, and will benefit from open software and hardware tools for increased educational equity.

Towards a successful construction of "Engineering Education 5.0", this chapter analyses and discusses trends in PBL methodologies, in connection with these new industrial and educational paradigms. Besides, basic guidelines for synergically implementing PBL experiences within engineering programmes oriented to Society 5.0 and pursuing a global promotion of students' professional outcomes are also presented. Finally, several types of innovative PBL are described, numerous topics for implementation, covering most engineering specialties and professional roles, are presented, and useful supporting resources for professors and students are summarized. The gathered proposals are based on the author's personal experience and views, on inspiring discussions with colleagues and a systematic search within the literature, as regards modern engineering education.

2. Features of Engineering Education 5.0 and modern PBL

Engineering Education 5.0, according to its seminal publication [9], should be characterized by 16 interwoven key features listed in **Figure 1**. Some of these attributes have been also mentioned off late in relevant reports focusing on engineering education trends [11–13], which explain educational methodologies and learning styles quite connected to Education 5.0.

In the author's opinion, modern PBL should take account of these key features, to keep pace with the continuous evolutions within Engineering Education 5.0. At the same time modern PBL, built upon these elements, may liberate engineering programmes from the usually fixed frameworks and let them endlessly change, while supporting and mentoring the technological advances of Industry 5.0 for the successful construction of Society 5.0. Arguably, transforming PBL with Engineering Education 5.0 in mind, may turn out to be a very adequate strategy for empowering and deploying the technological revolutions ahead, whose positive industrial, economic, and social impacts can be essential. Counting with engineering education as one of the more relevant drivers of social change is always rewarding.

Figure 2, in alignment with other studies focused on strategies for the design and implementation of successful and transformative PBL [14–16], presents a selection of good practices for adjusting PBL methods to better consider the different pivotal aspects of Engineering Education 5.0. For instance, modern PBL in the Engineering Education 5.0 paradigm should change dynamically, evolving with technologies, as the state-of-the-art rapidly flows. To this end, annual modifications to the projects' topics present a double intention: on the one hand keeping the PBL experiences alive, helping students to focus on avant-garde techniques and methods; on the other, avoiding malpractice and copying or taking too much inspiration from previous years' results. Besides, modularity and flexibility are necessary for promoting resource-effective and personalized education and for swiftly spreading PBL across engineering programmes and universities. These aspects can benefit from counting with a fundamental or core module (i.e., engineering design methodologies for innovative product development), which may be central to different

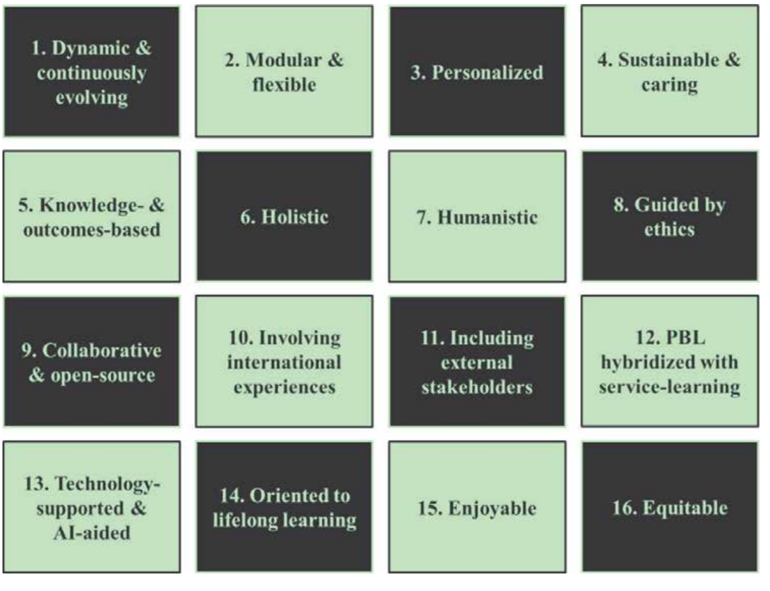

Figure 1.
The 16 interwoven key features of Engineering Education 5.0.

1. Dynamic & continuously evolving
- Change the projects' topics every course to keep the experiences alive and to avoid copying.
- Continuously monitor learning results and outcomes, correct and improve as needed.

2. Modular & flexible
- Design a fundamentals or core module that can be the central part of different PBL experiences.
- Combine modules for adapting successful PBL experiences to different engineering programmes.

3. Personalized
- Let students select the needs to work on and the specific topics for their projects.
- Be flexible to incorporate specific learning activities, as required for concrete projects.

4. Sustainable & caring
- Include a learning module focused on the evaluation of sustainability and social impacts.
- Ask students to perform quantitative assessments about projects' sustainability and impacts.

5. Knowledge- & outcomes-based
- Complement core modules on engineering design and project management with technical issues.
- Dedicate time to focus on soft skills: teamwork, communication, creativity, leadership…

6. Holistic
- Modern PBL should be integrative, allowing students to apply scientific-technical knowledge from a whole degree, for which projects should be necessarily complex and demanding.
- PBL experiences should help students master technological tools used in real professional practice.

7. Humanistic
- Best projects tell a personal stories, help students focus on human-centered design strategies.
- Consider projects' connections to art, literature, cultures, history… relevant and evaluate accordingly.

8. Guided by ethics
- Introduce students to the more relevant regulations and standards in their projects' areas.
- Motivate students to design according to standards and to work in a socially responsible way, behaving also ethically with their peers, especially through peer-assessment activities.

9. Collaborative & open-source
- PBL benefits from sharing best practices, for which delivering projects' results (products & processes and their subsystems) as open-source materials may be strategic.
- Motivate students to collaborate with colleagues, to use and share open-source results.

10. Involving international experiences
- Encourage students to participate in international PBL competitions and link them to credits.
- Foster the application of e-twinning methods to PBL experiences, create international PBL courses, benefit from e-/b-/m-learning methods for incorporating invited international speakers.

11. Involving external stakeholders
- Connect the PBL experiences to real social & industrial needs, involving companies as sponsors.
- Arrange a team of external advisors that help to monitor and evaluate students' outcomes.

12. PBL hybridized with service-learning
- Ideally, students' projects transform society through science and technology: focus on real needs.
- Involve, as part of the advisors' committee, representatives from the emergent fourth sector.

13. Technology supported and AI-aided
- Use PBL experiences to keep engineering programmes up to date with *avant-garde* technologies.
- Explore the potential of artificial intelligence (AI) in different sectors through PBL and, hence, educate a generation of engineers capable of ethically mentoring AI-related advances in the future.

14. Oriented to lifelong learning
- During effective PBL experiences, students learn to learn, which prepares them for lifelong learning.
- Stimulate students to go beyond course contents and to autonomously learn, in connection with their projects, through participation in external seminars, webinars, MOOCs…

15. Enjoyable (learning through play)
- Make PBL experiences enjoyable, dedicate time to celebrating learning and fostering creativity.
- Design PBL so that students play the leading role and enjoy the process of becoming engineers.

16. Equitable (engineering education for all)
- Select students on the basis of merit and apply PBL to work against any kind of discrimination.
- Spread successful PBL experiences by applying the "MOOC" concept and make PBL reach everywhere and everywhen (i.e. remote regions, LMI settings) for fostering learning on demand for all.

Figure 2.
Summary of good practices for incorporating the key features of Engineering Education 5.0 to modern PBL.

experiences and degrees. A combination of basic and specialization modules can foster fruitful adaptation of PBL to a wide set of programmes.

Other interesting good practices deal with making PBL more holistic, taking inspiration from the engineers of the Renaissance, putting ethics in the foreground, better synergizing with key stakeholders and society, increasing societal impacts and making education more equitable. The hybridization of project-based learning and service learning [17], intensive use of e-Twinning and e-/b-/m-learning methods for supporting an affordable internationalization and for taking benefit from diversity [18], the employment of artificial intelligence tools for supporting educational practice [19] or resorting to open-source software and hardware resources [20], are also relevant strategies with synergic effects.

Ideally, through their projects, students learn how to transform society taking benefit from the ongoing technological revolutions and focusing on real needs and unsolved or partially solved societal problems. During the process, they learn to learn, feel more responsible for their learning, take decisions along a plethora of elective PBL experiences, which helps to personalize education, communicate and celebrate their results, and enjoy the process of becoming engineers. Sharing of methods and experiences, in the project-based learning field, is also fundamental towards high-quality engineering education for all.

3. Implementing PBL in Engineering Education 5.0 programmes

3.1 Synergic integration of PBL within innovative engineering studies

The structures and contents of Engineering programmes in the 5.0 paradigm will necessarily suffer important transformations. A proposal for a universal engineering programme structure, considering contemporary and future engineering roles, has been recently detailed [9]. To summarizing, a whole 6-year programme, integrating a 4-year bachelor's degree plus a 2-year master's degree, can very adequately provide students with fundamental scientific-technological knowledge, specialized professional and transversal skills, necessary ethical values, and even give them important opportunities for personalization and professional planning. This can be achieved through modularity, through collaboration with other programmes, universities and institutions, through the promotion of international mobility and external internships and through a more flexible understanding of all the possible types of experiences that contribute to a holistic training of engineers, as already explained [9].

Let us consider the CDIO initiative, probably the most transformative and international action in the engineering education of the twenty-first century, and the current version of the CDIO standards (version 3.0) [21]. CDIO (from conceive-design-implement-operate) relies on the wise application of PBL principles for making engineering education more effective, through the engineering of different products, processes, and systems. Usually, CDIO-inspired engineering programmes benefit from at least one intensive hands-on or PBL course per training year, and the curricula are methodically designed *with an explicit plan to integrate personal and interpersonal skills, and product, process, system, and service building skills*.

In the author's belief, engineering studies in the 5.0 paradigm should rely on project-based methods even more than in current CDIO-inspired programmes. The use of PBL, not only as a methodology for fostering the ABET professional skills [22, 23], but also for delivering purposeful and continuously updated content, linked to the scientific-technological fundamentals of Industry 4.0 and 5.0, may prove strategic.

Accordingly, this section proposes a general plan for the synergic integration of PBL within engineering studies. The plan incorporates at least one intensive hands-on or PBL course or highly formative student-centered experience per semester, as schematically shown in **Table 1** and further described in **Table 2**.

Different types of project-based activities are considered, all of them relevant and mutually supportive, from the more straightforward and descriptive, to the more complex and integrative. These are classified with some parallelism to Bloom's taxonomy, starting with descriptive and analytical PBL experiences, following with synthetic PBL experiences, and ending up with complete CDIO approaches and final theses. There is also space for local and international competitions, as a way for promoting personalization, for more easily adapting the engineering programmes to relevant engineering trends and for promoting peer learning approaches, in a way bringing *Montessorian* style to higher education. The possibility of linking PBL experiences with R&D tasks, both within universities' departments and laboratories and within research centers and enterprises, reinforces the necessary focus on lifelong learning and the rewarding connection of engineering programmes with the industrial environment. The inclusion of at least one service-learning experience, in the general structure, supports students' orientation to real societal challenges and may stress the fundamental ethical aspects and implications of science and technology. Again, it is necessary to highlight that the varied plethora of PBL initiatives can be an excellent way of helping students follow their paths.

The above-proposed mapping of PBL initiatives along an integral 6-year Bachelor's and Master's Degree in Engineering for Society 5.0 can be adapted to any engineering programme of the 5.0 paradigm. The initial PBL experiences (years 1st–2nd) have a clear focus on knowledge acquisition and concentrate on the promotion of analytical skills, while those from the 3rd to 6th years are directed towards knowledge application and foster more technical and professional skills.

Countless examples can be provided for each type of PBL experience and **Table 2** just aims at providing a brief description, of the different types of modern PBL experiences, and some implementation examples in the context of Engineering Education 5.0. Many of the cited examples apply the techniques

Programme level	Academic year	First semester experiences		Second semester experiences		Total PBL credits/year
		Type of PBL experience	PBL credits	Type of PBL experience	PBL credits	
Master's Degree in Engineering for Society 5.0 (120 ECTS)	6th	R&D PBL	6	Final degree thesis	12	18
	5th	CDIO PBL	6	In-company PBL	6	12
Bachelor's Degree in Engineering for Society 5.0 (240 ECTS)	4th	CDIO PBL	6	Final degree thesis	12	18
	3rd	Synthetic PBL	6	International competition	6	12
	2nd	Analytical PBL	3	Service-learning experience	6	9
	1st	Descriptive PBL	3	Local competition	3	6

Table 1.
Proposal for mapping different types of PBL initiatives along with an integral 6-year Bachelor's and Master's Degree in Engineering for Society 5.0.

Types of PBL experiences	Description	Implementation examples
Final degree thesis	Holistic and highly integrative PBL experience, in which students, normally on their own and supported by a mentor, design de novo an engineering solution or optimize an existing product or system.	• Develop a lightweight structure. • Optimize a system's eco-impacts. • Design a vehicle suspension.
R&D PBL	In-depth study of a specific problem, within an ongoing R&D project of a university department and supporting project's team. As in capstone projects, a paper based on results may be written as a conclusion.	• Design a biomedical MEMS. • Develop an AI-aided device. • Research an innovative material.
In-company PBL	Immersive industrial experience, through which students live a professional practice helping to solve a real problem or trying to optimize a company's processes, products, or solutions.	• Enhance a production line. • Select subsystems for a new plant. • Help with a marketing strategy.
CDIO PBL	Highly integrative PBL experiences, in which students' groups live through the complete conceive-design-implement-operate cycle of innovative engineering products, processes or systems.	• Design & build a medical device. • Prototype a 3D printing machine. • Create a pump for remote regions.
Synthetic PBL	PBL experiences focused on reaching a solution proposal for an engineering problem. Typically, students detect a need, develop a concept, and reach a design of an engineering product, process, or system.	• Design a specified gearbox. • Define the layout of a factory. • Model an eco-house.
Analytical PBL	PBL experiences focused on the study of an existing engineering system, which is normally divided into subsystems and components for understanding and modeling its functional principles and behaviour.	• Simulate a production chain. • Model robotic arm kinematics. • Reverse engineer a solar panel.
Descriptive PBL	PBL experiences, in which students, in some cases following a case study approach, describe a relevant need and existing solutions, documenting one of the possible solutions in detail.	• Select and describe a machine. • Document a factory's subsystems. • List down materials of a satellite.
Service-learning experience	Formative experiences with a clear social purpose, in which students are connected to a real societal problem and asked to provide an engineering-related solution after interaction with key stakeholders.	• Design campus recycling strategy. • Organize a social fundraising fair. • Conceive a purposeful network.
International competition	Like the local competitions, but international and normally involving more challenging problems and requiring the delivery of a final product prototype-.	• Formula SAE/Student. • Solar Decathlon. • Robot design competitions.
Local competition	Focused design competitions, usually for first-year students and with a socialization purpose, together with the formative objective, in which teams provide engineering solutions to open-ended questions.	• Creativity weeks/challenges. • App design competition. • Applied maths hackathons.

Table 2.
Description and implementation examples of modern PBL experiences in the Engineering Education 5.0 paradigm.

from Industry 4.0 and 5.0, like artificial intelligence, big data, internet of things, cyberphysical interfaces, multi-physical/chemical simulations, digital twins, additive manufacturing, collaborative robots, autonomous systems …, to solving problems in different industries and engineering fields. In other cases, the PBL

	Students' outcomes as proposed by ABET										
Types of PBL experiences	**a. an ability to apply knowledge of mathematics, science and engineering**	**b. an ability to design and conduct experiments and analyze data**	**c. an ability to design a system or component to meet specifications**	**d. an ability to function on multidisciplinary teams**	**e. an ability to identify, formulate and solve engineering problems**	**f. an understanding of professional and ethical responsibility**	**g. an ability to communicate effectively**	**h. a broad education to understand the impact of engineering solutions**	**i. a recognition of the need for and an ability to engage with lifelong learning**	**j. a knowledge of contemporary issues**	**k. an ability to use the techniques, skills and tools for engineering practice**
Final degree thesis	XX	X	X		XX	X	X	X	X	X	X
R&D PBL	X	XX	X		X			X	X	X	X
In-company PBL	X			X	X	X	X	X	XX	X	X
CDIO PBL	X	X	XX	X	X	X	X	XX	X	X	X
Synthetic PBL	X		X		X	X					XX
Analytical PBL	XX	X						X			X
Descriptive PBL	X						X			XX	
Service-learning experience	X			X	X	XX	X	X		X	
International competition	X			XX			X				X
Local competition	X			X			XX				X

Table 3.
Different types of PBL experiences and their connections with students' outcomes, employing the ABET professional skills as reference.

initiatives are focused on designing or further developing such technologies. The redesign or reengineering of existing products, processes or systems, with sustainability principles in mind, can be also a source for highly rewarding PBL experiences, in connection with all Sustainable Development Goals.

Pioneering experiences in the PBL arena will, of course, continue enlightening the new generations of engineers. Among them, it is important to mention: the "Formula SAE/Student" automotive challenges (dating back to 1981), the "IARC" competition on aerial robotics (since 1991), the "CAN-SAT" satellite construction challenges (since 1998), the "FIRST Lego League" robotics competitions (since 1998), the "Solar Decathlon" competitions focused on efficient buildings (since 2002), the James Dyson Design Competitions (since 2007) and the "UBORA" medical device design schools (since 2017), to cite some examples in varied engineering fields. Most of them have taken benefit from the methods and techniques from Industry 4.0 and 5.0, well before the coining of such terms, and have also helped to research and develop several working methods and technologies that are central to current industrial revolutions.

3.2 Systematic promotion of students' outcomes through modern PBL

The previous section has mapped the different types of PBL experiences along with an integral 6-year Bachelor's and Master's Degree in Engineering for Society 5.0, as an example of how any engineering programme may be transformed through truly transformative student-centered activities. Now, it is also necessary to integrate these experiences in a synergic or mutually supportive way, to systematically promote students' outcomes.

Employing the ABET professional skills as a reference, **Table 3** presents an example of how different types of PBL experiences connect with students' outcomes, considering that each outcome should be specifically covered by at least one PBL experience of the engineering programme (see also **Table 2**). The more integrative PBL experiences (final theses, R&D PBL and CDIO experiences), for instance, may well synergize for fostering students' abilities to apply knowledge from maths, science and engineering, to identify, formulate and solve engineering problems, to design systems and components to meet specifications and to understand the impacts of engineering solutions. Other more focused PBL experiences (in-company PBL, competitions, analytical/synthetic) may promote ABET's skills d, f, g, i, j, k.

4. From Industry 4.0 to Society 5.0 through modern PBL

4.1 Advancing technologies from Industry 4.0 towards Society 5.0

Once explained how different types of PBL experiences may be mapped along a universal 6-year engineering programme for Society 5.0 and how the different kinds of experiences support each other for the promotion of students outcomes, this section concentrates on how PBL may help to further develop the technologies from Industry 4.0 towards Society 5.0, considering also the roles of modern engineering professional practice and providing an application example of how PBL may vertebrate a specific engineering programme for Society 5.0. **Table 4** presents several examples of PBL teaching-learning experiences for deploying the technologies from Industry 4.0 and hence constructing Society 5.0. Depending on the outcomes and industrial area of the specific engineering programme and on students' wishes a myriad of combinations is possible.

	Key topics	Possible PBL teaching-learning experiences for deploying Industry 4.0 and constructing Society 5.0	Types of PBL experiences
Technologies from the Industry 4.0 paradigm	Artificial intelligence	• Prototype a skin cancer diagnostic app. • Describe and discuss AI-related ethical issues.	• Competition/ CDIO-PBL. • Descriptive PBL.
	Big data	• Develop and test a pandemic simulator. • Develop a predictor for environmental collapse.	• Synthetic/CDIO-PBL. • Synthetic/CDIO-PBL.
	Smart factories	• Implement a quality control artificial vision. • Reengineer a production unit using a digital-twin.	• In-company/ CDIO-PBL. • In-company/ CDIO-PBL
	Autonomous robots	• Design soft robot swarms for space colonization. • Train a drone for fragile parcel delivery.	• R&D PBL. • Competition/ CDIO-PBL.
	3D printing & flexible production	• Redesign a car's chassis oriented to 3D printing. • Create an innovative metamaterial by 3D printing.	• Final degree thesis. • R&D PBL.
	Internet of things	• Design and construct a smart mini-bar for hotels. • Develop wearable sensors for Alzheimer's control.	• CDIO-PBL. • Service learning.
	Cybersecurity	• Cybersecurity and privacy issues in smart cities • Map & model a company's cybersecurity threats.	• Descriptive PBL. • Analytical PBL.
Expected transformations within Society 5.0	Sustainable mobility	• Create an app for reduced mobility persons. • Implement an app for predicting traffic jams.	• Service learning. • Competition/ CDIO-PBL.
	Better health management	• Design and prototype a health monitoring shirt. • Develop a medical passport app.	• Synthetic/CDIO-PBL. • Final degree thesis.
	Customized products	• Create an app for eyewear mass customization. • Design and prototype a personalized prosthesis.	• In-company/ CDIO-PBL. • Final degree thesis.
	Reformed organizations	• Analyze and model the processes of a company. • Reengineer a hospital's emergency unit processes.	• Analytical PBL. • In-company PBL.
	Improved services	• Design an AI-tool for supporting career planning. • Develop an app for supporting exchange students.	• Service learning. • Service learning.
	Smart cities & environments	• Model the security processes of a smart building. • Model the autonomous operation of a whole city.	• Analytical PBL. • Analytical PBL.

Table 4.
Examples of PBL teaching-learning experiences for deploying the technologies from Industry 4.0 and hence constructing Society 5.0.

4.2 PBL oriented to the professional engineering roles in Society 5.0

Besides, the increasing connection between engineering disciplines may contribute to a progressive dissolution of borders between the classical specializations of the programmes of studies. Probably, structuring Engineering Education 5.0 programmes according to the modern professional roles of engineers, which are more stable than the continuously evolving and nascent engineering majors, may be an adequate solution for constructing universal engineering programmes [9]. With this perspective, **Table 5** describes and exemplifies PBL oriented to the different professional engineering roles in Society 5.0.

4.3 Example: PBL in a Biomedical Engineering 5.0 programme

Considering all previous sections, **Table 6** presents the concrete mapping of modern PBL experiences throughout an integral 6-year Bachelor's and Master's Degree in Biomedical Engineering for Society 5.0. In the scheme, all types of PBL experiences synergize for providing students with basic and applied knowledge, for letting them acquire technical and professional skills, liked to most areas of Industry 4.0 and several challenges of healthcare within Society 5.0.

4.4 Discussion and future implementation pathways

The presented perspective is based on an analysis of the recent evolution of PBL-experiences and engineering education, in general, and follows the findings and continuation proposals of transformative educational experiences described in the selected references. However, it also derives from the author's personal and highly rewarding experiences in the design and implementation of different kinds of PBL experiences in six different degrees of studies at UPM, carried out at bachelor's, master's and doctoral levels, as well as in international onsite and online hackathons, bootcamps and engineering design schools.

Some of these successful stories, in connection with different types of PBL experiences already including some features of Engineering Education 5.0, have been previously reported [15, 19, 20, 24]. Nevertheless, the creation of a whole 6-year engineering programme, completely structured around PBL experiences focusing on the technologies from Industry 5.0, as schematically presented in **Tables 1** and **6**, is still an educational dream. The author intends to progress towards the implementation of this kind of educational model, which connects with the pioneering example and aims of the International CDIO Initiative, perhaps taken to the extreme, until its last consequences and interwoven with continuously evolving technologies, which requires more dynamic programmes.

Such real-life implementation can follow differently and mutually supporting strategies. A first and straightforward strategy could rely on the gathering of successful PBL experiences, across programmes of a university, and on letting students select (initially as one or two electives per year), those more in line with their interests. A second strategy, now that inter-university campuses are being created across Europe (Erasmus+ European Universities programme), would be to organize biannual international PBL events within these new communities, offering different types of PBL experiences related to Industry 5.0 and with a common credit transfer system. This would also help to vertebrate the new European universities. A third option would be to update the contents and methods of already existing engineering programmes and transform them through modern PBL. To this end, the bottom-up changes introduced by professors, already carrying out transformative PBL in their courses, can act as seminal examples. Finally, a fourth alternative is

Modern engineering professional roles	Description of PBL experiences and features oriented to the different roles	Possible implementation examples
1. Products, processes, and systems engineers	Students live through the specification, conception, design, prototyping and testing of innovative products, processes, or systems, usually employing CAD-CAE-CAM programs and AM technologies and rapid prototyping tools as resources.	• CDIO PBL of an innovative product. • CDIO PBL of an innovative process. • Development of robots, vehicles, satellites, machines, chemical reactors, building models, apps, simulators…
2. Management and business engineers	Students live through the strategic planning of an enterprise and develop its business model or help to reengineer processes within existing industrial plants.	• Create a business plan for a product. • Set down the foundations of a spin-off. • Design a commercialization strategy. • Reengineer a factory's processes.
3. Scientific and research-oriented engineers	Students experience a research project, generally working within a university department or research center, working on basic or applied research tasks, solving a specific problem, and publishing a paper.	• Characterize & model a smart material. • Simulate a nanoparticle cancer therapy. • Optimize a plasma deposition system. • Prepare an experimental process.
4. Political engineers and regulators	Students understand the key relevance of standards, regulations, and policies for enabling technologies to reach those needing them most safely and effectively.	• Design a machine for CE marking. • Design a biodevice under a standard. • Investigate a system's safety. • Create a policy making working group.
5. Social and humanistic engineers	Students supervise the ethical implications of an innovative technology and promote human-centered design processes, working towards optimal societal impacts.	• Optimize a design for better usability. • Study the ethical issues of technology. • Evaluate a system's human impacts. • Study the viability of a social enterprise.
6. Media & arts and cultural engineers	Students experience and foster innovative connections between engineering and art by conceiving, designing, and developing new materials, designs, processes, and methods.	• R&D of CAD/AMT applications for art. • Define a heritage management strategy. • Apply new materials to the textile industry. • Organize an exhibition or performance.
7. Environmental and urban planning engineers	Students focus on human environments focusing on well-being and living through projects linked to improving buildings, cities, and communities in general.	• Intelligently document a building. • Restore creatively an ancient building. • Define a city's environmental strategy. • Conceive the layout for a new city.
8. Biomedical and biological systems engineers	Students design and develop technologies and processes in connection with the biomedical field and with biological systems and biotechnology in general.	• CDIO PBL of a medical device. • R&D of bio-MEMS for diagnosis. • Optimize a hospital's processes. • Design of a biorecycling facility.

Table 5.
Description of PBL experiences oriented to the different professional engineering roles in Society 5.0.

foreseen: evolving already existing PBL courses towards the concept and context of Engineering Education 5.0 (dynamically updating and incorporating new technologies, making knowledge-based and outcomes-based education compatible, focusing on the SDGs and sustainability, taking account for the human and ethical aspects of engineering, among others).

Programme level	Academic year	First semester experiences		Second semester experiences		Total PBL credits/ year
		Type of PBL experience	PBL credits	Type of PBL experience	PBL credits	
Master's Degree in Biomedical Engineering for Society 5.0 (120 ECTS)	6th	R&D PBL: Hands-on experience linked to the development of innovative tissue engineering and biofabrication solutions	6	Final MSc thesis: Develop a medical technology and set the foundations for a related spin-off company	12	18
	5th	CDIO PBL: Design and prototyping of an IoT device for health management	6	In-company PBL: Participate in the QA/QC of production and supply chain of a medical product	6	12
Bachelor's Degree in Biomedical Engineering for Society 5.0 (240 ECTS)	4th	CDIO PBL: Design and prototyping of an AI-based diagnostic device	6	Final BSc thesis: Develop an app benefiting from big data for health prognosis	12	18
	3rd	Synthetic PBL: Design, simulate and 3D print a personalized medical device	6	International competition: Participation in an "UBORA" competition and design school [24]	6	12
	2nd	Analytical PBL: Select a relevant medical device, check applicable standards for its safe development and propose a regulatory pathway towards commercialization	3	Service-learning experience: Select a hospital process, study it and propose improvements by collaborating with healthcare professionals	6	9
	1st	Descriptive PBL: Map biomedical technologies in connection with Industry 4.0 tools and the Society 5.0 paradigm	3	Local competition: Ideas challenge for approaching the "healthcare of the future"	3	6

Table 6.
Implementation example: concrete mapping of modern PBL experiences throughout an integral 6-year Bachelor's and Master's Degree in Biomedical Engineering for Society 5.0.

Top-down approaches and decisions might also support these directions and offer change in the mid-term future. One could foresee international accreditation agencies assuming these principles along the current decade, or a rectorate deciding to update the educational model of a whole university, which could be built around PBL and Industry 5.0. Despite these top-down possibilities, in the author's view, the more relevant educational changes at universities tend to follow bottom-up schemes, starting with an inspiring conversation in the classroom between students and professors or with a shared dream among colleagues from a department or faculty, which act as the crystallization seeds of change.

Accordingly, to favour the proposed transition towards PBL 5.0, the following scheme of **Figure 3** provides a guided set of steps and driving questions, through which PBL for Industry 5.0 experiences can be designed, managed and evaluated,

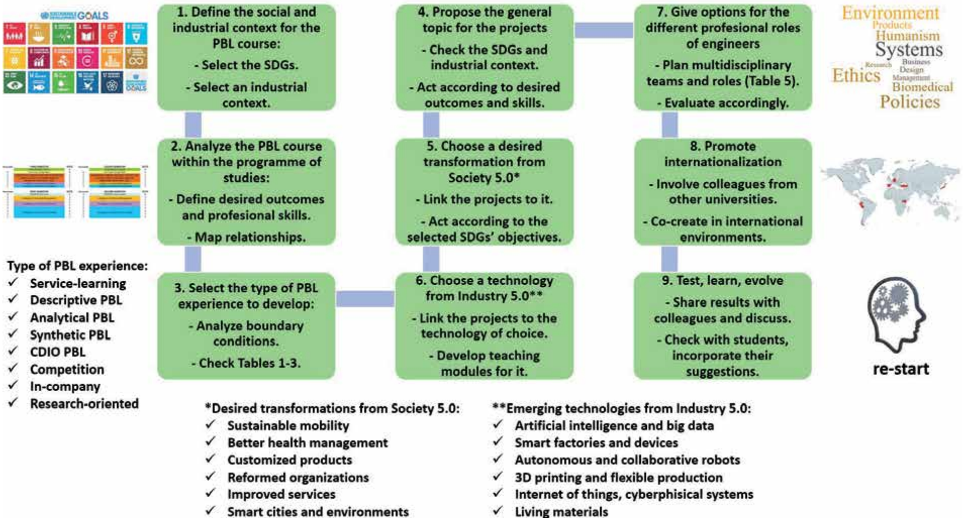

Figure 3.
Guided steps and driving issues for creating PBL 5.0 experiences.

Figure 4.
(a) Upper images: relaxed discussions and peer learning in international PBL experiences. (b) Lower images: PBL prototyping results of biodevices for good health and well-being (SDG3). Innovative Braille display, testing a 3D printed water filter, and face-protecting splints for safe sport practice. Courtesy of UBORA project.

with a focus on their steady integration in already existing engineering programmes, for acting as the previously cited seeds of change. Additional advice may be found in recent publications [25, 26].

Finally, **Figure 4** presents some examples of typical behaviours (students and professors learning together, more Socratic discussions than master classes), environments (international teams, tinkering possibilities, onsite and online interactions), and results (real working prototypes solving relevant needs) expectable in PBL 5.0 experiences mentored by the author.

5. Conclusions

Times are changing in engineering education, as a consequence of the current non-stop concatenation of scientific-technical breakthroughs and related technological revolutions. The age of untouchable decades-lasting engineering programmes is over, and dynamism, evolution, flexibility, and equity are paramount to modern engineering education. In a personal definition, modern engineering may correspond to *the development and application of scientific and technical knowledge to the discovery, creation and mentoring of technologies, capable of transforming human societies and environments, for increased well-being and life quality and, hence, necessarily following sustainability and equity principles*.

In consequence, strategies for enabling the continuous improvement and adjustment of engineering programmes, in a world of changing boundary conditions, are needed. To this end, PBL methodologies and experiences may vertebrate or serve as a scaffold for constructing the engineering programs in the Education 5.0 paradigm. This has been discussed and supported with varied implementation examples and methods, for the successful integration of PBL within modern engineering curricula. In this new context, PBL methodologies are not only hands-on activities for knowledge application, but play also an essential role, within the global educational strategy, for delivering purposeful and continuously updated content, for knowledge acquisition and for developing descriptive, analytical, synthetic, technical and personal skills.

Conflict of interest

The author declares no conflict of interest.

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Chapter 3

Teaching IIoT through Hands-on Activities

Gustavo Sanchez and Devika Kataria

Abstract

This chapter describes a hands-on educational approach to teach Industrial Internet of Things (IIoT), including activities like problem analysis, programming, testing and debugging. Students are given autonomy to propose and evaluate different solutions, using adequate tools and following best practices. In parallel, key competencies like team management, project planning, costing and time scheduling, are imbibed in students to prepare them to become deployable automation engineers. To illustrate the proposed approach, we elaborate on the experience gained from teaching an elective course to undergraduate engineering students, in terms of learning outcomes, methodology, assessment and feedback. This course was centered on the Node Red platform (based on Node.js), using hardware devices like Arduino Uno, Nano and Raspberry Pi. Sensors commonly used and protocols like Modbus RTU/TCP, OPC UA, MQTT are discussed in the framework of common industrial applications.

Keywords: IIoT, experiential learning, Node Red, communication protocols, development boards

1. Introduction

The skill gap for careers in a changing industrial sector has been identified by numerous authors [1], which has prompted educators to quickly adapt their courses, in order to prepare future engineers to excel in this new environment.

Typically, the following basic skills are in general required for engineers to succeed:

- ability to design, operate and troubleshoot processes and equipment, following best recommended practices, to maximize efficiency and productivity.

- teamwork, discipline and time management.

More formally, a document defining the skills and competencies needed in the automation field was proposed by The Automation Federation and International Society of Automation (ISA) [2]. It is made up of following tiers: personal effectiveness, academic, workplace, industry-wide technical, automation technical, occupation-specific knowledge, occupation-specific technical, occupation-specific requirements, and management (see **Figure 1**).

In this model, it is possible to observe that competencies related to Communication, Integration, Software and Cybersecurity are placed in tier 5.

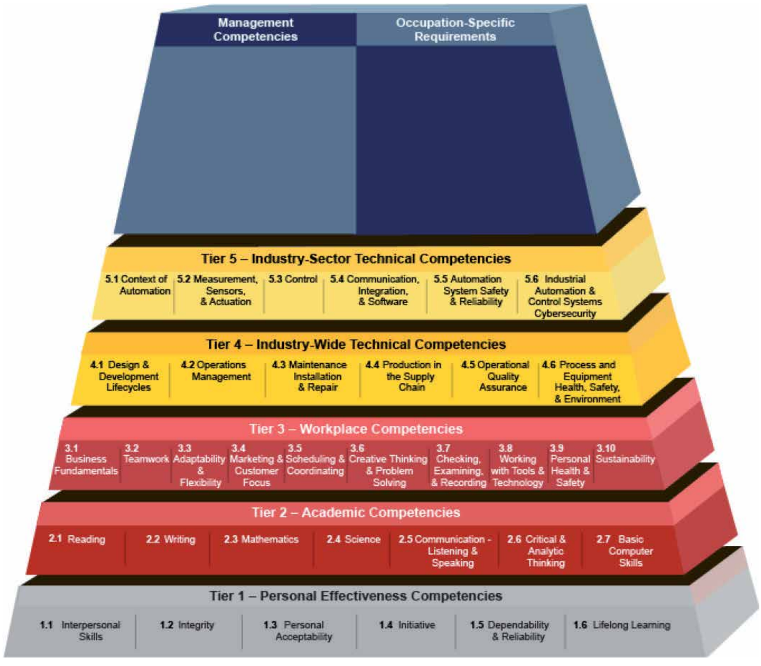

Figure 1.
Automation competency model [2].

Therefore, this is the natural place for the training program that will be described in next sections.

The Internet of Things (IoT) can be defined as a global dynamic network where physical and virtual objects interact to enable a set of services. In this context, the Industrial Internet of Things (IIoT) is the extension of this network to industrial sectors like logistics, transportation, manufacturing, utilities, oil and gas, etc. This extension enables to gather real-time data, necessary to make better decisions across all business functions: procurement, production, shipping, maintenance, etc.

To prepare for this chapter, several reports of teaching experiences related to IIoT have been consulted. In [1], the author describes his personal experience, working with educators and practitioners. It is stated that the path toward creating the Industry 5.0 workforce should begin in elementary school, and a specific curriculum is proposed for each level.

In [3] an on-line learning infrastructure is proposed, that allows to engage in a range of programming of real-world sensing applications, using a board based on the Arduino microcontroller, with several onboard I/O devices, including a slider, a pushbutton switch, a bank of six LEDs, and analog inputs for additional sensors. In [4] a syllabus is proposed, which offers guidelines for the quality assurance and safeguarding of IoT solutions, suitable for advanced studies at postgraduate level.

This chapter describes a hands-on educational approach to teach IIoT. In Section 2, we discuss common educational challenges in this domain and how to overcome them. In Section 3, we elaborate on the experience gained from teaching an elective course to undergraduate engineering students, in terms of learning outcomes, methodology, assessment and feedback. Wherever possible, we provide the link to possible solutions of proposed problems, that we have developed in order to make it available for interested readers to test and adapt them for their own projects. Finally, we conclude this chapter.

2. Educational challenges

To the best of our knowledge, there is no official document specifically describing desired competencies in the field of IIoT. Therefore, we have extracted from [2], the following main technical IIoT-related desired competencies:

- Design, document, install, and support the integration of automation systems with other systems, including Enterprise Resource Planning (ERP) and Manufacturing Operations Management (MOM)
- Design and operate databases for automation systems. Perform data historian duties: curation, archiving, retrieval
- Determine and implement the appropriate tools and methods for cybersecurity

The required technical knowledge includes:

- Network configuration, diagnostics and management
- Industrial digital field protocols (including but not limited to): AS-I, Ethernet/IP, DeviceNet, Foundation fieldbus, HART, INTERBUS, Modbus, PROFIBUS
- Industrial communication protocols (including but not limited to) XML, JSON, ASN.1, BACnet, ControlNet, Ethernet-TCP/IP, LonWorks, OPC UA, PROFINET
- Data contextualization (online/offline), modeling (UML, Entity Relation), storage and retrieval

Therefore, it is possible to observe that there is a broad range of topics to be addressed, which is the first pedagogical challenge that instructors will encounter when trying to design an IIoT course. Here, we propose to select only a basic sub-set of skills and content, which is equivalent to focus on the expected quality and depth of learning, rather than on the number of tools or protocols included in the syllabus (see **Table 1**, Section 3).

Unit	Topic	Content
1	IIoT Fundamentals 3 weeks	Industrial communication: principles, protocols and technologies. IIoT definition, architectures and use cases. Convergence of IT and OT. Design methodology.
2	Interfacing sensors and actuators 3 weeks	Proximity sensors, temperature sensors, vibration sensor, color sensors. Controlling DC/AC motors.
3	Programming with Node Red 3 weeks	Injecting nodes, debugging, managing palettes, designing dashboard.
4	Cloud services 3 weeks	Basic concepts. Device management. Applications: predictive maintenance, quality monitoring, personalized dashboards.

Table 1.
Course units: Theoretical content.

The second challenge is the complexity of real world IIoT applications, which may impede their study, keeping in mind time and resource constraints [5]. Here, we propose to break down problems into simpler sub-problems, which can be solved within the allocated time, using available tools.

For example, the typical integration problem of a given control system to a remote dashboard can be divided into the following 5 sub-problems:

1. Design and implementation of a local dashboard, considering only devices able to communicate through Modbus RTU

2. Assuming the previous system is working, integration of devices able to communicate through Modbus TCP/IP

3. Integration of devices able to communicate through OPC UA

4. Setting up communication to remote broker through MQTT protocol

5. Implementation of more complex applications like computer vision, anomaly detection, etc.

These problems will be further explained in next section, in the framework of a case study centered in our experience teaching an elective course to undergraduate engineering students.

3. Case study

The course Industrial Internet of Things (IIoT) aims at creating the fundamentals skills required to design, implement, and maintain industrial IoT systems. It is taught as elective course to undergraduate engineering students in their prefinal year. A previous exposure to embedded system programming, instrumentation and control systems is recommended. On successful completion of this course students are able to:

- Explain the key components that make up an Industrial IoT system.

- Discuss protocols and standards employed at each layer of the IIoT stack.

- Design, deploy and test a basic Industrial IoT system, including data analysis functionalities.

- Apply best practices to meet desired requirements for IIoT applications.

- Analyze the environmental effects and incorporate robustness in design of IIoT system.

- Choose technology for constrained nodes and network while maintaining real time data collection.

- Explain the importance of cybersecurity for IIoT networks.

The course delivery is planned in online mode and three sessions per week are conducted for 18 weeks. These sessions include concept discussions, hands-on activities, projects, and assessments. The course description document containing the syllabus (see **Table 1**), learning outcomes, assessment rubric and references for learning materials is shared with students at the beginning of course. All the software is open source and sessions to install Node-Red, VNC viewer, Raspbian Busters operating systems, etc. are held at the beginning of the course. It is recommended for students to have a Desktop/Laptop able to run Windows 10.

3.1 Learning and assessment activities

The hands-on, problem-based learning or experiential learning approach means students are given a set of problems, and while trying to solve them they learn theoretical concepts. **Figure 2** summarizes the concept map for the learnings in this course, showing the topics discussed and demonstrated during hands-on sessions.

Next, we describe the set of problems that were proposed to students. Note that, as discussed in previous section, they correspond to the breaking down of a more complex control system integration problem.

3.1.1 Problem 1. Design and implementation of a local dashboard, considering only devices able to communicate through Modbus RTU

Consider the input/output variables shown in **Table 2**. We assume they correspond to a set of sensors and actuators connected to a device, e.g., PLC, Raspberry Pi, Arduino board, etc., able to act as a Modbus RTU slave, at address 01. It is required to design and implement a dashboard to supervise and control this process, which will also run at edge level, in a second device able to run Node Red [6], e.g., Desktop PC, Laptop or Raspberry Pi. This second device will act as Modbus RTU master.

A low-cost solution for this problem is to set up an Arduino/Genuino Uno as MODBUS slave, which is a microcontroller board based on the ATmega328P microprocessor. It has 14 digital input/output pins, of which 6 can be used as PWM outputs, 6 analog inputs, and runs with a 16 MHz quartz crystal (see **Figure 3**). Note that, in this problem, no real sensors/actuators will be connected to this board, because we are only interested in testing communication features. This means that the board will always be sending "dummy" data to the master. This also means that students do not need to have any sensor or actuator at home during on-line classes, to work on this problem.

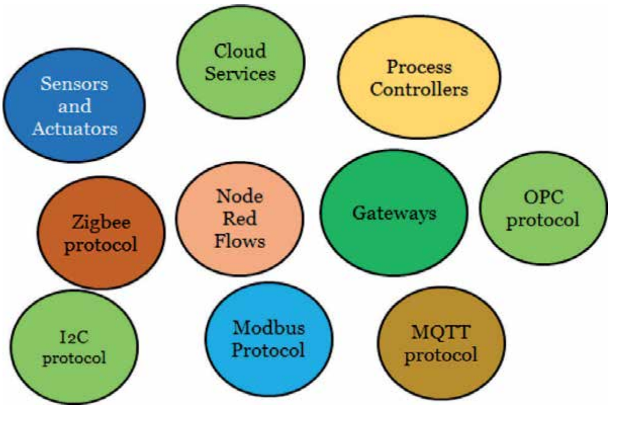

Figure 2.
Concept map for the domain knowledge imparted in IIoT course.

Data address	Type	Internal tag	ISA S5.1Tag	Range
0	Analog input register – read only	AI0	TC01.PV	0–100°C
1	Analog input register – read only	AI1	FC02.PV	0–150 lt/min
2	Analog input register – read only	AI2	PC03.PV	0–200 psi
3	Analog input register – read only	AI3	SC04.PV	0–1000 RPM
4	Analog input register – read only	AI4	VC05.PV	0–10 mm/s
5	Analog output register – read/write	AW0	TC01.SP	0–100°C
6	Analog output register – read/write	AW1	FC02.SP	0–150 lt/min
7	Analog output register – read/write	AW2	PC03.SP	0–200 psi
8	Analog output register – read/write	AW3	SC04.SP	0–1000 RPM
9	Analog output register – read/write	AW4	VC05.SP	0–10 mm/s
10	Discrete input coil – read only	DI0	YC06.PV	0/1
11	Discrete input coil – read only	DI1	YC07.PV	0/1
12	Discrete input coil – read only	DI2	YC08.PV	0/1
13	Discrete input coil – read only	DI3	YC09.PV	0/1
14	Discrete input coil – read only	DI4	YC10.PV	0/1
15	Discrete output coil – read/write	DW0	YC06.SP	0/1
16	Discrete output coil – read/write	DW1	YC07.SP	0/1
17	Discrete output coil – read/write	DW2	YC08.SP	0/1
18	Discrete output coil – read/write	DW3	YC09.SP	0/1
19	Discrete output coil – read/write	DW4	YC10.SP	0/1

Table 2.
Input/output variables for Problem 1.

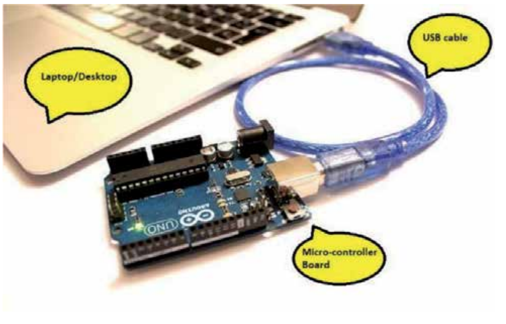

Figure 3.
Example of required set-up for Problem 1.

We propose to use the library SimpleModbusSlave [7] which allows the Arduino board to communicate using Modbus RTU protocol. Note however that it does not fully comply with Modbus specifications, as only functions 3, 6 and 16 are implemented. Similarly, the check for inter character time-out and frame time-out are combined by checking a maximum time allowable when reading from the message stream. This library implements an unsigned int. return value on a call to modbus_update(), which is the total error count since the slave started. Once this function is called, the input/output register defined during setup with function modbus_configure() will be updated. Note that we have also successfully tested this library with Arduino Nano.

In addition to communication setup, it is possible to add other features in this Arduino program, to make it dynamic when visualizing the dashboard, as follows:

- For variable TC01.PV it is required to program a counter that increments from 0 to 100 and then is reset to 0.

- Between variables VC05.PV and VC05.SP it is required to implement a first order transfer function, to simulate a real process.

- Status of discrete output variable YC06.SP must be updated to YC06. PV and Arduino built-in LED.

An example of code complying with these specifications is available in this link: https://bit.ly/3eqHmxB. It is possible to test this code, previously to developing user dashboard, with QModbus, which implements a master application through a graphical user interface, allowing communication with slaves over serial line interface [8]. Students are able to analyze Modbus frames, from master and slave.

The previous explanation corresponds to the edge layer. Now considering the gateway layer, Node Red is able to run in different devices. We have used a laptop for convenience. The following palettes must be installed:

- node-red-contrib-modbus, version 5.13.3

- node-red-dashboard, version 2.28.1

An example of Node-Red code is available in this link https://bit.ly/2RnA9q0, as shown in **Figure 4**. The corresponding dashboard is shown in **Figure 5**.

3.1.2 Problem 2. Integration of devices able to communicate through Modbus TCP/IP

For the same process described in problem 1, include the input/output variables shown in **Table 3**, connected through Modbus TCP/IP at address 02.

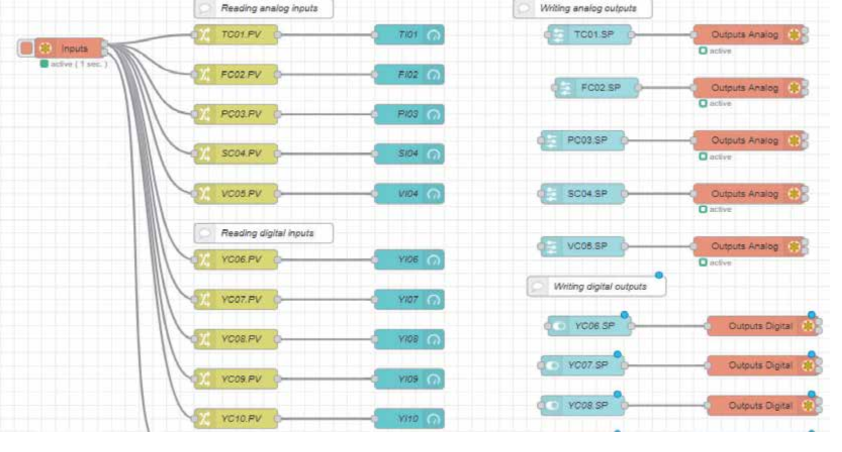

Figure 4.
Example of Node-Red code for Problem 1.

Figure 5.
Example of Node-Red dashboard for Problem 1.

Data address	Type	ISA S5.1Tag	Range
0	Analog input register – read only	TC11.PV	0–100°C
1	Analog output register – read/write	FC12.SP	0–150 lt/min
2	Discrete input coil – read only	YC13.PV	0/1
3	Discrete output coil – read/write	YC14.SP	0/1

Table 3.
Input/output variables for Problem 2.

An example of Node-Red code for Problem 2 is available in this link https://bit.ly/3tpnv7x. It is possible to test this code with ModbusSlave, which enables simulation of slave devices [9]. The limitation is that this software runs only in Windows operating system. The dashboard integrating measurements from both sources Modbus RTU and TCP is shown in **Figure 6**.

3.1.3 Problem 3. Integration of devices able to communicate through OPC UA

Design a dashboard to display the OPC UA tags shown in following **Table 4**, which will be randomly generated by Integration Objects' Server Simulator, which is a free to use tool [10].

An example of Node-Red code to solve this problem is available in this link https://bit.ly/3er1QqZ. The following palette must be previously installed: node-red-contrib-opcua. The dashboard displaying required OPC UA tags is shown in **Figure 7**.

3.1.4 Problem 4. Setting up communication to remote broker through MQTT protocol

It is required to design and implement a remote dashboard, which will run in Cloud, using Message Queueing Telemetry Transport (MQTT) protocol.

It is recommended to have at least some hardware setup (sensors, micro-controllers, power supply, etc.) available with the instructor. In case students do not have any hardware at home, they write the code and send it to the instructor for testing purpose. A schematic diagram showing the architecture for interfacing sensors and uploading the data to Cloud is shown in **Figure 8**. The data from the analog pin is sent to serial port of Arduino. The data from the controller board serial port is sent to the Internet gateway. Node-Red flow is run on the gateway and enable the data to be sent to Cloud.

DOI: http://dx.doi.org/10.5772/intechopen.100217

Figure 6.
Example of Node-Red dashboard for Problem 2.

Tag	Address	Type
Tag11	ns = 2; s = Tag11	Int16
Tag12	ns = 2; s = Tag12	Int32
Tag13	ns = 2; s = Tag13	Int64
Tag14	ns = 2; s = Tag14	UInt16
Tag15	ns = 2; s = Tag15	UInt32
Tag16	ns = 2; s = Tag16	UInt64
Tag17	ns = 2; s = Tag17	Double
Tag18	ns = 2; s = Tag18	String
Tag19	ns = 2; s = Tag19	Byte
Tag20	ns = 2; s = Tag20	Boolean

Table 4.
OPC UA tags for Problem 3.

A snapshot of flow where a SW-420 vibration sensor has been interfaced to an Arduino Nano, which sends the values to dashboard and display them in form of chart, is shown in **Figure 9**.

The sensors may be interfaced to the microcontrollers using various protocols. An example of this is the Zigbee protocol where sensors communicate with an end point device, which in turn sends the sensor data through routers to the Zigbee coordinator. The advantage of this type of connection is that multiple sensors can be connected to endpoint devices, and many such endpoint devices may be connected in star topologies to the controller through routers.

The Zigbee protocol is known to be secure and low power consuming as the endpoints which are inactive may sleep for the inactive duration. A typical application could be connecting crop monitoring sensors to end points and sending the data from endpoints to coordinator, which in turn may send the data to an MQTT server using the node-red-contrib-zigbee pallete (see **Figure 10**).

Various other wireless protocols like the Sigfox and LoRa WAN may be used for interfacing the sensors to the master coordinator/controller. The advantage of some of these emerging protocols are low power consumption and high data rates [11, 12]. The IoT Gateway is used to convert the data format received from any of these protocols to internet protocols like the HTTP, MQTT, XMPP or any other light weight protocol. The Gateway also implements security for the Endpoint and Coordinator devices and may do some edge computing or data analytics before sending the data to the Cloud storage.

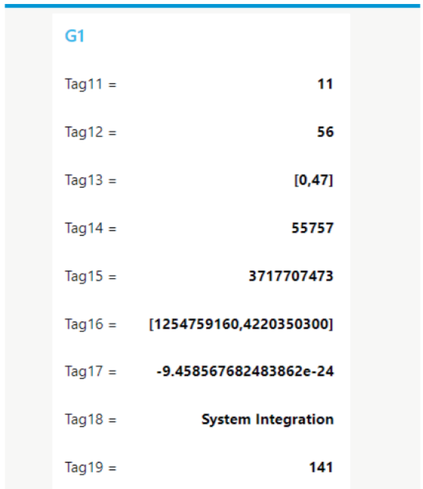

Figure 7.
Dashboard displaying required OPC UA tags.

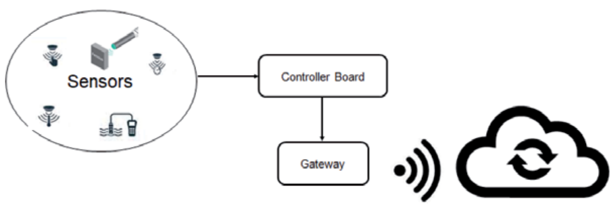

Figure 8.
Architecture for interfacing and uploading data to Cloud.

3.1.5 Problem 5. Implementation of more complex applications like computer vision, anomaly detection, etc

Students were able to interface the Raspberry Pi camera to upload images to Cloud, trying to optimize bandwidth usage. MQTT protocol and associated libraries for image transmission using Python programming are used in some of these projects for uploading data to Cloud. The Node-Red palletes required for implementing the flows were identified and installed.

Machine Learning services available on Cloud like IBM Watson were used by students, where algorithms for image recognition and classification, text recognition and other resources of AI/ML deployed. Knowledge of Raspberry Pi boards and Python programming as well as running Node-Red using Docker container was introduced. Node-Red flow was used to upload camera images and to classify objects using pretrained models from Tensorflow.js (Common Objects in Context dataset), available from pallete node-red-contribtensorflow [13, 14]. A simple flow for interfacing the camera and sending images to Cloud is shown in **Figure 11**. The flow consists of an inject node followed by execute node which contains the command to run the python program and a message payload node to debug the messages.

3.2 Project

Once students have completed all the previous hands-on activities, they were requested to work on a project, so they can apply the methods they have learned. First, they must submit a project charter, describing the project goals,

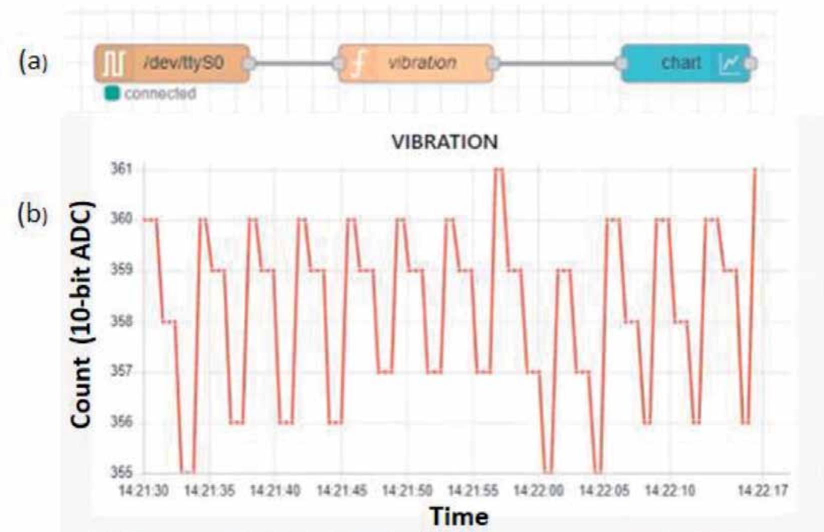

Figure 9.
Displaying SW-420 vibration sensor data in form of chart.

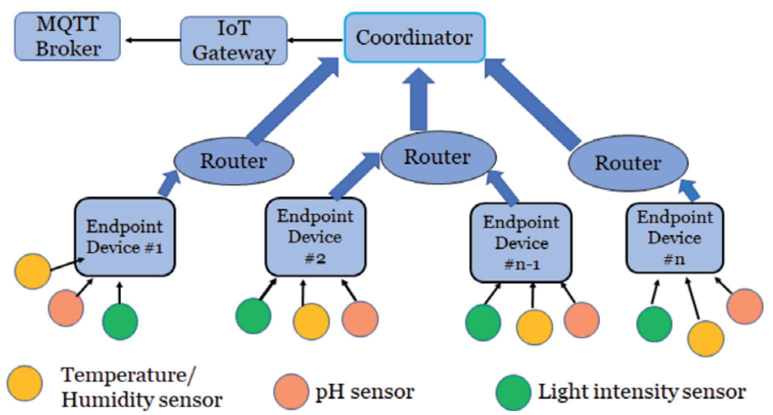

Figure 10.
Example of Zigbee architecture for agriculture application.

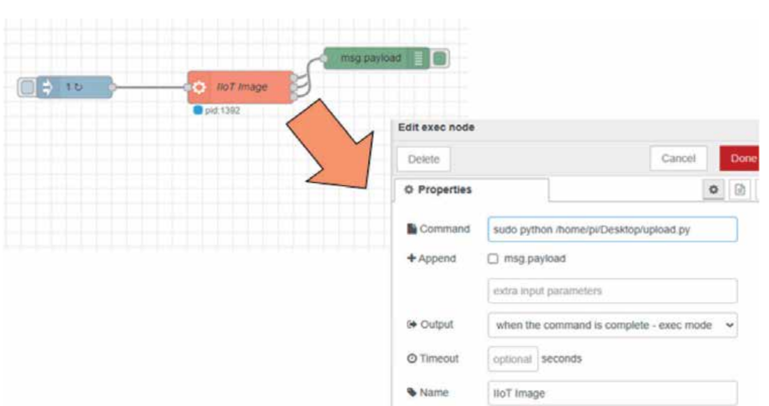

Figure 11.
Simple flow for interfacing the camera and sending images to Cloud.

responsibilities of team members, resources/bill of materials, references to literature and timing charts. Students should be made conscious of the professional ethics while working on this project. We consider the following facts as academic dishonesty offenses:

- Cheating: using unauthorized information. Receiving or giving unauthorized assistance.
- Fabrication: invention or falsification of any information.
- Plagiarism: deliberately representing the ideas, results, reports, drawings, notes, computational code, or any other product prepared by another person as one's own.

Some of the project ideas identified by the students for this course are:

a. monitoring safety in personnel in industry by monitoring camera images for helmet usage,

b. facemask detection for crowd at public places using live video transmission.

c. home automation using Zigbee and MQTT protocol and Node-Red flow(s),

d. language translation: speech to text and vice versa for real time audio signal,

e. surveillance using infrared camera and live video transmission to remote control station.

3.3 Assessment

Quizzes are recommended to be conducted periodically for assessing the learning outcomes. The aim of these evaluations should be to determine the understanding of concepts for implementation. As a sample a quiz may comprise following questions (with marks break) as follows:

Q1. Write Node-Red and Arduino code to solve the following problem:

a. Communication between Arduino and Node-Red can be implemented using any protocol (4 marks)

b. Two values A in [0, 100] and B in [0, 100] will be generated through Node-Red dashboard and written to Arduino board (3 marks)

c. Average M of these A and B will be calculated by Arduino board (3 marks)

d. Average M needs to be displayed back in Node-Red dashboard (3 marks)

e. If M is greater than 80 during 5 seconds, an alarm H will be displayed in the Node Red dashboard and Arduino built-in LED, until a RESET button (also in dashboard) is pressed (3 marks)

f. All values A, B, M and H will be published to Mosquitto MQTT broker, to following topics: IIoTQuiz1/Name/A, IIoTQuiz1/Name/B, IIoTQuiz1/Name/M, IIoTQuiz1/Name/H, where Name is student's name. (4 marks)

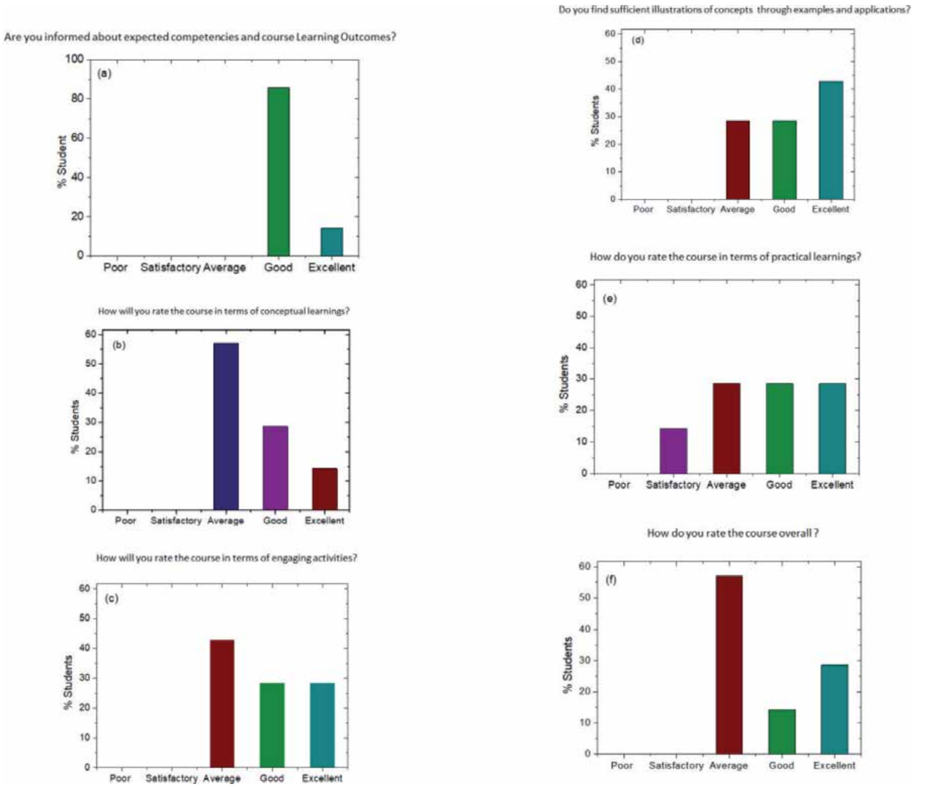

Figure 12.
(a–f) Feedback questionnaire and responses by students for the first time launch of the course.

3.4 Learners feedback

Feedback is recommended fortnightly to understand the learning process. A sample questionnaire and the responses are shown in **Figure 12** here for the course conducted by the authors for the first time for undergraduate students. The bar charts are self-explanatory and the feedback will be considered for further improvements.

4. Conclusion

In this chapter, a hands-on educational approach to teach Industrial Internet of Things (IIoT) was proposed. Because the set of required skills is large, we propose to focus on a basic sub-set of skills and content, trying to achieve the best possible quality and depth of learning. To overcome the complexity of real world IIoT projects, we propose to identify simpler sub-problems, which can be solved within the allocated time, using available tools. To illustrate our approach, specific examples, in terms of learning outcomes, methodology, assessment and feedback were presented. Wherever possible, link to solutions was provided for interested readers to test and adapt them for their own projects. The feedback received from students and their final performance is encouraging, as they seem to appreciate the proposed approach. We believe the same can be extended to teach similar courses like Digital Computer Networks, SCADA systems, Programmable Logic Controllers, etc. Currently, authors are planning to scale up this course, as an international MOOC, to reach a broader audience.

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Chapter 4

Fusion Skills and Industry 5.0: Conceptions and Challenges

John Mitchell and David Guile

Abstract

The nature of work is changing rapidly, driven by the digital technologies that underpin industry 5.0. It has been argued worldwide that engineering education must adapt to these changes which have the potential to rewrite the core curriculum across engineering as a broader range of skills compete with traditional engineering knowledge. Although it is clear that skills such as data science, machine learning and AI will become fundamental skills of the future it is less clear how these should be integrated into existing engineering education curricula to ensure relevance of graduates. This chapter looks at the nature of future fusion skills and the range of strategies that might be adopted to integrated these into the existing engineering education curriculum.

Keywords: Digital Skills, Curriculum Development

1. Introduction

Up until the impact of the global pandemic known colloquially as Covid-19, the engineering education community and the industry sectors its graduates support had been involved in a debate over the necessary skills of an engineering graduate for some time. That debate in the UK reflected, on the one hand, the longstanding concern as, for example, the IET's annual Skills and Demand in Industry Survey [1] highlighted, an "estimated annual shortfall of 59,000 new engineering graduates and technicians, a deficit which only continues to get worse." ([1], p. 2), with 48% reporting difficulties in respect to the skills available – of these 73% attributed this to "Problem with candidates who have academic knowledge but lack workplace skills" ([1], p. 16). And, on the other hand, a response to the perceived challenge posed by some developments associated with the *4th Industrial Revolution* and prospect of Industry 5.0 that will require new, rather than additional, engineering skills [2].

Since the future is open to debate and discussion, the aim of this chapter is to present scenario-based perspectives [3, 4] on the development of global engineering education in response to them. The chapter is therefore structured as follows. It starts by offering a concise explanation of the concept of *the 4th Industrial Revolution* and its associated promise (elimination of environmental problems) and threats (automation). It then traces the emergence of Industry and Society 5.0 out of the 4IR to show their close association with, and significant difference from, one another. Next, the chapter addresses the issue of engineering and specialisation by considering the relationship between recent innovations in engineering education and current projections of new digital skill needs, and the extent to which the former will provide the foundation for delivering the latter. The chapter problematises this assumed trajectory of development by introducing the concept of *fusion skills* [5]. This concept represents an attempt to rethink the longstanding debate about the extent to which 'machines' are deployed to automate or augment human work through the deployment of AI in workplaces and occupations, by identifying eight new skills that are far more radical and far reaching than the concept of digital skills. Having done so, the chapter concludes by outlining 2 scenarios depicting different options for the development of the *engineering degree for Industry 5.0*, based on the introduction of fusion skills into traditional single subject and integrated or interdisciplinary engineering degrees.

2. From the 4th industrial revolution to industry and society 5.0

Over the last thirty years, the concept of *industrial revolution* has been elevated from its academic origins in literature addressing the economics, history, sociology and politics of technological change into mainstream media discussions and debates about the future trajectory of direction of societies. The concept that has generated most discussion in the last decade is the *4th Industrial Revolution* (4IR). The 4IR is an "umbrella" [6] concept, in other words, it packages together a number of technological developments, including recent and expected advances in machine learning (ML), artificial intelligence (AI), robotics, 3-D printing and the Internet of Things (IoT), to forecast the future direction of economic, social and technological development in the 21st century. Part of the reason the 4IR has become a commonplace term and a feature of the popular, policy and research vocabulary across the globe as a result of its promotion by the World Economic Forum [7]. The WEF – a not-for-profit organisation – is chaired by Founder and Executive Chairman Professor Klaus Schwab and is guided by a Board of Trustees made up of global leaders from business, politics, academia and civil society. It defines its mission as "committed to improving the state of the world by engaging business, political, academic, and other leaders of society to shape global, regional, and industry agendas" [8]. In the context of its mission statement, one of the WEF's concerns is to serve as a global platform for interaction, insight and impact on the scientific and technological changes that are changing the way we live, work and relate to one another.

To advance and popularise this concern, Schwab wrote in 2017 the first book to be published with the title *The 4th Industrial Revolution* [9]. Drawing, lightly, on the well-established tradition of the historical chronology of the invention of technological tools and techniques [10, 11], Schwab presents a compelling narrative about technological change. He argues it is possible to identify four distinctive phases of technological change or in his more flamboyant term "revolutions." They are summarised as follows [9]:

- The First Industrial Revolution was characterised by the use of water and steam power to mechanise production;
- the Second was characterised by the use of electric power to create mass production;
- the Third was characterised by the use of electronics and information technology to automate production.

The Fourth is however, according to Schwab ([9], p. 1–2) very different, because it is "characterised by a fusion of technologies that is blurring the lines between the physical, digital, and biological spheres, collectively referred to as cyber-physical systems". This fusion or blurring is occurring as a result of technological breakthroughs, such as artificial intelligence, nanotechnology, biotechnology and robotics, becoming firstly, commercialised via additive manufacture/3D printing and autonomous transport and secondly, interconnected through the Internet of Things underpinned by fifth-generation wireless technologies (5G) (**Figure 1**).

There are two discernible perspectives – promise and threats – on the 4IR.

2.1 The promise of the 4IR

The underpinning assumption of the promise perspectives is that all the technological developments associated with the 4IR have one key feature in common Schwab ([9] p. 1–3): they are underpinned by cumulative and exponential developments in digitization and computer science impacting on their own development (i.e. continuous development of the next generation of algorithms and technological artefacts and services) as much as on the material and biological worlds.

The main systemic development enabled by the 4IR is the Internet of Things (IoT), that is, a network comprised of machine-to-machine communication empowered by computers that can gather and interpret information [13]. In its simplest form, the IoT will, as a result of convergence of multiple technologies such as real-time analytics, machine learning, commodity sensors and embedded systems, "connect everything with everyone in an integrated global network. People, machines, natural resources, production lines, logistics networks, consumption habits, recycling flows, and virtually every other aspect of economic and social life will be linked by sensors and software to the IoT platform, continually feeding Big Data to every node – businesses, homes, vehicles – moment to moment, in real time" ([13] p. 11). Rifkin's somewhat Panglossian vision of the IoT can be illustrated through reference to the role of 3D printing. This form of printing, which is sometimes called additive manufacturing employs, as Ford ([14], p. 171) explains, "a computer-controlled print head that fabricates solid objects by repeatedly depositing thin layers of material." Depending on the object to be created, 3D printing

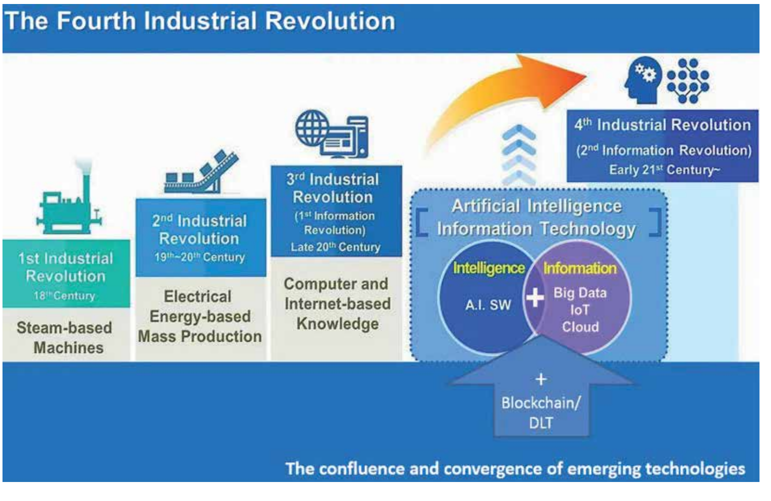

Figure 1.
The fourth industrial revolution – *Created by William Genovese on behalf of the Chinese telecommunication company Huawei [12].*

starts with a decision about which material will be used and then proceeds to builds an object into a three-dimensional shape using a digital template. Currently, 3D printing is primarily limited to applications in the automotive, aerospace and medical industries, where it is being "integrated with traditional manufacturing" ([14], p. 173). Looking to the future, it is anticipated that as size, cost and speed constraints are reduced, 3D printing will become "more pervasive to include integrated electronic components such as circuit boards and even human cells and organs" ([9], p. 17).

Turning our attention to the 4IR's potential through the use of technologies and intelligent systems design to not only restore and regenerate our natural environment, but also support a "great reset' [15] after Covid we encounter the promotion of a new natural and social Panglossian vision. At its heart is a tantalising suggestion that the 4IR can be harnessed to "build entirely new foundations for our economic and social systems [15]. This great reset would, according to Schwab, have three main components. The first would steer the market toward fairer outcomes. To this end, governments should improve coordination (for example, in tax, regulatory, and fiscal policy), upgrade trade arrangements, and create the conditions for a "stakeholder economy." The second component of a Great Reset agenda would ensure that investments, especially in AI, advance shared goals, such as equality and sustainability. Here, the large-scale spending programs that many governments are implementing, for example, the "Biden" plan, represent a major opportunity for progress. One way is to ensure funds are used to create a more resilient, equitable, and sustainable society by using AI to assist with, for example, building "green" urban infrastructure and creating incentives for industries to improve their track record on environmental, social, and governance metrics. The third and final priority is to harness the innovations of the Fourth Industrial Revolution to support the public good, especially by addressing health and social challenges. During the COVID-19 crisis, companies, universities, and others have joined forces to develop diagnostics, therapeutics, and possible vaccines; establish testing centers; create mechanisms for tracing infections; and deliver telemedicine. Imagine what could be possible if similar concerted efforts were made in every sector.

2.2 The threat posed by the 4IR

Alongside the above Panglosian vision of the 4IR, its market-focused advocates also acknowledge the possibility that it might result in a world without work. Reports from global professional service companies, such as Deloitte, Forbes McKinsey, PEW and Price Waterhouse Coopers, all contain sections contrasting the impact of emerging technologies on the labour market. At the heart of this dystopian view of about the potential outcomes of the 4IR lies the issue of *automation.* The threat that the development of new technology might pose to employment has been a subject of debate in History of Technology, Labour Economics, and Political Economy for many decades (see [16] for a recent overview). The scene was set however for the current debate among think tanks, professional service firms and researchers about the effects of automation on employment by the report [17]. Their report has achieved near totemic status as regards the forms of employment 'at risk' of automation issue because, as Frey and Osborne ([17], p. 5) note, they forecast before more or less any other researchers "what recent technological progress is likely to mean for the future of employment." **Figure 2**, using data from the Data from McKinsey Global Institute [18] gives an indication of the scale of the shift required, predicting that up to 800 million workers worldwide, approximately 30% of the workforce, may be impacted with up to 375 million needing to change occupation category as a consequence.

Figure 2.
The impact and threat of 4IR on employability and jobs by 2030. Data from McKinsey global institute analysis [18].

They achieved this goal by focusing on the susceptibility of jobs to computerisation in the following way. Selecting the technological advances in Machine Learning (ML) and Mobile Robotics (MR), Frey and Osborne demonstrated the ways in which such technologies are now able to perform tasks which have until recently been considered genuinely human and this state of affairs is escalating rapidly. Moreover, Frey and Osborne concluded based on this possibility and their prediction employers would automate work processes that this enhanced technological performance was no longer confined to routine tasks as has been the assumption of most studies in labour economics in the past decade (see [19] and [20] for reviews of the literature). It is increasingly the case that machines are capable of performing non-routine cognitive tasks such as driving or legal writing. Frey and Osborne noted that advances in the field of ML facilitated the automation of cognitive tasks, the only exception to this threat was "Engineering Bottlenecks" ([17], p. 33), in other words, tasks related to perception and manipulation that, at present, cannot be substituted by machines since they cannot be defined in terms of codifiable rules and thus algorithms.

Subsequent research has also produced equally eye-catching, albeit slightly different, forecasts about the threat of job loss. One notable example is the report from the Brookings Institute – "What jobs are affected by AI?" The report argues the reason it has been difficult to "get a specific read" on AIs implications for work is because "the technologies have not yet been widely adopted" ([21], p. 3). Consequently, analyses from "Oxford (i.e. [17]), OECD, and McKinsey have had to rely either on case studies or subjective assessments by experts to determine which occupations might be susceptible to an AI takeover" ([21], p. 4). The report also points out that none of these analyses focused solely and specifically on AI, mainly concentrating on an "undifferentiated array" of automation technologies including robotics, software, and AI all at once. In contrast, the Brookings Report claims that it is drawing on a "new approach … [based on]… quantifying the overlap between the text of AI patents and the text of job descriptions … to identify the kinds of tasks and occupations likely to be affected by particular AI capabilities ([21], p. 4). The former provide a way to predict the commercial relevance of specific technological applications, for example, applicants willingness to pay nontrivial fees to file them is a proxy measure of patents likely uptake, and the latter because they provide a textured insight into economic activities at the scale of the whole economy. Using this method, the Brooking team undertook a granular, statistical analysis of the specific documented task content of occupations in a number of sectors, that are, potentially, exposed to emerging AI capabilities, for example, agriculture, finance etc., and drew the following conclusions: AI could affect work in virtually every occupational group and that better-paid, white collar occupation may be most exposed to AI, with business, technology and finance being particularly vulnerable (**Figure 3**).

2.3 Further perspectives on the 4IR

In parallel to the above developments, two sub-concepts have slipped into some media debates and discussions – Industry or Society 4.0 or 5.0. The former emerged from discussions between leading industrial and academic figures in Germany [22] and is a subset of the 4IR since Industrie 4.0 is predicated on the role of the IoT in facilitating the establishment of smart factories *guided by* sensors and other devices. This core assumption being that the above set of connections will alter the classic distinction between the production and consumption of material products, because it introduces the possibility of supply chains being managed by producers, suppliers and consumers to monitor and optimise assets and activities to a very granular level, in accordance with agreed societal values.

In contrast, the concept of Society/Industry 5.0 originated in Japan in 2016 in the Japanese Government's policy document the *Fifth Science and Technology Basic Plan* [23]. The defining difference between the two slightly different, but nonetheless related, societal and industrial conceptions, is that Society/Industry 5.0 is based much more comprehensively on the principle of *personalisation* than the 4IR. It affirms new forms of cooperation between man and machine and industry and higher education as human intelligence works with machine intelligence, to produce

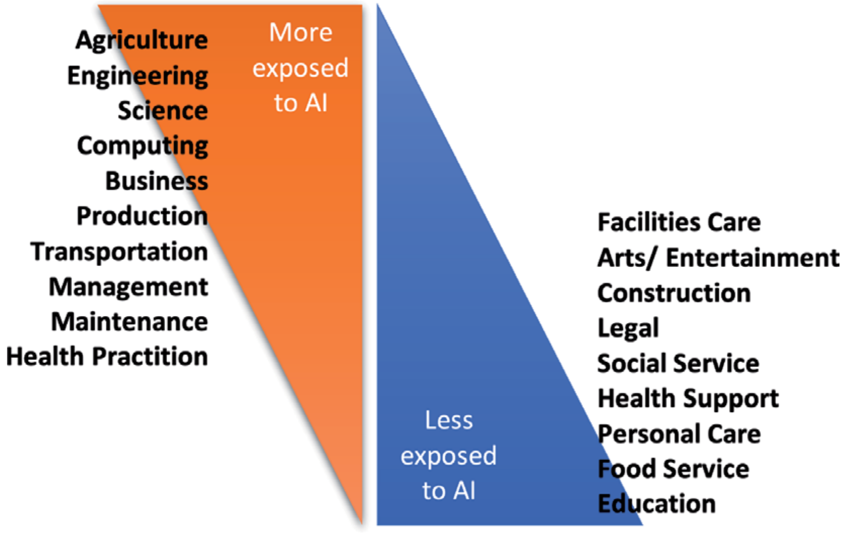

Figure 3.
Analysis of AI exposure scores in the US for major occupational groups. From Muro et al. [21].

products, services and systems that are genuine co-constructions between the state, market and civil society, and education and industry and communities [23]. This development elevates "knowledge exchange" between the private, public and third sector into a principle of co-construction rather a beneficial by-product of that way of working [24]. We return to this issue in the conclusion.

3. The 4IR and engineering

In parallel to the above developments engineering education has been in the grip of its own revolution for some time. Starting slowly in a small number of universities and pioneered by new schools of engineering such as Olin College [25] and The Lassonde School of Engineering "home of the Renaissance Engineer™" [26] there has been a growing debate on the skill set needed by the engineering graduate of the future. The core of these developments can be distilled to two main directions. The first is the inclusion of a boarder skill set into discipline-specific engineering degrees. Proponents argue that the 'math-science death march' [27] whereby multiple years of fundamental maths and science knowledge is required before students are able to engage in creative practical activities should be replaced with a more holistic approach to the formation of engineers with authentic, open and societally relevant projects from early in the curriculum [28]. The second, connected, direction is the need for engineers to have an interdisciplinary perspective. This follows from the first in that, if students are to be challenged with authentic, open and societally relevant projects, then these projects will no longer respect established disciplinary boundaries: they imply more integrate or interdisciplinary approaches. Therefore, the student teams assembled to address them must be interdisciplinary in nature unless the context is to be boiled down to 'toy' versions of the true problem [29]. Few, if any of the great challenges that we face as a society will be solved by a single discipline, while the emergence of new technologies created in a vacuum is already having a profound and often arguably negative impact on humanity.

The current work in reimagining skills for future industry strongly supports this direction of travel calling for interdisciplinarity to be at the heart of the design of future education systems. The report 'The skills implications of Industry 4.0' cites an industry example where the requirement is for "employees who are Industry 4.0 specialists with interdisciplinary skills for example uniting class mechatronics with good IT knowledge and strong social skills." ([2], p. 3). This example is supported by the outcome of the EU workshop on Enabling Technologies for Industry 5.0 where they identify a need in the workforce to be "Interdisciplinarity and transdisciplinarity, the requirement to integrate different research disciplines (e.g., life sciences, engineering, social sciences and humanities) is complex and must be understood in a systems approach." ([30], p. 6).

All the emerging models described above share a renewed focusing on creativity and interdisciplinarity within the engineering curriculum. While these are undoubted important skills for the modern role of the engineer and in the near future, will they be sufficient to prepare students for the future industrial landscape of digitisation, automation and eventually personalisation?

If we consider the future where "by 2025, humans and machines will split work-related tasks 50-50, while 97 million new jobs will emerge in AI, the Green economy and Care economy." [7] we see that there is both considerable need and significant opportunity for new skills. This dispels the views of some that I4.0 will replace existing jobs, as the Manpower report "Skills revolution reboot: The 3Rs - Renew, Reskill, Redeploy" [31] argues strongly, automation and hiring seem to go hand in hand. However, the Deloitte Global Millennial Survey 2020 [32], which concluded that 70% of young people believe they only have some of the skills that will be required to succeed in the work of the future raised significant concern about the perception of the current preparation.

However, we do note differences in the tone surrounding the key focus of industry 4.0/5.0. Although there is no universal definition. In the US and in China, for example in the 'Made in China 2025' governmental initiative [33] there is a heightened emphasis on the economic benefits of this revolution. Whereas in Europe, the European Commission provides a more human-centric voice with their definition, which states: "Industry 5.0 recognises the power of industry to achieve societal goals beyond jobs and growth to become a provider of prosperity, by making production respect the boundaries of our planet and placing the wellbeing of the industry worker at the centre of the production process." ([30], p. 6). In linking 'Industry 5.0' to 'Society 5.0' [34] they argue that a key focus of this revolution should be committed to achieving Sustainable Development Goals, including equality, climate change, peace, justice, eradicating poverty, and prosperity.

A message of global responsibility and societal good chimes with research in engineering education [35] as well as survey data, presented in the PricewaterhouseCoopers report, "Millennials at work – Reshaping the workplace", which suggests for millennials, once their basic needs such as adequate pay and working conditions, are met, the social values of the company become highly important when choosing an employer. The report states: "millennials want their work to have a purpose, to contribute something to the world and they want to be proud of their employer." [36].

In the UK there has been an emphasis on the process by which new graduates will obtain the skills of the future and how existing employees will be upskilled rather than focusing on the skills themselves. This is in line with the broader skills agenda of the UK Government and the longer-term industrial strategy which has necessarily had a change of perspective in light of BREXIT. The report "Manufacturing the future workforce" by the high-value manufacturing catapult calls for new models of education including the use of modular content related to emerging technologies to support the achievement of amended and new skills requirements ([37], p. 11). It also a follows a recognisable path of describing the need for co-creation between industry and academia in the development of such material ([37], p. 11). A similar recommendation is made by WorkSkillsUK in a report sponsored by the UK Department of Education - "greater co-operation between industry and educational institutions will be vital in ensuring the sector has the Industry 4.0 skills it needs for the future." ([2], p. 3) echoing the message of the European commission which suggests "increasing university-industry collaboration" and "Acknowledging the role of industry partners as educational, research and employment partners, and ensuring their engagement in the full student's learning experience," ([38], p. 17).

More recently there have been a number of reports that look to address the skills issue more directly. For example, a report for the European Commission in 2020 observed that "The main emphasis still needs to be put on the technical skills forming the core of this profession." ([38], p. 13) although then proceeds to offer a more cautionary tone, noting "However, rapidly advancing technology requires a general mind-set for continuous improvement and lifelong learning. It is no longer just about what one knows, but increasingly about one's ability to adapt to continuously changing circumstances and to constantly advance one's knowledge and skills. Focussing on technical skills only is thus not enough" ([38], p. 13), before supporting the agreement for the current direction of change saying "crucial non-technical skills … , among others, to critical thinking, creativity, communication skills and ability to work in teams." ([38], p. 14). This work is part of the EU's goal of "Europe Fit for the Digital Age" making digital innovation a priority within the member states. In achieving this it looks firmly toward skills: "Education, training, re-skilling and up-skilling are certainly among the most pressing issues to address when accommodating the digital transition in industries, as qualified human capital is of the utmost importance to make it a reality." ([38], p. 28).

Although the range of sectors considered is huge there is some agreement on the types of skills that the future workforce will require. One example of how they are could be broadly grouped comes from the World Manufacturing Forum's Top Ten Skills for the Future of Manufacturing [39]:

1. Digital Literacy
2. AL and Data Analytics
3. Creative problem solving
4. Entrepreneurial Mindset
5. Ability to work physically and psychologically safely and effectively with new technologies
6. Inter-cultural and -disciplinary inclusive and diversity-oriented mindset
7. Privacy and data/information mindfulness.
8. Handle increasing complexity
9. Communications skills
10. Open-mindedness toward constant change

This example is not atypical and demonstrates the mix of aspects that is usually seen in such work. It stimulates a debate as to the structures and processes best place to develop these skills [40]. However, most striking is the contrast between the typically formulation of current skill sets, heavily focused on knowledge of operations and the much more holistic requirements of the skills suggested of the future age. Although, not surprisingly, digital skills come top of the list, digital skills are not the only skills that will be pertinent for industry workers in the future. As can see, only four of the areas set out directly refer to digital skills: "digital literacy, AI and data analytics," "working with new technologies," "cybersecurity", and "data-mindfulness". The remaining 'skills' are more transversal skills linked to habits of the mind or ways of thinking. .

Although these lists provide an interesting starting point for the discussion of education of the future, the skills presented here are very much still framed in current terms. To be able to delve deeper into future needs, further interrogation is required of the role of the workforce in future industry to draw out more specific challenges to the education system of Industry 5.0.

4. Engineering and specialisation: current and future perspectives

Around the world, engineering in higher education responded positively during the latter decades of the 20th Century to support the move from standardised to customised and bespoke models of production in all spheres of industry. In the last 30 years for example, shifts have occurred in curricula and pedagogy, internationally as well as in the UK, and we have seen an increase in the models of engineering education that have moved from single-discipline siloes of engineering theory that prepared graduates for highly technical work in isolated domains, to increasingly practical educational compositions, focusing on engineering design. This development has, however, been uneven within departments of engineering in different countries. One common reason is that departments of engineering have continued to emphasise the value of foundational skills in mathematics and engineering sciences alongside the introduction of more practically-orientated approaches, and have selectively adopted appropriate curricula and pedagogic models.

From the discussion of future skills needs above, it is clear that this approach to education is going to be problematic. In the majority of universities, the disciplines do not just function as collectives based on thematic areas but are typically woven into the fundamental administrative structures of the organisation. Of course, organisation restructuring is not impossible, albeit considerably less common in the academy than in industry. However, the breaking down of such structures to enable evolutions in teaching approaches requires a multifaceted approach to leadership, that encompasses administration, research and teaching interest simultaneously. These systemic barriers to implementing, what is often seen in this context as radical change, are not to be underestimated. Although, despite many institutions still struggling to find the inertia to break free of these institutional bonds, we argue that such transformations are necessary if the truly integrated programmes required to deliver the skills requirements we identify are to be achieved.

4.1 Integrated approaches to engineering curricula

Despite, these challenges, there are many positive signs of developments that are excellent starting points to demonstrate the value of an integrated approach. For example, an increasing set of institutions have looked to frame their engineering curriculum in the profound societal needs of the 21st Century (e.g. Global Grand Challenges [41], 21st Century Grand Challenges [42], Grand Challenges for Engineering in the 21.st Century [43]), typically via the UN sustainable development goals to provide context to the technical education being provided. However, despite the progress in some quarters, there are continuing requests from industry for an improvement in graduates' communication and teamwork skills and to enhance their appreciation for, or experience with, the non-technical aspects of engineering solutions and innovation processes but, in addition, there is an emerging industry clamour for new technical competences and skills to match new technologies. Another challenge is that "Recently, a more comprehensive view of innovation has emerged which has led to educational interventions that aim at fostering creativity and thinking skills, as well as non-disciplinary skills such as entrepreneurial capacities, in a wide number of contexts, for all pupils and students, irrespective of their field of study" ([44], p. 206). There is a strong call for educators to instil qualities of resilience, creativity, empathy, flexibility and teamwork, as well as technical and analytical expertise, so as to enable students to be more innovative and entrepreneurial [45]. Given the pressing need for engineering competences, teaching that continues to be confined to single subjects (e.g. heat transfer in one course, thermodynamics in another, environmental engineering in another, technical writing in another, etc.) with little reference to one another, delays the development of proficiency in the fundamentals, methods of modern engineering practice, cultural literacy, and the generic competences required for success [46].

This drive toward greater interdisciplinarity is not new. As discussed earlier, this has been the direction many revisionist engineering educators have travelled from some time. However, we argue that as the 4IR takes hold, this will no longer be a beneficial approach to the formation of future engineers, but a necessary one. Current developments have been encouraged and supported by industry [47] and driven on by wide range of commentaries that have lamented the shortage of skilled graduate engineering that are available to enter the workforce [1, 48, 49]. The resulting innovations and developments have followed the principles outlined above, a focus on a broader skill set of creativity, team-work, and communications and an emphasis on interdisciplinary and authentic problem solving.

One of the first and most wide-ranging model came with the founding of Aalborg University in 1974 with an all-pervasive model of Problem- and Project-Based Learning [50]. The developments drew on the principles popularised by Barrows [51] of using problems as the central point around which the learning experience is based. In engineering, the problems typically are elicited as group projects, which occupy approximately half of the students' time. In the years since a number of notable new entrants have developed innovative models of engineering that balance the acquisition of knowledge and skills through problem or practice led curricula. In the late 90's the F.W. Olin Foundation founded the Franklin W. Olin College of Engineering in Needham, Massachusetts, USA with a vision of holistic approach to engineering education embracing creativity, innovation and entrepreneurship and design. A three-stage curriculum with design projects in each year is described, with a Multidisciplinary Foundation, followed by a specialisation phase and a realisation phase incorporating authentic capstone project experiences [25]. By taking this approach, the university has already attained several higher education goals in engineering education: their student body is gender balanced, they have the highest graduation rates in the US and graduates have successful pathways including graduate school attendance, employment and entrepreneurship. Olin especially expects to make a difference in terms of the supply of engineers into the US economy, and the world, and thus actively pursues collaborations with other higher education engineering institutes as well as industry, governments and other engineering stakeholders. Their ambitious goal is to revolutionise engineering education by treating students as engineers from day-one so they hit the ground running since the curriculum and pedagogy emphasise real-world scenarios with everything from project proposal to meeting minutes, to progress reports and plans on innovation iterations [52].

A decade later saw schools such as the Singapore University of Technology and Design (SUTD) and the Lassonde School of Engineering at York University in Canada admit their first students in 2012 and 2013 respectively. SUTD formed with a collaborated between MIT and Zhejiang University is a research-intensive university built on a multi-disciplinary foundation of no departments or schools. The curriculum is highly active and design-centred with a collaborative approach to maker-based learning in specialised 'fab labs' or make-spaces [52]. With a mission to create renaissance engineers, the Lassonde School of Engineering emphasised an entrepreneurial mind-set with a social conscience and a sense of global citizenship. It set out to have a 50:50 gender balance, something that would set it apart from the majority of engineering majors and through co-operative education and industry partnerships [26].

In recent years more have emerged. In 2016 Charles Sturt University in Australia established their new degree in Civil Systems engineering, with a heavy focus on entrepreneurial engineers in their local regional. The intense, fast-track programme offers a significant work-place learning complimented by a 'topic-tree' approach to learning that offers around 1000 topics arranged in branches that offer a flexible learning environment to the cohort. In the UK, two new entrants gained approval to accept their first cohort in 2021. TEDI London, part of a collaboration between Arizona State University, King's College London and UNSW Sydney offers an Industry-led and project-based curriculum in global design engineering. Conceived as an inherent interdisciplinary programme it arranges projects in themes (for example smart cities or user-centred design) rather than disciplines. NMITE, the New Model Institute for Technology and Engineering offers an accelerated degree in Integrated Engineering. Structured more like a job with 46 weeks of 9–5 Monday to Friday activity, it utilises real-world challenges in the form of 3 ½ week 'sprints' as part of a lecture-less and exam-less approach.

While some of the most innovative approaches have appeared in new entrants, that is not to say that significant innovation has not also occurred in traditional, incumbent universities. The nature of the reform is often different due to the need to navigate legacy structures and in most cases the reforms very much reflect the context of the institution. However, the scale at which these developments occur is often considerably larger that the that seen in the emerging schools.

One significant and globally supported response to reimagining engineering education is CDIO [53], a worldwide community of practice, that developed new pathways through an inspired set of principles that engineering education could use in strengthening its approaches to the thinking, becoming and doing of engineering. Educating through a process of Conceive, Design, Implement, Operate, CDIO describes engineers as professionals that contributed not only to a specific part of innovation, but holistically; solving problems identified by others. It identifies engineers as conceiving problems and areas of enhancement on their own and working with divergent groups of experts - being creative, as well as technical and theoretical - grasping that inventing is not enough if routes to implementation are not well understood or better, experienced, and that abstract models and complex logic had to result in something useful that could serve a purpose in the world. Becoming an engineer meant you could tap into many more facets of innovation that make use of hard-skills without limits as to the scope of activity. The importance of engineering processes is elevated to its current position: equal footing to the technical aspects of engineering. Yet implementing the new curriculum objectives, pedagogy and engineering education management would take on several forms and even meet resistance, contributing to the enduring imbalances in engineering education and offerings by HEI still apparent today.

Perhaps one of the best know reform programmes started in 2007 at the University of Illinois Urbana-Champaign. The Illinois Foundry for Innovation in Engineering Education or iFoundry, started offering cross-disciplinary curriculum options citing founding principles of the joy of engineering, learning, and community [27]. Today it is hardly visible as a programme in its own right, but instead has driven reform in engineering education across the school.

At UCL in London, UK, problem-based learning was first introduced in electronic and electrical engineering in 2004 in response to recommendations made by the Institution of Electrical Engineers (now IET) Industry Course Working Party. Over a number of years, it expanded and developed to integrate curriculum knowledge from various specific areas (e.g. electronics, communications, control, etc.) by emphasising learning that uses a problem/scenario as a starting point for learning, integrating knowledge, rather than compartmentalising and sequencing learning in individual silos. In 2014 UCL Engineering introduced a new programme that encompassed all engineering programmes in the faculty. The Integrated Engineering Programme (IEP) has an intake of around 1000 students and introduces problem-based and project-based learning to first-year engineering students across all departments, emphasising the success of this pedagogical approach. This familiarises students with self-directed learning at the start of their university studies, which will carry them through to lifelong learning in the workplace. It implemented Engineering Challenges, which give first-year students an opportunity to put their learning into practice through interdisciplinary, problem-based learning with a design focus in two major five-week design projects starting from the first day of term [54]. To support students, a strand of professional practice, including teamwork and communications skills, has been introduced. This builds through a pattern of interdisciplinary and disciplinary project-based activities culminating, at the end of the second year, in a two-week intensive programme, called How to Change the World, where interdisciplinary teams address 'wicked' problems within major global challenges such as sustainable energy or water provision [28].

Similarly, Purdue University, has adapted to the changing demands from engineering professionals by offering more than 25 different engineering programmes. For instance, a concentration in "Interdisciplinary Engineering Studies (IDES) and Multidisciplinary Engineering (MDE)" can encompass a specialisation in: acoustical engineering, engineering management, general engineering, international engineering studies, pre-professional (law, medicine, etc.) engineering, theatre engineering studies and visual design engineering. Open and tailored programmes such as these demarcate the new work engineers are preparing for, which is likewise highly specialised, comprehensive and holistic. The new structures encourage students to approach engineering as their vocation from the start of their studies; professionalisation into the field is therefore initiated from day-one.

Of the more recent developments, the inception of NEET or New Engineering Education Transformation at MIT is perhaps one of the most significant. Launched in 2017, this cross-departmental endeavour with a focus on integrative, project-centric learning, creates a series of 'threads' in the curriculum linking taught modules – some new but many existing – to projects framed around the new machines of the 21st Century. Advanced Materials Machines, Autonomous Machines, Digital Cities, Living Machines and renewable energy machines. This provides a model similar to that of the IEP at UCL where a curriculum transformation is brought about by augmenting elements of the traditional programmes through the introduction of cross cutting and interdisciplinary elements [55].

Although we are not widely seeing the impact of the 4th and 5th Industrial revolutions on universities, the potential implications are already reverberating across the majority of industry sectors. Discussions typically take the form of short-term opportunities, long terms challenges but almost always conclude with concern that a skills shortage will ultimately be a limiting factor in the pace of progress. It is clear that 4IR will impact in some way in all areas of life and business. Some, manufacturing for example, are naturally closest to the cutting edge of innovation where 3D and additive printing have been evolving for some time and in certain areas are already reaching maturity [37]. In service sectors, the availability of large datasets and rich potential of data mining are opening up vast new possibility. Although accusations of a wild west environment were lack of regulation and lack of understanding of the implications of these new technologies from law makers abound. Further into the future whole new sectors are being imagined that simply do not exist today. As a research field, quantum engineering blossomed in the last decade with prediction of its emergence as a mainstream technology in the next 10 to 20 years. This begs the questions; What will the Quantum Computing Engineering of 2035 look like? What skills and competencies will they need in this new role?

Many in each of these specialisms are already starting to address these questions. However, one common thread is emerging. The skills, knowledge and competencies no longer find neatly into the disciplinary boxes that we have used to categorise engineering for the past hundred years. These new engineering graduates will need to be interdisciplinary in ways we have not imagined in the past.

5. The concept of "fusion" skills

Research and discourse about the impact of the 4IR has, to a large extent as we saw earlier, focused on the aspect of substitution and automation: what tasks and activities smart machines currently are or soon will be able to perform and what the implications for the labour market are [17, 21, 56]. An alternative perspective has however been present by Daugherty and Wilson [5] in their book *Human + Machine: Reimagining Work in the Age of AI*. They argue that the above debate has been constructed around a separate focus on either tasks that are performed by humans or alternatively tasks performed by machines. As a consequence, an important range of activities is lost out of sight: hybrid activities where humans and machines closely collaborate – as exemplified in the case of robotic surgery. This is a radically different way of identifying not only the 4IR's or Society and Industry 5.0's skill needs compared with the production of lists of digital skills, but also the implication of these skill needs for engineering, as we explain below.

Employing a forecasting methodology, in common with the advocates of the substitution perspective, Daugherty and Wilson [5] nonetheless adopt a very different approach. Instead of asking the question – how might AI impact on jobs? – they ask – how might result in new jobs or new roles? To do so, Daugherty and Wilson [5] distinguish between three types of work activity: human-only activity, such as leading, empathising, creating and judging; machine-only activity, such as transacting, iterating, predicting and adapting; and human and machine hybrid activities. They sub-divide the latter into two categories: activities where humans complement machines, such as training, explaining, sustaining; and activities where AI gives humans "superpowers", such as amplifying, interacting and embodying. Based on this distinction about different types of human + machine hybrid activities, Daugherty and Wilson make the following inter-connected argument. Firstly, that: "the novel jobs that grow from the human-machine partnerships are happening in what they "call the missing middle – new ways of working that are largely missing from today's economic research and reporting of jobs." Secondly, the emerging human machine hybrid activities will require "fusion skills". Thirdly, the most important fusion skill will be to "reimagine" how AI can be used as a resource to transform working, living and learning. As conceived by Daugherty and Wilson [5], each of the skills they identify draws on a fusion of human and machine talents within a business process to create better outcomes. Their eight fusion skills are:

- *rehumanising time* – devoting more time to conductive creative research to address pressing problems.
- *responsible normalising* – the act of responsibly shaping the purpose and perception of human-machine interaction as it relates to individuals, businesses and societies.
- *judgement-integration* – the judgement-based ability to decide a course of action when a machine is uncertain what to do
- *intelligent interrogation* – knowing how best to ask questions of AI, across levels of abstraction to get the insights you and others need.

- *bot-based empowerment* – working well with AI agents to extend human capabilities and create superpowers in business processes and professional careers.
- *holistic (mental and physical) melding* – humans creating working mental models of how machines work and learn, and machines capturing user-performance data to update their interactions.
- *reciprocal apprenticing* – performing task alongside AI agents so people can learn new skills and on-the-job training for people so they can work well within AI-enhanced processes.
- *relentless reimagining* – the rigorous discipline of creating new processes and business models from scratch, rather than simply automating old processes.

These skills are, unlike the digital skill list we presented earlier that merely constituted a series of additions to extant interpersonal and technical skill such as, data analytics, based on forecasts about how humans will in future work with machines. Daugherty and Wilson formulated their fusion skills by analysing extant human-machine interaction and identifying human-only and machine-only skills, and then identifying on the basis of the future deployment or development of AI the new kinds of interactions that could occur between humans and machines in the context of work. This approach is therefore also radically different from Frey and Osborne [17] and Muro *et al*. [21] who operated with a classic social science binary assumption – automation or continuation – of work. Furthermore, unlike the advocates of the substitution perspective who steer clear of discussing the implications of their forecasts for organisational strategy, Daugherty and Wilson ([5], p. 3) argue that in order for companies to gain the most value from AI they will need to "reimagine" their operations and identify the requisite fusion skills.

6. Fusion skills and engineering degrees of the future

Working for Accenture – a global consultancy company – Daugherty and Wilson explore the reimagining of work processes through the introduction of fusion skills by presenting case studies of organisational change. We employ a slightly different strategy to reimagine engineering programmes. We draw on the scenario tradition, that is, combinations and permutations of the current state of affairs and anticipated social and technological change [3, 4]. Our scenarios are plausible, in the sense that they draw on current philosophy and design of engineering degrees, and they include significant developments – fusion skills – that exist in some small form in the present day and are anticipated to escalate in importance and significance over the next few years. The two scenarios we present both include features that are both possible and uncomfortable, for example, they highlight that although integrated/interdisciplinary degrees are positioned more favourably to engage with the challenge posed by fusion skills compared with single subject degrees, the development will have implications for the way in which members of those departments of engineering work with one another in future.

We present our scenarios to help departments of engineering identify different starting points for engaging with the challenge posed by fusion skills and to identify the way in which they might initiate discussions among academics about how to reduce those challenges, rather than to imply one scenario is inevitably better than the other.

We formulate our scenarios by drawing on the distinction Hoskin and Anderton Gough [57] made when looking at the development of interdisciplinary knowledge and skill in accountancy programmes. They distinguished between – "collection" and "integrated" approaches to programme and module design. The former refers to traditional discipline-specific programmes where the essential aim is to transmit blocks of knowledge in distinct specialist packages. In contrast, the latter promote and enable the integration of disciplinary knowledges, through breaking the old classifications and enabling learners to see knowledge in what we may call a more contextual way, through having a more integrated or interdisciplinary structure based around the use of projects, problems etc. These approaches are analytical distinctions, in other words, it is possible to characterise a degree in ideal typical terms as either consistent with the definition of collection, integrated or a combination of both approaches.

We use the distinction between collection or traditional single subject and integrated and interdisciplinary degrees to present our two scenarios of the engineering degree of the future. We do so to acknowledge that, despite the array of innovations in the design and delivery of engineering programmes, many departments of engineering remain firmly attached to the former type of degree. Our argument is that a homology exists between integrated/interdisciplinary degrees and fusion skills, which positions the former to embed fusions skills more comprehensively into programmes of study than would be the case with single subject degrees. Integrated/interdisciplinary degrees and fusion skills are both predicated on *contextualisation*: the former seeks to contextualise knowledge in relation to way in which an engineer, irrespective of their specialism may work with and relate to other engineers and their knowledge, once they are in the field of practice; the latter seeks to contextualise fusion skills in relation to future work practice. These are slightly different conceptions of contextualisation – curriculum contextualisation and work contextualisation. They are nonetheless complimentary because they are both concerned with relationships: relationships between engineers and relationships between humans and machines. It is this shared relational perspective that provides the basis for identifying how to embed fusion skills into integrated/interdisciplinary engineering degrees. In contrast, single subject degrees are far less contextual. They tend to prioritise offering engineering students depth of knowledge in their chosen specialism, rather than opportunities to explore the contextual basis of both the specialist knowledge being studied and its future relationship to engineering work practice. One way such degrees do sometimes mitigate the concern for depth is by offering students work placements.

We can see, at a glance, the significant difference between the way in which fusion skills could become part of single subject and integrated/interdisciplinary degrees in **Table 1**. below. The starting question is similar for both types of degree – to follow Daugherty and Wilson and identify ways in which AI might enable staff & students to secure an improved work-life balance by rehumanising time. We see swiftly, however, significant divergence when we consider the way in which the different degrees are positioned to respond to the challenge of agreeing philosophy, pedagogy & assessment to incorporate AI into their extant designs. The difference is encapsulated in the terms – embed or include.

If we take one of the fusions skills, 'judgement-integration', we can see that to fully appreciate the complexity of the judgements that will be necessary in the design of, for example, autonomous vehicles, we see that the range of expertise necessary extended well beyond any single discipline. Fleetwood [58] frames the issues related to ethics judgements in the design of autonomous systems in term of public health and captures the range of competing considerations that are required of students. While we would never suggest that any single engineering student could

Traditional single subject degree	Fusion skills	Degree with integrated/interdisciplinary elements
Identifying ways in which AI might enable staff & students to secure an improved work-life balance	*rehumanising time*	Identifying ways in which AI might enable staff & students to secure an improved work-life balance
Agreeing philosophy, pedagogy & assessment to add AI into modules	*responsible normalising*	Agreeing philosophy, pedagogy & assessment to incorporate AI into project & problem-based activity
Include examples of machine 'failure' or 'worrying' results in modules	*judgement-integration*	Embed examples of machine 'failure' or 'worrying' results & opportunities into project & problem-based activity to provide students with opportunities to decide appropriate response
Include examples of how experts have asked questions of AI, across increasing levels of abstraction, in modules	*intelligent interrogation*	Embed opportunities into project & problem-based activity for students to learn how to ask questions of AI, across increasing levels of abstraction throughout their degree
Include opportunities in some modules for students to work with AI to extend their capabilities	*bot-based empowerment*	Embed opportunities into project & problem-based activity for students to work with AI to develop AI-capacity & understand how AI solutions cut across engineering specialisms
Include examples of how AI works and learns to capture user-performance data to update their interactions	*holistic melding*	Embed opportunities into project & problem-based activity for students to create mental models of how AI works and learns and also to work with examples of how AI has captured user-performance data to update its interactions, to understand the difference AI learning has made for the field of engineering
Include case studies of how engineers are working alongside AI so students understand the skills they will need to develop when working in engineering research or professional contexts	*reciprocal apprenticing*	Embed opportunities into project & problem-based activity for students to perform task alongside AI agents so they can learn new skills and begin to work within AI-enhanced processes
Include case studies of how new processes being developed from scratch in engineering research or professional contexts	*relentless reimagining*	Embed opportunities into project & problem-based activity for students to gain experience of new processes being developed from scratch
Discipline-specific understanding, with practical awareness	**Outcome**	Holistic conceptual understanding & practical experience

Table 1.
Engineering degrees of the future: 2 fusion skill scenarios.

reasonably be expected to be expert on all of the areas necessary, from the AI to the sociology, psychology and fundamentals of human-computer interaction, it is undoubtably the case the opportunities to engage students in a nuanced and diverse exploration of the issues at hand is limited in a single discipline. In an integrated curriculum model, these no longer become the preserve of the just computer scientist. This argument apes some of the original discussions that led to the integrated forms of degrees that we see today. If we take the design thinking framing of Brown [59] and IDEO we see engineering design and decision making consisting of potentially competing evaluations of feasibility, desirability and viability. Inherent this calls for a broad palette of skills and deemphasises the validity of single disciplinary view-point in decision making. If we continue to compare and contrast activities typical of a single subject degree with those possible in an integrated and interdisciplinary context, we see further evidence of the support these broader contextual framings provide for fusion skills.

There are, however, some areas where the contrast is not so stark which highlights a second key aspect that we argue is necessary in future skills development but that might also be viewed under the heading of integration. That is Industry-Academia integration. For many, a linear model of professional formation still pervades, a degree in the academy followed by profession experience in the workplace. Although, placements and year in industry programmes are not uncommon, reductions in student funding, and competition for industry support, for examples in the UK from apprenticeships and T-Level qualifications, show that while not necessarily at risk, this model is unlikely to expand significantly as currently formulated. Additional, while undoubted positive for the student, it is hard to argue that the majority are truly integrated – where training and experience in the workplace and education in the academy combine to make a learning experience that is greater than the sum of its parts. There are successful examples. Some of the best degree apprenticeships achieve this, as do models such as Charles Sturt discussed above. However, we would argue that a complete reimagining of industry-academia interaction in the formation of professional engineers is required to address the necessity of fusion skills in the future workforce.

Whilst we have shown that an integrated degree offers the best opportunity to elicit the environment for students to explore fusion skills within a university programme, the level of authenticity possible is always constrained by the bounds of the academic environment. The later skills discussed in **Table 1**, ideally call for authenticity that may best be provided by industry partners. *Relentless Reimagining* calls for 'creating new processes and business models from scratch' and while this can be developed at a distance from industry, it is undoubted challenging to replicate the full and nuanced range of competing design requirements that interplay in the conception of a successful business process. The danger is that without access to the realities of the workplace, even the projects delivered with an integrated degree regress to the 'toy' problems that drove educators away from single discipline projects in the first place.

A model where workplace learning integrated into the engineering curriculum and the formation of a professional engineering is necessary development. Two considerations will have to be borne in mind: the role of AI and the insights that can be accrued from short placements/internships. In the case of the former, it will be important to commission research on models of reciprocal apprenticeship in university research teams and companies who are either introducing or developing fusion skills in their teams, to identify their new hybrid learning processes. In the case of work placements/internships it will be important to identify best learning practices. Both sources of intelligence can then be used to ensure workplace learning is connected to both university- and company-based learning, with explicit interrelationships drawn. This is likely to be especially relevant in the short-term for companies as they reimagining their development processes and formulate new procedures for user-engagement and product/process design, and for departments of engineering as they consider the implications of our two scenarios.

7. The post-Covid challenge for universities and departments of engineering

Having identified the type of challenges associated with the embedding of fusion skills into engineering degrees, we now locate that challenge in the post-Covid context. We paved the way for this discussion earlier when we referred to Schwab's argument that responding to Covid will involve a *great reset*: governments working together to orientate the market toward fairer outcomes, targeting investments, especially in AI, to advance shared goals, such as equality and sustainability, and harnessing the innovations of the Fourth Industrial Revolution to support the public good, especially by addressing health and social challenges. Clearly, the fusion -kill reimagining of engineering and engineering education outlined above is central to all of these reset goals. To demonstrate why and how, we conclude by drawing on Crawley and colleagues' [55] argument that universities perform best as engines of economic and social development when they systematically exchange knowledge with their partners in industry and government.

For too long, this "exchange" has operated, according to Crawley and colleagues [55] like a one-way street, with universities sending graduates and research out into the world without considering how they can best contribute to the goals of accelerated innovation, economic growth, and now recovery in the face of the challenges of the Covid-19 pandemic. To combat this tendency Crawley and colleagues put forward some practical suggestions to assist universities to reimagine in their educational and research activities as well as catalysing innovation to strengthen knowledge exchange — the flow of people, ideas, and technologies — between universities and their partners in a way that is more aligned with the great reset.

Our argument above about the fusion skills clearly presupposes knowledge exchange between universities and employers, with explicit intention of improving the social outcomes of engineering. We propose therefore that the development of fusion skills requires a reimagining of *the design and delivery of engineering degrees*. And, we have identified two scenarios to assist universities to address this challenge.

In advancing this argument, we also recognise with Crawley and colleagues that, research needs to be reimagined. The development and implementation of fusion skills will require collaborative research within and across scientific disciplines — or even rejecting the idea of a discipline as an organising principle for university research – and assemble teams of 21st-century thinker and doers" to conduct research that is problem-oriented, and not disciplinary, and involving industrial partners and collaborators since they are, as we have indicated above, essential to the development and implementation of fusion skills. This suggestion, in turn, implies *reimaging of the field of engineering education so that it acquires a reputation for reporting these developments to academic and industrial audiences.*

The engineering degrees and research of the future also calls for a catalysing of innovation, in other words, universities moving beyond research to create technologies, business models, health-care systems, and other products.

We recognise that responding to this agenda requires changes to universities' faculty development, facilities, governance, and outreach to external partners, and that there may well be some tension about departments of engineering discarding some of their, and universities, historic roles and values. In accordance with the spirit of the great reset, we suggest this debate should be held and given serious attention.

8. Conclusion

The core argument running through this chapter about the implications of Society 5.0/Industry 5.0 for engineering education is that they presuppose new, rather than, additional skills which we have defined as *fusion* skills. We have, however, given an additional twist to the source of inspiration for our chapter and this edited collection by locating our argument in relation to the challenges associated with the great reset. We have therefore argued that what initially might have appeared to be only an issue of *technique* [60] is also an issue of *vision* about the type of society and life that imaginative, talented and environmentally responsible departments of engineering and the engineers of the future they produce can help to bring to fruition.

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Chapter 5

An Engineering Education of Holism: Einstein's Imperative

Linda Vanasupa and Gilda Barabino

Abstract

In the aftermath of World War II, Einstein urged scientists to develop a substantively new thinking, lest we suffer a technology-enabled self-destruction. In this chapter, we will unfold the emerging scientific findings that serve as vectors, pointing to the same conclusion: the educational foundation that has brought about Industry 5.0 is causal to brain development that not only undermines our ability to address our emerging complex societal challenges, but biases us toward inhumane logic. We will outline a science of holism, the profoundly new thinking urged by Einstein. This science is rooted in nature's ontology of dynamic complexity. An engineering education reflecting this new thinking will be described along with the novel developmental capacities afforded by it. The chapter will end by considering questions that need to be resolved to manifest such a radical shift in engineering education.

Keywords: holism, holistic science, dynamic complexity, autopoiesis, emergence, health

1. Introduction: health intended; fragmentation produced

As we share these insights, we are aware that engineering education varies across cultures. Any insights are likely limited to the things we have in common. So, we begin with making clear our point of view (POV), which is derived from being immersed in engineering education in the United States since 1981. This education system is theoretically intended as the means to a profession that is dedicated to serving the well-being of society above all other considerations [1]. This purported purpose of engineering was not the core of our engineering education and subsequent teaching. The core was math and science, by which we are referring to the schools of western scientific thought, taught in English and traced to Thomas Aquinas, Francis Bacon, René Descartes, and Isaac Newton. Very briefly, as described by Capra and Luisi [2], Aquinas integrated scientific reason with faith, elevating what was scientific philosophy to God-given truth. The works of Bacon, Descartes and Newton served to produce an organized study of inanimate objects—changed only when acted on by force—and methods suitable for the study of such objects. Hidden in these paradigmatic shifts from philosophy to truth were assumptions and values that have functioned to shape our world as we know it today. Language is also relevant for its intimate coupling to our neurology [3]; like assumptions and values, its hidden structure unconsciously shapes our behavior [4, 5].

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Our aspiration for engineering education, or all of education, is that of global health—societal and environmental, which we believe to be inextricably intertwined. However, at the moment of writing this, our country is reeling from what is apparently a systemic education gone wrong, writ large, and enabled by science and engineering. We 'westerners' imagine that our science and education support peaceful citizenship and democratic governance. Hundreds of years into this grand social experiment, the evidence suggests otherwise. Systemic patterns reveal our western education is most reliably producing fragmentation rather than health. In some ways, it is not surprising that a methodology of learning ("science") that is based on fragmenting the whole into its constituent parts does not produce health, the root of which is Old English hælþ "wholeness, a being whole, sound or well' [6]. As physicist David Bohm observed, "fragmentation is now very widespread, not only throughout society, but also in each individual; and this is leading to a kind of general confusion of the mind, which creates an endless series of problems and interferes with our clarity of perception so seriously as to prevent us from being able to solve most of them." (p. 1, [7]).

What we did not account for in our social experiment with 'western' scientific education, was the effect that education would have on our selves. In a recent book, Henrich [8] documents the research that shows that brains and behavior of western-educated adults differ in dramatic ways from their global peers. Specifically, these individuals, which Henrich describes as western-educated, industrialized, rich and democratic (WEIRD), have a default tendency to focus on parts within a visual field, whereas their non-WEIRD peers see the whole. Unsurprisingly, WEIRD individuals tend to view the world with the analytical thinking of the reductionist science that is core to western and engineering education. Reductionism and its methods assume a world of objects, held separate from and independent of the observer; its aim is to prove or disprove hypotheses about cause and effect. Reductionism is useful for manipulating the physical world for predictable outcomes but is not fit for the purpose of working with living beings. What this means for WEIRD people is a tendency to see human behavior as caused by traits of the individual whereas their non-WEIRD peers are more likely to reason that peoples' behavior is a reaction to the systemic conditions—a more holistic interpretation. WEIRD people tend to employ limited moral logics that rely on what are viewed as "autonomous" actions by individuals [9]. Non-WEIRD subjects draw on a multitude of moral logics that include autonomous action and presume ones' inseparability from communities. In short, western education conditions people to see the world in a fragmented, rather than holistic way.

Henrich's analysis of WEIRD subjects does not address the effects of the English language as the medium of WEIRD-ness. However, cognitive scientists recognize that language is neurologically embodied [5, 10]. For example, Lakoff and Johnson describe semantic frames in the English language which focus attention to what are considered salient features, causing unconscious entailments on peoples' behavior [4]. Might the language of engineering, deriving from military roots in the U.S., subconsciously condition behavior? Even the basic syntax of English-- *subject acts (on) object*--is noteworthy as a mental model of change. The English syntax is both linear and self-assertive. In contrast, the meaning of Chinese characters change with context; one must be attentive to context to understand meaning. Learning from written Chinese characters is essentially a practice in attentiveness to context. These brain practices required by the language may contribute to the results seen in a test for analytical v. holistic logic: Sixty percent of people from English speaking countries like the U.S., U.K. and Australia used analytical logic whereas sixty to ninety percent of people from China (depending on region) used holistic logic [11]. This result suggests that one's first language and its structure strongly condition one's attention, with Chinese students practicing more holistic logics. There is a dramatic increase of Chinese college students studying in English speaking countries (i.e., U.S., U.K., Canada and Australia), from the early 2000's on [12]. How do the logics of these Chinese students compare to their western-educated peers? This is an important question that the research literature in English does not yet seem to address.

Functional MRI studies of WEIRD subjects by Jack et al. [13, 14] point to patterns akin to what Henrich and others reported. They found that the neural networks active in reasoning about objects in the physical world have an antagonistic relationship between the activity regions that require social and moral reasoning (i.e., one's relationship to the whole of society). When one is using the logics needed for working with objects, the neural circuitry that considers others, emotion and context, is inactive. The finding that different regions of the brain are accessed for different logics is not in itself surprising or problematic. However, in a follow up study by Jack et al. involving WEIRD subjects, they found moral concern and analytical reasoning to be inversely related [15]. In particular, people biased toward analytical reasoning were also inclined to draw upon these same dehumanized logics in situations that call for contextual, humanized reasoning, particularly when the situation involved ambiguity. Other studies involving western educated and non-western educated subjects have shown that priming subjects to use analytical reasoning results in less humane and less altruistic decisions [16, 17].

While some engineering curricula require general education, the engineering appetite for technical knowledge in the U.S. has had a magnetic pull on our attention as predicted by the sociologist, Jürgen Habermas. He suggested that knowledge and the methods for acquiring it are constituted by the purpose, whether that is to control the physical world (*technical*), to work with people (*practical*) or to liberate one from their thinking (*emancipatory*). These knowledge-constituent interests produce three types of sciences that hold different assumptions, **Table 1**. Habermas predicted that technical understanding would take on a life of its own in modern societies, becoming the sole means, even when it is not fit for purpose [18]. Examples of using technical approaches for issues that require practical approaches are high-stakes educational tests for 'improving' education and the increasing use

Type of science:	Natural	Social	Critical
Frame and habits of mind	Positivist, Analytical	Constructivist, Hermeneutic	Deconstructivist, Emancipatory
Interest	Technical: Predictable outcome of practical skills for employment	Practical/Meaning: Intellectual development and communication	Liberation*: Enlightenment to enact conscious choices
Assumptions about reality (ontology)	Reductionist: simple cause & effect; reduce variation in experiments to validate	Constructivist: complicated; attempt to examine all variables to see cause & effect	Holistic: complex; acknowledge unknowable variables create emergence
some practices derived from science	Engineering, western medicine	Education, counseling	Performing arts, spirituality

**Liberation indicates the process by which models and paradigms are revealed as such, introducing both consciousness and choice where they were artificially constrained.*

Table 1.
Habermas' types of sciences produced by his theorized knowledge-constitutive interests. From [19], adapted [20]. Used with permission.

of technology to police society. These approaches amplify rather than solve the problems.

These patterns are pointing to a simple principle that legacy engineering education does not account for: Learning/knowing alters our minds [21]; structure conditions behavior. Most significantly for education, our neurological structure conditions our attention and thought. These emerging findings are weak signals of a concerning pattern: engineering education based on a foundation of reductionist science contains the risk of educating professionals who are diminished in their ability to see, feel and reason in humane, holistic ways. From Bohm,

> *"...each individual human being has been fragmented into a large number of separate and conflicting compartments, according to his different desires, aims, ambitions, loyalties, psychological characteristics, etc., to such an extent that it is generally accepted that some degree of neurosis is inevitable, ...the attempt to live according to the notion that the fragments are really separate is, in essence, what has led to the growing series of extremely urgent crises that [are] confronting us today...this way of life has brought about pollution, destruction of the balance of nature, over-population, world-wide economic and political disorder, and the creation of an overall environment that is neither physically nor mentally healthy for most of the people who have to live in it." (p. 176 [7]).*

In short, a global engineering education at the emergence of Industry 5.0 must reframe engineering and develop a substantively new thinking as Einstein urged [22], lest we suffer a technology-enabled self-destruction.

2. Re-new thinking: embrace holism for engineering education

> *"A human being is a part of the whole, called by us 'Universe,' a part limited in time and space. He experiences himself, his thoughts and feelings as something separated from the rest— a kind of optical delusion of this consciousness. This delusion is a kind of prison for us, restricting us to our personal desires and to affection for a few persons nearest to us. Our task must be to free ourselves from this prison by widening our circle of compassion to embrace all living creatures and the whole nature in its beauty." (p. 20 [23]).*

What Einstein asserts is that the nature of the Universe is whole. Wholeness or Health, is a non-separable condition that exists prior to us. The fragmentation in 'western' science can be traced to Eurocentric philosophies from the 13-16th centuries, as described by Capra and Luisi [2]. By 1926, the South African statesman Jan Smuts advocated a return to the ancient Greek philosophy that he called "holism",

> *"the ultimate synthetic, ordering, organizing, regulative activity in the universe which accounts for all the structural groupings and synthesis in it, from the atom and the physico-chemical structures, [through] the cell and organisms, through Mind in animals, to Personality of man. The all-pervading and ever-increasing character of synthetic unity or wholeness in these structures leads to the concept of Holism as the fundamental activity underlying and co-ordinating all others, and to the view of the universe as a Holistic Universe." (p. 317 [24]).*

This notion of holism is not new; it has been embedded in indigenous cultures for centuries in many forms. For example, Native Americans like the Iroquois tribes

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believed that every decision should be made in consideration of how it will affect seven generations (i.e., 7 x 100 years) into the future, recognizing their present moment to be intertwined with a future one. They also viewed themselves as part of a web of life with nature as a collaborator, leading to a sustainable relationship with nature, prior to the genocide inflicted upon them by white men. As seen in such indigenous societies, adopting wholeness and health as the fundamental nature of reality opens onto a landscape of radically different interpretations, methods, practices and capacities.

Consider that our societal challenges, amplified by technology, are holistic in nature (e.g., anthropogenic climate change). They therefore require an engineering that is grounded in holism. In other words, reductionism is a mental model incommensurate with the phenomena it is attempting to address; by analogy, an engineer cannot incorrectly conceive of gravity as a force that operates parallel to the surface of the earth and expect a gravity-reliant design to function as planned. Even in cultures that are traditionally more holistic, such as the case for China, there is recent advocacy for holistic research approaches [25–27].

To be more effective in engineering, our challenge is to develop an organized practice of working with holism. Such a science would encompass and use reductionist knowledge when fit for purpose, but would expand our POV and methods in important ways. How would a holistic science differ from the legacy science? How would a holistic science provide benefit to society? We explore these questions in the following sections.

2.1 Holism paradigm v. fragmentation paradigm

If we take 'science' to be an organized study for the purpose of insight, a holistic science suggests a paradigm that radically differs from reductionist science. As can be seen in **Table 2**, the reductionist world view is one of separate objects that mechanistically interact; understanding comes through analyzing a system as simple, cause-and-effect interactions. A holistic world view embraces the whole of humanity and presumes unity, where forms arise though recursive interactions in the presence of energetic fields; understanding is inherently tentative and situational, producing heuristics. Reductionist principles are suitable for working with inanimate matter. They are not fit for working with living matter, humans or

	Reductionism	**Holism**
Nature of reality	Separate objects, independent from one another, inanimate, consisting of fundamental building blocks	Inseparable, interconnected whole, animate, recursive patterns repeat at different scales ("fractal")
Behavioral phenomena	Mechanistic: interaction by simple, generalizable cause-and-effect relationships (e.g., Force = mass x acceleration); predictable as the sum of the part-level interactions, often linear	Emergent: from an innumerable, recursive interaction among self-organizing components in the presence of fields; unpredictable with qualities that are not necessarily found in the parts—non-linear, cyclic
Lens of understanding	Equilibrium/stasis or time-independence Analysis– breaking down complicated into simple, quantifiable and verifiable principles	Non-equilibrium/order from chaos Synthesis and Apprehension – Combining theory, action and observation in an ever expanding perception of patterns reflected in weak signals

Table 2.
The ontological assumptions of reductionism and holism.

sentient beings. To point out the obvious, engineering to serve society inherently involves living beings.

Paradigms have far-reaching consequences due to the profound and often invisible effects that mental models have on our expectations, thoughts and actions. For this reason, the pioneering systems thinker, Donella Meadows, identified "transcending paradigms" as the highest leverage intervention for systemic change [28]. Many of our present-day societal challenges—pollution, climate change, poverty, economic inequity, education inequity, and health crises, emerge from the whole and simply cannot be addressed through reductionist means. Engineering education based on holism holds the possibility of aiding our ability to more effectively address global challenges. What might such an engineering education produce?

While we cannot clearly see into what a future of engineering from holism might produce, viewing holism and reductionism through the lens of Aristotle's causality, **Figure 1**, gives us a glimpse into a possible future. Aristotle, who assumed what we would now recognize as holism, modeled phenomena as emerging from the synthesis of four causalities: material, efficient, formal and final.

The causality in the physical domain concerns matter ("material cause") and techniques of shaping matter ("efficient cause"). The domain of relationships concerns structures that inform the phenomenon ("formal cause") and the ultimate ends or intent of the phenomenon ("final cause"). Engineering education in the U.S. has largely been focused on the physical domain, giving rise to the engineered world we inhabit today. What might it look like to design an engineering education with a holistic causality? What if we situated engineering as a sociotechnical discipline? What changes might we make if we centered our purpose or final cause to serve societal well-being? How would we change informing structures like Advisory Boards, faculty hiring and retention criteria or student acceptance criteria? With a final cause of health, how might we address the structural discrimination (e.g, laws, policies, practices) against those who have historically been denied social and economic power, such as Black and Brown bodied humans? How might education develop the whole neurological structure of human intelligence, cognitive and somatic? Clearly, this holism paradigm as a POV, opens our attention, causing us to literally see, understand, and act in different ways.

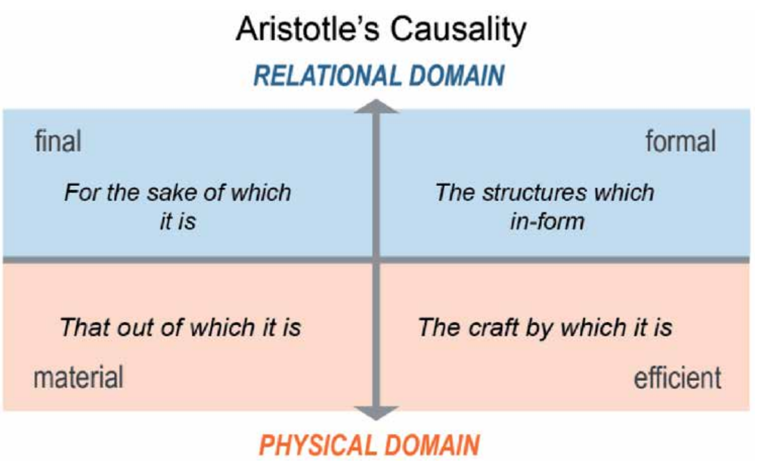

Figure 1.
Aristotle's causality. The bottom half represents causality from the domain of the physical world, suitable to reductionism: material and efficient causes. The upper half is the domain of relationships that is suitable for holism.

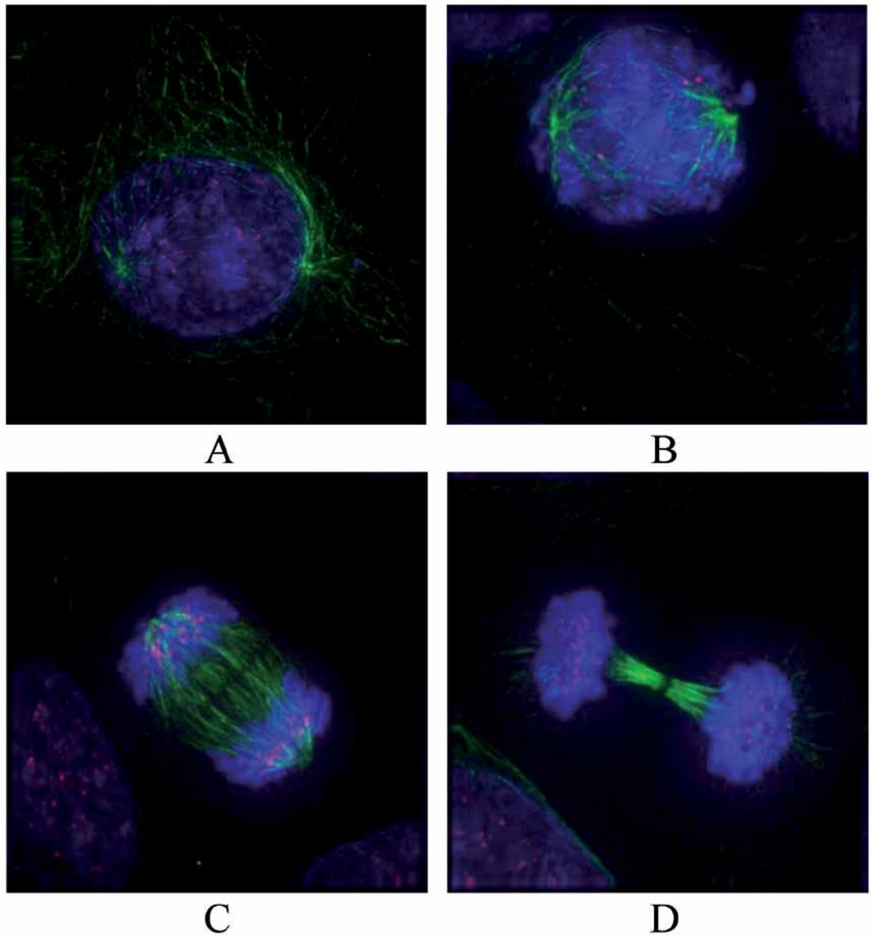

Figure 2.
Four stages of cell mitosis. A. Prophase B. Prometaphase C. Anaphase D. Telophase. By Roy van Heesbeen - Delta Vision Roy van Heesbeen, Public Domain, https://commons.wikimedia.org/wiki/Mitosis.

2.2 The cell as living system archetype

Let us consider how we might gain insight from a holism foundation by using a bacteria cell as an archetype. That is, we use here a biological model to illustrate a holistic lens for working with systems for any science, technology, engineering and math discipline. This living system cannot be separated from the universe, although we might consider the cell wall a boundary that defines the *system* from its *surroundings*. The term *system* is conceptual and refers to a set of interacting parts with a shared purpose—in the cell's case, the purpose is (presumably) living. At first glance, one might imagine that a living cell can be physically moved from its natural surroundings to a Petri dish. However, living requires the cell to exchange nutrients with its surroundings; in this way, we see that this living 'system' has an unbreakable connection with its 'surroundings'. The cell is living through its ability to maintain and replicate the conditions for its living. In what might be described as elaborate dances between molecules, the cell metabolizes nutrients and eliminates wastes or even replicates itself as shown in **Figure 2**. This property is termed *auto-poiesis* ('self creation') [29]. In this system archetype we see the following properties and behaviors:

- Interconnectedness which entails a network of countless *relationships*;
- *Self-organization* of the components through structural coupling in energetic *fields*;
- Recursive *patterns* of action among self-organizing components, which lead to emergent phenomena that are not directly traceable to its parts, such as autopoiesis.

The cell itself, viewed holistically, is an emergent form that is defined by its global, self-sustaining purpose. Using systems concepts, we view the cell as an open system, communicating across its boundary. This living organism provides insight as a metaphorical archetype for effectively working with systems. Its dynamically complex properties and behavior are fractal; the fractal nature of reality is captured in the aphorism by the microbiologist Albert Jan Kluyver, "From elephant to butyric acid bacterium—it is all the same." [30].

As indicated in **Figure 3**, the recursive patterns that result in autopoiesis exist at the scale of a single cell, an ecosystem of organisms and social culture. Using a systems lens, one can identify fields at each scale within which structures interact in self-organizing and recursive ways. At the scale of an ecosystem, nutrients are exchanged by producers, consumers and decomposers. Together, they symbiotically maintain the life-giving status of the ecosystem. Within an organizational scale, the social and historical expectations, norms and states of being--such as anger, fear, joy, or relaxation--function to create social fields. One can also identify structural analogs to the cell archetype in social systems. From a holism POV, the system is 'defined' by a shared global property, such as 'living' (cell & ecosystem), or student learning (college). At the cell level, the cell-wall creates the boundary that separates the conceptual system from the surroundings. For a college, the shared goal is student learning. Other structural features of an organization are the values and beliefs that govern peoples' behavior. In a social system, such as a college, these thought structures interact with the institutional structures of rules, policies, practices and identities to produce the phenomena of learning and enculturation.

In using the cell as the archetype, we are not claiming identical features found at the cell scale and at the societal scale. We're suggesting that the patterns of the cell provide insight for working with larger dynamically complex systems. The concept of a 'system' as being defined by a global intent is an example of a pattern that crosses scales: For the bacterium and organisms in the ecosystem, the shared intent is *living*; for something like a college, the shared intent is *learning*. Because of the

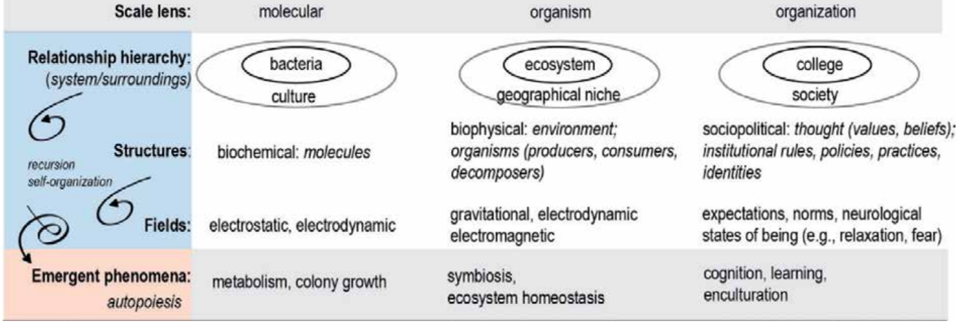

Figure 3.
Fractal view of systems of different scales.

fractal nature, working with dynamically complex phenomena would involve being attentive to *structures*, *patterns* of behavior, the quality of *relationships* and *field* conditions that might favor the emergence of one outcome over another.

What would be the appropriate scientific methods? In the next section, we will describe the relationship between methods and outcomes and suggest a holistic practice to account for this relationship.

2.3 Autopoiesis in scientific methodologies: knowledge informs the mind

As we consider the cell as an archetypal system for holistic science, one is likely to notice that there remains a great deal of unresolved mystery. What is causing these cells to undergo changes? Why exactly is it alive? What exactly is causing cells to differentiate in the emergence of a complex organism? Simply put, we do not know. Yet these questions highlight an essential difference in legacy science compared to a holistic science: reductionist science aims to answer questions, holistic science prioritizes achieving intended outcomes. Heuristic understanding occurs as a by-product in a holistic science, but it is secondary. In this way, holistic science is more aligned with engineering than reductionist science.

Holism recognizes that final cause has powerful and lasting ramifications; it functions as a seed out of which the tree and subsequent fruit arise. We can see the influence of final causality in the methods of reductionist science. They can be traced to Sir Francis Bacon, an English aristocrat and father of the empirical science method. Bacon advocated torture as a means to reveal truth [31]. He conceived of Nature as a female who hid her secrets from men, maintaining that "nature itself is something to be vexed and tortured, and that, once vexed and tortured, it will continue [as] the compliant slave of man" [32]. Bacon envisioned a utopian society, his formal causality, "for the Interpreting of Nature, and the Producing of Great and Marvelous Workes (sic) for the Benefit of Men" [33]. It was no doubt that his final cause of benefiting "man/men" was a reference to males of means, as women were often treated as property in 17th century England, a 14-year old version of which Bacon acquired as a wife at his age of 45 years [33]. Bacon represented an ethic where knowledge meant power and the interest of powerful men were deemed valuable by virtue of their (presumed) God-given superior social status. Bacon's cultural milieu, identity and position in society established a scientific practice that does not include questions about who defines the research questions and methods, whether they are socially just, or whether they are humane. Furthermore, Bacon's ideologies were influential in establishing thought in the U.S. which contributed to racists, sexist and inhumane 'scientific' practices; Bacon's ethics persist in U.S. science cultures through discriminatory practices and structures [34, 35]. For example, medical scientists in the U.S. abused African Americans for the sake of benefiting others [36–38], a rationale often used in cases of non-consensual experimentation on humans [39–41]. Such ideologies produced a biased 'science' [42] and scientists who believed that science cannot be an activity relegated to the "socially inferior" [38]; this assertion implies the reductionist fallacy that a condition that exists only in relationship to the whole (society), such as poverty, is explained by some inherent 'trait' of the individual. A science of holism would instead recognize any so-called "inferior" social condition in the U.S. as emerging from the historic, systemic effects of genocide, slavery, colonialism and legalized discrimination (e.g., see [43, 44]).

These reductionist patterns of thought and behavior ironically suggest an ontology of holism. Specifically, the condition of non-separability includes the observer as causal to what is 'observed.' Seeing co-arises with knowing so that the mind of the observer is literally *informed,* meaning that it has been physically formed, by knowledge. In other words, knowing is an autopoietic activity. From the POV of holism, it is not surprising that a view of the world as separate objects that will reveal their truths when tortured produces objectifying science, behaviors and conclusions.

In a holistic science, rather than attempt to eliminate distortion introduced by the observer, one accounts for it by holding a disposition of recursive inquiry throughout (p. 23 [45]), asking four essential questions: How do we know our understandings are accurate? How do we know whether our practice makes sense? How do we know whether we are acting morally right and appropriate in the circumstances? How do we know we are not self-deceptive in our responses?

3. Holistic science in action: navigating to shared aims

As mentioned, holistic science is concerned with achieving the intended aims. In this way, a holistic science is a theory in action which might be better described by the word *praxis*. It is more akin to the situational navigation used by ancient cultures in navigating across open bodies of water. In order to do so, they were attentive to nuanced changes in their environment, such as the direction and quality of wind, features in and on the water, the appearance of the night sky. In response to these signals, they continually adjusted their course so they might arrive at their destination. If one were conducting a traditional laboratory experiment, changing course during the experiment would most certainly ruin one's ability to validate the hypothesis. And, a holistic praxis, which would be more suited to working in human systems, would be more concerned with serving the shared human goals and less concerned, or not at all concerned with proving cause-and-effect. Methodologies like Critical Emancipatory Action Research, or Participatory Action Research, are holistic praxes. These social science approaches share the assumptions about the holistic, inseparable nature of reality, and purpose [46] as shown in **Figure 4**.

Participatory action methods are aimed at collectively achieving a social purpose and often used in community-based social change efforts or co-design. We submit that the assumptions and aims of the participatory action methods are more strongly aligned with those of engineering.

The conception of how change takes place when working in a social system starkly contrasts with reductionism. From reductionism, Newton's laws of motion condition us to believe that force must be applied to induce change ("An object in motion stays in motion unless it is acted on by a force."); Newton's laws are certainly useful in working with non-living matter. However, using force on people raises ethical dilemmas. Returning to the cell as a system archetype, the cause of action is mysterious, yet governed by the quality of relationships, structures and fields (**Table 3**).

As an educator, the notion that the quality of relationships, structures and fields condition change is easy to see. For example, imagine that learning is the change, a classroom the setting. Imagine that a human we call "student' is living remotely to their college. They lack the infrastructure for a stable, high-speed interconnection, yet the instructor has mandated "engagement" through synchronous course dialog. Imagine that the human we call "student" is in a social field of threat and fear because of the systemic conditions of a global pandemic and insufficient internet. In this scenario, it is perhaps obvious that the quality of the learning will be conditioned by the quality of connectedness, structures and fields.

What is less obvious is the profound shaping produced by the hidden value systems in our science.

	objective experimental research	critical emancipatory participatory action research
researcher perspective	objective, outside of system of study; can be individual investigator	subjective, included within field of observation; requires collaboration, social.
researcher narative	third person (they, them, theirs)	first person (I, me, my) and second person (we, us, ours)
epistemic paradigm	Objective truth can be known through research methods and techniques sufficient to prove relationships; adherence to known or hypothesized relationships considered proof of validity.	Real human systems are dynamic and complex in ways that are unique to each situation; Ultimate criterion of "success" is whether it yields valid data that enables system to function more effectively.
assumptions	Methods are ethically neutral and objective; Principles and methods considered scientifically sound when implemented according to standard practices.	All research is carried out by people and therefore subject to biases at every point in the process; critical group dialogue used to uncover unexamined assumptions.
aims	Increased understanding of reality by discovering mechanistic interactions that can be generalized to larger populations; theory.	Functioning more effectively by freeing people from the unexamined constraints embedded in the language, modes of work and social relationships of power; practice.
managing complexity	Minimized through controlled experimental conditions	Acknowledged as inherent to real systems; accounted for through transparent documentation of situational factors
process	Variables and hypotheses fixed prior to initiating study; measurement of variables of interest through reliable instruments with predictable uncertainty.	Structured variables to be studied are not always predefined, may change through dialogue and course of research; reflexive dialogue used to find areas of conflict and explore them.
outliers in data	Considered aberrent if conflicting with expected behavior; Deleted if it can be justified through a known source of variation; Can be considered a point of inquiry of further investigation.	Considered an indication that something was left out of the original thinking on the change; Used as a point of further inquiry.
results	Generalizable to other situations.	Situational; provides insight through revealing situational patterns of behavior.
research medium	Empirical data, accurate and reliable instrumenta-tion, standardized methods.	Attention that can interpenetrate and see connections between empirical, intuitive, theoretical and sensual data.

Figure 4.
Contrast of social science research approaches. Critical emancipatory action research is a collective form of action research. The numbers should be listed in sequential order.

	Reductionism	Holism
Governing principles of change	Magnitude and nature of applied force	The quality of relationships, structures and fields
Change metaphor	Leverage	Transformation (e.g. chemical reaction)

Table 3.
The nature of change from the POV of reductionism and holism.

3.1 Hidden values live in the science of engineering education

As alluded to in the history of Francis Bacon, the value system of any science is embedded in its methods. As illustrated in **Figure 5**, the values that give rise to thought structures within the reductionist and holistic POV are quite different. **Figure 5** invites us

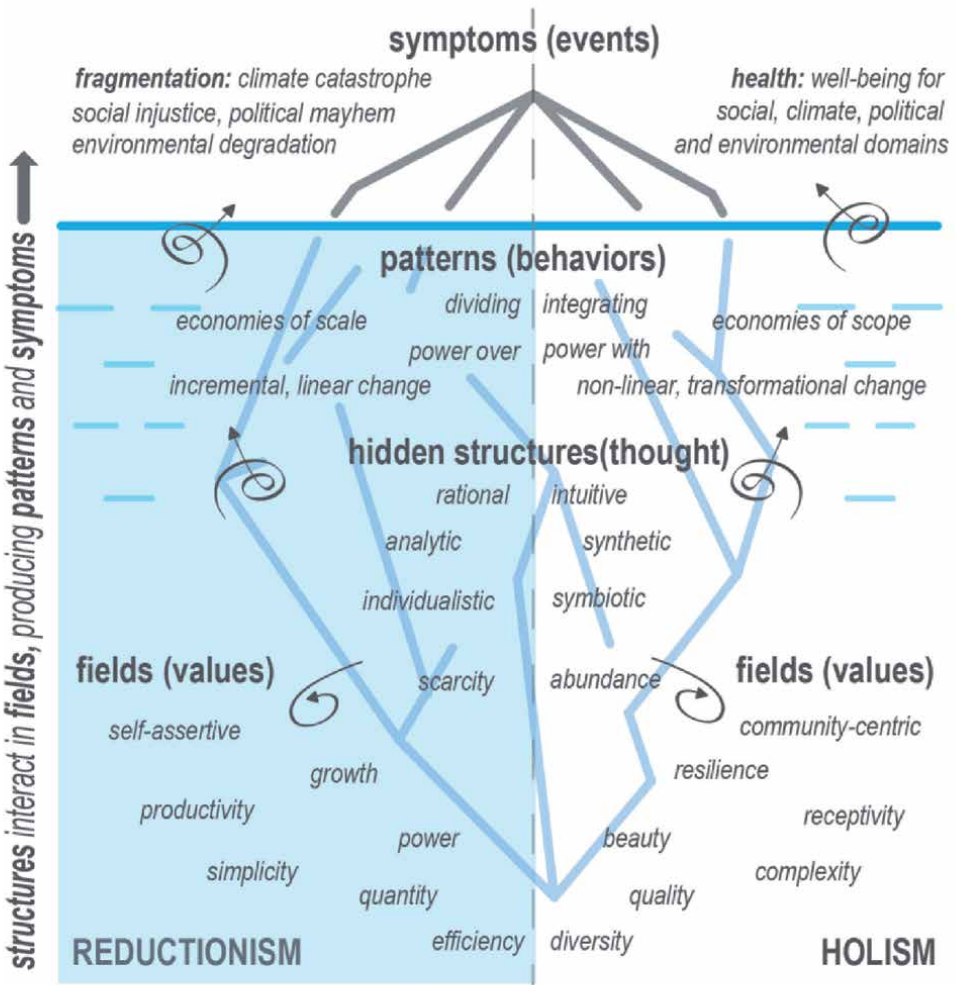

Figure 5.
Reductionist and holistic values and thinking. The metaphor of an iceberg is in the background. Holism, while pictured for contrast on the right, encompasses the left and right areas of the figure. Adapted from [2, 48, 49].

to see engineering education as a whole, arising from the force field produced by hidden values that instantiate thought structures and subsequent patterns of behavior.

Figure 5 uses an iceberg as a metaphorical backdrop to call our attention to dynamic systemic patterns. Briefly, the inseparable coupling of gravity, the structure of the water molecule and the thermal conditions produce a buoyancy force that causes ~10% of the iceberg volume to protrude. The tip is symptomatic of dynamics that are hidden beneath the surface. One could destroy the tip (i.e., metaphorically address the symptoms) but it will be reproduced through the systemic dynamics: the gravitational field's coupling relationship with the H_2O structures. Metaphorically, *values* play the role of gravity in the phenomenon that produces the tip of the iceberg; *thought structures* are like the water molecule structure; the *patterns of behavior* are like the buoyancy that results from water expanding upon freezing; the symptomatic events that emerge from the whole represent the tip. Our legacy engineering education has left us with symptoms of anthropogenic climate catastrophe, social injustice, stark inequities, political volatility and environmental degradation. We propose that an engineering education based on holism would instead produce Health.

What would an engineering education based on holism look like? We invite the global community to begin the creative process of answering that question. We offer a few thoughts, based on the principle that an autopoietic process will produce itself. In other words, the educational means of achieving the ends of health/wholeness must also have the quality of wholeness/health.

We first point out that holism includes reductionism. Reductionist science has value and we would first need to reflect on what we might conserve from our legacy methods. An ideal holistic engineering education would be balanced in its values and methods, producing discernment for choosing the methods that are fit for the purpose at hand. The value system in a Holism stance is captured in this simple imperative: *Honor the whole.* Here, the emphasis is on the whole, not just its parts. Similarly, an engineering education based on holism would embrace diversity in all its forms, not privileging one way of being over others, but dignifying all in an ethic of mutual respect. Such an education would honor the whole person as well, embracing emotions as natural and essential to meaningful learning, rather than something to suppress.

Some who feel strongly aligned with legacy science might argue that thought and emotion are separate realms with science falling within the domain of 'reason'. This logic is ironic on at least two counts. The first is that this view originated with Descartes. He deduced his idea to separate the intellect from intuition through *dreaming* [47], a highly irrational phenomenon. Secondly, from the second law of thermodynamics, we see that the spontaneous direction of change in the universe is in the direction of increasing diversity of states of being. Another way of looking at this second law principle is to conclude that where a lack of diversity exists, one can be assured that energy is being exerted to make that happen. While we are speaking in metaphor, the reader can readily test the clarity of this metaphor; do emotions arise spontaneously? (Here we are treating the different emotions as different states of being) Does it take energy, chemical or otherwise, to maintain a single emotional state? The same tests can be applied to other social systems. Let us say engineering education programs are somewhat uniform in their developmental outcomes; are there energetic forcing functions that produce such uniformity or is this uniformity occurring spontaneously? From these simple tests for coherence, we can see that a fragmented view is neither grounded in nor consistent with its own science; fragmentation is socially-constructed.

An engineering education derived from holism would be attentive to the quality of relationships in the learning environment. By relationships, we refer to the nature of what connects people: a holistic education would invite people to connect through purposes that transcend self-assertive interests. In the face of conflict people would turn to their shared purpose, larger than their self-interests, to resolve issues. One who viewed the world and work of an engineer as dynamically complex would expect conflict ("chaos") as a natural part of the process, rather than something to be eliminated. In other words, engineers would embrace the messy process of collaboration in social and political settings as a central and essential activity.

An engineering education that recognized the truth of holism would be attentive to the quality of structures that condition the learning. For example, the rise of academic capitalism [50] in the U.S. has institutionalized standardized testing for college entrance [51]. Because the standardized test was developed to validate a theory of white supremacy, this college entrance structure has produced structural discrimination against non-white populations. In the U.S., the engineering profession is depleted of diversity in perspectives by structural barriers at different scales: familial, classroom, institutional, regional, societal, and historical. To honor the whole of our collective humanity, an engineering education would do the painstaking work of revisioning just and equitable educational structures, policies and practices.

The work of revisioning just and equitable structures must recognize the fallacy of framing engineering as totally objective, meritocratic and free of social influences. This framing has been challenged by Cech and others in noting a Eurocentic discipline that fails to recognize the influence of race and gender on epistemologies and practice [52–54]. From the POV of holism, the framing is not a fact, it is an artifact: the autopoietic result of legacy science's originating mental models.

Honoring the whole would translate to honoring the whole of our humanity, recognizing the Descartes fallacy of "thinking" as primary. What we are learning from neuroscientists is that human intelligence is distributed throughout the body, rather than centrally controlled from the cerebral cortex as once believed. That is, the structure of our whole intelligence includes bodily sensations, often outside our conscious awareness. Feelings, presumed irrelevant to engineering curricula, are now recognized as essential to learning [55]. It is perhaps obvious that emotions are essential to empathy and moral reasoning; they are what humanizes us. A holistic engineering education would cultivate our ability to constructively work with our whole intelligence, managing our neurological states of being and honoring ways of knowing that include intuition, artistic expression and the lived experience. Of critical importance is cultivating our appetite for beauty. As Maxine Greene has taught us, beauty feeds the social imagination necessary to envision just alternatives to the world we have [56]. Given the autopoietic nature of our minds, the value of putting our attention on beauty is the possibility of generating beauty.

Finally, an engineering education from holism would develop skillful means in working with *social fields*. The notion of social fields was proposed by Lewin in his work with Holocaust survivors [57]. In his treatise, he used the analog and mathematics of electromagnetism to describe *social fields*—conceived as an energetic force that produced action at a distance—using reductionist concepts. However, the concept of an energetic social field can easily be seen in phenomena like social contagion or mob mentality. Additionally, the activity of mirror neural networks [58, 59] from a holistic POV confirms that shared, visceral human experiences can co-arise through observing another person; a witness can mirror the same neurological activation *as if* they were engaged in the observed activity. In terms of learning, a holistic engineering education would recognize how the quality of the social field conditions the ability for learning. For example, recent findings reveal the wide scale prevalence of trauma in the young adult population in the U.S. [60]. Such adverse childhood experiences become neurologically embodied, compromising peoples' ability to self-regulate and remain calm—the only state in which one can integrate new knowledge [61], **Figure 6**. Trauma effectively shrinks our "window of tolerance" for distress. An engineering education from holism would support learners' ability to manage their neurological state of being and metabolize adaptations that displace us from learning.

3.2 Preliminaries: where do we start?

In a world of urgency, we ironically feel our first action is to pause and reflect. If learning is an autopoietic action, we who have been conditioned through a western education may first need to unlearn. At minimum we will need to expand our ability to sense beyond what is presently available to us. The danger is that any action we take from our present condition will arise from the structures of our western education and thereby worsen the situation. So, our first need is to renounce the primacy of thought and cultivate a holistic neurological intelligence that includes abilities to sense and integrate our feelings. Perhaps coincident with unlearning

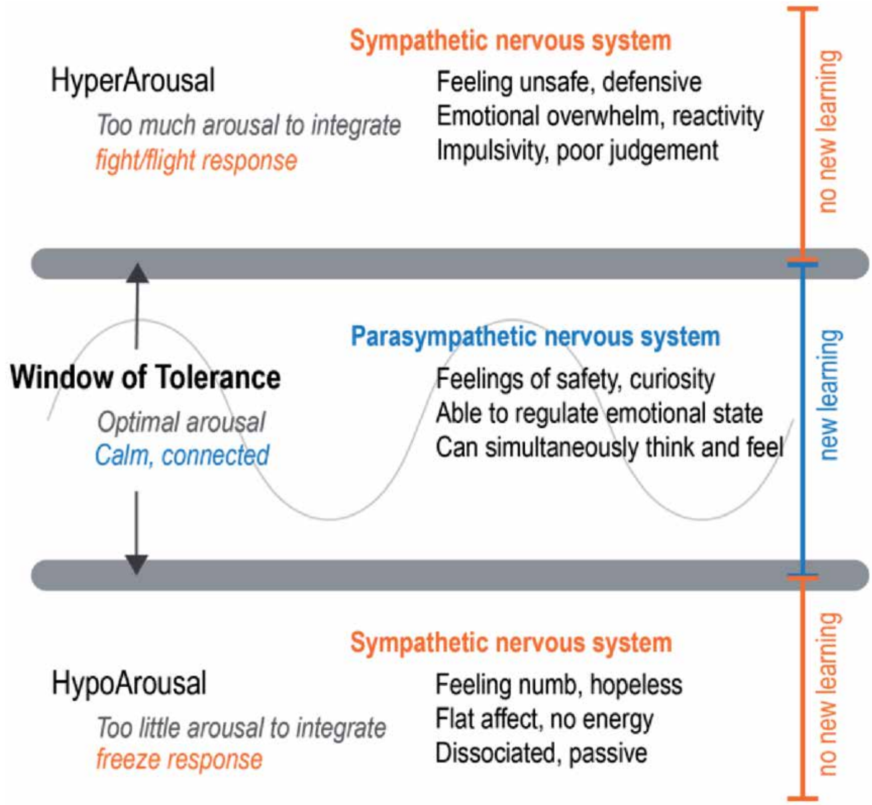

Figure 6.
Nerve activation states from polyvagal theory. (Adapted from [61, 64]). The vertical axis represents the level of nervous system arousal, which naturally varies. One is able to self-regulate natural variations in arousal state within the window of tolerance. Chronic stress diminishes one's resilience (i.e., effectively shrinks the window of tolerance).

the hidden dynamics of reductionism, we will need to apprehend the language and methods of holism. Engineering classrooms, as evidenced by syllabi, can draw on semantic frames which foster social fields of fear in classrooms [62]. We will need to re-language engineering if we desire safe social fields.

Another task is to identify what to conserve from reductionism. What balance of competencies are relevant for engineers to be humane and effective in a world of dynamic complexity? Surely reductionist science is important and applicable. What concepts do we preserve in a holistic engineering education? We, as an engineering community, need to do the difficult work to unlearn, rethink and learn. As educators, learning the skillful means of managing our neurological states of being would benefit ourselves and the people we call 'students.' Chari and Singh have developed such neuroscience-grounded training [63]. We have field-tested their methods in a recent online course; we and our students experienced their practices as significantly aiding our learning.

Within this new direction of holistic learning, we will also need to generate new methods for understanding our effectiveness. There are those who are skilled at working with managing change through holism [65]. However, the challenge for us disciples of reductionist science is to suspend judgment that arises from our unexamined mental models. A helpful heuristic is to notice when we react with strong emotions in the context of academic questions. That is an opportunity to reflect on the four essential questions: How do we know our understandings are accurate? How do we know whether our practice makes sense? How do we know whether we are acting morally right and appropriate in the circumstances? How do we know we are not self-deceptive in our responses?

3.3 A notional proposal for a holistic engineering learning method

We have laid out the case for a method of learning engineering grounded in a holistic world view. This means that any engineering curriculum would recognize its relationship to its local history and culture. At the same time, we imagine that engineering learning methods across cultures share some learning outcomes. Such outcomes, as we are suggesting in Section 3.2, would reflect not only the reductionist threshold capacities that the engineering community desires to preserve, but include those that are relevant to living in a dynamically complex world that is far from equilibrium. Such a systemic state, as Prigogine and Nicolis [66] have recognized, does not behave in linear ways, where the outcomes are predictable extensions of a plan; systems far from equilibrium are characterized by emergent, spontaneous changes of state which are non-linear, neither predictable nor sourced in the synthesis of the systems components [66]. Such state changes, while not predictable in the conventional meaning of the word, represent outcomes produced by the emergent conditions. The operative question in such systems becomes: What conditions favor the outcomes that we desire?

As a notional proposal, we suggest the threshold technical capacities and holistic enrichments for an engineering education grounded in holism as listed in **Table 4**. The detailed experience of a program based on these capacities is out-of-scope for this chapter, but available in a pending publication by the authors. However, we provide concrete example below. **Table 4** focuses on technical knowledge thresholds ("Reductionist technical content") that fall in the category of technical interests (**Table 1**). It also includes what we conceive of as enrichments ("Enriched by Holism") to support liberal and practical interests (**Table 1**). We acknowledge that **Table 4** is not comprehensive and omits many practical interests that we touch upon in our example below.

As stated, we would expect engineering education grounded in holism to reflect the rich diversity and cultural heritage that exists on the planet. However, to illustrate a practical example, consider this vignette of an example of an engineering learning method in the north eastern United States. It takes the form of a four-year experience.

The central tenets of this holistic learning method include:

1. everyone (students, faculty, staff, administrators) is a learner,

2. everyone is an educator,

3. we are not separate from the systems imagine: we are part of an interconnected web of relationships,

4. we are always practicing something in a recursive loop of theories, action and learning in the spirit of Critical emancipatory action research, **Figure 4**.

These tenets translate to a culture of mutual respect. Everyone is valuable and worthy of dignity, regardless of formal role. In a holism model, a community mantra might be, "Honor the whole." As a community member, one would feel a sense of care and responsibility for one another's well-being.

The faculty create the *least* structure required for learning. Of course, this would vary from institution to institution, but what is shared as humans is our innate

	Reductionist technical content preserved	Enriched by Holism
Energetics	The first and second laws of thermodynamics and their implications Newton's laws of linear and rotational motion applied to simple rigid bodies, Basic static and dynamic concepts and relationships	Power and energy flow within, between, among people and the planet (anthropogenic climate dynamics). Conceptual understanding of force as a change mechanism in social and political systems (past, present and future).
Action in fields	Elementary chemical reactions near equilibrium conditions Basic electrostatic and electrodynamic concepts and relationships	Far-from equilibrium dynamics (state changes, emergence, dynamic complexity). Emergence in the presence of force fields (social, political); self-organization, structural coupling of outcomes to systems behavior.
Flow	One-dimensional flow of charge and thermal energy (steady and transient states) Control through sensing and feedback	Neurological basis of sensing (perception, reception, interoception, proprioception). Reflection, dialog and narrative in support of participatory, systems transformation. Managing one's attention and state of being. Making conscious choices.
Measurement	Math (curated competencies from: algebra, calculus, linear systems, statistics)	Ontological and epistemic boundaries of quantitative and qualitative data. Dynamic complexity (concept of strange attractor, curated systems behavior and properties of scale, scope, resilience).
Aliveness	Biology (curated set of principles about the structure and function of organisms, and ecosystems; metabolism, immune response).	Living systems dynamics (autopoiesis, recursion, self-organization, emergence, structural coupling). Threshold conditions for thriving (well-ness, fairness, whole person and community development). Art, joy and beauty as basis for creativity that is just and equitable.

Table 4.
Proposed threshold holistic engineering capacities, grouped into themes.

motion toward learning when it is personally meaningful, it interests us and we can discover with a sense of psychological, emotional, academic and physical safety. The traditional "grading" system might be replaced with developmental milestones and reflection.

In this model, there would likely be an agreed-upon time where the parties convene to co-learn (i.e., a "class"), however, the primary means of learning would be collaborative (i.e., shared power), support self-organization, self-directed learning and peer-to-peer learning. The institutional schedule would structure blocks of time to accommodate collaborative project teams that transgress traditional boundaries.

Imagine that the curriculum was organized around the holistic themes of **Table 4**: *Energetics, Actions in fields, Flow, Measurement, Aliveness* and *Flow*. Over the four years, the curriculum would involve broader and deeper applications of these revisited themes considered at different scales. That is, we might conceive of ourselves as centered at the core of several interpenetrating systems, from most personal (the smallest scale) to transcendent (the whole): self, family, institutional, societal, historical and perhaps spiritual.

As a contextual backdrop, the present U.S. culture is simultaneously alive with the hope of freedom and toxified by its foundational history of genocide of indigenous people, enslavement of Black and Asian people, and violence against women. The myriad violences committed in building our nation have autopoietically reproduced through implicit cultural biases against people of color and women; such biases frequently escalate to lethal violence, such as the pattern of targeting Black men, women and children by law-enforcement agents, fragmenting our communities. A holistic engineering education in the U.S. historical culture could be organized around building the capacities listed in **Table 4** for the purpose of dissolving and healing these cultural dynamics while growing the Aliveness that we aspire to.

In the first year, among the many activities, learners would build capacities to access their whole neurology through such practices as mindfulness, meditation, yoga, martial arts or spiritual expression. Simultaneously, they would be learning about sensing, instrumentation and measurement by building electronic circuits. These human-centered and technological activities would be integrated to communicate the value in one's whole development. Such an integration of the fragmented Western so-called "mind"—abstract, cognitive thought—and so-called "body"—somatic sensations and feelings—would autopoietically produce holistic solutions.

They might also engage in learning history of the region and country, mapping the autopoietic results of these events as institutional structures, policies and practices at different scales: personal, social, regional, nation state, planetary. Simultaneously students would apply mathematics to simulate dynamic systems behavior through computer modeling. Using reflective dialog, they would make meaning together of systemic patterns, perhaps metabolizing residual effects in cases where their lives have been adversely affected.

They might develop their identity through weaving a story of their past, present and future selves in an engineered world. The sharing of these oral histories would be a celebrated community tradition. While developing their narratives of personal power, they would learn about power and energy viewed from the laws of thermodynamics. They would also learn how force works together with motion, equilibrium or stasis through Newton's laws of motion. Artistic expression, dance, music or theater would be practiced and celebrated with joy. Such activities serve to enrich their vision of who they are becoming and the influence they aspire to have in the world.

The theme of Aliveness could be addressed by studying Nature's designs. In addition to the basic concepts of chemistry and biology, students would learn the principles of autopoiesis and structural coupling. As an introduction to design, learners would be trained on the use of available prototyping tools so they can design a nature-inspired "Hopper." They would also draw connections between structural coupling in autopoiesis and inequities in our country's economic, health and environmental patterns. During this time, computational skills would be developed to analyze data.

In the following years, learners would return to the holistic themes of *Energetics, Action in fields, Flow, Measurement* and *Aliveness.* They may also expand their view and application of ideas to larger social scales. The learning might take the form of project-based learning in collaborative partnership with regional communities. For example, along with learning about energy and heat transfer, they could create data-based stock and flow maps of energy at institutional, regional and planetary scales. Such maps could serve as the basis to co-design highly-leveraged interventions for carbon-negative systems with community partners. Or, they may partner to co-develop technologies appropriate to the community setting. What is important in these later years is the process of collaborative discovery in the world outside of the campus.

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The curriculum could include partnerships where learners live together situated on a site to demonstrate sustainable communities. They would continue embodied practices and learning related to *Energetics, Action in fields, Flow, Measurement* and *Aliveness.* They can deepen their technical knowledge around feedback and controls as they consider how these can be used to provide needed renewable power. Again, such questions of renewable power would be undertaken in metaphorical ways at different scales: self, family, institutions, community, society, history and future. On such demonstration sites, they could also deepen their practices by collaboratively working with regional partners to co-design carbon neutral exchanges of goods and services aimed at creating meaningful livelihood for those experiencing low income.

In this section, we have offered a glimpse into what learning engineering from holism might look like. In its essence, we have offered a vision of learning that is itself, autopoietic. That is, we have described a living, learning organization situated in the U.S. that sustains itself through a recursive return to global themes of *Energetics, Action in fields, Flow, Measurement and Aliveness,* including themselves as part of the systems they study. Projects, co-created and chosen by learners, figure prominently in the curriculum as does collaboration across boundaries. Embodied practices and dialog play central roles in dissolving power inequities in the learning environment; they enable people to manage their state for better learning and collaboration. Later years expand the scale of co-learning to encompass regional partnerships; sites serve as living laboratories to demonstrate the viability of beneficial, just and equitable alternatives to our current systems.

While this description may seem unrealistic, it is a narrative derived from our institution's myriad learning experiments over the last 20 years. The vision we describe above coheres to an explicit holistic model that was not a cohering principle of our institution's past curriculum. However, we offer it as a glimpse into one incarnation that is possible, recognizing it as something singular to our context. From the point of view of holism, we would expect a diversity of expressions of engineering curricula, relevant to the regional situation.

4. Conclusions

Reductionist science and practices are fit for limited purpose and have indeed resulted in the remarkable technological advances we see in Industry 5.0. However, emerging global patterns underscore the fact that our legacy reductionist science is insufficient to meet the moment. Disturbingly, a confluence of findings from different fields point to the pattern of self-replication in learning. An attention fixated on technical 'problems' creates an existence filled with technical problems. As predicted by Bateson [67], and later documented by O'Neil [68], without a profound educational shift, legacy science and engineering is likely to lead to self-destruction by extending the power of technology, uninformed by our humanity. Our challenge is to heed Einstein's imperative to adopt the paradigm of holism or face a future fraught with the increasing social, political, environmental dis-ease produced by fragmentation. Not only is holism more aligned with the nature of the universe, it more accurately describes the dynamically complex, sociotechnical realities that engineers work with. Its methods, drawing from existing social science praxes, are also more aligned in their assumptions and purpose to the profession of engineering. When we consider what a holistic engineering education might involve, we recognize that we can only see dimly. We have offered a working model organized around a recursive consideration of *Energetics, Action in fields, Flow, Measurement* and *Aliveness.* This proposed learning model, appropriate to our particular context, is only one of many incarnations of engineering education that we would expect to take form in a model of holism. There is a great deal of work to be done, yet we know that an engineering education for health/wholeness will itself honor the whole of ourselves and our societies. It will include reductionist science yet be attentive to the quality of relationships, structures and fields that condition what is learned. At minimum, an engineering education from holism will embrace our whole humanity, recovering our intrinsic motion toward beauty, joy, fairness and compassion—our vital humanizing qualities that are missing in our legacy engineering education.

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Conflict of interest

The authors declare no conflict of interest.

Declarations

The ideas in this chapter are solely those of the authors and do not necessarily represent those of the Coalition for Life Transformative Education.

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Chapter 6

Using ICT and Energy Technologies for Improving Global Engineering Education

Pritpal Singh

Abstract

Information, communication, and energy technologies have the potential to improve engineering education worldwide. With the availability of low cost, open-source microcontrollers/microcomputers, such as the Arduino and Raspberry Pi platforms, and a wide variety of sensors and communication tools, a range of engineering applications and innovations may be developed at a low price. Furthermore, the cost of solar panels and LED lamps have also dropped dramatically in recent years and these also allow for improved energy support in regions that lack energy access or require autonomous monitoring/processing. Also, low-cost 3D printers are now widely available for making simple prototypes of hardware. Finally, low-cost educational software tools have also become available. Combining these technologies enables engineering education to be brought into traditionally inaccessible communities in the world. In this book chapter, examples of how ICT and energy technologies are being used to teach students engineering technologies in under-served communities will be described. Application areas to be described will include environmental monitoring, clean water systems, and remote learning.

Keywords: ICT4D, open-source hardware, solar electric systems, 3D printers, Information and Communication technologies, sustainable development goals, global engagement

1. Introduction

Since the development of the first integrated circuit by J. Kilby in 1958 [1], microchips have advanced enormously growing to include billions of transistors on a single chip. These advances have fueled the growth of the information technology industry with high performance computers and high-speed communications. Data can be communicated at lightning speeds over fiber optic networks and stored in large data centers or in the cloud.

Yet, while these tremendous advancements are available to students attending universities in well-resourced settings, universities in low resource settings often lack even basic information and communication technology (ICT) infrastructure including computers, software, and Internet access. This lack of ICT resources greatly limits the quality of engineering education that can be delivered to students in these low resource settings. Many of the universities with low levels of ICT resources are in developing countries, especially in sub-Saharan Africa, Latin America and the

Caribbean, and in parts of Asia. This further exacerbates the digital divide between communities in low resource settings compared to those in higher resource settings. This results in limited innovation and modern economic development opportunities for students in low resource communities. Additionally, the lack of reliable electricity in low resource settings is another barrier to delivering quality education in these environments. Furthermore, the cost and energy requirements for conventional prototyping equipment, e.g. lathes, bandsaws, drill presses, etc. prevents them from being integrated into engineering curricula in low resource settings. Finally, the professors in these low resource settings do not have the training and education in the use of modern technologies. This results in much of the pedagogical approach to teaching engineering in low resource settings to be mostly theoretical and out of date. There has been very little opportunity for students to get hands-on prototyping experience that they can use to innovate engineering solutions to local societal problems.

Recent technology advances in the area of low-cost, open-source hardware and software are opening up new possibilities for professors at universities in low- and middle-income countries (LMICs) to provide their students with hands-on, experiential learning opportunities in developing engineering solutions to real-world problems. Microcontroller and microcomputer hardware platforms, such as the Arduino and Raspberry Pi platforms provide several input/output interfaces for sensors, displays, and transducers, significant memory storage, and quite powerful processing capability. When combined with an array of open-source software tools, such as the Linux and Android (a derivative of Linux) operating systems, Mozilla Firefox, Libre Office, Wikipedia, Khan Academy, Python programming language, etc. a powerful array of capabilities become available to developers at low cost. Furthermore, the cost of solar panels and solar electric systems have also come down dramatically over the last decade to the point where they are competitive with grid-generated electricity in many locations. This allows for reliable power to be provided in areas that have previously lacked access to energy. A fourth technology that has emerged over the last decade is the advent of low cost 3-D printers. This development has also added to the suite of low-cost technologies that are now available for low-cost prototyping of engineered products. Finally, affordable mobile phones are available everywhere. At a minimum, almost everyone in the world has access to feature phones and smart phones are owned by almost 50% of the world's population [2]. This ubiquitous availability of mobile phones throughout the world has provided relatively low-cost connectivity everywhere.

These five technological advances have opened many new opportunities for ubiquitous, project-based, learning of engineering, even in low resource settings. To fully take advantage of the opportunities afforded by the vision of Industry 5.0, a broader, more diverse array of engineers need to be educated to enhance the creativity needed to address broader challenges as described by the UN Sustainable Development Goals [3] or National Academy of Engineers Grand Challenges [4].

The focus of this chapter is to show how the combination of low-cost energy and information and communication technology (ICT) platforms along with 3D printers offer the opportunity to educate students in engineering in global, low resource settings to create a more inclusive and diverse workforce to support the Industry 5.0 initiative. Examples of hands-on initiatives in various LMICs including Nicaragua, Ecuador, Guatemala, Malawi, Sri Lanka, and Tanzania will be presented.

2. ICT, energy and 3-D printing technologies

Low-cost open-source hardware was first introduced by Arduino in 2005 [5]. The philosophy behind the development of the Arduino microcontroller was to make an easy-to-use platform for non-engineers to prototype electronic circuits. The basic Arduino Uno single board microcontroller (see **Figure 1**) plugs into the USB port of a computer and has its own integrated development environment (IDE) that is relatively easy to program (and can even be programmed with a basic, block-based programming tool). The features of the Arduino microcontroller are provided in **Table 1**. In addition to the basic device, there are shields that may be added to extend the capabilities of the Arduino microcontroller, such as a Wifi shield that allows for connectivity to a wireless communication network. There are also more powerful versions of the microcontroller, such as the Arduino Mega as well as devices of different form factor, e.g. circular devices that can be housed in circular housings.

A second open-source hardware device that has become very popular is the Raspberry Pi microcomputer. This low-cost device is a fully integrated computer. The features of the Raspberry Pi 3 Model B are illustrated in **Figure 2** and provided in **Table 2**. The Raspberry Pi has a built-in Google Chrome browser and supports programming in Python. There are also many application software packages that come with the basic device including Wolfram's Mathematica, MIT's Scratch, and Wikipedia. Many other software packages may be downloaded onto this microcomputer platform.

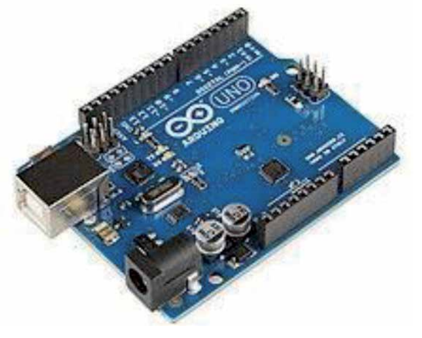

Figure 1.
Photograph of an Arduino Uno microcontroller [6].

Feature	Description
Processor type	8-bit 16 MHz Atmel AVR
Memory type	32kB Flash, 1kB EEPROM and 2kB SRAM
Analog Input/Output pins (includes PWM and SPI interfaces)	6
Digital Input/Output pins	14
Common input devices	Light sensors, temperature sensors, ultrasound sensors
Common output devices	LED's, LCD displays, motors, speakers
Size	Approx. 5 cm. x 7 cm.
Power supply requirements	3.3 V or 5 V input; 50 mA
Cost	~$20

Table 1.
Features of Arduino Uno microcontroller.

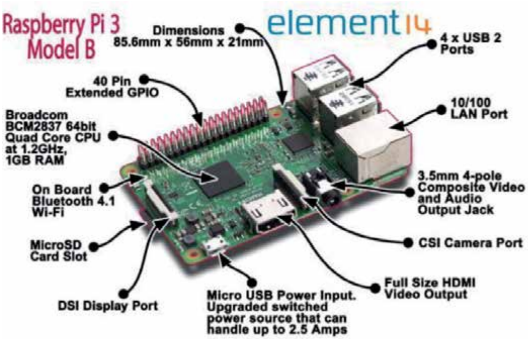

Figure 2.
Features of the Raspberry Pi 3 Model B microcomputer [7].

Feature	Description
Processor type	Broadcom BCN2837 64-bit Quad Core 1.2 GHz CPU
Memory type	1GB RAM + SD Card slot (up to 256GB)
Analog and Digital Input/Output pins	40 pin General Purpose I/O bus
Input ports/common devices	4 USB ports; Keyboard, mouse, display, camera
Output ports	Full HDMI video port, audio output port
Communication port	10/100 LAN Ethernet RJ45
Size	Approx. 9 cm. x 5 cm.
Power supply requirements	5 V input; 400 mA
Cost	~$35

Table 2.
Features of the Raspberry Pi 3 Model B microcomputer.

A third set of open-source hardware technologies that has emerged in the last decade is 3D printers. While 3D printers were available in university research labs in the 1990's, they were very expensive and so were economically out of reach of members living in low resource communities. The RepRap project was started in 2005 by Dr. Adrian Bowyer with the goal of developing low-cost 3D printers that could be replicated around the world [8]. This has led to the development of low-cost 3D printers that can now be purchased for under $200 in the US. Furthermore, open-source designs are available so that people can make their own units. **Figure 3** shows an example of a low-cost 3D printer available on the market today [9]. In addition to the 3D printer hardware, there are many open-source software tools, including 3D builder [10] that are easy to use by beginners. Also, free designs may be downloaded from various websites in standard file formats, such as.stl files. A comprehensive list of resources for 3D printing, including software tools, 3D printer models, example designs, etc. are available from github.com [11].

Many so-called "Fab-Labs" have now opened in many countries to take advantage of these industry trends to support open-source, low-cost design of engineered parts. In addition to 3D printers, these Fab-Labs include other prototyping tools in a workshop setting. A global mapping of Fab-Labs is available at the website: https://www.fablabs.io/labs/map [12].

Finally, the cost of solar panels has dropped dramatically in the past decade as shown in **Figure 4** [13]. This allows relatively low-cost solar electric systems (<$2 per Watt) to be installed in remote schools to provide consistent and reliable power even

Figure 3.
Lulz Bot Taz 6 low-cost 3D printer [9].

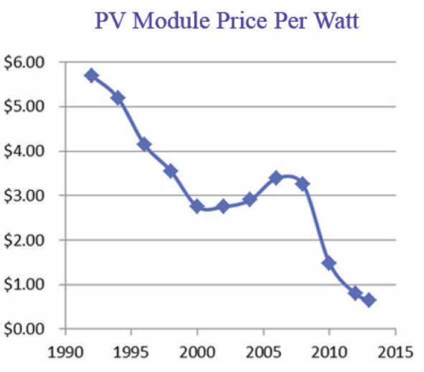

Figure 4.
Price of solar panels per watt from 1990 to 2015 [13].

Figure 5.
The "Digital Drum" solar-power computer kiosk in Uganda [14].

in areas that lack access to grid electricity. An example of a creative approach to setting up a solar computer kiosk is the "Digital Drum" that was developed by UNICEF. The design of the solar-powered computer kiosk employs modified oil drums to create the kiosk. A picture of this implementation at a school in Uganda is shown in **Figure 5** [14].

Bringing all these technological advances together offers the opportunity to educate students in low-resource settings in basic engineering skills. These students offer unique creativity and enthusiasm, resulting in a potentially more diverse array of products to emerge from these designers. There is a further trend in global engineering education where students from more privileged communities are interested in doing community service in low resource communities [15]. Students work with rural communities to identify needs and then co-develop engineering solutions for these communities [16]. These needs can span improving basic digital literacy in remote communities to developing applications to detect contaminants in drinking water. The next section describes more detailed case studies of improving engineering education in various universities in low resource settings.

3. Case studies of applying low-cost technologies in low-resource communities

Each of the subsections in this section focus on a particular application area framed by the UN Sustainable Development Goals (UN SDGs). The specific goals to be addressed here are:

- UN SDG Goal 3: Good Health and Well Being
- UN SDG Goal 4: Quality Education
- UN SDG Goal 6: Clean Water and Sanitation
- UN SDG Goal 8: Decent Work and Economic Growth

3.1 Enhancing the quality of education in low resource settings (UN SDG Goal 4)

3.1.1 Raspberry Pi workshops at Landivar University in Guatemala

The quality of education in rural communities is often very limited for many reasons including lack of trained teachers, lack of funding for the schools, and lack of technologies in the classrooms (including lack of connectivity). In 2009, World Possible, curated a package of creative commons resources (such as Wikipedia, Khan Academy, CK12 textbooks, etc.) for offline distribution to communities that lacked internet access [17] The organization coupled the content with the open-source web browser, Google Chrome, and created the Remote Area Community Hotspots for Education and Learning (RACHEL). They established this platform on the Raspberry Pi Model 3 and named it the Rachel Pi. The educational content stored in the unit's memory or on the micro-SD card could be accessed by computers, tablets or smart phones through a wireless router. Content on this device has been further developed in local contexts by local developers. A good example of this is the work done in Guatemala by Israel Quic, a native Mayan who produced materials based on his Mayan heritage in various Mayan languages for the local communities [18].

The Rachel Pi has been deployed all over the world from Tunisia, to Uganda to Papua New Guinea [19, 20]. A specific example is described in more detail next.

Landivar University is a Catholic, Jesuit university which has a campus in Quetzaltenango, Guatemala. The university is well-established and its professors in the Computer Science Department have a reasonably good curriculum including elective topics at a very basic level in the areas of artificial intelligence and Blockchain. The Arduino microcontroller is used in some project work at the university but only to a limited extent. However, the students and professors had not received any exposure to the Raspberry Pi until the author and his students conducted workshops at the university. Students at the university have access to laptop computers and the classrooms are well equipped with projectors and screens.

On the other hand, the region around the town of Quetzaltenango is very poor. Much of the population in the region is indigenous Mayan people who predominantly speak Quechua. The schools in the region of Totonicapan rarely have computer labs and many of them have no access to the Internet, although most of them do have access to electricity. The teachers also have limited technical skills. Catholic Relief Services (CRS) has been supporting a bilingual education program (in Quechua and Spanish) at the schools through a food and nutrition program as well as an infrastructure program (primarily building kitchens and latrines at the schools). The author and his students delivered two workshops on the Raspberry Pi to computer science students and professors at Landivar University in May 2019 and November 2019. Each workshop was held for two days. The first workshop provided an orientation to the Raspberry Pi and the second workshop was a more advanced workshop on configuring the Raspberry Pi for setting up a network and sharing resources from a server to individual computers.

The team from Landivar University working in partnership with a software engineer from CRS were able to obtain funding from the IEEE Humanitarian Activities Committee (IEEE HAC) [21] to establish a computer laboratory in a remote school in the community of Santa Maria Chiquimula in Totonicapan, Guatemala. This system was configured and deployed by the computer science students in early 2020 but because of the COVID-19 situation, has not been accessible to students and teachers at the school because the schools in the region have been closed since then. A photograph showing the students in the computer laboratory in early March 2020 as it was being set up is shown in **Figure 6**.

This example shows how a group of motivated university students in a low resource setting were able to address a local social challenge around the quality of education being delivered to school children in a remote, poor rural community.

A qualitative assessment of the November 2019 workshop on the Raspberry Pi was conducted. Two main questions were asked: What were the positive aspects of the workshop and what were the negative aspects of the workshop? The students indicated that they really enjoyed the practical, hands-on aspects of the workshop and the negative comment was simply that they wish the workshop had been longer!

3.1.2 Arduino workshops at Bluefields Indian and Caribbean University in Nicaragua

Engineering using the Arduino microcontroller can also be taught in low resource settings. Since the Arduino microcontroller may be interfaced to a variety of sensors and transducers, there is a large variety of possibilities for performing experiments with these devices. For example, the Arduino microcontroller can be interfaced to a temperature sensor and an LCD display and programmed to show

Figure 6.
Students at a school in Santa Maria Chiqimula, Totonicapan, Guatemala accessing content on a Rachel Pi server.

the ambient temperature of the environment. Another simple application is to use a light sensor as the input and display the ambient lighting level on an LCD display. More sophisticated applications, such as a line following robot can be produced by interfacing the unit to a mobile robotic platform and using a light sensor to follow a white line painted on the floor [22]. Another somewhat sophisticated application that offers students the opportunity to demonstrate their creativity is a wearable array of colored LEDs that are programmed to light up based on sound volume (through interfacing with acoustic sensors). There is a block programming interface to the Arduino microcontroller, like Scratch, that can be used with elementary/ middle school children who are just beginning to learn basic programming skills for them to perform simple experiments with the Arduino microcontroller.

Bluefields is a town located on the Caribbean coast of Nicaragua. Most of the population in Nicaragua resides in the southwest, Pacific region of the country near the capital city of Managua. This part of the country has the highest economic development in the country while the Caribbean coast is relatively under-developed. The population of Bluefields comprises a variety of indigenous populations who are mostly fisherman. There are many social problems in this region and UNICEF has been working in this part of the country to pilot solutions to address these social problems, particularly as it affects children and youth. Bluefields Indian and Caribbean University (BICU) has as its mission to educate the minority students from the Caribbean coastal region (including Bluefields). Since the social problems affect members of the communities in the indigenous population, UNICEF established an innovation laboratory at BICU to support the university's students and professors to develop innovative solutions to local problems. While there is a computer science program and a computer laboratory at the university, it is relatively ill-equipped. The quality of education and resources in this university are significantly limited compared to the universities on the Pacific side of the country. In collaboration with UNICEF, the author along with his students delivered a two day workshop to the students and professors at BICU in May 2017. The first day of the workshop was focused on the Arduino microcontroller while the second day was focused on using Android Studio for developing mobile phone applications for Android phones [23, 24]. Arduino microcontroller development kits were donated to the university and the students were able to develop applications after the workshops were delivered. While no formal assessment was conducted following the workshops, the informal feedback provided by the students was that they were very excited by the hands-on, practical experience of building electronic circuits.

The students at BICU were so excited about designing and building electronic devices that they launched a robotics club later in 2017. The students from this robotics club competed and won a national robotics competition in 2018 as underdogs in the competition. As winners of the national competition, they were invited to compete in an international competition [25]. Many of the students at BICU were at-risk youth. Witnessing these underserved students' ability to embrace and apply electronics technology to win a national competition clearly demonstrates how the quality of education in low resource settings can be dramatically improved using low-cost hardware and effective mentoring.

3.2 Improving quality of health care in low resource settings (UN SDG 3)

3.2.1 Improving quality of health care in rural Nicaragua

The quality of health care in rural communities is often very limited. Community health workers (CHWs) with limited medical knowledge and training are often the front-line administrators of local health care to members of their communities. Rural medical clinics may also have limited facilities. Two examples of how quality health care may be improved in these rural settings using technology are described in this section.

The first example focuses on a project conducted in the rural part of northeastern Nicaragua in the area surrounding the town of Waslala. This region of Nicaragua is very poor and the community members in this area tend to be subsistence farmers who grow crops and raise livestock. The mountainous terrain is very rugged with relatively few paved roads as illustrated by the photograph in **Figure 7**.

The author and his students as well as students and professors from the M. Louise Fitzpatrick College of Nursing at Villanova University, worked with the local Catholic parish and two Nicaraguan universities to develop a telehealth system for this region [26]. The CHWs were trained to make basic measurements of blood pressure, temperature, respirations and, in the case of pregnant women, fundal height. In the case of babies, they were also taught to measure baby head circumference and baby weight. All these trainings were done by the Nursing professors and students from both Villanova University and a partner university, the Universidad Nacional Autonoma de Nicaragua (UNAN) branch in Matagalpa, Nicaragua. The CHWs were then trained in texting the collected vital sign data to a central database on a computer server that was located at the Universidad Nacional de Ingenieria (UNI) in Managua, Nicaragua. They were also trained in using solar chargers to recharge their cell phones since many of the CHWs did not have access to electricity in their communities. An application program was written using an open-source UNICEF software tool, RapidSMS, that could accept text messages and display them as patient records in a database. This data could be reviewed by trained health care professionals and feedback provided to the CHWs in case a patient needed medical attention. While the initial software application was developed by students at Villanova University, further development of the software was conducted by students from UNI. These students were able to use the open source software to again address real world challenges having understood the context of the communities through engagement with the community members and the CHWs. The students performed competently and really enjoyed the experience of doing hands-on, practical application development using open source software to address a social need.

The telehealth project was further expanded to other regions in Nicaragua. One particular expansion was to the under-served Caribbean coast and students from BICU were engaged in the software development. Since RapidSMS requires significant programming skills (that were somewhat lacking at BICU at the time), a simpler cloud-based software tool, Rapid Pro, also from UNICEF, was used in this application. A comparison of these two software tools for telehealth project development is provided in [27]. Health care software tools are growing extensively

Figure 7.
A photograph of farmers in the Waslala region of Nicaragua.

worldwide to enhance the quality of healthcare in under-served communities. A good example of this is the DHIS 2 health information management system that is being used in many LMICs throughout the world [28].

3.2.2 Teaching students to repair medical equipment in low resource settings

Repairing medical equipment in low resource settings can be challenging because of the lack of availability of spare parts. This is because, oftentimes, the equipment is old and spare parts may not be available. Furthermore, medical instrumentation can also be difficult to obtain in low resource settings because of lack of funds. In these cases, 3D printing becomes an option to print replacement parts as well as medical instruments. A start-of-the-art review of additive manufacturing of medical instruments was published by a group of researchers from the Delft University of Technology in the Netherlands [29]. While this paper provides a very comprehensive review of a range of medical instruments that may be 3D printed, for the purposes of low resource settings, some basic tools are shown in **Figure 8**. The figure shows a surgical kit comprising a scalpel, hemostat, forceps, and tweezers. This is particularly important in low resource settings since there may be a very limited supply chain to remote medical clinics. In many developing countries, the medical system is a national system and remote clinics often receive little funding from the central government. Local production of these instruments allows surgeons to be able to have low-cost but very capable tools for their use.

Additionally, local doctors can develop their own instrument designs based on their needs and therefore promotes more local creativity in the design of medical instrumentation.

3.3 Clean water confidence indicator (UN SDG goal 6)

Chemical and biological contamination of water sources is a major problem all over the world. A low cost means of disinfecting water in remote communities is to put the water into a bottle and place it in the sun for a period of time. In this solar disinfection technique, the UV radiation from the sun kills bacteria in the water resulting in potable water for drinking [30]. Yet, while there are some indicators that can show that the water has received sufficient treatment, these are relatively expensive or may need periodic replacement.

An innovation developed by students at Villanova University uses a UV sensor to accumulate the UV radiation using an Arduino microcontroller. When the

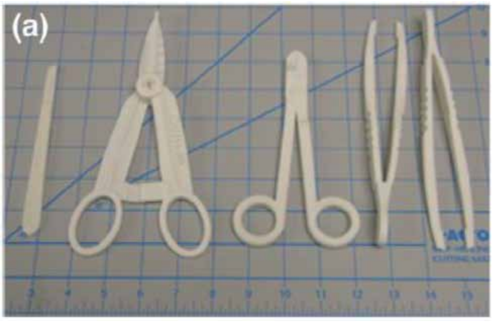

Figure 8.
Common medical instruments printed in a 3D printer.

accumulated UV radiation crosses a threshold, an indicator displays that the water is safe to drink. This system can be used for several bottles at a time in a community setting [31].

Another example of using an Arduino microcontroller to evaluate the quality of water for potable consumption was described in [32]. The authors of this paper from Brunei used an array of sensors, including a turbidity sensor, a total dissolved solids (TDS) sensor, a pH sensor and a temperature sensor that were interfaced to an Arduino unit as shown in **Figure 9**. The unit was tested in a stream on the Universiti Brunei Darussalam campus. Preliminary results of their system show good promise for assessing water quality, but they are planning to upgrade the system to incorporate a Raspberry Pi microcomputer to give remote data collection and more powerful computation capabilities.

3.4 Enhancing productivity and economic growth (UN SDG 8)

3.4.1 Soil moisture sensor design

Precision agriculture is becoming an important area in farming. While this technology has been applied to large holder farms it is still in its infancy regarding small holder farmers. One area of importance in small holder farms in developing countries is only irrigating farms when soil moisture content falls below some threshold value. Combining moisture sensing with drip irrigation technology offers the opportunity to minimize the amount of water used in irrigating farms.

Engineering design instruction at the University of Malawi Polytechnic in Blantyre, Malawi used to almost exclusively focus on paper designs because of the lack of prototyping materials and facilities. This meant that the students would just work on the first half of the design process, i.e. understanding the problem, brainstorm design solutions, settle on a particular solution and then sketch out the solution. They did not get to prototype the design, test and troubleshoot it, or iterate on design improvements [33]. Through a collaboration with Rice University in the US, a maker space facility was established at the University of Malawi Polytechnic in 2016. This Polytechnic Innovation Design Studio (PIDS) includes a variety of prototyping equipment Arduinos and Raspberry Pis, 3D printers, a laser cutter, a CNC machine, and hand tools. These tools are used at all levels beginning in the first-year design classes through to the final year capstone design classes in both the electrical engineering (EE) and mechanical engineering (ME) curricula.

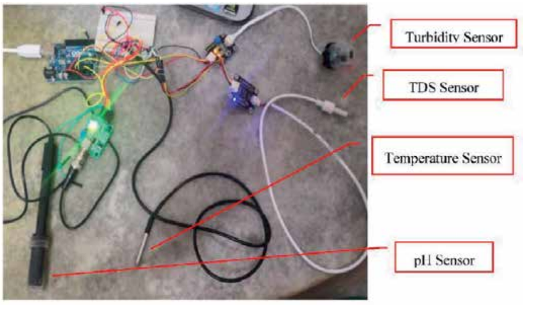

Figure 9.
Picture of Arduino-based water quality sensing unit.

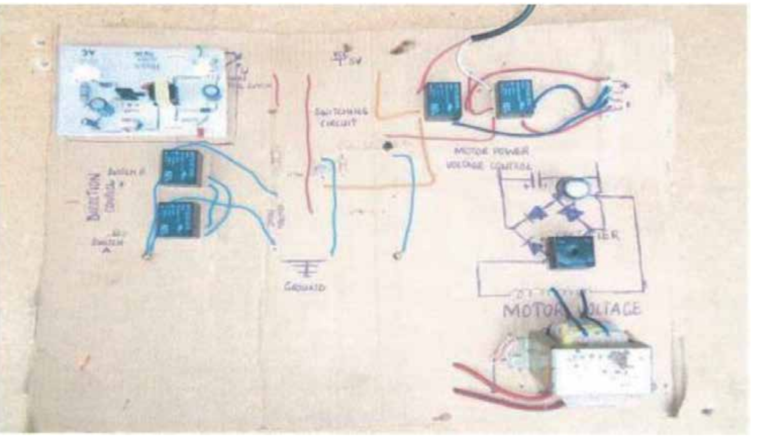

Figure 10.
Pre-PIDS circuit prototype using a cardboard backing and organizational structure for the circuit [33].

Figure 10 shows a highly rated EE student prototype circuit design prior to the establishment of the PIDS facility. The design includes the circuit components mounted to a cardboard backing. After the PIDS facility was established, the designs were significantly improved. **Figure 11** shows a moisture sensor using an Arduino microcontroller as part of a drip irrigation system to minimize water use in irrigating farms. Clearly, the quality of the design is much more advanced than the prototype circuit shown in **Figure 10**.

An assessment of the quality of the prototype and design process level were conducted for both EE and ME students using a five-point Likert scale. **Figure 12** shows the results of this assessment. The prototype quality has been seen to considerably improve by the presence of the PIDS facility. The change in the design process level was also observed to improve but the upper end of the design process levels did not change.

3.4.2 Improving productivity of small and medium sized enterprises in rural parts of Europe

An interesting approach to teaching 3D printing to remote communities is the Fab Bus mobile STEM education platform developed in Aachen, Germany [34]. This mobile education unit is deployed in a converted double decker bus as shown in **Figure 13**. Eight seats on the upper deck of the bus house 3D printers for students and a teacher's seat. There are also computers at each station with 3D CAD software

Figure 11.
Soil moisture sensor and Arduino reader with LCD display [33].

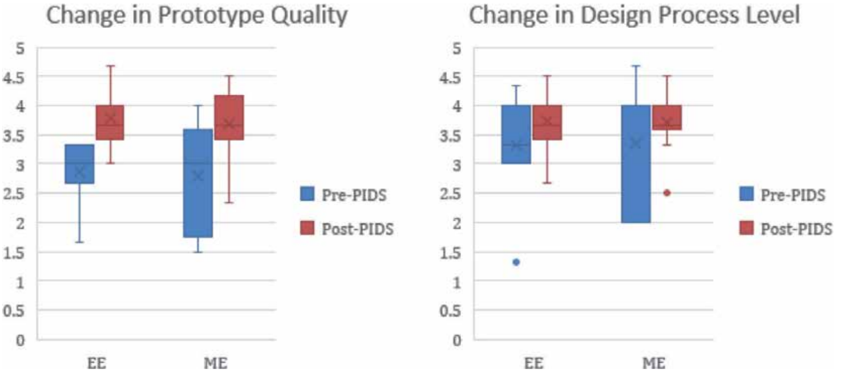

Figure 12.
Assessment results for pre-PIDS and post-PIDS designs [33].

Figure 13.
Mobile 3D printing educational unit (Fab Bus) [34].

tools. The upper deck can be used as a classroom to teach students how to design and print 3D models. A layout of the upper deck is shown in **Figure 14**. The lower deck houses a showroom with industry-grade machines and various professionally made parts, including metal parts. Short courses are taught in this mobile classroom to high school and university students as well as to small and medium sized businesses.

Figure 14.
Upper deck layout of the Fab Bus [34].

This innovative teaching platform has toured three countries – Germany, Belgium and the Netherlands and has been well received in all three countries.

4. Conclusions

In his best-selling book, "The World is Flat", journalist Tom Friedman observed that a youth with access to a computer and the Internet can contribute to economic development from anywhere in the world [35]. Fifteen years since the first edition of that book, this statement is even more true. Industry 4.0 brought us massively interconnected devices which led to the accumulation of large amounts of data (so-called "big data") that required artificial intelligence and machine learning to interpret. Industry 5.0 is bringing humans back into the equation to work with machines and is the motivation of this next phase of the industrial revolution. The ubiquity of low-cost ICT and energy technologies as well as low-cost manufacturing technologies, offers an opportunity to bring a more diverse youth, including those from low resource settings, to be educated in engineering product development and to thereby contribute to local economic development.

The technology trends in low-cost ICT technologies, including ubiquitous access to mobile phones, low-cost energy access via solar panels, and open-source software and hardware systems have been reviewed in this chapter. A few application sector examples, built around the UN SDG frameworks, including quality education, clean water and sanitation, good health and wellbeing, and decent work and economic growth have been explored. These technological developments are driving a revolution in global engineering education bringing in historically neglected youth into the worldwide community of engineers. This creates the potential for unique and potentially transformative solutions to global challenges to be invented by students from low resource settings given their unique perspectives on the world.

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Conflict of interest

The author declares no conflict of interest.

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Chapter 7

Teaching and Learning Mathematics for Understanding, Enjoyment and Everyday Life Experiences

William Deng Tap

Abstract

This chapter expresses the views of a teacher-researcher who advocates and argues for the use of humor in the classroom setting, especially in the mathematics classroom. While existing research based literature has shown the use of humor to be promising and encouraging effecting teaching and learning tool, very little instructional humor or classroom humor–an appropriate type of humor often related to the content materials being discussed–has been used in the classroom setting–especially in the mathematics classrooms. The chapter explores, surveys and highlights ways in which the existing-related literature about the effective and appropriate use of humor in the classroom setting can be implemented in practice, especially in the teaching and learning of mathematics, in this challenging era of the increasingly rapid technological advancements referred to as 21th century technological revolution or the re-engineering of industrial education 5.0 relative to STEM subjects study areas. The use of humor as teaching and learning tool in the classroom setting has been shown to have so many associated benefits ranging from but not limited to a conducive-relaxed learning environment, enhanced students' learning experience, motivating and inspiring the students to learn more and even the improvement of student-teacher classroom rapport, just to mention a few. Hence, the literature recommends that classroom teachers should make more use of humor as an effective teaching and learning tool, especially the contextualized-appropriate humor types that are related to the content materials being discussed.

Keywords: Classroom humor, mathematical humor, interest in mathematics, teaching and learning

1. Introduction and background

With the increasingly rapid technological advancements such as the birth of the industrial technology based education 5.0, sometimes popularly described as the looming 5G or 6G and its successive next generation technologies or the 21th century technological revolution, there are suggestions, demands and even requirements that the traditional-classroom education needs to be re-engineered, that is, the traditional roles of classroom teachers should as well be re-examined and change along the way to adjust accordingly. Therefore, the birth of continuously re-engineering education leaves not only unanswered questions to be asked, but also a lot of acceptable old answers or assumptions to be questioned and re-examined such as whether or not classroom teachers, researchers as well as other practitioners should embrace the re-engineering of education, or whether teachers' primary-traditional roles would survive such an emerging-continuous revolution. Certainly and indeed, the current wave of technological trends and changes that are accompanied by huge explosion of knowledge through the popular World Wide Web, brought about by the 21th century technological revolution (which demands the re-engineering of education), through Internet based independent learning aids or tools such as YouTube channels, TED Talks and Google searches, one wonders whether the basic traditional-primary role of teachers long held perceptions as being the only knowledge sources, knowledge containers and even walking libraries (e.g., being regarded as the only single source of knowledge–the unnecessary burden of having to carry heavy load of knowledge in the head, a skill now made obsolete by the era of Internet and Google) would survive at all, if not already phased out and perhaps made obsolete in the face of increasingly competent high quality YouTube-based lectures as well as attractive, interesting and inspiring TED Talks, popular Internet sites and even TV based talk shows.

Surely, in the era of the 21th century technological advances in the forms of continuously improving World Wide Web, Internet connection or Google search engine, one does not need to be a knowledge container or walking library with a head fully loaded with facts, unnecessary details and teachers' lectures, since such facts and details can be Google searched in blink of an eye in nanoseconds and openly accessed with just a click of mouse away.

Nowadays, traditional classroom teachers no longer have the monopoly and sole privileges of being the only walking libraries in the face of Google or the only single sources of knowledge as used to be, given various Internet based independent learning facilities freely available in the World Wide Web along with the competing as well as competent high quality 21th century technologically revolutionized independent learning aids or tools openly and freely accessible such as Khan Academy, MIT's open course ware, to mention a few. With the inevitable knowledge rapid expanding, approaching but diverging toward infinity through YouTube lectures, the primary-traditional role of classroom teachers have to transform along the way to new advisory, supervisory and managerial roles [1] such as knowledge managers, classroom moderators and even knowledge consultants.

In fact, and addition to transforming, adjusting and adapting to the continuous emerging demands and requirements of 21th century technological advancements, classroom teachers and practitioners are already embracing and utilizing interdisciplinary collegial cooperation and collaboration with each other [2], while at the time encouraging individual creative-innovative explorations in their own unique ways, which they deem to be suitable for the teachers' various individual styles of teaching and learning in different classroom settings.

Therefore, not everything or all is lost for classroom practitioners as the consequence of the 21th century technology advancements as classroom teachers as well as researchers are now exploring in the form of action research new ways of teaching and learning, such as the classroom teachers' creative-innovative teaching techniques and strategies that emphasize, for example, understanding, enjoyment and connection to everyday real world life experiences. Exploring new ways of teaching and learning [3–5] is essential if the classroom teachers are to survive the 21th century technological revolutionary changes, combined along with the open attitude of welcoming and embracing such emerging technological trends instead of resisting them. Indeed, teachers cannot only survive but can even thrive and flourish in the face of the fierce competitions with those machine based-driven technological advancements, by not only welcoming or embracing the technological advancements, but also by being versatile, transformative, cooperative, innovative and relying more on alternative-innovative effective teaching technique and strategies, areas where machines are not known to do well on their own. Teachers can stay relevant and can continue to do so effective by recognizing, appealing and utilizing traits that are uniquely humane (e.g., utilizing human emotions such as the tendency to enjoy having fun, humor use, playing music and even singing songs in the classroom), techniques and strategies that make human beings different from those powerful–seemingly unlimited and apparently endless-high energy robotic machines based tools such as Google, YouTube or Facebook.

Human beings may not have unlimited, automatic and endless-high energy as robots do, but they do have an equivalent powerful-seamless energy source called emotions, which allow humans to acquire feelings, purposes, goals and meanings (not to mention that human beings are naturally endowed with moral ethics which they use to make big decisions, judgments, plans and preparations; and even the fact that humans are the original inventors of those impressive self-regulated automatic machines). Emotions provide humans with a powerful-significant source of emotional energy which humans can apply and utilize effectively by exploring the associated and often ignored affective learning domains of a subject matter such as enjoyment of mathematics, rather than the usual one-dimensional focus on the pursuit of only the cognitive domains of the subject such as competition based performance, computation or rote memorization, things which are better performed by machines such as high speed calculators or computers. Affective learning domains of the subject such as the enjoyment, gratification and satisfaction with mathematics concepts allow learners to acquire high order thinking skills such as understanding or comprehension, analysis, synthesis, critical thinking, logic and reasoning. Therefore, cognitive domains are not the only path to such important high order thinking skills, and if anything at all, a well-balanced combination of the applications of both the cognitive and affective domains of the subject matter is best suited for achieving the desired goal of overall learning outcomes.

One of the teachers' creative-innovative teaching techniques and strategies, which are uniquely human traits rather than the machine based, is a technique such as the deployment of an instructional humor (classroom humor), the use of contextualized-appropriate types of humor in the classroom setting [6]. To enhance students' interest in the subject matter, teachers can deploy, infuse and lace appropriate humor in into their lesson plans. Typical example of human traits based classroom strategies or technique is a humor-laced instruction delivered in the form of a lesson plan in a mathematic classroom. Mathematics classrooms are often regarded as stressful learning environments by many learners, and humor use as teaching and learning tool has a potential to make such dreadful environments conducive for learning [7].

2. The call and need for the use of humor in the mathematics classroom

It is generally accepted that mathematics is a difficult subject to teach and learn effectively, and therefore anything that claims to facilitate the learning of mathematics or learning in general is worth a look [8–10]. Hence, the 'teaching of mathematics with humour' as a proposed pedagogical toolkit, referred to as humor-supported instructional approach (H-SIA) as compared to its regular counterpart known as regular instructional approach (RIA), is an attempt to make mathematics an everyday real-world-life experience and its probable impact on students' learning experience. The idea of teaching mathematics with humor is an attempt to make mathematics part of everyday life experiences, something that has not been seriously considered in mathematics classrooms. Teaching with humor, as a proposed pedagogical toolkit, is an intervention (teaching experiment) through an action research [11], which originated from a classroom teacher's desire to minimize students' boredom in mathematics by finding ways of triggering or capturing the opposite of boredom known as interest—the whole idea is to generate and maintain interest in mathematics through humor as a teaching tool for that purpose–turning the learning of mathematics into an enjoyment experience [12]. This intervention tries to address students' widely perceived lack of interest in mathematics classes in general [13, 14] and in South Sudanese mathematics classroom in particular. The usual main purpose of the intervention is for classroom teachers to investigate and explore for the purpose of improving their own practices in the classroom [11, 15]. In action research, for example, classroom teachers or practitioners in general deal with classroom issues they are concerned with such as, in this case, lack of student's interest in learning mathematics as a subject. Besides diminishing student's interest in the learning of mathematics, boredom in the classroom or subject matter, if left unaddressed, could lead to more serious classroom related negative emotional issues or negative feelings such as anger, frustration, anxiety, hopelessness, shame, guilt and even unnecessary outrageous violence in the classroom [16].

Meanwhile the opposite of boredom such as interest in a subject matter always leads to positively welcome and desirable classroom positive emotional states, variables, or experiences such as enjoyment, excitement, engagement, inspiration, motivation and satisfaction with the subject matter [16]. Being generally viewed as a difficult subject to teach and learn, mathematics often makes students report and even complain that they frequently get bored in class as they are bombarded daily with too many dry, dismal and boring lectures–making students ending up viewing many of their classes as triple-threat, which to students means not only difficult, stressful and intimidating but also boring and frustrating to learn [16–18]. The triple-threat or the so called dreaded courses are the ones that students sometimes avoid due to lack of self-confidence, perceived difficulty of the material or perceived negative experience in a content area in courses such as mathematics [17, 19]. Overcoming these kinds of students' negative perceptions and lack of interest in mathematics remains a big challenge in teaching, especially if teachers want to motivate and inspire students to learn further in the dreaded courses such as mathematics.

And this is exactly where the teaching of mathematics with humor comes in as a proposed teaching method, technique or strategy for attracting students' interest in mathematics. The proposed approach, the method of humor–supported instructional approach (H-SIA), as a technique for overcoming students' negative perceptions and lack of interest, can be seen as an appetizer, if not a pain reliever, which means making mathematics enjoyable and satisfying, by making learning sound fun, amusing, engaging, thrilling, exciting, inspiring, motivating and satisfactory to learn as mathematics is generally considered one of the most difficult subjects to learn by students. While the intention of this newly proposed H-SIA method of instruction is to capture interest, it also tries to relax the learning environment as a necessary preparation so that the classroom becomes encouraging and conducive for the learning of mathematics.

If the learning of mathematics is a formidable task by itself, then it can be claimed and argued that it is even a more difficult subject to teach effectively, appropriately and more often than not, many teachers end up (not surprisingly) focusing and relying heavily only on what to teach rather than exploring how to teach effectively as well as appropriately [17, 20]. Teaching effectively and appropriately implies that teachers of mathematics need to "learn not only the mathematics they teach but also interesting methods of delivery and useful applications of mathematical concepts" ([21], p. 8). The so called what to teach and how to teach factors are respectively what are referred to as the technical competency in the subject matter as well as the necessary continuous professional development for mathematics teachers. It is the how to teach factor rather than what to teach that can lead to approaches which may either reduce the perceived triple-threat-ness of the subject matter or at least alleviate students' anxiety, fear and frustration [22, 23], and thereby encouraging them to further pursue the subject matter.

Interesting methods of delivery include introducing humor into the classroom setting, especially humor related to the content materials, as the use of humor in teaching benefits students by reducing anxiety or anticipated fear of the subject and therefore facilitating learning [21, 23]. This can be done through the use of "mathematical cartoons, jokes, puns, riddles, stories, and even certain spontaneous behavior that contain unexpected or out of context elements" ([21], p. 9). This is because elements of interesting methods of delivery such as humorous examples are known to promote and enhance comprehension (understanding), information recall or long-term retention [21]; and therefore such elements or methods of delivery may be helpful to students in the learning of mathematics. When used properly, humor can be helpful in creating group identity and to regulate negative emotions such as anxiety, frustration, uncertainty, boredom and classroom disappointment [24].

The incorporation of how into what to teach, the technical competency aspect versus the professional growth in a subject matter [20], however, only further complicates the teaching of mathematics—making it a difficult subject to teach and thereby making the learning of mathematics not only a teaching problem but also a continuous-researchable problem as well. Therefore, if the learning of mathematics is a problem on its own, then teaching mathematics effectively is another issue altogether whereas searching for more alternative solutions—techniques and strategies—only compounds and complicates the tasks at hand. Hence, there may be no single word, description or clear cut neat distinction between these classroom's related problems in the teaching of mathematics, as they may after all be better addressed simultaneously and not in isolation.

The difficulties involved in effectively teaching mathematics to the students in the classroom can be compared to the difficulties in teaching a child or a baby to walk. When learning to walk for the first time, a child may not be interested in the act of walking in itself, but may be interested in a toy placed at a distance or ahead of him/her by a guardian. As the child reaches for a toy, the child unknowingly ends up learning the task of walking: Here the child may not be interested in walking neither is the parent interested in the toy per se, but the learning still takes place in that way. Similarly, a student may not be interested in mathematics at first glance, focusing instead on the related mathematical humor, which would play the role of a toy and the learning may take place in this fashion, similar to a child learning to walk. This analogy of viewing mathematical humor as a toy for attracting student's interest in mathematics is in line with literature recommendation that teachers should always have courage to teach creatively, effectively, imaginatively as well as appropriately as Dieter [17] observes:

> *Dullness in the classroom can kill student intellectual interest in any subject and destroy all student desire to pursue additional study in the subject matter area. Teaching effectively requires imagination and creativity to turn students on by turning off negative perceptions. Using humor can be a successful teaching tool for that purpose. ([17], p. 20).*

Teaching creatively, effectively, imaginatively and appropriately, the how to teach factor that facilitates the learning of what to teach, means teaching that raises student's interest in the learning process and this is critical in the subject area such as mathematics that many students experience as difficult and even terrifying. Therefore, this piece of writing advocates for the use of humor in the classroom to facilitate students' learning of mathematics, with a focus on mathematical–couched humor—humor related to mathematics content area in order to help students develop interest in mathematics in the war affected re-settled communities or areas such as in South Sudan. The aim of using humor as a tool for teaching and learning or as an instructional approach is to liven or fire-up students' learning experience, inspire or motivate them to develop liking–interest for the subject matter and perhaps increase, along the way, their achievement or attainment in mathematics [8, 25, 26].

This new orientation in teaching, referred to as the humor–supported instructional approach (H-SIA) as compared to the popular-regular instructional approach (RIA), could even be seen as essential with students such as those living and residing in displaced and resettled communities in South Sudan. These students have experienced severely disrupted socio-cultural-economic lives [27], and are therefore consumed more by their day-to-day survival concerns than learning of mathematics in the classroom setting.

If a teacher is unable to grab students' immediate attention or attract their interest, it can be difficult, if not impossible to teach in a classroom—let alone making students understand a subject such as mathematics. This is because students' interest, "attention as well as participation" precedes learning or understanding ([28], p. 137). However, it is still the teacher's responsibility to make students pay attention and get them interested so that learning proceeds in an organized and meaningful way. Perhaps the old saying expresses it better as "one can lead a horse to a water source, but one cannot force it to drink." As the use of force is inappropriate in almost any interesting, effective and appropriate learning environment, teachers with interesting teaching styles find other strategies to employ and this is where mathematical humor in a mathematics classroom may come in handy as a teaching and learning tool. Sometimes creative teachers just rely on their artistic and creative skills in order to win student's interest in the learning process: A science teacher dressing and acting like a mad scientist—in order to attract students' interest and curiosity in the learning process—is an example of classroom artistic activity which is similar to the use of mathematical humor in a mathematics classroom.

3. Myths against the use of humor in the classroom setting

There are some voices and even stiff opposition to the use of humor in the classroom as a teaching and learning tool, most of which come from teaching and research communities themselves, and not necessarily from the well-known classroom critics where such criticism is often expected such as parents, policy makers (politicians), teaching supervisors or school administrators. These voices, however, are based professional myths or conspiracies against the use of humor as a teaching and learning tool in the classroom and are reported as follows: (1) humor is nothing more than the telling of jokes–is only a comedy and nothing serious, (2) teachers should not try to use humor because they do not have anything humorous to present as they lack training on the use of humor, and (3) humor is just a waste of precious classroom time and is also demeaning to teaching as a profession ([17], p. 20). However, according to research and some experienced humor practitioners in the classroom [17, 29, 30], these allegations are just what they really are, just myths or allegations. These allegations are just lame duck excuses for those teaching professionals who are often reluctant and even afraid to pursue excellence–exploration in the area of how to teach creatively, effectively and appropriately. The alleged conspirators responsible for generating such myths are the ones who prefer to focus only on what to teach while ignoring the other part of how to teach and teach effectively, all of which is due to fear of taking risks in the classroom. Teachers who only focus on what to teach while ignoring the how to teach factor risk increasingly becoming perceived as the so called content persons instead of being viewed positively as overall well rounded professionals. A content person, sometimes called a restricted or limited professional [31], is a common derogatory term in education literature used to describe teachers who ignore or fear the other aspect of teaching, the how to teach factor–the other effective teacher's pedagogical toolkit.

According to Davies and et al. (2005), there are three types of teachers practicing in the classroom, namely the unprofessional, limited/restricted professional and extended professional. The extended professional is a fully developed classroom teacher who regularly attends and participates in professional workshops, seminars or academic conferences. The unprofessional type is characterized by chronic absence from the work place, showing up to the class with unprepared or unrevised lessons, isolated from colleagues, hostile to students and reliance on the heavy use of corporal punishment as a teaching tool or strategy, e.g., they teach through fear and intimidation as a pedagogical strategy. The second type of teachers, described as the restricted/limited professionals, is concerned mostly with the mastery of the content materials and skills, usually in the form of drills or repeated recitations and rote memorization. These teachers are either self-centered, concerned only with basic competence and tend to blame students for the failure to learn the materials. They have little or no continuous professional development and are more often than not unimaginative. Hence, they are rigid as they rely on daily classroom routines as a teaching strategy. In contrast, the third type of teachers, known as extended professionals, is the one who go beyond the technical competency. They master not only what to teach but also how to teach effectively. They take active responsibilities not only for themselves but also their students. In short, these teachers are student-centered, adaptive and reflective, are highly flexible and independent minded as well as creative thinkers [31]: These are the ones who would be expected go the extra mile in terms of exploration of humor as a possible pedagogical teaching tool.

Even if teachers are unable or afraid to tell jokes, they can still be good at telling funny-humorous stories in their own unique ways as stressed and argued by Maguire [30] that "no one ever had difficulty producing a story, and no two stories have ever been quite the same" (p. 110). Therefore teachers have the freedom to choose, relive and tell stories as they see fit into their teaching and learning contexts in the classroom settings.

Maguire [30] stresses that a story is a valuable uniting-social factor, and according to Kane [28], Catherine Bateson, a long-time advocate of authentic curriculum in education, a curriculum connected to everyday life experiences, could not agree more although Bateson puts it differently by arguing as follows:

> *In a world that emphasizes the one-dimension, autonomous individual, stories tie complex, deeply feeling protagonists to particular social traditions, loyalties and histories. In a world that myopically promotes the development of rational and decision making skills, stories expand the imagination, enlarging visions of what life may be. ([28], p. 87).*

Perhaps the most misplaced myth, that is probably placed way out of context, is that humor is demeaning to the teaching as a profession, especially when it comes to the use of self-disparaging or self-depreciating humor–humor directed toward the teacher or teaching profession–in the classroom [17, 18, 32, 33]. Some, if not most teachers, see the use of humor in the classroom as demeaning simply because they are afraid it may undermine their own authority as well as credibility in the classroom. Chesser [34], along with Hellman [35], however, point out that most or all teachers on this matter should be aware of the fact that they themselves are already walking and laughing stoke in the eyes of their students. Therefore, the earlier the teachers start making fun of themselves in front of the students in the classroom, the better for teachers, according to Chesser [34] who practices and recommends about at least "50 different ways to bring laughter into any classroom's lesson" Chesser [34].

Instead of being fearful to the use of self-disparaging or self-deprecating humor, Chesser [34] insists that teachers should be able to embrace the idea of humor use by just being themselves, enjoying the moment without worrying too much about any associated minor negative consequences when practicing humor as a teaching tool. That also means there has to be willingness to be honest, weird, gross and even messy. The following is a long winded explanation of what Chesser [34] means by the above statement of 'being your-self' when practicing or using humor as a teaching tool in the classroom:

> *Be yourself: too often, teachers are the walking jokes to students, so the sooner you make fun of yourself, the better...slip some self-depreciating/disparaging remarks in there--right away from the start and students will know that you are for real. Be honest: the best comedy stems from blatant honesty. Telling students that you once walked from the bath room through half of a school day with a toilet paper hanging from the back of your pants does not just garner laughter at a humiliating moment, but it makes them feel not so bad about their daily disappointment. Be weird: there is absolutely nothing more refreshing than a strange teacher. Wear your bell bottoms or your bow tie. The hair that flies everywhere or the bright yellow shirt makes students giggle and feel like they met a real character. Be gross: tell them about a time a bird pooped on your head when you were talking to that person whom you adored. Or, ask why students pick their noses right in front of you, even when you look at them, your eyes widening, hoping for an end to the madness. Be messy: we are all a mess sometimes. When your papers go flying or you trip, do not profess defeat too soon. May be you are used to being orderly, but that cannot always happen. So when you are messy, enjoy it. Show them you not only have grace but can laugh at yourself too. ([34], p. 10)*

Similar to 50 different ways by Chesser [34] is the Hellman's [35] recommended seven simple steps for successful use of instructional humor, classroom humor or humor related to content material, by the classroom teachers.

4. Benefits associated with the use of humor in the classroom setting

The use of humor in the classroom is often very rare, if not almost none existent. In order to see or explore what are the benefits of humor in the classroom, one has to first take a look elsewhere, e.g., outside the classroom setting, so that such benefits could be imported into the classroom as well. According to Wanzer, Frymier, Wojtaszczyk, & Smith [18], the benefits of humor are well enjoyed far away from and beyond the classroom context. This is because professionals from other fields (outside the classroom setting) use humor as means to generating positive affects in their areas of practice. Examples of these outside professionals are primary care physicians, medical doctors or business managers who use humor with their patients or clients [36–38]. Because the use of humor helps build up positive relationships between the doctors and their patients, the doctors are less likely to have medical malpractice law suits brought up against them by their patients Wanzer et al. [18]. It is also reported that business managers, who use humor, are more liked and are perceived as more effective by their employees [3, 5, 17, 18, 39]. Therefore, outside the classroom, the use of humor has been recommended as (1) a business management tool that promotes a productive work environment [39], (2) an effective health care tool, and (3) a possible tool to improve interpersonal relationships [17, 18].

Many experts outside of education have incorporated the use of humor in their fields for various physiological and psychological benefits that are believed to be associated with laughter. Some of these physiological benefits include muscle relaxation, stimulated circulation, improved respiration and exercise of the lungs and chest muscles, increased production of the body's natural pain killers called endorphins, as well as lowered pulse rate and blood pressure [17, 18, 23]. Therefore, for those who do not like physical exercise such as running, the use of humor has even been suggested as a tempting alternative because intense physical exercise can now be replaced with a humorous session of smile and laugher for those who cannot physically exercise [23]. Positive psychological effects of laughter–one of the effects or functions of humor–include reduced anxiety and stress, greater self-esteem, and increased self-motivation [3, 5, 17, 18, 23, 29].

While there are those noted physiological and psychological benefits associated with humor, e.g., students' reported less anxiety and relieved stress, encouraged creativity, students' motivation, inspiration, participation and engagement, one of the main reasons for using humor in the classroom is to improve student learning [3, 17, 18]. Therefore, the creative use of humor in the classroom deals with the idea of how to teach effectively and appropriately, and not necessarily what to teach in the classroom: The pedagogical content knowledge versus technical competency [20, 40]. The use of humor in the classroom is a considerable teaching tool that, if used creatively, effectively and appropriately, may increase the amount of what is taught–that is, what is actually learned by students [17, 18, 32, 41].

When it comes to learning, there are three different types of students' learning in the classroom, namely *affective*, *perceived* and *cognitive* learning [42]. And so far, however, only the first two types of learning (affective and perceived learning) are known to have some degree of correlation with the use of humor or teacher's non-verbal immediacy behaviors [18]. The reported correlation, however, is nothing more than student's self-reported-assessed learning through students' opinion surveys and course evaluations and therefore somehow problematic or inconclusive. Student's self-reported-assessed learning is problematic because it cannot be measured independently while at the same time, it cannot be ignored as well as it is also widely quoted by students as one of their sources of motivation and inspiration–if not their best source of motivation and inspiration for learning [18, 42].

Therefore, very little is known about correlation or association between humor–an immediacy behavior–and the desired increase in cognitive learning, e.g., learning outcomes as measured independently through grades or testing, because mathematics itself is widely considered a cognitive activity as opposed to perceived and affective domains of the subject matter. Until a strong correlation is observed between humor and cognitive learning, the link between the two constructs may still remain an exploratory hypothesis [18]. While the main focus of this study is to generate and maintain interest through the use of humor, as informed through correlates of interest such as positive attitudes, beliefs, motivation and values placed toward mathematics, it also tries to see or explore if there is any link or if indeed humor does increase the amount of what is learned for both self-reported-assessed affective learning, perceived learning, and the cognitive learning. In this study, for example, a cognitive performance in a mathematics task of two independence samples is compared—as measured independently through performance on mathematics tasks by means of grades or testing as opposed to students' self-reported opinion surveys.

Overall, researchers have so far reported that the use of humor in the classroom can help to (a) create a more positive learning environment by breaking down barriers to communication, which are also barriers to learning, between the teachers and the students, (b) help students retain subject matter, especially if the humor reinforces the class material, (c) give students a reason to attend class, and (d) increase or enhance comprehension and cognitive retention; and this enhancement is presumably due to less stress and anxiety, reduced student negativism or hostility regarding potentially confrontational issues (e.g., grading) in the classroom, as well as improved student attitudes toward the subject and the teacher [17, 18].

Researchers also report that students have consistently evaluated humor strategies and techniques as effective at reducing their anxiety, improving their ability to learn, and helping them to do their best; and the last but not the least suggested benefit of humor, primarily from the teacher's perspective is that a teacher who effectively prepares and appropriately uses humor regularly in the classroom will find that teaching is more fun, enjoyable, thrilling and exciting [17, 18]. Trying to achieve excellent in how to teach, whether through humor or something else, requires creativity and can bring some of the challenge–one of the requirements for continued improvement–back to teaching for those who may have lost it because they think they have already mastered the what to teach part of the teaching business [17]. Humor can be, if not already, one of the important components of how to teach effectively and appropriately because watching students who seem to be enjoying listening to you and hearing them laugh at your humor is very rewarding experience [3, 5, 17, 18, 34]. Besides the rewarding experience, humor use shows students that the teacher is immediately one of them, that is, the teacher is indeed closer, approachable, and friendly both in and outside the classroom environment. This is because "humor can serve as a bridge between educators and students by demonstrating a shared understanding and a common psychological bond" ([4], p. 177).

5. The existence of various teaching styles in the classroom setting

There are various teaching and learning styles as there are different classroom environments [41]. However, what exactly is an effective and interesting teaching style in a classroom? Concerning this question, there are at least two perspectives or explanations in the education literature about effective and interesting teaching styles in the classroom:

> *(1) Teaching as a science-based theory which argues that "Psychologists have spent decade [sic] studying how human (students) think and feel, how learning occurs, what influence motivation, and how teaching affects learning. These general and abstract conceptions apply to a wide range of situations, therefore, teachers should not have to reinvent all this knowledge" ([43], p. 199); and (2) Teaching as an artistic skill-a creative process that argues "The hallmark of an excellent teacher is not the ability to apply techniques but the artistry of being reflective, thoughtful and inventive-about teaching. So teaching is so complex that it must be reinvented with every new subject and class." ([44], p. 7)*

While teachers may not agree on whether teaching is strictly a science—a set of procedures and techniques—or an art (a creative endeavor), they do, however, understand that the "real world rarely consists of neat packages or either-situations" ([45], p. 77; [20]). Therefore, not only is teaching an art, a science or a combination of both, but also a way of life which must be continuously reinvented or improved over time [20, 40], and that is because "each time a lesson is taught, it will be different and that is a hallmark and the beauty of teaching" ([30], p. 137).

Just as there are two different perspectives on effective and interesting teaching styles among practicing-teaching professionals, there are also at least two different types of communication in mathematics classes among mathematics teachers. These types of communication are classified as (1) the traditional patterns of communication and (2) the alternative patterns of communication [46]. The manner in which teachers and students interact in the classroom "reflects not only the routines for harmonious functioning in the class but also the nature of the learning opportunities that may occur for children. Lessons in mathematics classrooms can be characterized by interaction patterns and ways of communicating that, to the observer, reveals the different views about teaching and learning mathematics that are held by the participants"(Wood, 1998, p. 167). Therefore, the dialog, discussion or the conversation that is found in the classrooms marks the "stance of the speaker towards the event being represented, toward the occasion of utterance, and towards the manner in which the speaker expects the listener to view the world and use his mind" ([46], p. 167). This means that there are at least two competing communication and teaching styles in mathematics classrooms and regardless of which style a teacher prefers, a teacher is expected to be an overall competent communicator of mathematical concepts in mathematics classroom.

A mathematics teacher's desire and effort to be competent communicator in the subject matter such as mathematics shows willingness and continued improvement in pursuit of excellence, continuous professional development, on not only what to teach (pedagogical content knowledge), but also on how to teach (strategies and techniques) effectively as well as appropriately [17, 20, 21, 46]. Therefore, mathematics teachers should be aware that their students always expect them to be competent communicators in the subject matter, a skill most mathematics teachers are arguably not known to possess—given the fact that mathematics teachers are always blamed and even accused, through teacher evaluations or in the eyes and the courts of public opinions, by many of their students for not always well explaining and even sometimes failing to explain mathematical concepts in ways that are easily understandable to their students. Most of these allegations are due to mathematics teachers' widely perceived lack of communication competence in the subject matter [46], which is compounded by the perceived difficulties of the subject matter itself.

As a consequence of the lack of communication competence in the mathematics classrooms, there is reportedly prevailing and widespread complaints of students' boredom accompanied by lack of interest in mathematics classrooms; and this piece of writing tackles this widely reported factor, the students' boredom in mathematics classrooms, which interferes negatively with the learning of mathematics and results into the total loss of interest all together in the subject matter.

6. The factors that interfere with the teaching and learning of mathematics

As can be seen in the above discussion, there are many factors that can interfere with the teaching and learning of mathematics in the classroom setting. These include factors such as the difficulties associated with the learning of the subject, the difficulties involved in teaching the subject due to various competing teachers' teaching styles in the classroom [31, 47–49], and the various competing corresponding methods of delivery, the communication competence aspect and the critical issue of going beyond technical competency in the form of continuous professional development or growth. All of these factors interfere with the learning of mathematics in the guise of boredom, due to the belief that boredom is closely associated with lack of interest in the subject matter and therefore if students are interested in the subject, they will always find ways to overcome any obstacles that are associated negatively with the learning of mathematics. Hence, a question arises: How or in what ways can interest be generated, captured and even maintained in mathematics classrooms so that students' boredom is at least minimized? Humor has been shown to have a potential for that purpose of capturing students' interest in the learning process because humor itself is part of everyday real world life experience, and it therefore has the possibility to make mathematics a part of everyday life experience. Making mathematics an everyday life experience through the use of mathematical humor or other mathematics content related humor would make mathematics accessible to a wide range of students and not just the most curious or serious ones.

As repeatedly mentioned in the discussion, mathematics is generally a painful subject to learn for anyone–including even mathematicians, mathematics teachers or educators in general [50–52]. However, for those who manage to learn it successfully and eventually became good at it, especially mathematics teachers, mathematicians as well as physicists and to some extent, statisticians or accountants, the resulting rewards for apparently understanding such a difficult language are huge. These rewards include popular social recognition by the general public for doing something regarded as difficult, accompanied by a great deal of personal satisfaction in the form of both the instant and delayed gratifications, e.g., feelings such as joy, thrill or excitement, especially after successfully performing a mathematics task or even for trying such a task.

7. Humor provides for much needed instant gratification in the classroom setting

Humor in the classroom provides the needed and often lacking momentary feelings of joy (instant gratification), thrill, excitement or satisfaction. Such short term feelings of joy, also known as situational interest in the subject matter, can be experienced by students-learners either as the results of the teacher's use of humor in the classroom setting; or from a successful completion and performing of a mathematical task, joyful feelings which are comparable (for lack of better analogy or metaphors) to the same feelings or effects people who drink usually get as a result of getting high with a substance such as an alcohol, a cigarette, a physical exercise and even sexual experience. Perhaps a silly example, but these afterward consequential feelings or effects after experiencing such events or actions of drinking or smoking are probably the same reasons people keep craving for more and keep getting drunk or smoking despite knowing the risks and negative consequences associated with heavy drinking or smoking: Even an excessive use of something regarded positively such as physical exercise or sexual experience can be harmful, whenever the proper ratio of the limit of pleasure to pain is exceeded.

Therefore, instead of getting high with undesirable-harmful substances such as alcohol or cigarettes, it should be related and pointed out to students that there are alternatives out there such as doing or performing mathematical tasks. This implies a person can actually get drunk from successfully doing a mathematics task and, as a bonus in getting high with mathematics concepts and the satisfactory feelings that follow, a person also gets popular social recognition in the form of praises and positive publicity. It is amazing how mathematicians tend to get high on daily basis with their apparent heavy doses of mathematics concepts, only to get praised and be recognized positively rather than shunned as is the case in getting high with alcohol or other harmful substances: This irony is something which does not happen anywhere else, except in the world of mathematics or physics.

This is the part where mathematicians or teachers of mathematics felt short to convey, perhaps in humorous fashion, to their students or the general public at large—the real hidden secret behind the continuous love for continuously doing and pursuing seemingly hard subjects such as mathematics, physics or chemistry. Perhaps for the lack of better metaphors, all is claimed and argued, in an attempt to sell mathematics to students or general public, is that mathematics is a beautiful subject—needed as a strategic gateway for other related careers—without frankly going into details as to exactly why it is such a beautiful subject in the first place. For the students and general public, however, mathematics equations are not as so beautiful as otherwise claimed or argued because, if anything at all to students or general public, the equations actually look and appear very intimidating if not too ugly in appearance. If anything at all, it is the ideas hidden behind those apparent ugly equations that are so beautiful—but if and only when one understands the ideas expressed behind those seemingly ugly symbols. Therefore, the mathematics community with mathematics teachers in particular needs to do a better job at selling mathematics to the general public, particularly students in the mathematics classroom and related fields.

One way to sell mathematics among others (such as the use of an advanced-attractive technology based instruction, interactive games, small groups work and even playing music or singing songs in the classroom) is to make use of an appropriate classroom humor as a pedagogical toolkit—teaching tool—especially mathematics humor and other content related humor as this would help make mathematics appear to be part of everyday real world life experiences. The introduction of humor into the classroom may be the needed remedy to this age-old multidimensional classroom problem summarized as follows: (a) mathematics is more often than not a terribly difficult subject to teach and learn, (b) students often perceive the learning of subject as dreaded or triple-threat, which means stressful, frustrating and intimating; and students often complain under the guise of boredom in the mathematics classroom, leading to the total loss of interest in the subject altogether, and (c) the current-popular regular instructional approach (RIA) as the teachers' preferred current method of teaching (although it is also a student-centred approach in its design) tends to focus only on cognitive aspects while ignoring the affective domains of the subject: For example, regular RIA's method of instruction focus is more often than not on competition-based performance, aimless computations, rote memorization or repetitive drills, which although effective to some degree as an integral part of the overall learning outcomes, can be claimed and argued as sort of achievement of a success through exhaustion rather than pure enjoyment of the subject, with the aim of making the learning of the subject fun, amusing, engaging, thrilling, exciting, inspiring, motivating and even satisfying learning experience. In the classroom where humor is used as teaching and learning tool, students often express these feelings of enjoyment (instant gratification) in the form of smiling, noise making, laughing out loud, arguing and debating with classmates as the students actively participate in their learning process.

Stressing the idea that competence as a skill is not equals or the same as competition, that is, fierce competition in the classroom is unnecessary in any effective learning environment, it is a well-known fact and also self-evident that some of the most admired-respected people are highly competent professionals, who tend to value cooperation and collaboration without being competitive, and are still highly regarded as effective- successful individuals in whatever they do: The same idea applies to students-learners as well in a classroom setting where humor is used as a teaching and learning tool, not only to relax the learning environment, but also to inspire and motivate students in their learning process.

8. Wrap-up summary of the chapter

As a round up-summary to this chapter, it is extra-ordinarily claimed and argued with literature-based evidence earlier in the above discussion that classroom teachers can not only survive the 21th century technological revolution–the re-engineering of industrial education 5.0–but also they can thrive as well in the presence of those challenges. However, these desired-important educational goals or objectives of not only the survival of teaching as a profession, but also the demanded-required continuing professional improvement or growth, are possible if and only if teachers are willing to welcome and embrace the continually emerging technological advancements that are happening on almost daily basis. This is in addition to teachers being open and willing to take the risks necessary to achieve the desired-overall educational goals or outcomes, risks such as willingness to not only explore, discover and experiment with new ways of teaching and learning, but also the classroom teachers expected responsibility to take part (through action research) in such innovative-creative activities that help in the creation of those novice ways of teaching and learning in the classroom setting. Not only being open, welcoming, embracing and willingness to take risks, but also teachers must be willing to take up emerging roles that are brought about as the inevitable consequences of the 21th century technological advancements, new roles such as knowledge advisors, knowledge supervisors and even knowledge managers.

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