Creativity first, Science follows.

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Abstract

Digital Signal Processing (DSP) education has traditionally employed more demanding mathematics than most topics found among courses in Electrical/Electronic/Computer Engineering. In some cases, the technical challenges posed by some courses have made it difficult for students to complete those courses successfully. Here, we advocate for creativity to be nurtured in the first place, after which the science will flow naturally. To foster creativity, our pedagogical approach includes a variety of solutions incorporating exploratory exercises, open-ended multidisciplinary coursework, blended lecture-laboratory sessions, and a colourful working environment. We firmly believe that creativity is the way forward. Student feedbacks support our approach.

Introduction

Royal Holloway, University of London, took the decision to open a new Department of Electronic Engineering, with its first cohort of students enrolling in 2017 [1]. This gave us a welcome opportunity to develop our Electronic Engineering course, and subsequently Computer Systems Engineering, around a strong strand of DSP, adopting an experimental perspective free from legacy commitments that will foster the creativity so readily achievable in modern-day DSP practice.

The common trend indicates that research and academia tend to focus on the theoretical solution (by proposing new mathematical models and algorithms), whereas industry spends more time on solving the problem (by understanding the data) [2]. We are of the opinion that these two elements need to be balanced out. To strike such balance, we aim to assess student understanding and performance proficiency by a mix of approaches that incorporates computer-supported simulations, data exploration, and traditional hand calculations.

Related works

Creativity stems from divergent thinking (i.e. the generation of ideas) rather than convergent thinking (i.e. analysis and evaluation) [3]. Analysis and mathematical rigour are part and parcel of signal processing such as BIBO stability for filters, convergence, and steady state analyses for adaptive filters. As such, it is typically difficult to inculcate creativity in DSP-oriented modules. However, there are many research efforts in other engineering disciplines that help creative thinking/learning. As there is not one kind of education that fits all [4], a set of good practices and their corresponding learning outcomes for creativity are listed as follows:

- L1. Exploratory exercises allowing students to **investigate/explore new ideas or concepts or models** on their own [5].
- L2. Open-ended problems which can be solved in a multitude of ways for students **to think independently** [6].
- L3. Learning opportunities for students **to take independent responsibilities or initiatives** [6].
- L4. Collaborative work for students **to brainstorm and generate ideas** [7].
- L5. Multidisciplinary approaches whereby students **borrow principles from other engineering** domains to solve problems [8].

Most importantly, the value of instructors to believe in creativity was particularly highlighted in [9], which is per se not a good practice to teach creativity, but a decisive factor in teaching creativity [7]-[8]. However, these works did not consider the particularities of DSP education. To this end, our course development focuses on practical skill sets and promotes creativity by considering all these pedagogical set of good practices; we have designed three final year DSP modules, namely:

- Digital Signal Processing Design (EE3010) providing grounding in DSP practicalities;
- Fundamentals of Biomedical Engineering (EE3060) giving the opportunity for students to explore biomedical signals and systems;

- Voice Technologies (EE3050) offering diverse applications of speech signal processing ranging from voice cloning to voice forensics.

The rationale for these DSP modules stem from the demands from industry for qualified graduates in such enabling technology for communications, sensors and instrumentation, medical applications, VLSI, avionics, audio industries, radar and many other key sectors. To put into context how these three DSP modules fit into the undergraduate study, Table 1 shows our overall programme; the pathway highlighted in yellow shows the DSP theme. For example, the prerequisites for EE3010 is the course “Signals, Systems and Communications” (Year 2) and that of EE3050 is EE3010. However, there is also some degree of interdependence between the different pathways. For instance, the Fourier series taught in Mathematics for Engineers II (the General Engineering theme) could be used to model the periodicity of electrocardiograms in Fundamentals of Biomedical Engineering (DSP theme). Students exploit their background of electronic circuit designs from the blue pathway and embedded systems from the purple pathway, and DSP knowledge from the yellow pathway in EE3060.

Digital Signal Processing Design (EE3010): One of the innovations of this module is to adopt a blended approach by delivering the lecture session in a laboratory environment. Thus, the students move between theoretical concepts and immediate practical illustrations – a teaching strategy to make the mathematical content more engaging. On the other hand, the other courses EE3050 and EE3060 do not take this blended approach, as they are inherently application-oriented (which students can more readily contextualise their usefulness). At the end of the course EE3010, the students are expected to be able to

- Examine the scientific principles underpinning practical signal processing and apply the knowledge gained from major aspects of digital signal processing to solve problems efficiently;
- Apply a modelling approach to engineering problems to appreciate the application of relevant technologies in signal processing;

- Design systems using effective software instrumentation tools which facilitate rapid proof of concept.

Table 1: Creativity is inherently embedded into our undergraduate programme, e.g. Creative Team Project 1. The colour-coded legends show the themes of courses, i.e. yellow (DSP), blue (electronic circuit design), orange (computer science), grey (general engineering), purple (project), and green (sustainable and power engineering). All courses are mandatory except for those labelled with (O).

Year 1		**Year 2**		**Year 3**	
Term 1	Term 2	Term 1	Term 2	Term 1	Term 2
Embedded Systems Creative Team Project 1		Embedded Systems Creative Team Project 2		Final Year Project	
Electronic Circuits & Components	Communications Engineering	Signals, Systems & Comms	Electronic Materials & Devices	Introduction to Project Management	Digital Systems Design
Programming in C++	Internet Services	Analogue Electronic Systems	Professional & Sustainable Engineering	Digital Signal Processing Design	Power Systems (O)
Maths for Engineers 1	Maths for Engineers 2	Software Engineering	Control Engineering	Fundamentals of Biomedical Engineering (O)	Advanced Communication Systems (O)
(O) = Optional				Information Security (O)	Voice Technologies (O)

Our DSP analysis emphasis is on verification of DSP time-domain and transform-domain relationships closely supported by illustrative simulation experiments relying on MATLAB, Simulink and DSP_Speedster [10], the latter allowing for a virtual instrumentation environment that piggybacks on the previous two. We are especially keen on Simulink models because they convey dynamic DSP scenarios which are nearly as effective as benchtop instrumentation exercises while also furnishing flexibility through easy program/parameter changes. This is aided by simultaneously appealing to students' visual and auditory senses, through observing soft-instrumentation scopes and listening to outputs. Such time-varying/adaptive model usage far surpasses motivational impacts provided by static analysis through pencil and paper exercises or even MATLAB-powered numerical tabulated solutions.

The DSP_Speedster labkit environment is especially helpful when dynamic evolutionary situations (such as time-varying filtering or adaptive processing) require monitoring and control. "Snap-shotting" through static MATLAB computations often falls short of providing the required operations insight where benchtop instrumentation could excel. Yet this is where Simulink modelling delivers a computationally attractive virtual instrumentation alternative. Simulink/DSP_Speedster modelling is quick and natural, establishing a bridge to later, more extensive design and prototype refinement activity.

We fully appreciate and acknowledge the necessity for tight coupling between theory and practical realisations. All experimental work is motivated and focussed as follow-up to preliminary theoretical background, which is always pivotal in a field like DSP, having such exceptional and intrinsic alignment with mathematical underpinnings. Our approach is to blend analysis and preparatory hand calculations with MATLAB-supported analysis and plots of expected performance. This is what we feel is the static phase of the Student's journey toward Creative Design. The dynamic phase comprises instrumentation and exercising of the operational aspects of solution implementations. This stage typically involves bench top activity with extensive laboratory equipment, alongside Simulink modelling and performance assessments. Finally, assimilation of findings and reflection on results informs a fresh wave of experimentation and refinement.

The two examples below are typical scenarios that our students experience in the third year of EE3010, DSP Design module. There are similar experiments that second-year students undertake as well to bolster their understanding of modulation and modern communication trends, such as Software-Defined Radio. The learning outcomes for creativity of these two examples encourage students to: i) explore new models on their own through the development and evaluation of those models; iii) take independent responsibility and initiative.

Example 1: Bounded-Input-Bounded-Output (BIBO) Stability Experiment

Students are expected i) to build the model given in Figure 1 and ii) to investigate the behaviour of this system (running at 20 kilo samples per second) under dynamic conditions; for example, by first varying the feedback parameter in the Slider Gain block. The input is a periodic impulse train with a period of 300 samples. Here "del" is a Differencer and "TPMA" is a Two Point Moving Averager with impulse responses {1, –1} and {0.5, 0.5} respectively.

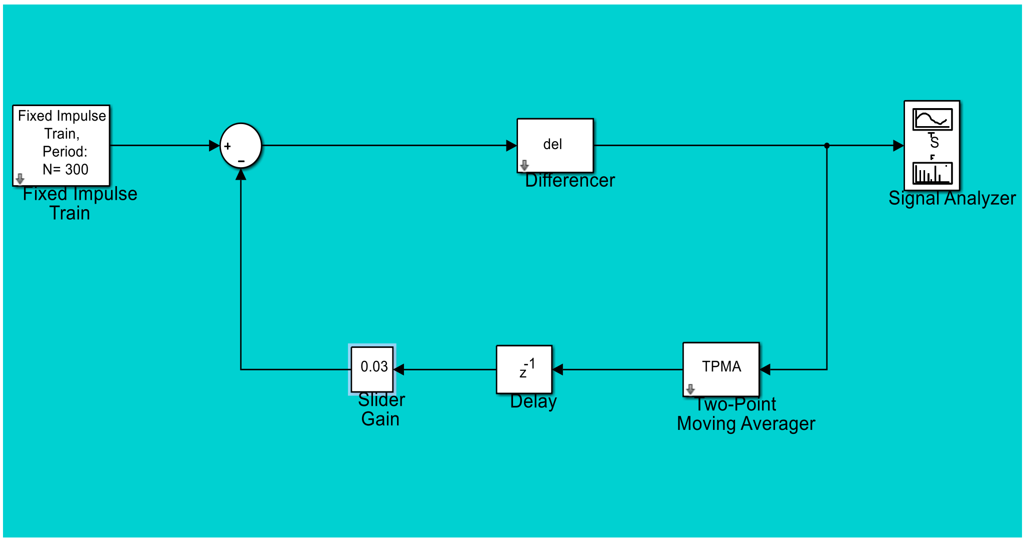

Figure 1: Stability investigation of a feedback system.

Each student builds the model shown in Figure 1 and commences experimentation. The questions they need to answer are (a) whether the system is BIBO-stable [11, pp. 24] as the model is initially specified, and then (b) which range of the feedback parameter values will make the system become stable/unstable. Consequently, students are invited to explore and be curious about this system at first. So far, no equations are needed. They realise early on how a system that they built can become unstable *very quickly* under certain conditions. Normally, this is not experienced by students in most courses; they are given either a stable or an unstable system and once they find out the poles are outside the unit circle, they declare instability – with little appreciation of the journey that led to it.

In this scenario, students have to explain why the system behaves this way by obtaining the z-domain transfer function and analysing its Pole Zero Pattern (PZP) after they encounter the unbounded nature of the output. This gives the motivation for analytical exploration; students see the “what” first and now they have to answer the “why”. Extensions to the investigation involve swapping the “del” and “TPMA” blocks and other configurations in the feedforward and feedback paths to investigate the model behaviour. Within DSP_Speedster they have access to many other blocks, such as more exotic filters that can be introduced. Immediately, the investigation becomes not only individualised (thus avoiding collusion), but also it also enables students to think creatively to design an overall BIBO-stable system. A further extension is to design a compensator to guarantee an overall set of specifications by exploring cascade and parallel compensator configurations.

All results, models, and plots, including impulse response behaviour, spectral gain, PZP, are then submitted online together with a brief report. A typical plot of the unstable response is given in Figure 2.

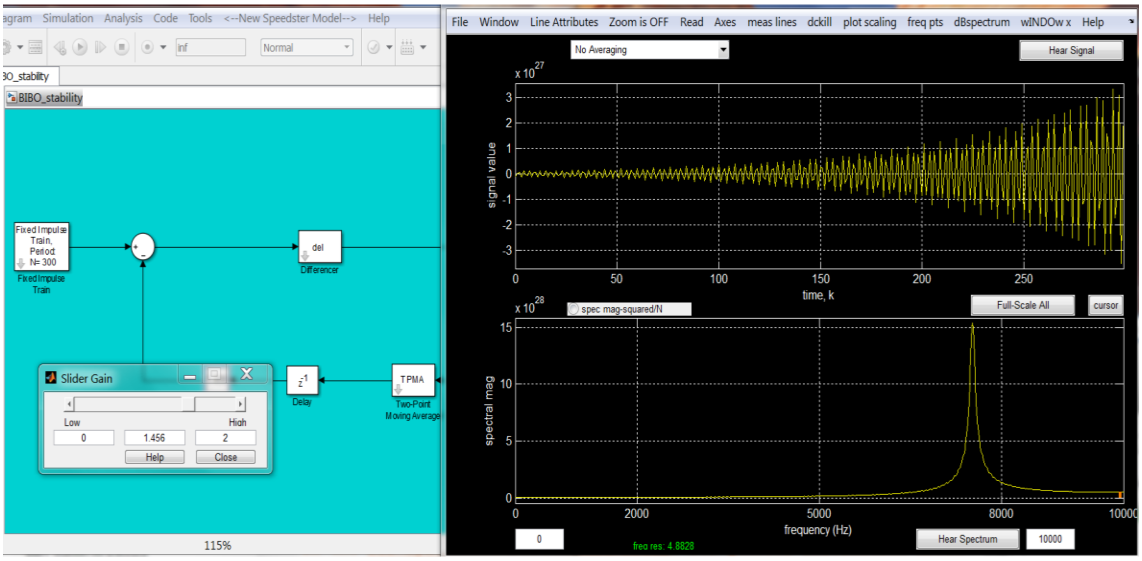

Figure 2: A snapshot showing BIBO-instability.

This style of experimental activity has provided an excellent framework for practical MATLAB/Simulink-based tests and examinations during the academic term. Feedback from past students indicated a strong preference for these rather than the classical pen and paper examination. After all, this is very much how we engineers operate in the real world – by being curious and creative with the support of well-crafted tools solving open-ended problems.

Example 2: Adaptive Notch Filtering

This experiment primarily aims at eliminating additive tonal interference from a background random white process using an adaptive notch filter. Meanwhile, an alternative learning viewpoint is that – as well as achieving tone removal – this system moreover furnishes a useful frequency estimation capability for noisy tone-hopping situations [12],[13]. Students design and operate the system shown in Figure 3, where they manipulate the sinusoid frequency, the convergence factor (mu), and the Signal-to-Interference-Ratio (SIR).

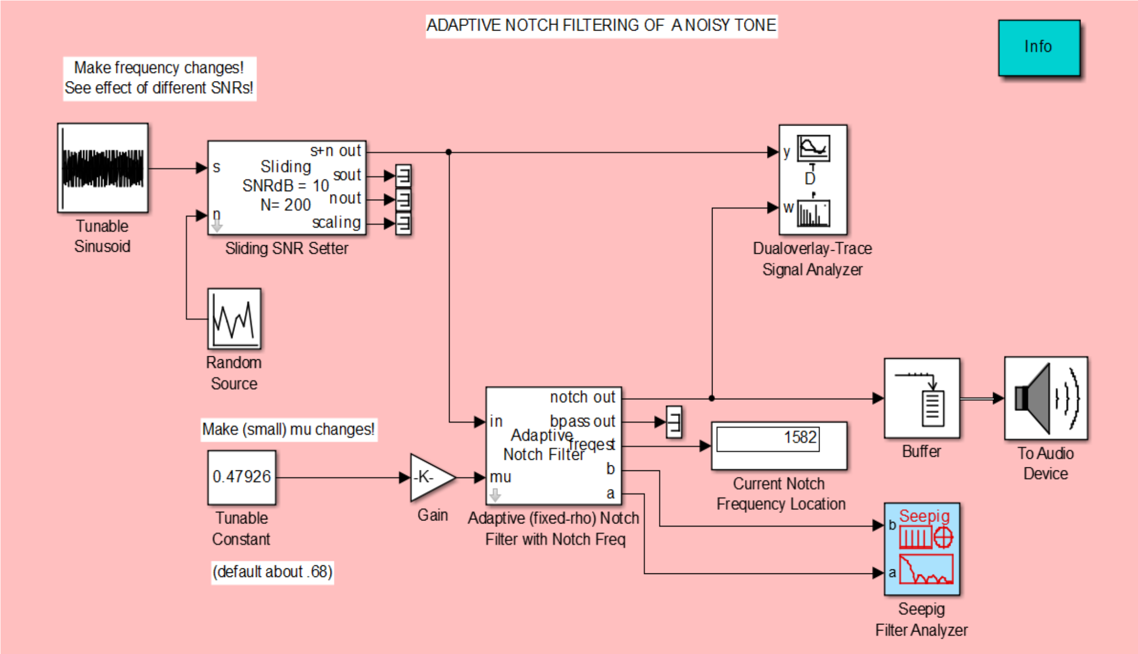

Figure 3: Adaptive notch filtering model.

The students adjust parameters in the signalling environment such that the system is able to satisfactorily home onto and suppress the contaminating tone. The “Seepig Filter Analyzer”, which is not available in mainstream Simulink [10] but is part of DSP_Speedster, enables the *instantaneous* tracking and visualisation of any changes in PZP, impulse response, and the gain of the filter. Whilst it is not highlighted here, other filter characteristics such as group delay, phase, phase delay, zero-phase gain, total impulse response energy, average delay, and impulse response centre of gravity are readily available for *dynamic* measurement and display. No gradient-search adaptive notch filter such as DSP_Speedster block seems to be furnished in standard Simulink or in DSP Toolbox. The entire search algorithm is realised in elemental Simulink blocks and its detailed action can be viewed by students.

The green plots in Figure 4 are time and spectrum plots before the experiment starts, and red plots indicate when the tuning error has converged to zero.

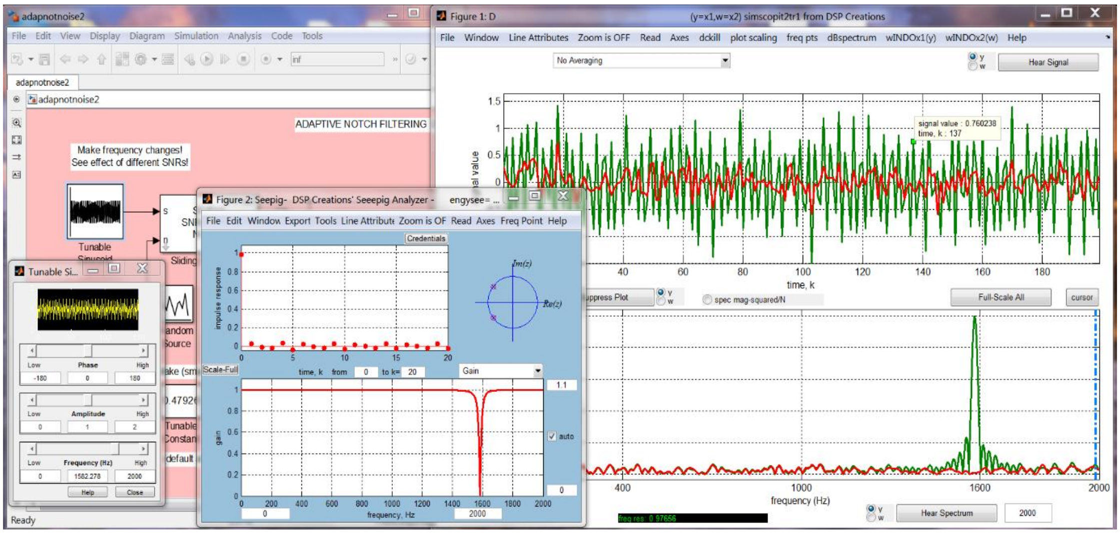

Figure 4: Notch filter adaptation for a noisy sinusoid.

All the exercises are totally paperless; students receive their instructions by opening the blue “info” box in the top right corner of the model. Of course, it must be noted that students also experience the sound of the tone before it is extinguished as well as the narrowband sweeping chirp as the notch filter steers toward the tone’s spectral location. So, they see, they hear, they absorb – they are being creative in their exploration.

For conciseness, only isolated specimen experiments are presented. Students have undertaken MATLAB-based (which includes Speedster) practical exams and feedback is strongly in favour of the approach that we have reported here, as indicated by Table 3.

Fundamentals of Biomedical Engineering (EE3060): In this course, the students learn about bio-signal processing techniques (e.g. time-frequency analysis) as well as the particularities of the bio-signals. However, bio-signal processing goes beyond these two elementary know-hows. To have a more holistic view on bio-signal processing, students are expected to exploit their practical knowledge gained from *non-signal processing* courses (e.g. analogue electronics and embedded systems) to solve signal processing problems. As such, by the end of this course the students should be able to work in teams to

- Address and analyse problem-driven (instead of theory-driven) DSP tasks with *no unique solution* and with *no constraints* except financial constraint. This type of open-ended assignment gives the opportunity for students to be creative. An example of such problem-based assignment is to develop a smart system to detect drowsiness and alert the individual as shown in Figure 5.
- Build a complete DSP system *from start to finish*. This involves designing the data acquisition system (i.e. circuit analysis and implementation), investigating the appropriate bio-signal processing algorithm to undertake the real-time analysis (e.g. frequency analysis), developing a smart system (e.g. coding an embedded system) to actuate on the results of the DSP data analysis, and manufacturing 3D objects to improve the aesthetics of their DSP product.

Figure 5a: EEG sensing system in 3D printed enclosure to detect drowsiness.

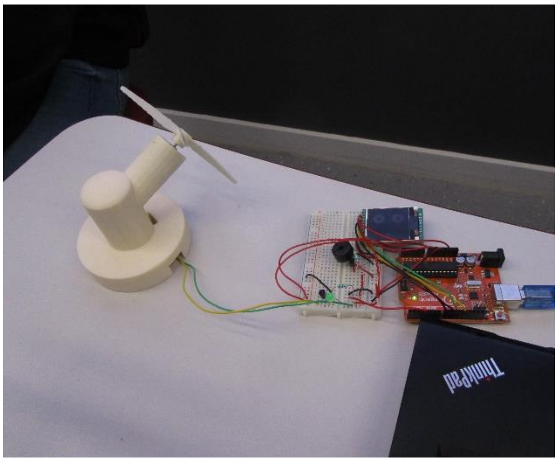

Figure 5b: Actuating system to provide response to drowsiness state via 3D printed fan, LCD display, and melody player (buzzer).

To achieve these outcomes, students learn about:

i) Bio-data exploration: To be able to exploit the properties of biomedical signals, the students learn about the particularities of electroencephalogram (EEG) for the brain, the electrocardiogram (ECG) and the photoplethysmogram (PPG) for the heart, and the electromyogram (EMG) for muscles. Moreover, the students also learn about medical imaging and appreciate the difference between anatomical and functional imaging.

ii) Bio-signal acquisition and instrumentation: The students design circuits for two main purposes: filtering and amplification. Examples of filtering applications include notch filtering to remove 50 Hz power line, high pass filtering to remove motion artefacts, and low pass filtering to alleviate unwanted noise outside the frequency range of the biomedical signal. Amplification of those bio-signals is achieved via both differential amplifiers and instrumentation amplifiers. Differential amplification is particularly useful for signals such as ECG, which is measured using the potential *difference* between the left and right side (polarity) of the body. This difference also helps in terms of denoising, as the instrumentation amplifier inherently cancels the common mode noise.

iii) Bio-signal processing and learning methods: Students learn about windowing and its effect on the spectral properties of the windowed data, time-frequency analysis, and signal-dependent methods such as for the detection of QRS complex in ECG and the segmentation of EMG in terms of muscle contraction and relaxation. Students also gain fundamental knowledge in terms of real-time learning algorithms (such as the perceptron). Thereafter, the students can take advantage of these learning methods to make automated decisions in their bio-DSP system.

For the group coursework on building a complete bio-DSP system, the learning outcomes for creative learning are to enable students to i) brainstorm and generate ideas; ii) borrow principles from other engineering modules to solve problems; iii) take independent initiatives.

Example 3 gives us a flavour of the type of experiment carried out in Fundamentals of Biomedical Engineering. In this exercise, the students are not only exposed to hardware experimentation to capture the bio-signal, but also take a "white box" approach to generate synthetically such bio-signals. This white box approach reflects one of the strengths of DSP, giving us control over the design parameters. And its learning outcomes for creative learning are to empower students to i) think independently; ii) take independent responsibility.

Example 3: QRS Analysis and Synthesis for ECG

In this experiment, the students "learn by doing" ECG analysis. The common approach is to acquire ECG signals and then undertake Peak-to-Peak analysis (such as between two R peaks). However, the students are then asked additionally to generate synthetically their own ECG signals. The value of such an experiment is that i) it gives the opportunity to the student to be creative (e.g. the periodicity of ECG cycle can be achieved in various ways, such as Fourier series of ECG cycle or looping an ECG cycle); ii) students appreciate the variability of biomedical signals; iii) it reinforces the learning of the student "by doing" rather than by memorisation; iv) the synthetic data can be used as "controlled data", as too often students overlook the importance of controlled experiments in biomedical analysis. An example of a real-world ECG signal and its corresponding synthetic version are shown in Figure 6.

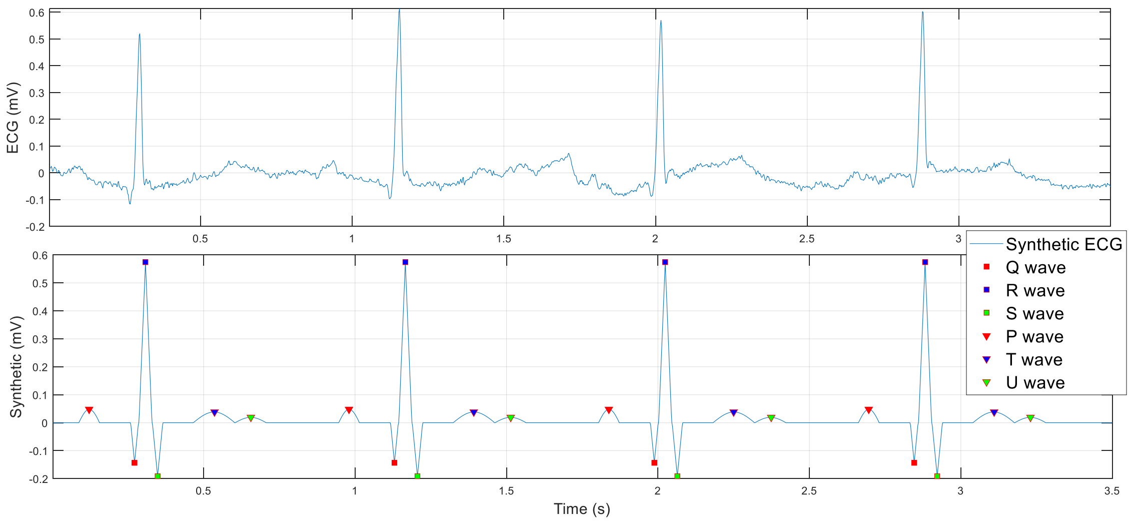

Figure 6: ECG signal (top) and its corresponding synthetic counterpart (bottom). This exercise encourages the students to appreciate heart variability and reflect more carefully on the different ECG wave components especially those not so visible in the ECG signal.

Voice Technologies (EE3050): The aim of this course is to provide students with advanced knowledge of voice production, synthesis, recognition, and processing in the context of present-day and future engineering systems that make use of a voice input or output. At the end of this course, the student should be able to:

- Examine the engineering principles and techniques necessary to understand analyse how voice can be created or recorded, processed, stored, and delivered to the user;
- Apply a holistic approach to voice synthesis, recognition and processing through the application of the relevant technologies;
- Show the context in which engineering knowledge can be applied to voice synthesis, recognition and processing;
- Extract and evaluate pertinent data and apply engineering analysis techniques in the solution of unfamiliar problems.

As such, the students have the opportunity to learn about (a) human voice production for speech and singing, (b) electronic synthesis of human speech and singing in terms of the sound source and sound modifiers to create synthetic voice signals, (c) signal processing techniques used for example, to track vocal pathologies, monitor the changes in vocal skills during voice trauma recovery speech therapy or the development in vocal skills during acting voice or singing voice training, enhance voice quality, remove background noise and improve perceived voice quality, (d) the design of hearing aids including cochlear implants and (e) techniques used for automatic speech recognition such as Apple's 'Siri' system.

The innovation in this course is to focus on the technologies rather than the mathematical models in speech processing. Students tend to learn and understand more about a subject if they can appreciate its application and therefore find it useful. Thus, the applicability of those speech technologies is illustrated in synthetic voice generation, hearing aid design, clinical and research voice monitoring systems and the impact on perceived voice quality and overall understanding of the spoken message. On the other hand, a traditional speech processing course would typically focus on the mathematical models such as the Levin-Durbin recursion for linear speech prediction or the derivation of the transfer function of the vocal-tract with poles and zeros. We do not take this traditional approach. As such, our laboratory sessions are based on voice technologies widely used in the speech community such as

- Audacity [14] – an open-source multi-track editor and recorder for audio recordings - students make a recording of their own voice in the first week which includes isolated words, counting forwards and backwards from 0 to 20, and a section of the read phonetic passage "Arthur the rat" [15] and then prepare their signals for analysis using Audacity, thereby having a hands-on learning experience directed towards the transmitted signal itself rather than any underlying mathematical models.
- Praat [16] – a free tool for phonetics research enabling the students to do speech capture, manipulation, waveform, and spectral analysis as well as formant and articulatory synthesis. In our laboratory sessions, Praat enables students' study of:

i) Time domain analysis: The students isolate individual spoken sounds and measure their durations where appropriate, whilst gaining understanding of the dynamic nature of running speech and transitions between phonemes.

ii) Frequency domain analysis: The students explore the formant structures of different vowels, with special exercises relating to the effect on the output of varying the analysis filter bandwidth in the context of wide-band and narrow-band spectrograms particularly in the context of the dynamic nature of formant transitions in diphthongs and the spectral nature of consonants during running speech.

iii) Time and/or frequency domain analysis: Fundamental frequency estimation is explored in the time and or frequency domain in the context of a hands-on experience of (a) the advantages and disadvantages of each approach in the context of human speech and (b) the acoustic analysis of 'connected' speech, such as the acoustic analysis of syllables and the analysis of a word in different contexts.

iv) Linear predictive coding (LPC): The students investigate the frequency response of the vocal-tract and that of the sound source through linear predictive coding and its application in telephony, and having used LPC to code and decode a speech signal, they attempt to resynthesize speech having replaced the larynx input with non-speech sources such as music for fun, along the lines of Sparky's Magic Piano [17].

v) Voice cloning: Students are able to explore time and frequency domain differences in the speech of different speakers in the context of why they sound different and yet the spoken message can still be understood firstly through the synthesis and analysis of different vowels, and then through running speech generation using the CereProc [18] on-line speech synthesis system.

vi) Hearing loss: Having had the principles of human hearing, students explore the frequency domain nature of their own hearing (via headphones and being aware of the local acoustic noise) using a simple audiometer implemented in Pure data or Pd – an open source graphical programming audio creation and manipulation system [19]. In addition, having explored noise induced hearing loss (NIHL) introduced in a lecture, students investigate which speech sounds should be affected adversely perceptually and then test their hypotheses by exploiting notch filters in their laboratory session to mimic the spectral (not the signal level as this would pose a direct Health and Safety threat) effects of NIHL and confirm or otherwise their predictions.

Example 4: Forensic Analysis of Curious Sounds

This experiment allows students to explore 'curious' voice sounds set in a context of forensic audio comparisons which have been discussed in the associated lecture, including an original voice of a person and other related voices such as:

1. His voice after inhaling helium saying the same words;

2. His voice mimicked by a professional;
3. Formants as sine waves [20];
4. A voice from a talking elephant and a seal;
5. The Laurel and 'Yanny' illusion voice [21].

Spectrographic analysis is linked to the basis of how the hearing system works and some creative lateral thinking is encouraged through consideration of non-speech sounds. Students are asked to analyse sounds such as those shown in Figure 7 and to think about how they have been created. As such, the learning outcomes for creative learning were to enable students to i) think independently; ii) take independent responsibility or initiative.

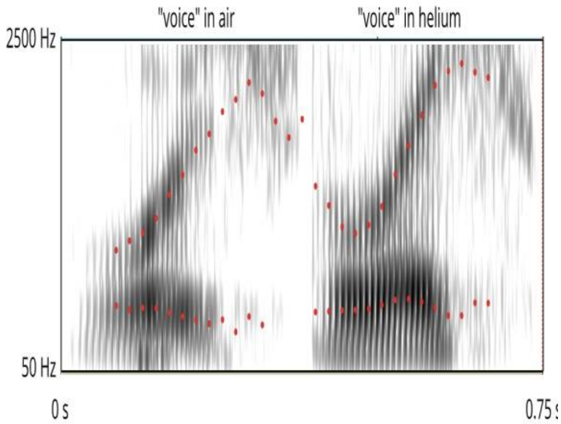

Figure 7a: Wideband spectrogram analysis of the word 'voice spoken in air (left) and in helium (right) with the first two formants indicated by the red dots showing the upward shift in formant frequencies due to helium.

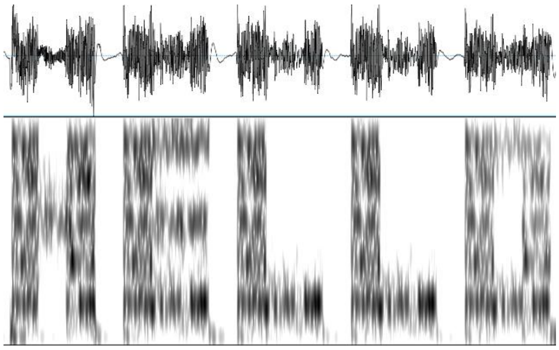

Figure 7b: Time waveform (upper) and wide-band spectrogram (lower) of a 'curious' sound that is left as a creative thinking exercise for the student to explain how it has been created.

To focus on the practical skills acquired by the students, the main assessment for voice technologies was a two-hour practical examination which ended up being taken remotely by students who had left campus due to the Covid-19 pandemic. Each student was given a different (to avoid any direct collusion of measured values) spoken version (16 bit, 44,100 Hz sampled mono .wav file) of this sentence "*She said to her friend, can I go out tonight to see the opera with you?*" to be phonetically transcribed and analysed in terms of: fundamental frequency statistics, formant frequencies of a selection of vowels to enable a link to be made with their tongue position within the vocal tract, the nature of frication energy for a few fricatives, acoustic similarities and differences in the three ‘n’ sounds in the sentence and the acoustic nature of sentences’ stresses. The assessment was designed as a creative exercise where students had the freedom to choose any DSP analyses. In their solution, the students carried out those analyses from which they were expected to appreciate the acoustic variation in speech output from an individual speaker – something that would be highly relevant for speech recognition, speech transmission, speech synthesis and speech storage.

Unlike traditional DSP courses that focused on communication-based problems, these three courses facilitate student learning in relation to their everyday life activities and experiences, e.g. their usefulness in wearables, healthcare tracking, and forensic technologies. However, these DSP courses (alone) are not adequate to foster creativity and the learning process, which leads us to the next factor in our endeavour to enhance learning: the environment.

The environment

In order to maximise student engagement, a lecture theatre (in Figure 8a) that was *designed jointly* by students and academics to

1. allow students to be seated in “teams”, so that peer learning can be facilitated;
2. enable the lecturer to roam around the class (including between each row of seats), so that students are not in their ‘comfort zone’, and the lecturer is not confined to the front of the class;
3. use different colour lighting to “gauge” the mood of the students. It has been reported in Chromotherapy [22] that red light can stimulate the body and mind and to increase circulation (e.g. during important parts of the lecture), whereas blue light is believed to soothe illnesses and treat pain (e.g. during breaks within a lecture).

Our lecture theatres are also equipped with the Panopto Video platform [23], which captures our lecture sessions. This allows our students to catch up with missed lectures or even revisit the lecture when things start ‘clicking’.

Figure 8a: Lecture theatre designed jointly by students and academics.

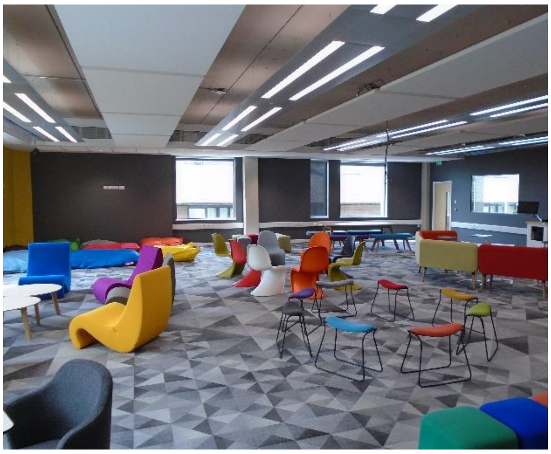

Figure 8b: Creative Thinking Room with funky furniture whose colours were inspired to reflect the resistor colour codes.

For brainstorming sessions where creativity is key, we have adopted the Google approach: we have our *Creative Thinking Room (*shown in Figure 8b) that provides ample and colourful space for students to have 'light-bulb' moments with *adaptable furniture* and *screen displays* for discussions.

Everyone is the same. All academics are seated in an open-plan office. This all-inclusivity does not stop to academics. *All* students of Electronic Engineering have access to the open-plan office. Our open door (office) policy encourages our students to engage with academics with impromptu discussions when creativity comes to light and science follows.

Feedback on the courses

To evaluate the impact of our innovative approach in teaching, Table 2 and 3 summarise two surveys from our students. The first survey in Table 2 was undertaken externally by an agency Ipsos MORI; this survey is known as the National Student Survey and therefore provides us a benchmark against other universities in the U.K [24]. However, the first survey does not focus specifically on creativity in teaching. To this end, a second survey on creativity in Table 3 was carried out to investigate the impact of our teaching on creativity. The first survey interviewed our first cohort of graduates (13 students), whereas the second survey was based on our current cohort (30 students).

Table 2: Feedbacks on our teaching from our first graduate cohort in 2020. More details available from National Student Survey [24]. Questions in bold font are relevant to our innovation in education, i.e. on creativity and openness including easy accessibility to staff.

Questionnaire	**Actual value**	**Sector Average in UK**
Teaching on my course		
Staff are good at explaining things	83%	84%
Staff have made the subject interesting	**83%**	**75%**
The course is intellectually stimulating	**92%**	**86%**
Learning Opportunities		
My course has provided me with opportunities to explore ideas or concepts in depth	**83%**	**78%**
My course has provided me with opportunities to bring information and ideas together from different topics	**83%**	**82%**
My course has provided me with opportunities to apply what I have learnt	**92%**	**78%**
Assessment and Feedback		
The criteria used in marking have been clear in advance	83%	67%
Marking and assessment has been fair	83%	74%
Feedback on my work has been timely	92%	61%
I have received helpful comments on my work	75%	64%
Academic Support		
I have been able to contact staff when I needed to	**92%**	**86%**
I have received sufficient advice and guidance in relation to my course	92%	76%
Good advice was available when I needed to make study choices on my course	83%	71%
Organisation and Management		
The course is well organised and is running smoothly	92%	65%
The timetable works efficiently for me	92%	78%
Any changes in the course or teaching have been communicated effectively	83%	75%
Learning Resources		
The IT resources and facilities provided have supported my learning well	83%	84%
The library resources (e.g. books, online services and learning spaces) have supported my learning well	75%	84%
I have been able to access course-specific resources (e.g. equipment, facilities, software, collections) when I needed to	83%	87%
Learning Community		
I feel part of a community of staff and students	83%	67%
I have had the right opportunities to work with other students as part of my course	**100%**	**89%**

Table 3: Student survey addressing specifically creativity and practical examinations.

Questionnaire	Yes	No	Neither
Practical-based examinations			
Q1. Do you feel that practical-based examinations are more appropriate than traditional paper-based examinations to assess your technical knowledge?	83%	7%	10%
Q2. Do you feel that practical-based examinations are more appropriate for students with disabilities than traditional paper-based examinations?	57%	17%	26%
Creativity			
Q3. Do you think creativity is an important aspect of engineering?	100%	0%	0%
Q4. Do you feel your creativity is stretched more by open-ended coursework than coursework with unique solutions?	83%	7%	10%
Q5. Have those open-ended courseworks motivated you research materials beyond the materials available for the module?	77%	17%	6%
Q6. Was the Creative Thinking Room helpful in your studies?	60%	13%	27%
Q7. Have learning opportunities that fostered your creativity at RHUL consolidated your independent thinking?	77%	10%	13%
Q8. Do you feel that you have been encouraged to be more creative by your study at Royal Holloway University?	70%	10%	20%

Discussion

Although not all questions in Table 2 are directly relevant to our approach on creativity, the survey does offer a useful benchmark at the national level. Relevant questions are highlighted in bold in Table 2, whereas all questions in Table 3 focus on creative and practical learning.

Student engagement initiatives: More than 8 out of 10 students found staff made the subject interesting. Perhaps, this is due to our ongoing effort to contextualise theories with applications, e.g. notch adaptive filtering in audio applications or ECGs in wearables [25]. We have always endeavoured to make our course intellectually stimulating by exposing students to open-ended problems or exploratory exercises (such as in Example 1-4). In fact, 9 out of 10 students agreed. Likewise, the statistics for the question on learning opportunities to explore ideas in depth in Table 2 corroborate with those of Question 5 in Table 3. Another contributing factor (not discussed in this article) that engages students whilst promoting their independent and creative thinking is research projects, as found in [26].

Practical-oriented teaching: Our project-led courseworks encouraged our students to bring information together from different topics. For instance, they had to apply concepts from circuits and embedded systems to solve a biomedical signal processing problem in EE3060. Our practical approach to teaching has been successful with 92% of our students acknowledging that they have applied what they have learnt. It is not a surprise, therefore, that most students prefer practical-based examination (see Question 1 on Table 3). The importance of the practical element in DSP education has already been highlighted [27].

Environment: Our open-door policy also facilitated students getting prompt feedbacks on their works as well as academic support in general. Table 2 confirms that is the case. Students believe creativity is crucial in engineering and they have been encouraged to be creative in their work – as shown in Question 3 and 8 in Table 3. On the other hand, the students did not value the working environment as much as other factors. Only 6 out of 10 students believed the Creative Thinking Room was helpful in their study. Although, the impact of this factor is not as apparent as the others, it is in the Creative Thinking Room where the students would typically brainstorm. We tend to value more the product design rather than the product process, which might explain lower statistics for the environment [9]. In fact, it was found by several researchers that colour and furniture play an important role in a creativity [28][29]. Our Creative Thinking Room (shown in Figure 8b) provides our students such environment.

Conclusion

Divergent thinking leads to creativity. Yet, we are trained to focus on convergent thinking when we emphasize on evaluation and analysis [3]. There is not just a single kind of education that can teach creativity. As such, we have adopted a variety of good practices to encourage our students to be creative. These include open-ended problems, exploratory laboratory exercises, project-based coursework that requires multidisciplinary and teamwork skills, and a creative working environment. Student feedbacks confirm that creativity is an important aspect of engineering. We hope that this article encourages educators to take more risks and embed creativity in their DSP teaching. We find it fitting to end this article by citing an old cliché used by Oppenheim, as (for many of us) our DSP journey started with his textbooks: 1+1 = 3 [30]. Be creative.

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