Large-Scale and Versatile Deployment of Biology Cloud Labs in Schools through Teacher Driven Curricula Design

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ABSTRACT

Cloud-based science labs allow science classrooms to engage in authentic science inquiry without the logistical and procedural complexities of real hands-on laboratories. A major challenge is to understand the variation of teaching contexts and needs and the implication for technology design. Utilizing an Biology Cloud Lab (BCL) for real-time experimentation that had been deployed as Massive Open Online Course (MOOC) previously, we now execute three in-depth case studies of how K-12 teachers (with ~200 students) adapt and deploy this BCL and MOOC material for their own class-room needs. We uncovered that teachers differed in their diverse range of learning objectives (e.g., large-scale data analysis vs. computational modeling based on real data), how the teachers were able to adapt the BCL and MOOC material differently to meet their respective curricular needs, and how logistically complex and time intensive processes can be automated to allow teachers and students to focus on key practices. This work reveals the need and design rules for well-standardized and modularized cloud-based science laboratories and accompanying learning materials to then enable rich inquiry based learning activities that work at scale while also being highly customizable to the local classroom contexts.

CCS CONCEPTS

• **Human-centered computing → Interaction design**; • **Applied computing** → *Interactive learning environments.*

KEYWORDS

Massive Open Online Course (MOOC), Biology Cloud Lab (BCL), Euglena gracilis, Classroom design, STEM Education, K-12 Education, Inquiry Based Learning

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1 INTRODUCTION

Educational reforms demand for K-12 STEM education to be centered on more practice-based or inquiry-based learning approaches that involve the active investigation and explanation of natural phenomena, and that allow students to develop and test models and hypotheses and to analyze and interpret their own data [1, 3, 6, 9–11, 36, 40, 47]. Online instruction could support these goals at scale, but many existing approaches are not yet well-suited for authentic inquiry due to limited affordances, logistical challenges, and lack of adaptability for teachers' specific needs [1, 5, 12, 17, 25, 47].

Cloud-based lab technologies have gained excitement as they could provide access for students to perform real experiments in a manner that is robust, scalable, collaborative, low cost, flexibly usable for teachers, and that capture the key elements of scientific practice [14, 18, 21, 23, 24]. Thus, cloud labs share benefits of virtual laboratories, e.g., low logistical requirements and costs on the users' end, yet they preserve some of the complex aspects of real phenomena that simulations cannot reproduce [18]. Most of these technologies have been designed for engineering and physics, but only a few for other domains like the life sciences [2, 7, 13, 18, 24, 33, 35, 38, 41].

Here we study the key question of how cloud lab technology that can potentially function at the scale of thousands of students can be adapted to the local contexts and needs of multiple individual

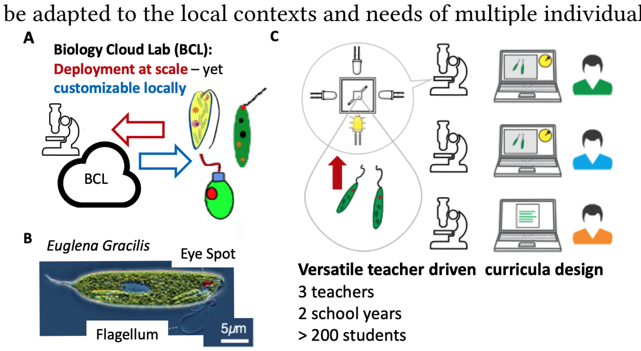

Figure 1: Project overview: (A) Large-scale Biology Cloud Lab (BCL) enables students to engage with key scientific practices (experimentation, data analysis, modeling) [20]. **(B)** Euglena performs phototaxis due to feedback between eye spot and motile flagellum. **(C)** BCL enables real-time phototaxis experiments with Euglena (B) moving away from light (red arrow). Our study evaluates how BCL technology can be adapted and deployed by individual K-12 science teachers based on versatile needs. (Figs. adapted from [20].)

	Teacher T1 / Y1	Teacher T1 / Y2	Teacher T2 / Y1	Teacher T2 / Y2	Teacher T3 / Y2
Years experience	5	6	17	18	12
Subject	Honors and AP Biology	SAPY	Science	SAPY	Honors and AP Biology
No. of students	80 (86)*	80 (88)*	22	19	10
School demographics	100% URM (97% Latino / 3% African American); 95% qualified for free lunch programs.	SAPY	A few neurodiverse students, i.e., with autism, reading challenges or lower math scores.	SAPY	97% URM (Hispanic, Latino, South Pacific); >50% qualified for free lunch programs.
Grade Level	11th	11th	6th	6th	9th
% Female	62	59	50	53	90
Learning goals as stated by teacher	Inquiry based scientific experiments; hands-on knowledge regarding biological organisms	SAPY	Microscopic experiment; hands-on experience on single celled organisms and their processes; online course completion; modeling	SAPY	Develop understanding of how science projects work; gain appreciation for hands-on way of how science is done; preparation for open project
Hours for activity	8.5	17	8	8	12.5
Weeks for activity	2	4	2+2	2+2	15
edX Course	Yes	No	Yes	Yes	Yes
Data analysis	Yes	Yes	No	No	No
Modeling	edX version	No modeling	edX version + Silk Weave	edX version + Scratch	edX version
Learning task sequencing	Clarify concept Hands-on experiment Quiz edX BCL experiment + modeling Define hypothesis Test hypothesis Data analysis (on spreadsheet) Lab report	Clarify concept Hands-on experiment Quiz BCL experiment w/o modeling Define hypothesis Test hypothesis Data analysis (on paper) Lab report	Clarify concept / worksheets Hands-on experiment Quiz edX BCL experiment Software modeling (Silk Weave)	Clarify concept / worksheets Hands-on experiment Quiz edX BCL experiment Software modeling (Scratch)	Clarify concept edX BCL experiment Hands-on experiment Open project design Self-chosen student project Project report

Table 1: Demographics, teachers' learning goals and course design. Curricula merged elements from existing edX BCL course [20] and teachers' own material. * Students distributed over multiple classes (20-30 students each), some students excluded from study due to not completing course or not providing consent. Y: Year; SAPY: Same As Previous Year; NA: Not Applicable; URM: Underrepresented Minorities.

teachers. We use a real-time interactive Biology Cloud Lab (BCL) and associated modular online course materials developed and tested previously (Fig. 1); this BCL scales to millions of annual users, experiments lasts one minute at cost of ~1 cent each [20, 21, 50]. This BCL is part of the emerging field of 'Interactive biology' that enables interactive experiences with microbiological systems in museums, as biotic games, and in DIY settings [8, 15, 21–23, 26–33, 39, 45, 46]. This BCL has multiple Biotic Processing Units (BPUs), i.e., microscopes with web cameras, microfluidic chambers with living cells (*Euglena gracilis*) [49], and four LEDs that are actuated remotely via a web interface to drive cells away from light along the four cardinal directions due to negative phototaxis (Fig. 1) (see [21, 26, 32] for details). Euglena are widely used in K-12 education [34], hence this BCL is well suited to support existing curricula. This BCL was incorporated into a MOOC course previously that was offered through the open edX platform, which took about 4 hours to complete, and progressed through 7 modular sections that implemented an inquiry-based approach; sections included reading assignments, quizzes, lab experiments, video watching, data collection and data analysis [20].

2 METHODS

We took a case study-based approach [42] to investigate how individual teachers use and adapt cloud labs to their teaching needs, and to identify emergent common and divergent themes. We recruited three US K-12 science teachers (**T1**, **T2**, **T3**; female, from different schools), they all took the original edX course [19, 20] themselves (**for more detail on following, see Table 1**). Teachers were tasked to develop and implement a learning sequence in their classrooms by adapting the BCL and edX content [20] in combination with other instructional materials to suit their own teaching needs (Fig. 2). We provided additional support if requested, e.g., we helped to develop a Scratch based modeling environment (Fig. 3) [26]. **T1** and **T2** participated a second year with additional adaptations.

We interviewed teachers before and after their classroom implementations, using semi-structured interviews with ~ 30 guiding questions about their previous learning sequences on similar content, their perceived affordances of the BCL, their evaluation of the BCL itself, their implementation and student learnings, and their suggestions for future classroom uses of the BCL. Interviewers recorded teacher responses in writing, not all questions were asked to all teachers, and during manuscript preparation teachers were asked additional questions via email for clarification as needed. Student class materials and lab reports were collected and qualitatively analyzed to deepen our assessment of the teachers' learning sequences and student activities (Fig. 2). An in-depth student data analysis was not performed as we did so previously [19–21]. Studies were performed under Stanford IRB protocol 18334.

3 RESULTS

3.1 Curricular Design and Integration

All teachers focused on hands-on / first-hand experimental science experiences, yet the **student populations, learning objectives and corresponding sequences of learning activities** were quite distinct (details in Table 1; typical activities in Figs. 2-3). In the following we highlight some key distinctions between teachers:

The **student work modality** varied: **T1** split the classes up into groups of 4-5 vs. 2 students for hands-on vs. BCL activities, respectively; students took turns using these technologies. **T2** had students work in groups of 4 vs. 2 for hands-on vs. BCL and edX activities, respectively. In case of **T3**, 4 out of 10 students chose Euglena for their final project, each working alone.

The **order between physical hands-on microscopy vs. BCL** varied: **T1** let students first passively observe living and non-living cells (Euglena, stained onion cells) using physical hands-on microscopes; interactive Euglena phototaxis was introduced afterwards via the BCL (Fig. 2A). **T2** introduced the biological content, then students tried to elicit phototactic Euglena responses with flashlights placed next to the hands-on microscope, and only afterwards did students work on the BCL and edX course (Fig. 2B). In contrast, **T3** let students take the BCL and edX course first, and then students decided of whether they wanted do a self-directed hands-on project with Euglena (e.g., exploring responses to different light colors; Fig. 2C), or to perform a non-Euglena project (e.g., on bacterial growth).

The teachers **integrated the edX course** in different ways, dedicated different overall time, selected different modules from the BCL and edX course, and paired them with different traditional hands-on school activities: **T1** and **T3** had students engage in the edX course without any additional activities around it. In contrast, **T2** included activities to help formative assessment of students' understanding and foster reflection, e.g., before experimentation, students took a quiz comparing Euglena to Amoeba.

The amount of focus on **experimental inquiry vs. data analysis** varied between teachers: **T1** had students pursue self-guided inquiry using the BCL, generate their own hypotheses about Euglena, test them by designing their own BCL experiments, collect and analyze their own data with google spreadsheets (Fig. 2A), and prepare a lab report. **T2** had student pursue structured experiments without any truly self-guided inquiry nor extensive data analysis, but still let them pursue the basic data logging activities from the edX course. **T2** then went beyond the edX activities, asking students to illustrate various Euglena behaviors due to different light stimuli schematically in text and image (Fig. 2B), and to model and animate Euglena behavior using the interactive generative art tool 'Silk Weave' (http://weavesilk.com/). **T3** tasked students with a multi-week self-guided inquiry on hands-on microscopes including data analysis (Fig. 2C) that was similar to the edX course.

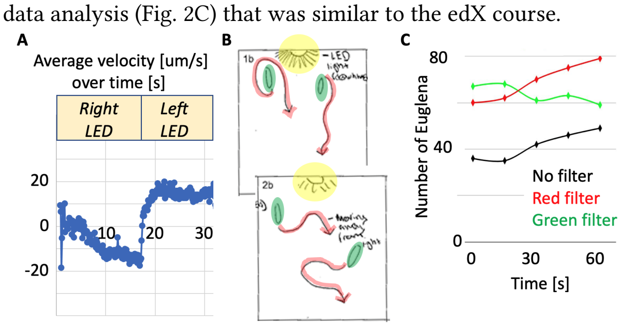

Figure 2: Student work examples: (A) T1: Data analysis in google sheets showing switching between negative and positive velocity due to changes in light direction (LED) from right to left. **(B) T2:** Euglena (green) swimming trajectories (red) captured qualitatively under different light intensities (yellow; high -'1b', medium - '2b'). Color overlays added by authors for clarity. **(C) T3:** Data analysis indicating that Euglena accumulates in regions of red and white light (no filter), but appear to avoid green light.

3.2 Assessing Deployment Success

From a **logistic perspective**, all three deployments were successful as all activities were executed by the students in the allocated time, and the BCL and edX content worked robustly. Teachers mentioned some technical challenges related to insufficient school resources, e.g., insufficient internet bandwidth, number of physical microscopes and computers, and they desired more online microscopes.

From an **instructional perspective**, all teachers reported successful deployment, which was primarily assessed based on how teachers' (and students') expectations were met, and how these new activities compared to existing approaches: **T1** stated that all students were able to carry out the lab activities, design and conduct experiments with similar performance levels as hands-on experiments, and write a lab report. She considered the learning sequence a unique experience for students (not achievable with existing teaching modalities) as it allowed to collect and analyze novel empirical data about live microorganisms, in contrast to previous years when students could only passively observe microorganisms without experimental manipulations. She was excited that students could self-generate data and then practice extended analysis in spreadsheets. The vast majority of students (>90%) stated that this was a worthwhile activity that should be repeated in future years, and that they appreciated the ability to design their own experiments with tools that 'real' scientists would use. **T2** stated that students appeared '100% engaged in all the Euglena activities,' especially when working with the physical microscope and the cloud lab, and as students could afterwards explain in detail Euglena phototaxis using domain-specific language. **T3** stated that students were enabled to work independently and to self-monitor their progress, could design and execute consistent experiments, were able to reflect on their own data in their reports, and that they 'really enjoyed the learning process and discovering the hidden world of euglena.'

3.3 Adaptations during 2nd Year Offerings

T1 and **T2** offered the course a second time, implementing multiple changes, which are already informative on the BCL utilities and challenges. Both teachers stated that students struggled during the first year with the interpretation of graphs generated in spreadsheets. **T1** then wanted to put more emphasis on data analysis, hence she dropped the edX course including modeling and substituted it by reading material and direct presentations. The overall class time for all activities was doubled, with much more time now devoted to data analysis. To give more agency in experimental design, students then used the real-time joystick as input device rather than running batch. Graphs were generated in the google spreed-sheet as before (Fig. 2A), but then printed out and further analysis was performed on paper, and which was repeated for many data sets. **T1** reported that these modifications made the activities more interactive and useful overall. **T2** stated that 6th grade students were challenged in dealing with positive and negative velocities in year 1, hence the spreadsheet activity was dropped in year 2 completely, and instead modeling became a bigger focus (Fig. 3). She substituted Silk Weave with an interactive Euglena phototaxis model implemented in the children friendly programming environment Scratch [26, 43] (Fig. 3), which enabled students to manipulate parameters like speed or response time to light. Hence both teachers made changes to better

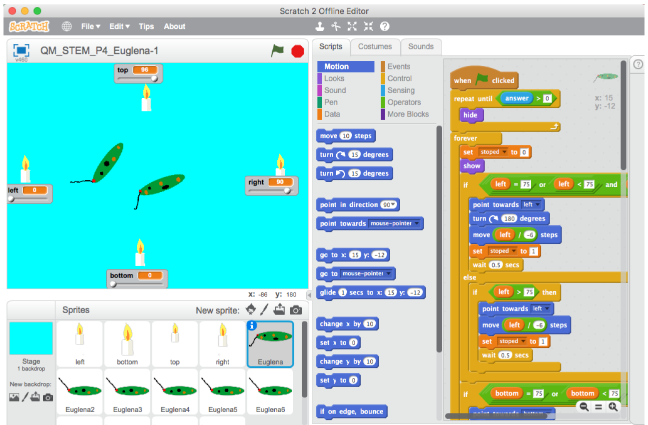

Figure 3: Modeling Euglena light responses using Scratch (T2; year 2). Upper left: Two cells and four directional light sources (candles) are simulated; light intensities are set with sliders. Right: Portion of code including equations determining cell behavior, students can change and explore relevant parameters (orange: speed and turning sensitivity to light) or even the underlying equations.

accomplish their educational goals, interestingly, they went into opposite directions regarding data analysis (**T1**) vs. modeling (**T2**); the different student grade levels likely played a role too (Table 1).

3.4 Cloud vs. Hands-on Experimentation

All teachers indicated that the BCL can significantly support the students' perceptions that these are actually real living organisms (and not just simulations), leading to an increase in student motivation, e.g., **T2** stated that being able to use a real science lab remotely was a 'big thing' and very motivating for the sixth graders. The teachers voiced differing opinions regarding the sequencing of the modalities: Hands-on, observational experiments with a physical microscope first helped students to appreciate that the BCL had real organisms and better motivated the data analysis (**T1**), vs. using the BCL first helped students to appreciate much more what they see with the hands-on microscope (**T3**). When asked to comment on the relative value of the BCL vs. hands-on experimentation, all teachers voiced that the cloud lab in combination with a traditional local hands-on microscope provides much synergy and increases student interest and motivation, while any modality on its own would have shortcomings, hence ideally both are available. For example, when only using the BCL, students might not realize that those are real cells (**T2**), while for hands-on only the experimental stimulation with regular flashlights was hardly consistent (**T2**).

3.5 Suggested Improvements for Future

Teachers **suggested improvements regarding the BCL technology and its presentation**: (1) Data analysis with google sheets could be too complex, instead reduced data sets and offline chart/plot review seemed to work better (**T1**). (2) Variability in Euglena responses should be reduced for more experimental consistency (**T1**). (3) Enhanced capabilities (e.g., ability to change microscope zoom level (**T1**) or higher quality video (**T2**)) could increase BCL authenticity and better relate to hands-on Euglena experiments (**T2**). (4) More BCLs should be available (one per student) to enable deeper engagement and better biological understanding (**T2**, **T3**). (5) Science cloud labs on other topics should be provided (**T2**).

Teachers **suggested curricular changes** in case of future deployments: **T1** stated that students should initially be asked more questions, be allowed to observe more to ask a wider range of experimental questions, and data collection and analysis should be structured as a more cyclic process to allow to iteratively address messy or inconclusive findings. Additional video guides on all activities would be helpful. **T2** reflected that a mini-lesson on data analysis should be embedded and that more modeling activities would be useful. **T3** stated that she would ask more questions to get students to process the information at more regular intervals.

4 DISCUSSION

The three case studies illustrate a surprising diversity in how the same technology and materials can be integrated in different classrooms and between years - in accordance with the different self-defined learning goals defined by the teachers. The teachers particularly valued **three key feature** about the BCL: (1) It is motivating for the students given that it is a new type of technology with unique interactions, (2) it enables quantitative data collection and analysis (and already in middle school), and (3) it is very flexible for teachers to select and to modify individual BCL and edX modules, and to then combine them with traditional teaching modules.

We identified several **design lessons** [16] for future cloud labs and inquiry-based education at scale: (1) Cloud lab features and experiment duration should provide an authentic experience. (2) The cloud lab should allow for thematically connected yet independent modular and customizable units consisting of activities and technological features that instructors can choose from - aligning with the 'low floor, wide wall, high ceiling paradigm' [37, 44]. (3) Relevant processes of experimentation and analysis should be automated, but not 'over-automated.' (4) Multi-dimensional, rich data formats should be provided that are accessible and modifiable for the instructor. (5) Professional development and scaffolding of learning materials should be provided to instructors to nurture their desire to develop agency over their course materials.

This study provides a possible **roadmap** to support various scientific inquiry-based or conventional learning. Scalable cloud experimentation platforms like this BCL can reach large numbers of K-12 teachers and students worldwide (e.g., millions of 1 minute long experiments per year at ~1 cent each [21]). Various student groups (incl. URM) can gain access to authentic science experiments remotely; moreover, the Covid-19 pandemic demonstrated the need for better online education technologies and learning approaches [4, 48]. Future studies should (1) involve more teachers and a deeper student assessment, (2) investigate other cloud labs, (3) investigate further synergy with local hands-on experiments and simulations, and (4) investigate how a wider distribution can be achieved, e.g., via commercialization or open access platforms.

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