Digital Video Representations for Teaching Mathematics and Coding to Middle School Students

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***Abstract*—We present an integrated mathematics and computer programming curriculum for teaching bilingual middle school students how to code using digital video representations. Building on the student's familiarity with digital video, we introduce them to number representations (e.g., binary and hexadecimals), NumPy arrays, coordinate systems, color, frames, and how to combine them into digital video content. The curriculum is fully integrated with middle school mathematics. Middle school students who completed the curriculum joined undergraduate students to co-teach the curriculum in a small group collaborative learning environment. We found evidence of successful implementations based on video recordings of student and facilitator interactions, attitude scales, student exit interviews, and samples of student work.**

Keywords— Collaborative learning, middle school mathematics, computing, image and video processing education

I. Introduction

At the middle school level, students are most likely to make long-term decisions about their future [1]. Thus, to broaden their participation in STEM, there is a strong need to provide middle school students, especially students from culturally and linguistically diverse (CLD) backgrounds, with college-going information and authentic experiences related to STEM careers [1].

The Advancing Out-of-School Learning in Mathematics and Engineering (AOLME, [2]) program brought together collaborators from the signal processing community and bilingual/mathematics education to provide a middle school curriculum that integrates mathematics with color image and video processing concepts. The project was introduced as an afterschool program implemented in urban and rural middle-schools [3]. Approximately 135 Latinx students participated in implementations of the curriculum.

Our previous experiences with image and video processing education were from the SIVA project [4], [5]. At UNM, the SIVA programs have been used for the last twenty years to teach fundamentals of image and video processing in the graduate course in image processing. As advocated by the authors [4][5], we have also witnessed that interactive visualization of basic image and video processing concepts has helped graduate students get a better grasp of the underlying concepts. Similarly, we have also participated in the J-DSP project [6]. J-DSP provides an interactive environment for understanding the basics of DSP through experimentation.

Fig. 1. Collaborative group learning setup at a rural middle school. The group includes an undergraduate facilitator, a middle school co-facilitator, and three middle school students.

For the AOLME project, we went through a process of development, formal evaluation and revision as documented in [7]. At the end, we focused the curriculum on understanding teaching digital video representations. In terms of DSP content, we wanted to teach the students how to code digital videos in Python using NumPy arrays while understanding the underlying mathematics. Thus, the curriculum taught binary and hexadecimal numbers so that the students could understand content down to level of zeros and ones. Furthermore, digital color was taught as tuple three hexadecimal numbers (Red, Green, Blue). The students described the video by programming the color representations in NumPy arrays that they then used to construct video frames. The video was constructed from its video frames. In level 2, they looked at color object detection using color histograms and also explored geometric transformations made of rotations, translations, and scalings. Here, it is important to note the importance of

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providing authentic Python coding experiences at the middle-school level [8][9].

We chose a collaborative environment where students make sense of the activities individually and collaboratively. Furthermore, as students interact, plan, and discuss their projects, their conceptual reasoning is linked to a meaning process through which students develop, use, and expand their discourse practices [10] [11].

We present an example of the collaborative learning environment in Fig. 1. The students were arranged in small groups of 3 to 4. For each group, we had an undergraduate student facilitator who was assigned to help them with initial tutorials and guide them through the activities. The students shared a large display and a single keyboard that was rotated among them. The facilitators were provided Professional Development (PD) sessions to prepare them to take on this role. The PD sessions focused on: 1) having facilitators experience the same content in the curriculum that the middle school students would cover; 2) learning to collaborate in a team to accomplish similar goals; and 3) drawing from students' cultures and languages as strengths. Specifically, facilitators were encouraged to have middle school students predict solutions, freely experiment, express themselves, and confirm their solutions. To encourage experimentation, we did not provide any solutions to any of the exercises. Furthermore, middle school students who completed the curriculum were invited to become co-facilitators and collaborate with typically an engineering undergraduate student facilitator teaching the middle school students. Both groups participated in a PD focused on pedagogy [12].

In Section II, we provide a summary of the curriculum. Example activities are provided in Section III. We then provide a summary of our formal assessment in Section IV and concluding remarks in Section V.

II. AN INTEGRATED CURRICULUM FOR MIDDLE SCHOOL STUDENTS FROM LATINA/O/X BACKGROUNDS

The curriculum, revised after each implementation, was specifically designed for bilingual (Spanish/English) students to access challenging tasks that integrated mathematics and computer programming. We supported bilingual students by developing a curriculum in English and Spanish, a multilingual approach that was strongly embraced among our foreign-born graduate students, Co-PIs, and Latinx undergraduate students. A link to the curriculum is given in [13].

The curriculum focused on helping the middle school students understand, create, explain, and then teach video representations. To develop this knowledge, the curriculum started with fundamentals of computer architecture, basic programming concepts, and number representations. Our focus on number representations enabled us to explain pixels using binary numbers down to the single bit level. In turn, binary numbers were used to introduce binary images and grayscale images. Then, color images were introduced as a collection of color pixels where each pixel was defined in terms of a mixture of red, green, and blue integers that were put together to generate arbitrary colors. Color videos were then presented as a sequence of color images. The students were strongly motivated to put together a story using color videos that were programmed in Python using NumPy arrays and run their code on the Raspberry Pi.

In terms of middle school mathematics, we reviewed and made connections to: algebra, number representations, coordinate systems, and geometry. Algebra was used to introduce the concept of programming variables, substitutions, and simple linear equations. We expanded on their exposure to number representations to develop binary numbers using 8-bits per pixel. We then introduced colored pixels using their 8-bit color components. Pixels were coded using hexadecimals to support understanding down to zeros and ones. We then introduced 2D arrays based on coordinate geometry to help them understand how to make images from pixels.

In terms of constructing video representations, the students programmed in a custom Python library to reinforce our educational objectives. Individual pixels were specified in hexadecimals. More complicated shapes were made using rectangular fill commands. The students were encouraged to use color variables to experiment with hexadecimal number representations. Videos were constructed using array copy functions followed by modifications made on each video frame.

The curriculum consisted of 12 afterschool sessions. The students focused on learning the curriculum in the first eight sessions. The last four sessions were dedicated to creating a custom video and to preparing students to present their final projects. The students were then asked to present and explain their code in a final graduation ceremony that was attended by their families, friends, and teachers on the last day of the program.

III. EXAMPLES OF CURRICULUM ACTIVITIES

The curriculum was implemented using interactive activities. Our goal was to support experiential learning, where the students learned through experimentation.

We provide an example of teaching color image representations in Fig. 2. The example followed a review of binary and hexadecimal numbers that is built upon number representations covered in middle school mathematics. Furthermore, we drew on the students' familiarity with Cartesian coordinates to introduce 2D array indexing based on rows and columns, as shown in the upper portion of the WebApp. Each pixel was entered as a 6-digit hexadecimal number. We used two hexadecimals for specifying red, green, and blue pixels, encouraging them to appreciate pixels down to the pixel level. After they entered the pixel values, the image was displayed right below so as to encourage interactive display. The WebApp [2] has proven to be very effective. The students enjoyed experimenting with colors and designs to generate different scenes or characters.

We provide an example of visual debugging for the final projects in Fig. 3. For the final project, the students were

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provided with three basic operations: (i) single-pixel specification using array access, (ii) a rectangular fill command, and (iii) a frame copy command. To bring several elements of the curriculum together, they were also encouraged to use comments so as to share code effectively and use variables to store hexadecimal values for each color, constructing a minimum of 6 frames. They interactively debugged the video pixel-by-pixel and then frame-by-frame.

We provide an example project in Fig. 3. In this project from the group "Champions", the entire frame was designed using the **im_fill** command. The command specifies the indices for a NumPy array using `[start_row,end_row]` and `[start_column,end_column]`. As an example, the command **im_fill**`(frame3,[9,9],[10,10],azul)` specifies a single pixel at `row=9` and `column=10` of color `azul` represented using 3 hexadecimal numbers (for red, green, blue).

Fig. 2. Web application for introducing 2D array cartesian coordinates and hexadecimal colors.

The middle-school students explained how their video depicted an alien leaving his farmhouse to eat the potatoes at a potato crop. Based on their final presentation, Fig. 3(a) depicts the alien character in the bottom left side of the frame, next to it the potatoes on the bottom right, while the title of project "Potato Corner" is shown at the top. Also, in Fig. 3(b) the scene represents the potato crop with the alien house in the back (in red). Finally, the pixel design for the sky was included as white pixels. During the presentation, the middle school students demonstrated their understanding of hexadecimals, the Python library, comments, and the meaning of controlling the number of frames per second.

The group associated with the project in Fig. 3 also demonstrated several of the successes of the project. None of the students spoke English. They relied on a fellow student, a bilingual co-facilitator, to understand the curriculum.

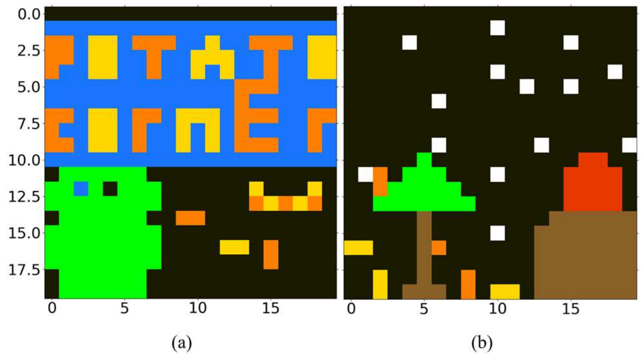

Fig. 3. Example of pixel design. Group "Champions" Rural Middle School Cohort 3 Level 1. (a) Frame 5. (b) Frame 6.

IV. Assessment Summary

To assess what students learned from the curriculum, we used multiple sources of data using qualitative research designs in education. First, we analyzed holistically the video recorded interactions between the students and the (co)facilitator and their related screen recordings showing students' code from twelve 1-1/2-hour sessions for each implementation in the spring and the summer conducted over three years. These video recordings and samples of student work show evidence of how students designed a final project, modeled with mathematics to code their images, and confirmed their results by using debugging when necessary [14]. As shown in [8], students learned about binary and hexadecimal numbers to design black and white and color images and videos, respectively.

Secondly, we administered pre-post attitude scales that assessed students' enjoyment, usefulness, motivation, and self-confidence in mathematics and computer programming. As illustrated in [14], the contrast of pre and post attitude scale results have shown greater increase in self-confidence, especially with middle school students who served as co-facilitators. Enjoyment proved to be another dimension in which increases took place. Total averages of the Computer Programming and Mathematics (CPM) attitude prescores were 63 for non-AOLME students, 72 for AOLME students, and 83.5 for cofacilitators. Respectively, the average post scores were 63, 73, and 87. Such differences point out the cofacilitators' greater initial and posterior connections to CPM practices as compared with most of students in AOLME. Thus, AOLME is recognizing the importance of a nurtured assigned responsibility in the case of the co-facilitators, especially those from the rural school. Co-facilitators also mentioned being able to 'learn' better given the fact that, as they taught the curriculum, they revisited and rearticulated the curriculum to support others' understanding of it. Additionally, co-facilitators identified their participation in the professional development helped them clarify ideas and questions of what they had learned and taught. Both the undergraduates and their middle school students expressed their excitement of getting the code to work as demonstrated by their video creations.

Thirdly, we conducted student exit interviews at the end of each implementation. Each student had the opportunity to

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indicate on a scale from 1 to 10 their liking and knowing mathematics and computer programming before and after the program. As shown in [12], on average, six co-facilitators reported knowing computer programming at 2.4 before and at 8 after the program; liking computer programming was at 4.6 before and 9.7 after the program. As shown in [15], the students spoke extensively about how they found it gratifying to apply mathematics through its connections with image and video representations in an interactive, visual debugging environment. We include samples from the students' exit interviews below (taken from [15]):

> Victoria: [Before,] I didn't know almost anything about computers. I've heard of it, but I didn't know what it was… [but now] I feel like I definitely learned all about computer programming from AOLME … I thought "Wow, maybe I should learn about it." I didn't even know RGB and the hexadecimal were a thing. … I knew what pixels were, I didn't know what their use was. Now, I know.

> Mauricio: [In AOLME,] I learned that numbers can actually mean colors. Like one, one, one zero, like zero is black and one is white. … And I was like, "How do numbers create colors?" Like they're just plain numbers. And then it, so then I didn't think it was possible at the time I came, [which is] before AOLME. … And then I was like, "that's pretty cool". How math can go into colors and programming. And then it creates an image.

V. Concluding Remarks

The AOLME project provided access to an integrated curriculum to middle-school students with authentic coding experiences. The students enjoyed programming digital color video representations using hexadecimal numbers. We also found an increase in enjoyment and self-confidence, with co-facilitators being strongly impacted.

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