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Teaching differently: The digital signal processing of multimedia content through the use of liberal arts

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***Abstract*—Generally, the curriculum design for undergraduate students enrolled on digital signal processing (DSP) related engineering programs covers hard topics from specific disciplines, namely mathematics, digital electronics, or programming. Typically, these topics are very demanding from the point of view of both students and teachers due to the inherent complexity of the mathematical formulation. However, improvements to the effectiveness of teaching can be achieved through a multisensorial approach supported by liberal arts. By including the development of art and literacy skills in the curriculum design, the fundamentals of DSP topics may be taught from a qualitative perspective, compared to the solely analytical standpoint taken by traditional curricula. We postulate that this approach increases both comprehension and memorization of abstract concepts by stimulating the students' creativity and curiosity. In this paper, we elaborate upon a methodology that incorporates liberal arts concepts into the teaching of signal processing techniques. We also illustrate the application of this methodology through specific classroom activities related to the digital processing of multimedia contents in undergraduate academic programmes. With this proposal, we also aim to lessen the perceived difficulty of the topic, stimulate critical thinking, and establish a framework within which non-engineering departments may contribute to the teaching of engineering subjects.**

***Index Terms*—Engineering Curriculum, DSP, Critical Thinking, Liberal Arts, Multisensorial Teaching.**

I. Introduction

ENGINEERING courses related to signal processing rely on strong mathematical methods such as linear-time invariant systems, complex analysis or transform theory, among others [1], These are topics that are very often difficult to grasp. They are also difficult to teach; the bottleneck is, most of the times, the complexity of the abstract mathematics underpinning the core concepts as *perceived* by the students. The development of attractive and effective comprehension methods to enlighten the fundamentals plays a major role to face the natural intellectual barriers in this highly specialized field. Thus, the application of new methodologies used to teach core concepts, which take a multisensorial approach through the use of liberal arts, may trigger self-motivation and critical-thinking abilities, allowing students to discover the meaning and implications of their analytical formulations.

Liberal arts education is commonly related to the discipline of social sciences, while mathematics and physics are typically addressed in pure sciences and electrical engineering programs. Consequently, a historical divide has been established in schools that separates arts from science, forming into two markedly different cultures: the literacy-based intellectuals and the natural scientists [2]. Mixing the schools, however, brings a variety of benefits worth considering. A better education, achieved by bringing the two branches together, will empower students, offering a more complete understanding of the role played by and impact of technology in society (this subject is largely ignored by current academic programs [3]). According to [4], educational skills related to the arts of reading, writing, communication, and the appreciation of fine arts could contribute to an improvement in critical thinking and creativity, leading to a better proficiency of engineers in their respective fields.

On the one hand, it is commonly accepted that the inductive experience of appreciating and producing a work of art stimulates the production, discovery and invention of novel technical solutions. However, deduction processes (which are commonly addressed in traditional courses) is more concerned to the particular application of a general theory in the context of engineering applications. Blending both approaches, inductive and deductive, leads to the formation of powerful skills that can deal with the challenging problems facing society today. In this regard, the application of art concepts into the academic engineering program may lay the foundations for new solutions, stimulating both inductive and deductive abilities [5], [6], [4].

In addition, a transition from STEM (Science, Technology, Engineering and Maths) to STEAM (Science, Technology, Engineering, Arts and Maths) [7], [8] has been advocated by several authors as a way to break down the distinction between disciplines traditionally seen as "creative" (like the arts or music) and STEM disciplines traditionally seen as more rigid or logical–mathematical [9], [10], [11], [12]. However, most of this research studies school education; it rarely includes university level classes. Moreover, this destruction of artificial boundaries could be a way to reduce the persistent gender gap found in STEM studies [13] [14] improving female take-up of STEM courses and, following this, of PECS (Physics,

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Engineering, and Computer Science) related careers [15], [16].

Nowadays, most engineering programs do not effectively integrate both cultures. Mixed academic programs provide courses that cover both technology and the appreciation of art. Some of these approaches allow engineering students to choose subjects offered by different departments; thereby promoting an interdisciplinary dialog between arts and engineering [3]. For instance, some programs motivate students to take part in cultural activities, such as museum visits or concerts, as in [17], they even offer the possibility of participating in academic projects that are coached by professors from both social sciences and STEM departments [18]. Other programs integrate arts and animation when teaching computer programming in order to increase student motivation in learning [19]. Besides, through the use of emoticoding, the integration of algebra, geometry, music, and 3D art, has been shown to improve student learning as well [20]. Another example involves web-designers, who cleverly combine technology, arts and psychology in order to attract the attention of potential customers [21]. Finally, in [22], the authors present abstract mathematical objects and concepts that have been turned into visual art using mathematical animations, thereby offering students a more tangible experience that can potentially improve and enrich their understanding.

Including arts and their corresponding inductive processes into engineering programs is a challenging endeavor. The previously mentioned approaches illustrate useful points of contact; however, the effect of a tighter integration of the arts with the teaching of core concepts is still unexplored. Our current research is part of an ongoing teaching innovation project to improve the understanding of engineering concepts using arts as the motor core of a more complex process. It is hoped that this will eventually lead to greater students engagement with their own learning development. When students are encouraged to interact with artistic production goals using engineering concepts, this will stimulate their internalization of key engineering topics. Ambitiously, we intend to *reinforce the understanding of key concepts* by promoting the *appreciation and creation* of small pieces of art during the teaching of engineering curricula.

In this paper we elaborate a methodology that integrates art and engineering in order to more effectively teach core engineering concepts. We illustrate the use of the proposed methodology through specific c lassroom a ctivities involving the use of signal processing techniques applied to multimedia coding. Using this approach, different engineering topics will be taught from a subjective standpoint. The tools used will include elaboration of narrative excerpts, their auditory representation by means of well-known musical scales, and the processing of images by appreciating their composition. Students are prompted to write their own thoughts and opinions about the topic at hand, and their textual contribution is then used as the media upon which digital-signal-processing (DSP) concepts are later implemented. In this way, students will have a *multisensorial* experience when learning the core concepts in their field. The meaning behind their analytical definitions and implications will be exposed by the analyses and production of art created by writing, listening, and visualization.

We have chosen to employ this methodology in a telecommunications engineering program in which DSP techniques play a major role. By doing so, we aim to provide proof that this integration can be effectively implemented. We also aim to provide inspiration and motivation for colleagues teaching similar but also totally different concepts to use non-engineering disciplines to educate better and more well-rounded engineering professionals. Some hints and suggestions regarding the further application of the methodology to other DSP-related subjects are also discussed.

The rest of this paper is organized as follows: Section II introduces the methodology used to attain the previous goal. Section III is an outline of the academic course, Multimedia Information Coding for Communications, which is where these proposals will be implemented (as described in Section IV). The assessment of this integration is reviewed in Section V, followed by a discussion in Section VI that considers how to extend the methodology to cover other DSP-related subjects. The conclusion is given in Section VII.

II. Methodology

As we have discussed in the previous section, the introduction of *arts* and *critical thinking* into an engineering curriculum is beneficial to the development of more creative and socially-aware engineers, and could also promote female vocations into STEM careers ([15], [16]). However, this is a challenging enterprise, mainly because the materials and resources need to be developed *ad hoc*. Some general principles, applicable to any subject, need to be observed during this process. In this regard, we have identified the following steps:

1) A small set of *key* or *core* concepts, underpinning the subject being taught need to be identified. These should be the main concepts that the students would need to retrieve from their memory in their future professional lives when facing new unforeseeable challenges. Therefore, the instructors' goal is to find ways of making these concepts more suggestive and thereby reinforcing their persistence in memory.
2) Original and suggestive *connections* between the previous *key or core concepts* and *arts* need to be found. This is a creative process that considers the connections' motivational ability, where elements of surprise and originality should be sought. It is a critical step that relies on the well-established benefits of surprise–the emotional response to outcomes that do not match our expectations [23]–to enhance learning [24]. Neuroscientific literature suggests that the prediction errors caused by this mismatch play a universal role in driving learning throughout the human brain [25], increasing attention that, in turn, leads to more effective memorization [26].
3) A set of *activities* to explore the previous *connections* needs to be designed. A requirement of these activities is that they promote *critical thinking* and *creativity*; that is, the application of mechanistic rules and closed solutions should be avoided. A proper balance of analysis and synthesis procedures should be sought, promoting

both deductive and inductive abilities in the students. In addition, these activities should be partially aligned with the multimedia learning theory proposed by [27], since our students will be learning concepts that include both verbal and written content, and more visually and auditory rewarding ideas. This will promote a more in-depth understanding.

4) An assessment procedure tailored to evaluate the degree to which the *core concepts* are understood needs to be put in place.

In the following pages, we illustrate the application of this methodology to enhance the learning of source coding theory in the field of communication systems.

III. Description of the academic course

We set out to apply the steps defined in Section II to "Multimedia Information Coding for Communications (MICC)", a compulsory subject in the third year of a four-year Bachelor degree in Mobile and Space Communications Engineering, taught at the University Carlos III of Madrid. The main goal of the course is to provide an understanding of coding and compression techniques used to process digital multimedia content such as speech, audio, image and video in order to reduce their storage needs, or equivalently, their transmission bit rate.

The original course is comprised of 14 lectures, with five seminars to develop problem-solving skills and eight labs of two hours duration each. The exercises we will describe in Section IV have been implemented during three of the lectures time slots. The academic program addresses common coding techniques that are based on the statistics or entropy of the source (Huffman, Arithmetic, Golomb-Rice, Lampel-Ziv) and on the perception of audio, images, and video (perceptual coding) to represent and transmit data. In addition, the evolution of the most relevant standards is presented, promoting discussion of the coding performance of the applications developed today; these standards include MP3 for audio compression, JPEG for image, and H.26x or the MPEG family for video (see, for example, [28], [29]). In addition during the lab sessions students develop hands-on skills by programming coding algorithms using MATLAB®[1].

The program surveys the following six topics:

1) **Fundamentals of the digitalization of multimedia information**: This topic provides a quick review of the fundamentals of analog-to-digital conversion, covers the representation by sequences, matrices and time-varying matrices of audio, image, and video, respectively; and gives an overview of the fundamentals of compressing information. The students are already familiar with these concepts so this is an introductory topic.
2) **Speech coding**: This topic establishes the mechanisms of human speech production as a way introduce the basis of coding. Vocoder, hybrid and waveform technologies are presented (together with their efficiency trade-offs) for speech transmission over communication channels such as those of mobile communication networks.
3) **Audio coding**: This topic covers a broader representation of sound in comparison to speech. Additional codes and a first survey of the related standards are taught. The concept of perceptual coding is also explained, based on a model of human hearing and associated psycho-acoustical phenomena.
4) **Image coding**: This topic includes the analysis of two dimensional data in contrast with the previous two sections, where audio and speech were considered. Two-dimensional transforms are presented as a way to apply coding in a different domain to reduce storage and transmission demands. The mixed solution of transformation and entropy coding is presented together with the evolution of standards.
5) **Video coding**: This topic introduces how redundancy is reduced in video through the efficient processing of the evolution of its frames to account for motion in the sequence of images. Video formats, general coding strategies and related standards are illustrated in this section.
6) **Transmission of multimedia information**: This final topic covers the requirements for universal access to multimedia. Technologies and methods are presented by means of illustrative approaches, standards and network protocols.

Topics 2–5 are accompanied by lab assignments to implement very simplified examples of each of the coder types where reference decoder implementations are provided. The student's goal is to produce coder implementations whose outputs can be properly decoded using the supplied reference decoders, as would be the situation in an organization that develops coding standards. Therefore, all these topics deal with the digital representation and processing of multimedia information. Implicitly, students need to implement basic digital signal processing techniques, such as filtering, downsampling, upsampling, and transformations in order to handle the proper functioning of these coders.

Generally speaking, multimedia content is a data source with specific characteristics or patterns that may be exploited for compression purposes. For instance, the speech recording of a *tenor* voice has major differences in comparison to a recording of a *bass* one. The fundamental frequency of the first is higher than that of the the second. A similar distinction can be observed in audio signals, since classical music presents different timbres and rhythms compared to jazz or soul. Images, on the other hand, exhibit huge differences in color and patterns depending of the age or art movement of their creation: paintings from the Baroque period contrast strongly with Cubist artwork, for example.

Coding techniques may exploit the peculiarities of media sources in order to give a better performance in terms of data storage–or equivalent rate of transmission–needed for a given quality of reproduction. This connection between the nature of the media source and the coding performance–either in terms of the compression rate or the quality (or distortion) of the outcome–is mediated by the concept of *redundancy* or *amount of information as measured by the entropy of the source*. As the importance of these ideas traverses all the topics

[1]MATLAB is a registered trademark of The MathWorks, Inc.

on this subject, they will be chosen as the *core concepts* to be identified in the first step of the methodology defined in Section II. The next Section is devoted to illustrating the teaching of these core concepts through the design of specific hands-on exercises that relay on the analysis and synthesis of small pieces of art.

IV. A proposal of activities regarding the engineering concepts and the arts

An appreciation of art may produce a better understanding of coding concepts and related applications to the digital processing of multimedia content, provided that original connections involving elements of surprise are included, as explained in Section II. In Section III, we identified *entropy* and *redundancy* as *core concepts* (step 1). We now need to find *suggestive connections* (step 2) between these concepts and a certain modality of art, and develop *open and creative* activities that will make these connections apparent (step 3).

To this end, the proposed exercises are divided into two separate parts designed to foster both deductive and inductive skills: first, illustrating the differences in coding performance through the appreciation of representative pieces of art from a qualitative standpoint (analysis); and second, challenging students to produce art based on the concepts and fundamentals of coding, thereby becoming part of an active process (synthesis). This organization resonates with several extremely important DSP concepts, such as dualities in linear transformations of sequences, and reinforces the complementarity of coding and decoding stages, which is essential in this subject. Analysis and synthesis assignments will involve the implementation of DSP techniques to process text, sounds and images. The following exercises describe these two directions in the topics of speech, audio, and image coding.

Exercise 1: Compressing the concept of Entropy

This exercise is related to the concept of entropy. The students will produce a brief essay, preferably related to their understanding of entropy. The whole process of writing, in itself, will make the students focus on the task at hand.

Once their excerpts are written, the students are asked to read and record them into a raw audio file. Notice that, semantically speaking, the informational content of both text and audio is the same, albeit in totally different modalities. Note here that the vagueness of the definition of *information*, a concept new to the students at this stage, is sought to trigger discussions that they must solve if they are to attain a solution.

In particular, the student should derive the following (analysis phase): a) The entropy of the written script; b) The entropy of the recorded speech; and c) A comparison and discussion based on the results of a) and b). In the second stage of this exercise, students must produce a new text reflecting the same content but with fewer words (synthesis phase). Notice that this is a procedure of compression itself, since students remove what they think is irrelevant or less informational in the texts that they have produced. The students must complete tasks a) to c) again.

We expect the students to understand not only the concept of entropy. During the discussion, we expect them to express their opinion about which of these two formats (the first or the second definition of entropy they have produced) seems to be more useful and comprehensible. This whole procedure will make them consider the usefulness of this process; that is, whether the concept is understandable or not after removing some of the irrelevant text, whether a person unrelated to engineering is capable of understanding it before and after the removal of redundant information, and to what extent uninformative data can be removed before the concept becomes unintelligible.

Additionally, students will develop DSP-related technical skills when implementing solutions to processing pieces of text. That is, obtaining histograms (when computing the entropy), recognizing patterns (when identifying the appearance of letters in the written text), and estimating their corresponding probabilities, etc.

Exercise 2: Listening to Redundancy

This exercise proposes to produce (non–speech) sounds from a given written script. This could globally be referred to as *sonification*, with applications not only in text-to-sound processes but also to images-to-sound and vice versa. Here we will focus on the production of sound from a written script in order to gain a subjective measure of *redundancy*, another *core concept* of coding theory.

Redundancy concerns the existence of multiple replicas of a given attribute. A good coder will try to reduce the redundancy of the coded sequence in order to produce a more compact representation, profiting from the fact that a redundant attribute (that is, an attribute with a high *a priori* probability), will be easier to predict.

In terms of sound, this may be reflected in multiple ways; for example, by assigning a chord to each of the symbols (i.e. each letter) used to code a text. If a particular letter is highly dominant or redundant in a text, this will be noticeable; it may even be interpreted as the tonic chord. If the given text presents too many different attributes that are almost identically distributed, the music produced would sound much more chaotic. However, if there is a high number of symbols, the sonification will be difficult to perceive and achieve.

Therefore, in this exercise we will resort to a more nuanced sonification method based on the perception of different timbres of a sound; in other words, the quality that allows us to distinguish between different musical instruments (related to the shape of the envelope of the spectra of the produced notes). A text with high redundancy will sound as a different musical instrument than other with less redundancy. Moreover, the reduction of redundancy produced by an effective coder (in comparison with a less effective one) could also be perceived as a different instrument.

Based on this interpretation, the analysis phase of this exercise containts the following steps: a) To produce a written script by explaining some of the learnt psycho-acoustic principles. Specifically, the script must provide definitions for the following aspects (of not less than 15 words per item): psycho-acoustic principle; the absolute threshold of hearing; time masking; and frequency masking. b) To encode the produced text and obtain a corresponding histogram of the produced symbols for two different coders: fixed length and Huffman. c) To apply sonification techniques in order to produce sounds from the two obtained histograms. d) Based on the produced sounds, to derive concluding remarks regarding the capacity to reduce redundancy by through the use of two coding techniques.

To illustrate a possible sonification strategy for item c) above, we start with a histogram representation of $L_i \cdot p_i$, where L_i is the length of the the code obtained for symbol i, and p_i represents the a priori probability as depicted in Figs. 1a and 1c for the fixed- and variable length- codes, respectively, used to code the letters of the alphabet. The histogram bars will be the attributes used to convert text into sound. The students must implement the following steps: 1) Reorder the histogram bars in decreasing order as depicted in Fig. 1b; then 2) Interpret them as a Fourier series in which the produced sound will be the linear combination of pure tones that are harmonically related to Fourier coefficients, corresponding to the amplitudes of the histogram bars. That is, if the first bar's amplitude is applied to a tone of 440 Hz (the musical note "A"), the second bar will be the amplitude of its first harmonic, $2 \cdot 440$ Hz, and so on. The superposition of these pure tones will have the same fundamental frequency but will exhibit a different *timbre* depending of the amplitudes of the bars.

The sonification of the written text must be comparatively analyzed for the two entropy coding techniques: fixed- and variable- length coding. Fixed-length methods will not introduce any additional compression on the given sequence based on redundancy (this is the case of the resulting bars in Figs. 1a and 1b). On the contrary, variable-length coding (exemplified by Huffman [30]) will profit from this redundancy, reducing the coded sequence length by assigning shorter-length codes to the most repeated (in someway redundant) letters and longer codes to the less repeated ones. The amplitudes of the histogram bars in Fig. 1c (variable-length) will be flatter than those in Fig. 1a as well as in Fig. 1d vs Fig. 1b, after reordering. By reproducing these two cases, in accordance with the sonification rule above, it should be possible to distinguish the sounds of the two coders.

In the second part of this exercise students must reduce redundancy by randomly erasing a quarter of the most repeated letters "A" and "E" (the synthesis phase). This random erasure of symbols is similar to the compressing efect that perceptual coding has on data, which students are addressing in this topic. After erasing these extra, redundant letters, it is expected that the meaning of the text will still be understandable, which is something to be assessed by each student. Based on the histogram of the reduced (compressed) text, students must produce the new related sound following the same steps as previously and devise comparative concluding remarks.

Students will also develop their DSP programming skills through this exercise. They must program the coding of text using fixed- and variable- length coding techniques and then produce musical notes according to the histograms. Implicitly, students will be operating with the digital representation of the reproduced musical notes, which in turn corresponds to an understanding of the digital sampling principles used to produce sound.

Exercise 3: A meeting between Pollock and Picasso through the concept of redundancy

This exercise attempts to illustrate the concept of information entropy in the perception of images. At the same time, we aim to develop technical skills related to the use and manipulation of the bidimensional Discrete Cosine Transform (DCT). The perception of entropy may be naturally inferred from images. To illustrate this, we have designed this exercise based on paintings by Picasso (see Fig. 2a, "The Blue Cup", 1902) and Pollock (see Fig. 2b, "Number 31", 1950). The upper left corner of Pollock's painting has been selected in order to obtain a picture that is the same size as Picasso's. Broadly speaking, the frame by Pollock seems to exhibit a higher entropy than that by Picasso, with reference to the variety of colors, intensities, and patterns used.

Again this exercise is divided into two parts. The first part drives the students to comparatively analyse the entropy present in Figs. 2a and 2b, based on which the analytical results are contrastingly considered regarding the perception of both images (analysis phase). In the second part, students are required to produce a new image (synthesis phase). This is derived by a combination of both paintings in the frequency domain through the use of the DCT. There, the entropy present in the frame by Picasso is increased to meet Pollock's entropy. The resulting frame is illustrated in Fig. 2c, where Pollock's style painting, included in the painting by Picasso, produces an increased perceived entropy.

Specifically, in the first part of the exercise, we suggest the representation of the image, as well as the computation of the entropy of the image through the use of the DCT (analysis phase). When generating the proper codes on MATLAB®, the student must address the following items: a) Obtain the matrix representation of these images and depict them in the proper plots; b) Apply the DCT transform to each image in blocks of 8×8 pixels; c) Based on the obtained DCT for each block, compute the histogram of the frequency components of the image and plot these as a one-dimensional graph; and d) Infer conclusions regarding the entropy of the frequency components. By solving this exercise, students are encouraged to develop a feeling for the redundancy and entropy in the frequency domain while interacting with the image and analysing the differences between the two frames. It is worth noting that the translation of such intuitions from the spatial domain to the frequency domain is conceptually quite complex and the fact that the students have to reach it using their own reasoning reinforces the persistence of this extremely important notion in their memories.

The second part of this exercise is related to the production of images based on the perception of entropy (synthesis phase). In this direction, the Pollock's *chaotic* style will be incorporated into Picasso's painting in the frequency domain through the DCT. Both styles will be mixed in order to devise a new frame, where the entropy of the Picasso's "Blue Cup" will

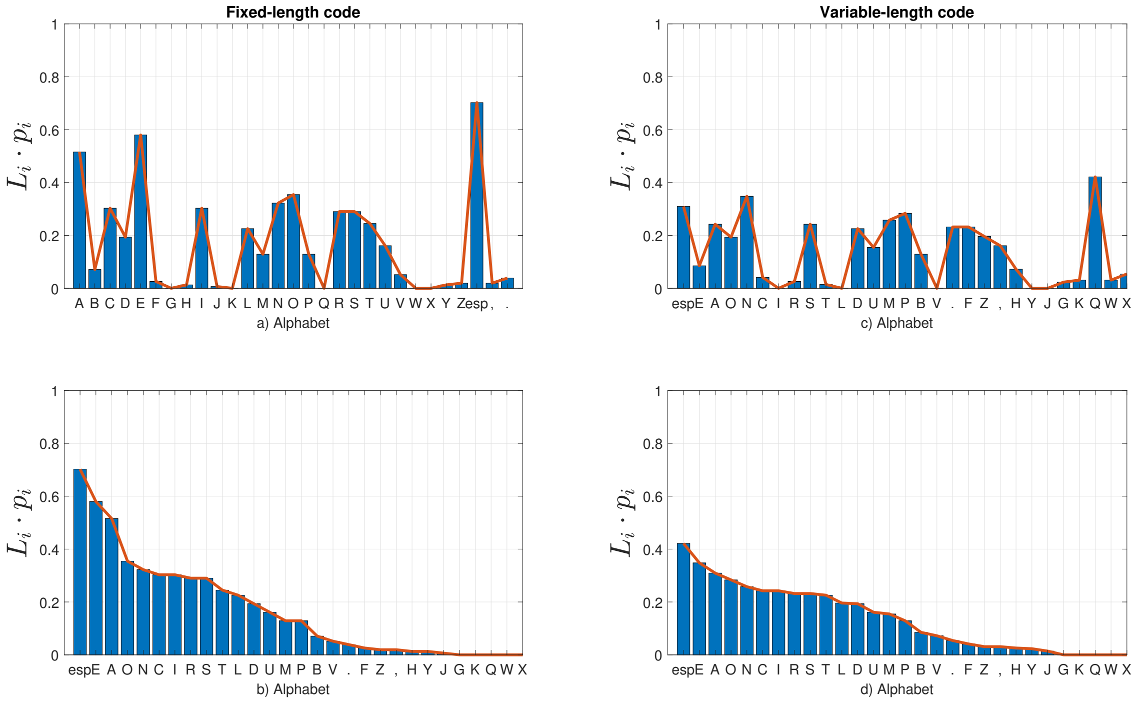

Fig. 1. Histogram plot of $L_i \cdot p_i$ for each of the letters of a given text. a) Alphabetical order (fixed-length). b) Descending order (fixed-length). c) Alphabetical order (Huffman). d) Descending order (Huffman).

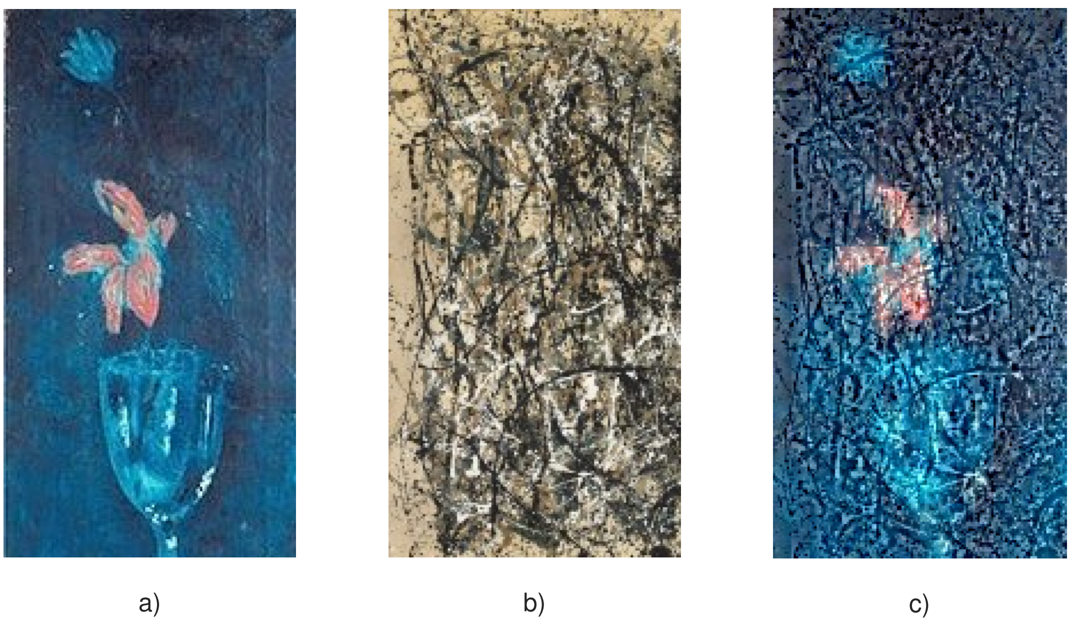

Fig. 2. Illustrative example of painter's and mixed styles. a) Picasso, "The Blue Cup", 1902. b) Pollock, "Number 31", 1950. c) The mixed style of Pollock and Picasso.

be increased through the replacement of its higher frequency portion by content obtained from the painting by Pollock. The resulting operation will produce frames similar to the ones depicted in Fig. 2c, where both styles are mixed, and thereby comparatively illustrate the impact of increased entropy.

To obtain the resulting frame in Fig. 2c, students must follow: 1) Obtain the DCT representation for both frames in Figs. 2a and 2b in a block resolution of 8×8 pixels; 2) Replace the higher frequency-portion of the obtained DCT's blocks from the painting by Picasso with the DCT content of the painting by Pollock; and 3) Apply the inverse DCT to the resulting operation. The second step is applied as explained in Fig. 3. The DCT blocks for each frame are obtained as indicated in Figs. 3a and 3c. Following this, a mask is defined, as depicted in Fig. 3b, to replace the higher frequency-portion of the DCT blocks from the Picasso painting with the DCT from Pollock's painting through the operation $\mathrm{DCT_{Pic\&Poll}} = \mathrm{DCT_{Pic}} \circ \mathrm{M} + \mathrm{DCT_{Poll}} \circ (1 - \mathrm{M})$, where '$\circ$' represents the Hadamard or element-wise product and $\mathrm{DCT_{Pic\&Poll}}$, $\mathrm{DCT_{Pic}}$, $\mathrm{DCT_{Poll}}$ and M are 8×8-square matrices representing the DCT transforms of the resulting operation, Picasso's frame, Pollock's frame, and a binary mask, respectively. After applying this linear operation, the resulting DCT is obtained as depicted in Fig. 3d.

As a result, when including the higher frequency-content from the painting by Pollock in the painting by Picasso, the resulting entropy will be increased. As depicted in Fig. 3c, the synthesized frame will exhibit much more randomness than the original frame in Fig. 3a, but still show the composition by Picasso. In some respect, we are meeting both painters through the use of the DCT in order to ignite a discussion about entropy and spatial and frequency duality thorough a comparison of the results. Finally, students will develop their DSP technical skills concerning image processing when implementing and analyzing the results of the direct and inverse DCT transforms.

V. Quantitative and qualitative evaluation

Two types of evaluations have been carried out: first, a quantitative questionnaire about the concepts that have been acquired; and, second, a qualitative questionnaire used to gather the student's opinions.

The quantitative questionnaire is the final exam in which a combination of theoretical and practical questions aim to assess the student's performance in both types of skill. The same type of exam was carried out in previous editions of this course[2]. The students are allowed to resit the exam only once, approximately one month later.

We have compared the results of the present questionnaires used with the average of the corresponding questionnaire in the last five editions of the course[3]. Our results show quite an improvement on the scores: a median of 56.71[4] and a mean of 56.64 with 23 students taking the examination versus a median of 48.86 and a mean of 47.54 with 20.20 students averaged over the previous five years. The standard deviations of the five-year average were 6.89, 5.22 and 2.58 for the median, mean, and number of students, respectively. Though the results are highly positive, we need to be cautious about the relatively low number of students and the fact that the COVID-19 pandemics has certainly had effects that are very difficult to quantify.

The results of the resit examination were not as promising; however, the number of students taking it was sensibly lower and their abilities are different (given that these are the students who did not pass the previous examination or had not taken it in the first call[5]: a median of 47.90 and a mean of 51.30 with seven students taking the examination versus a median of 51.66 and a mean of 51.60 with 8.80 students averaged over the previous five years. The standard deviations of the five-year average were 7.60, 9.80 and 3.56 for the median, mean, and number of students, respectively.

The qualitative test contained six questions, with several options for each of the three exercises (an average of 13.33 students answered this survey): 1) *The activity was (very interesting, interesting, barely interesting, not interesting)*, to which 91.07% of the students chose one of the first two options; 2) *The activity was (very complex, complex, barely complex, not complex)* where 92.16% chose one of the first two options; 3) *My previous knowledge on the contents was (enough, not enough) to complete the lab exercise* where half of the students answered 'enough'; 4) *The information provided for the lab exercise was (very adequate, adequate, scarce, very scarce)* with 64% chose one of the first two options; 5) *The instructor's explanations (greatly helped me, barely helped me)* with 78.47% of the students choosing 'greatly helped me', and the rest 21.53% 'barely helped me' and 6) *The lab exercise helped me (very much, somewhat, a few, nothing) to understand key concepts*, with 80.01% chose one of the first two options. The complete breakdown of the answers can be found in Table I.

From this we can conclude that the majority of the students found the exercises interesting and felt that they helped them to understand key concepts that were targeted. However, they also found the exercises somewhat complex (because of the efforts required to derive meaningful results) and some of them would have liked further guidance material. This under-specification was a feature we sought to keep the instructions open enough to foster creativity, and may be the reason why the instructor's indications were so highly appreciated.

An overall satisfaction questionnaire was also appended to the third qualitative test, containing four questions: 1) *The activities were (very, somewhat, barely, not at all) original and innovative*, with 71.43% of the students choosing one of the first two options; 2) *The activities were (very much, somewhat, barely, not at all) related to the engineering profession*, with 85.71% of the students choosing one of the first two options; 3) *The activities prepared me for critical thinking and reflection (very much, somewhat, barely, not at all)*, 78.57% of the students chose one of the first two options; 4) *The activities*

[2]Due to the COVID-19 pandemics, the present year examination had to be sat remotely and some adaptations had to be made to the content. Specifically, it was a synchronous test carried out using the assessment functions of the institutional Moodle-based learning platform. Specific measures to discourage answer sharing (randomization of questions, sequenciality and adequate time limitation) were implemented. In addition the exam was adapted to allow students to consult books, notes or others sources. Surveillance was implemented using Google Meet.

[3]This is the maximum number of editions we are allowed to retain data from according to the General Data Protection Regulation (GDPR) enforced in Europe.

[4]All the scores are over 100.

[5]Students are not allowed to resit the exam to improve their marks if they have already passed it.

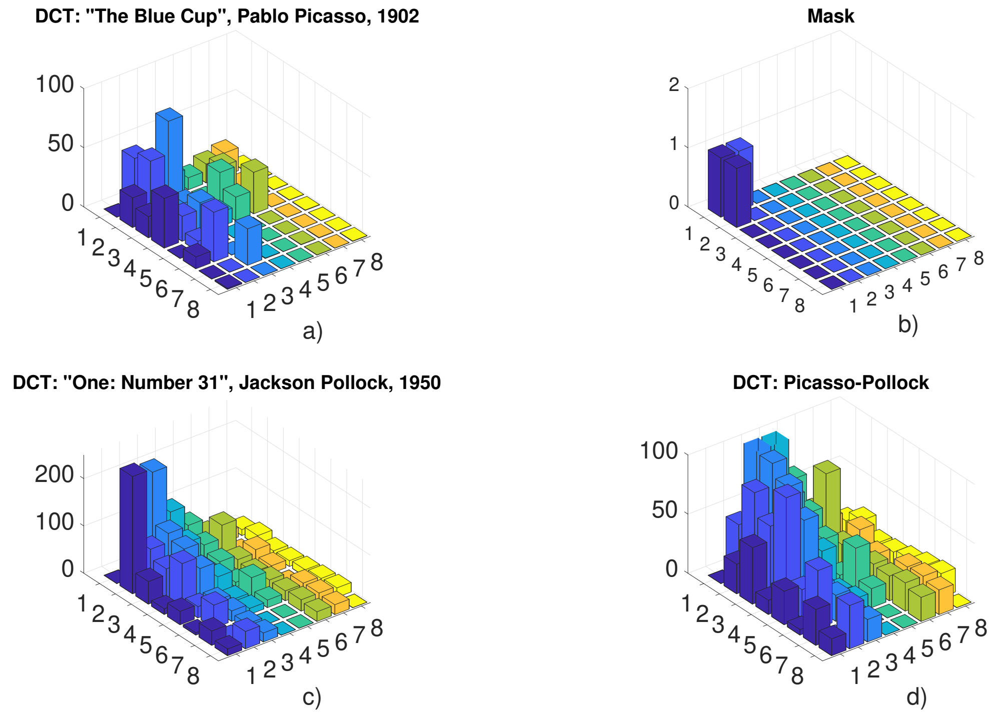

Fig. 3. Illustrative example of painter's and mixed styles. a) Picasso, "The Blue Cup", 1902. b) Pollock, "Number 31", 1950. c) A sample mask. d) The *mixed style* of Pollock and Picasso.

TABLE I

QUALITATIVE TESTS FOR EXERCISES 1–3 (AVERAGED PERCENTAGE, STANDARD DEVIATION). THE PARTICULAR TRANSCRIPTIONS OF THE OPTIONS FOR EACH OF THE QUESTIONS ARE DESCRIBED IN THE TEXT. IT IS WORTH NOTING THAT QUESTIONS 3 AND 5 ARE BINARY.

Q	Option 1	Option 2	Option 3	Option 4
1	(21.29, 18.74)	(69.78, 15.80)	(4.76, 8.25)	(4.17, 7.22)
2	(14.46, 20.17)	(77.70, 19.73)	(7.84, 13.58)	(0.00, 0.00)
3	(49.02, 1.70)	(50.98, 1.70)	-	-
4	(14.39, 8.36)	(49.61, 13.57)	(31.65, 15.92)	(2.38, 4.12)
5	(78.47, 8.22)	(13.03, 11.44)	-	-
6	(33.37, 10.50)	(46.68, 3.59)	(11.48,15.09)	(6.55, 6.27)

TABLE II

QUALITATIVE TESTS FOR OVERALL SATISFACTION (PERCENTAGE) ANSWERED BY 14 STUDENTS. THE PARTICULAR TRANSCRIPTIONS OF THE OPTIONS FOR EACH OF THE QUESTIONS ARE DESCRIBED IN THE TEXT. IT IS WORTH NOTING THAT QUESTION 4 IS BINARY.

Q	Option 1	Option 2	Option 3	Option 4
1	28.57	42.86	28.57	0.00
2	35.71	50.00	14.29	0.00
3	28.57	50.00	14.29	7.14
4	92.56	7.14	-	-

challenged me (yes, no), where 92.86% of the students chose 'yes'. The complete breakdown of the answers can be found in Table II.

We would like to highlight here that almost all of the students found the activities challenging which was one of our main aims. They also very clearly perceived the relationship the exercises had with professional engineering. The scores on originality and critical thinking were also very positive but slightly lower.

VI. DISCUSSION

We used the proposed exercises detailed above to raise our student's interest in the liberal arts. The students employed narrative techniques to produce their own scripts in Exercise 1, they made adjustments so that the sound produced had better sonority or acoustic properties in Exercise 2, and they appreciated the composition of paintings in Exercise 3.

The exercises were designed to combine both creative and more-guided learning processes. For example, Exercise 1 required that students participate actively when writing and recording their own ideas; we expected them to express their concerns and proposals about the topics under analysis. Following this, measuring the information entropy metric on a given text is a more standard procedure, during which they should follow straightforward specifications. Students should also become critical about the concept itself and its usefulness, which was verified empirically a posteriori once they had actively removed irrelevant content from their own excerpts of text. They proved themselves able to check that their text remains understandable but, observe at the same time, its length and entropy change, illustrating perceptual coding strategies.

Exercise 2 illustrates the concept of redundancy in terms of sound perception. Students may appreciate the concept of redundancy when they try to understand their own text after randomly erasing the most repeated letters. In this regard, redundancy is portrayed as the part of an object that may be removed without losing its descriptive ability. This idea is translated into sounds via sonification schemes,encouraging a perception of redundancy by listening.

Finally, Exercise 3 produces a visual representation of entropy to be contrasted with its value (analytically derived). Here, we can perceive comparatively higher and lower values of entropy in the graphical content of paintings. Students also produce a mixed style of painters by incorporating additional entropy from one frame to the other. When trying to balance both frames an information entropy standpoint, the higher-frequency portion of one frame is replaced by the other. This mixture of analytical operations and the perception of the resulting images naturally facilitates the assimilation of the concepts of entropy and redundancy.

At the same time, students discuss the core concepts of engineering and develop technical skills related to DSP subjects. In Exercise 1, students reflect their understanding of the concept of entropy without the support of any mathematical formula, which gives a broaden idea of their comprehension of the topic. Exercise 2 reflects the concept of redundancy in terms of sound perception, while Exercise 3 does the same through image. Considering the technical skills, hands-on activities involving core DSP techniques (sampling, representation, and transformation) are conducted when undertaken these exercises. Students develop the proper codes to read, store, analyze, processing, and produce multimedia content (text, sound, and image). In addition, students are introduced to the basic implementation of the most common standards used to transmit multimedia content. The application of encoders and signal processing through the DCT are basic elements of JPEG, MPEG, and H.26x standards.

Essentially, the proposed exercises are deliberately under-defined in order to give the students the chance to provide (and discuss) their own definitions of how redundancy should be measured for text, music, or images. In this respect, a connection with non-engineering departments may support the introduction of some basic liberal arts concepts. For instance, the teacher may introduce elementary techniques used to develop narrative skills; where students are introduced to script-writing to support the solutions to Exercises 1 and 2. A discussion of how to express the same concept but with less text and still preserving the meaning can be also carried out when developing solutions to Exercise 1. Alternatively, the teacher may prompt a discussion about the perception of redundancy in different musical rhythms; for example, they may pose questions such as *What is more redundant, classical music by Bach or the flamenco guitar by Paco de Lucía?, What sound attribute will be more useful to model and reduce redundancy?, Is there some correlation between redundancy and something as subjective as the quality of music?*[6]

[6]Note that these issues will inspire a discussion even among specialists in the subject since the connections we are trying to evoke here are by no means, straightforward.

The evaluation of this study has taken two directions: first, a quantitative questionnaire about the concepts to be acquired; and, second, a qualitative questionnaire aimed at gathering student feedback. Our results show a positive improvement in the scores, although the sample of students is rather small. The qualitative test was comprised of six questions related to the student's opinion of the three new exercises; the questionnaire covered student's opinion regarding thought-inspiration, the complexity of exercises, supporting theoretical background, and the completion of learning objectives. Four final questions concerning their overall opinion were appended to the last questionnaire; the response showed a very positive attitude towards the new materials.

A. Future Directions: Further DSP connections with the Arts

Our methodology relies on the identification of core concepts in the targeted course and their connection with the arts as the main driving force. Here, we suggest connections with other DSP core concepts. For example, the fundamentals of the digitalization of analog signals is mediated by Nyquist's *sampling theorem* and its requirements for valid representations of continuous-time signals and systems in a discrete-time domain. As is well-known, the sampling theorem allows the acquisition of equivalent discrete sequences from their analog counterparts. Similarly, discrete time-domain operations, such as discrete infinite impulse response filters, and most significantly, their discrete Fourier transforms, have equivalent output–input relationships to analog systems [1]. Both sampling and filtering, which allow the reproduction of analog signals and systems by their discrete-time counterparts, together with linear transformations such as Fourier's that bring a very convenient duality in time and frequency processing, are general and universal concepts in discrete-time signal processing.

Several connections with the arts can be identified to illustrate, for example, the meaning and implications of the sampling theorem. The impact of the sampling period on sound reproduction or the representation of images can be made (perceptually) very noticeable in several creative ways. Besides the obvious (but also interesting) dependencies that can be observed by down or up -sampling the signals, musical elements such as rhythm and style, instrument tessituras or vocal ranges can be exploited in relation to the sampling periods needed to process them in the discrete-time domain. For instance, Franz Schubert's *Ave Maria* (Op. 52 No. 6), interpreted on a violin, will provide a sharp contrast when compared to the main theme from the *Interstellar* soundtrack by Hans Zimmer, covered by a violoncello, due to the higher-frequency tones used in the former. Similarly, styles from certain art movements (pointillism techniques, for example) will require reduced sampling periods than will the blue period paintings by Picasso. Note that these last notions and their connection to the sampling frequency are more nuanced and conducive to discussion than purely engineering-based considerations.

In a similar fashion, the notion of filtering as applied to sound (a one-dimensional filter) or to a given frame or photograph (a two-dimensional filter) will modify our perception of the musical piece or the paint depending on the filter's specifications. T he i mpact o f t he d esign o f t he fi lters (low-pass, high-pass, etc) can be discussed in connection with the instrumentation of a musical piece. Additionally, the use of two-dimensional low-pass filters c an c ompare t he results of smoothing and sharpening effects on visual pieces of art from two different art schools or periods. Again, for instance, smoothing effects will be more pronounced on pointillism than on the blue paintings by Picasso.

VII. CONCLUSIONS

This ongoing research introduces the liberal arts as a way to improve the teaching of abstract concepts in engineering. By making innovative use of writing, sonification, a nd image production techniques, we introduce lab activities that interconnect the attributes of text, audio, and image with an active use of liberal arts concepts. We believe that this approach reinforces an understanding of key concepts and reduces student perceptions of their difficulty, not only through their analytical definition b ut a lso t hrough t he " feelings" or "vibe" they convey. This proposal also leads to integrate non-engineering departments to design mixed curricula where both schools are integrated. Our evaluations indicated positive outcomes regarding the learning objectives and the appreciation of the course. Future directions include devising new exercises to cover new topics and key concepts and broadening the number and type of students involved to test their impact.

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