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An interdisciplinary and application-oriented approach to teach microfluidics

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ABSTRACT

Microfluidics is a relatively novel interdisciplinary research area with broad applications in chemistry, physics, material science, and biology. Despite the rapid growth of the field, students' exposure to microfluidic technologies is still limited and often insufficient to appreciate the advantages over other commonly used technologies. To this end, we designed a five-day course, "Microfluidics for microbial ecology," in which students with very different backgrounds learn the basics of microfluidic technologies and sample a range of applications in microbial ecology. The course was created for Master and Ph.D. students interested in applying microfluidics to their research and, therefore, followed an application-oriented approach. The presentation of critical aspects of fluid flow phenomena at the microscale and an outline of the advantages and constraints of the technology provide students with the background to design and perform microfluidics-based experiments. In order to improve the effectiveness of learning in a class with diverse interests and backgrounds, two active learning exercises were implemented. The first comprised the design of an individualized microfluidics experiment in parallel with the lectures: students were guided to apply each module to their personalized application and discuss it in groups. The second was a group experimental activity, in which students jointly set up, performed, analyzed, and presented a microfluidics-based experiment. Given the multidisciplinary teaching context, the course was able to foster common conceptual ground and promote discussion among students. This application-oriented approach built upon experimental activities and in-class discussion is well suited to promote learning in a technology-related subject such as microfluidics.

I. INTRODUCTION

In recent decades, microfluidic technologies have made a significant impact in a number of fields of science.[1,2] Microfluidic devices take advantage of their small size and controlled flow conditions to allow an unprecedented degree of control over the experimental physico-chemical environment.[3,4] Microfluidics offers significant experimental advantages due to the reduced reagent volume required (and hence reduced cost), ease-of-use, reproducibility, full optical access, and an often high degree of biological inertness.[5,6] As a result, microfluidics is increasingly applied in the fields of human health, energy, and the environment.[1,7–10]

Due to its interdisciplinary nature, microfluidics provides a unique learning opportunity for students as they can apply it in a number of disciplines. However, despite these advances and applications, the development and use of microfluidic technology are not yet as well disseminated as its potential would suggest, especially among young scientists, or adequately represented in the literature on teaching.[11,12] Part of the challenge of teaching microfluidics is the range of interdisciplinary topics involved:

design and microfabrication, low Reynolds number fluid flow, microscopy and image analysis, in addition to the specific competencies needed to tackle the biology, chemistry, or physics of interest.[13] In the teaching context, the interdisciplinary nature of microfluidics can be exploited as a resource since crossing and uniting disciplines have been shown to promote students' engagement and stimulate critical thinking.[14,15]

The teaching of microfluidics in the literature has been categorized into two main groups: "teaching using microfluidics" and "teaching about microfluidics."[11,12] In the first category, microfluidics is used to facilitate learning in other disciplines and to illustrate fundamental physical, chemical, or biological principles. Chemistry has seen the most applications, both in high school[16] and undergraduate classes,[17–21] mainly due to the reduction of the quantity of reagents required[12] and the possibility offered by microfluidics to visualize chemical reactions in real time.[22] Based on the literature, microfluidics is currently less exploited in educational biology projects[12] with the exception of educational and artistic applications in the so-called biotic games, i.e., games that operate on biological processes.[23–25] Lab-on-a-chip platforms are increasingly being introduced in teaching,[26] motivated by positive outcomes in terms of student engagement and learning,[27] and increasing the number of publications on this topic would probably further increase their use. In contrast, in the second category, students learn about microfluidics itself: design and fabrication, physics of fluid flow at low Reynolds number, and chemical transport at the microscale. This second category is fundamental to educate future microfluidics users by making them aware of the practical advantages of this technology and capable of applying it to different research fields. However, the literature on teaching microfluidics is still very limited[12] and mostly focused on public engagement[23,25] and undergraduate teaching[11,16,17,22,26] rather than an audience directly involved in the research.

Given the need to prepare students with the ability to apply their knowledge to real-world situations, the STEM subjects (science, technology, engineering, and mathematics) are particularly suited to application-driven teaching, in which the basic principles of a discipline are taught by explicitly demonstrating their practical applications.[27–31] Application-driven teaching approaches include problem-based learning, which has revolutionized higher education, especially within professional training.[28,32] Application-driven teaching is often accomplished through a combination of interactive and animation-based tutorials, simulations, and associated hands-on experiments to demonstrate real-world applications. In addition, in-depth learning is fostered through a variety of active teaching and learning activities, like team projects, case studies, and instructor-assisted problem-solving sessions.[31] It has been shown that engineering principles are better understood when their practical implications are explained and demonstrated.[31] Problem-based learning has been fruitfully exploited to deliver the practical sessions of a microfluidic course.[27] However, to the best of our knowledge, the application-oriented approach has yet to be used to create a microfluidic course that includes both theoretical and practical teaching.

We here present an application-oriented microfluidics course, addressed to Master and Ph.D. students with different scientific backgrounds with the goal of enabling them to use microfluidic technologies in their own research. The core part of the five-day course was represented by two active learning activities integrated closely with lecturers. The first activity was the design of an individualized experiment in microfluidics that progressively incorporated the topics of the lectures. This activity was aimed at helping students to make a link between theory and application with a particular focus on their own research. Students were explicitly asked to find an application in which the use of microfluidic devices would enable an experiment that would otherwise be difficult or impossible to realize. The development of the idea was guided during the course and promoted through in-class discussions. The second activity was an experimental group activity, aimed at fostering learning and removing practical barriers to the application of the new knowledge. In groups, students designed and performed an experiment on a topic chosen by instructors to highlight fundamental physical phenomena relevant at the microscale, as well as the advantages and disadvantages of microfluidics. In this paper, we present the structure and benefits of the active learning activities implemented in the course and discuss how this approach assisted in the teaching of microfluidics to an audience with diverse research and educational backgrounds.

II. TEACHING APPROACH

A. Description of the course

The general learning objective of the course "Microfluidics for Microbial Ecology" was to teach students how to perform an experiment using microfluidics from the design through the data analysis. For logistic reasons, admission to the course was limited to 16 Master and Ph.D. level students. Students had very diverse backgrounds, including microbiology, chemical engineering, material sciences, and environmental engineering.

The course took place over five consecutive days. In the first three days, mornings were dedicated to lectures on theoretical and experimental principles of microfluidics, in which students were given a background in microfluidics and asked to interpret this information in the context of their specific fields. The lectures were specifically designed to provide an application-oriented knowledge of the basic notions required to understand and perform a simple microfluidic experiment. At the end of each lecture, the first active learning activity took place: students performed an individual learning activity in which they were assigned a written question that provided step-by-step guidance and inspiration to design an individualized experiment in microfluidics (see the supplementary material). In the afternoons, students were involved in the second activity, an experimental group activity in which they designed and performed an experiment with the aim of applying the notions learned and discovering first-hand the advantages and limitations of microfluidics (Fig. 1). The fourth day was dedicated to an overview of advanced applications of microfluidics to microbial ecology in order to illustrate how the general concepts could be adapted to and exploited in a specific field. In our case, the choice of microbial ecology was motivated by the background of the organizing groups and the yet-very-limited application of microfluidics in that field. Three postdoctoral researchers described their experiments during morning lectures with a particular focus on technical and applied aspects and presented live demos in the laboratory during the afternoon. The fifth and last day was allotted to the analysis of the data acquired during the group experimental activities and to the presentation of the results. In

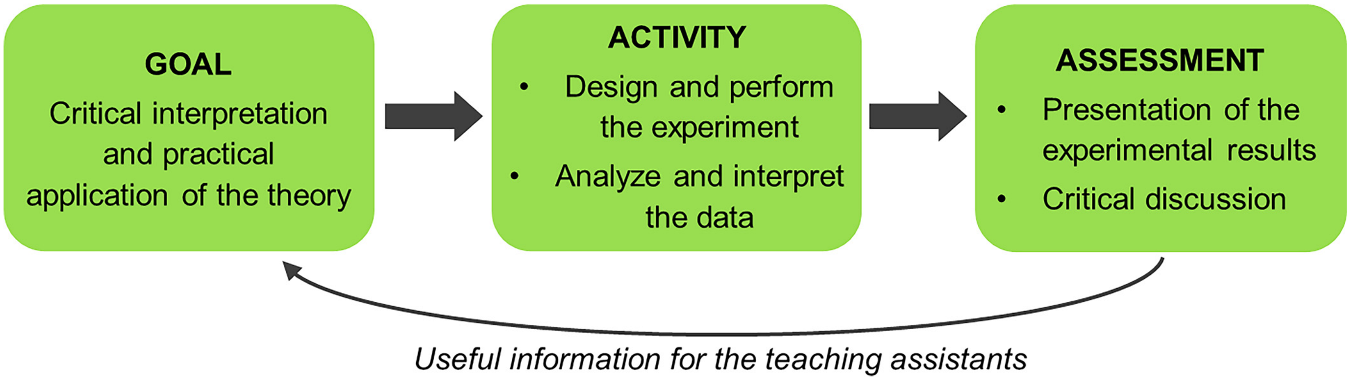

FIG. 1. The interactive nature of the group learning activity. Workflow of the group active learning activity developed in the course.

Table I, the program of the course held in 2018 is presented together with the learning objectives for each topic.

B. Description of the individual learning activity

The first active learning activity involved students individually developing a complete experimental plan for an application of microfluidics to their research. It was designed as a step-by-step activity after each theoretical lecture on the first three days in order to provide opportunities for students to directly explore the interface between the new material and their individual research interests. The goal was to help students to link the different theoretical topics while personalizing the information. To provide a foundation for this task, the lectures contained practical examples of applications. Students were encouraged to critically discuss their developing ideas in small groups and with the lecturers in order to benefit from the diversity of perspectives given by the interdisciplinary environment.

After the introductory lecture on microfluidics, students were asked to identify a question in their research where they considered that a microfluidic experiment could provide advantages in comparison with their current approaches. In the ensuing sessions, they progressively defined the experiment by adding technical details on the experimental setup, the type of data to be gathered, and the data analysis to be performed. The task was guided by specific questions that were provided to students after each lecture (supplementary material). The questions and format were based on our experience in designing microfluidic experiments and on the guidelines given to former Ph.D. and Master students working in our group when teaching them how to start their own projects. After each step, students were encouraged to refine their previous work based on the additional knowledge acquired. Typically, 15 min were allotted to answer the questions after each theoretical lecture with the lecturers available to provide feedback.

While specific questions are reported in the supplementary material, the topics covered can be summarized as follows:

- *Introduction to microfluidics:* Students formulate their scientific question and underline the benefits of using microfluidics for their application.
- *Setup and fabrication:* Students design the experimental setup, focusing on the microfluidic chip geometry.
- *Methods:* Students identify the most suitable experimental technique, in terms of which biotic and abiotic parameters will be varied, and what data will be collected.
- *Simulation:* Students describe the expected hydrodynamic conditions in the microchannel and identify those aspects that they would further investigate with simulations.
- *Post-processing:* Students identify the data that would be gathered and decide how they would be analyzed.

During the discussions with lecturers and peers at the end of each session, students were asked to discuss their choices based on the criteria given during the lectures, allowing the lecturers to probe the level of understanding and to further explore, individually or with the whole class, difficult or unclear concepts. By fostering discussion between students, the design of this activity allowed students to benefit from the advantages of peer learning and peer assessment, which has been shown to promote responsibility for individual learning and to deepen the understanding of specific course content.[33–35]

C. Description of the group learning activity

The second active learning activity was an experimental group activity designed to provide a hands-on learning experience. It was designed to give students experience in developing and performing a simple microfluidic experiment, collecting and analyzing data, and presenting results with topics chosen by the lecturers to illustrate one of the basic principles of microfluidics presented during the lectures. The preparation and execution of an experiment is an authentic research task for students that promote critical thinking skills and collaboration (Fig. 1). As we describe below in the evaluation of the course, the choice of topics enhanced the benefits of the active learning activity: students gained a sense of the practical advantages and also of the challenges of microfluidic experiments and obtained direct experience of the concepts presented during the lectures.

The activity was explained at the beginning of the course in the context of the learning objectives (Table I). Information about the logistics, milestones, and expected outcomes were explained by the

TABLE I: Program of the "Microfluidics for Microbial Ecology" course held in 2018 at ETH Zurich (Course code No. 102-1248-00L).

	Lectures	*Learning objectives*
Day 1		
Morning and afternoon	- Introduction to fluid dynamics for microfluidics (1 h) - Microfabrication techniques for microfluidics (2 h) - PDMS casting and plasma bonding (Practical activity, 2 h)	Students are able to identify the differences in the physics at the macroscale and at the microscale They understand the different microfabrication techniques and can compare them. They can design the device suited for their individual project (*individual learning activity*)
Day 2		
Morning	- Swimming at low *Re*: bacterial behavior in microfluidics (1 h) - Computational fluid dynamics (CFD) (1 h) - Microfluidics experiments: tips and tricks (1 h)	Students are able to identify the peculiarities of hydrodynamics at the microscale. They are able to predict the flow conditions in their experimental geometry by generalizing the information given in the lectures and estimate the impact on mass transport (*individual learning activity*)
Afternoon	*Group experimental activity (block 1)* Design of the experiment (1 h) and group discussion (1 h)	Students are able to combine the information given by teaching assistants with the notions learned during the lectures, in order to design the experimental conditions they want to implement in the laboratory
Day 3		
Morning	- Image processing applied to microfluidics (3 h)	Students are able to identify the data acquisition and analysis protocol suited to both group and individual microfluidics experiment and to predict the possible challenges *(individual learning activity)*
Afternoon	*Group experimental activity (block 2)* Experimental session in the laboratory (5 h)	Students are able to perform the experiment in the lab, with the help of teaching assistants
Day 4		
Morning/afternoon	- Ecological dynamics in microfluidics (2 h) - Droplet-based microfluidics (2 h) - Microfluidics-based chemotaxis studies (2 h)	Students are able to analyze the advantages and disadvantages of the technology, based on demonstrations of practical applications of the information given in the previous days to microbial ecology
Day 5		
Morning	*Group experimental activity (block 3)* Data analysis and preparation of the presentation (4 h)	Students are able to analyze the data and interpret the results, based on the theoretical notions presented during the course
Afternoon	*Group experimental activity (block 4)* Presentation of the results and collective discussion (2 h)	Students are able to present their work and critically compare experimental approaches

organizer and provided in a written document. The sixteen students were divided into four groups. Before the start of the course, students had provided information about their training and about the reasons why they were interested in microfluidic technologies. This information allowed the organization of groups composed of students with different backgrounds and educational levels. The group composition was crucial to foster interdisciplinary interaction, promote the sharing of previously acquired knowledge, and provide heterogeneous perspectives, which we found to be highly beneficial in learning an interdisciplinary technology like microfluidics. The experiments were different for each group and were assigned (as far as possible) based on the students' interests and the potential to aid them in later applying microfluidic technologies to their own research project. The experimental activity was performed using the research laboratory space and equipment of the organizing groups. In order to provide troubleshooting and ensure the proper use of the equipment, each group was supervised by a teaching assistant, chosen among experienced Ph.D. researchers from the organizing groups.

The experimental group activity was divided into four blocks with the following content and goals (Table I):

- *Block 1*: Each group was given supporting material in the form of one or two research papers, a list of available equipment and consumables, and guidelines to help students at different stages of the activity. Each group planned how to set up the experimental activity during a group discussion. This first block had a duration of 2 h, the first hour dedicated to an individual examination of the material and the second hour to the discussion. Comprehension and analysis skills were trained during the examination of the supporting materials, while the discussion step provided practice in evaluation and planning. The discussion took place under the supervision of the teaching assistants, who provided feedback on the feasibility of each phase of the experiment, estimated its duration, and highlighted potential problems that could arise. The supervision during this block was essential to ensure efficient use of time and resources in the laboratory.

- *Block 2:* Students performed the experiment and collected data, making decisions based on the experimental plan developed during block 1. During the laboratory session, troubleshooting was required and the students were supported and helped to make the next step themselves by the teaching assistants, who monitored group activity and intervened when doubts or difficulties emerged. In order for students to think on their feet, they had to employ deductive reasoning, practical thinking, and understand what was happening in the lab to react and solve problems in real time.
- *Block 3*: Students analyzed data, critically discussed the results in light of the notions presented in the lectures, prepared the presentation, and assisted by teaching assistants during the analysis.
- *Block 4*: Groups presented and discussed the results in front of the class. The presentation (10 min) was followed by a discussion (15 min) with the class, in which students were actively involved and were able to critically revise the concepts presented in the lectures. Learning was consolidated by promoting discussion in the class and comparing the results of the different groups based on the notions presented during the lectures.

During this course, the organization of the experimental activity in groups facilitated the accomplishment of the tasks, enhancing the students' transdisciplinary competences[33,34] and promoting the sharing of experimental skills previously acquired in very diverse scientific and engineering fields.[36] In addition, the benefits of peer learning and peer assessment were exploited both during the execution of the experiment and during the presentation of the data.[33–35]

The experiments performed by students during the group activity, summarized below, were chosen to illustrate important concepts in microfluidics that had been presented during the lectures. All experiments were performed on inverted microscopes (Ti-Eclipse, *Nikon*, Japan) equipped with digital cameras (ORCA-Flash4.0 V3 Digital CMOS camera, *Hamamatsu Photonics*, Japan). The microfluidic devices were made using polydimethylsiloxane (PDMS) and bonded to glass slides following standard procedures.[5] The results obtained by the students are reported in the figures.

- **Group activity 1: Glucose detection in a microfluidic chip.**

The goal of the experiment was to measure the glucose concentration of a solution using a glucose assay kit (MAK013—glucose and sucrose assay kit, *Sigma-Aldrich*). In the assay, glucose is oxidized via glucose oxidase, resulting in the emission of a fluorescent signal ($\lambda_{ex} = 535$ nm, $\lambda_{em} = 587$ nm) proportional to the glucose present. The kit is routinely used to assess the glucose concentration in biological fluids. In the experiment run by students, a glucose solution at a known concentration (1 mM or 0.01 mM) was flown through one arm of a Y-shaped microfluidic channel [channel width 600 μm, height 100 μm, and total length 5 cm; geometry shown in Fig. 3(a)], while the solution of the assay kit was flown in the other arm. Images at different positions in the channel were acquired using epifluorescence microscopy [10× magnification; Fig. 2(a)], and average fluorescence intensity [Fig. 2(b)] was measured using ImageJ (NIH). Through this experiment, students were able to quantify mixing using the fluorescent signal emitted as glucose was oxidized and gain a sense of the time required for mixing of solutions in a laminar regime.

- **Group activity 2: Viscosimeter on a microfluidic chip.**

The goal of the experiment was to measure the viscosity of a Newtonian and a non-Newtonian solution using the microfluidic viscosimeter presented in Refs. 37 and 38 [Fig. 3(a)]. Students determined the viscosity of glycerol (G9012—glycerol, *Sigma-Aldrich*) aqueous solutions at different concentrations [Fig. 3(b)] and of a 0.5% xanthan gum (*Jungbunzlauer AG*) solution as a function of shear rate [Figs. 3(c) and 3(d)] using a Y-shaped microfluidic channel [channel width 600 μm, height 100 μm, and total length 5 cm; Fig. 3(a)], following the procedure described in Ref. 38. Fluorescein at a final concentration of 0.1 mM was added to the reference solution. Images were acquired using phase-contrast and epifluorescence microscopy, and image analysis was performed using ImageJ (NIH). Through this experiment, students were able to see how conventional instruments can be miniaturized using microfluidic technologies, allowing the reduction of experimental costs and the possibility of parallelization via multiple chips.

- **Group activity 3: Flow characterization in a model porous medium.**

The goal of the experiment was to characterize the flow field within a pore of a model porous medium [microfluidic channel width 5 mm, height 100 μm, and length 3 cm, containing pillars of diameter 100 μm at an edge to nearest edge spacing of 100 μm; Fig. 4(a)]. Suspensions of polystyrene particles (diameter 0.5 μm; 3000 Series Nanosphere™ Size Standards, *Thermo Scientific*) at different concentrations (volume fraction ranging from 10^{-3} to 10^{-5}) were flown through the channel, and images were acquired using phase-contrast microscopy and a digital camera (20× magnification and 200 fps). Depending on particle concentration, the velocity field [Fig. 4(b)] was quantified using algorithms for particle tracking velocimetry (PTV; volume fraction 10^{-5}) or with particle image velocimetry (PIV; volume fraction 10^{-3}). The image analysis was performed in Matlab (The Mathworks) using in-house algorithms. Through this experiment, students were able to characterize a laminar flow field around obstacles and understand the advantages and limitations of different velocimetry techniques. Besides being a powerful tool for the characterization of velocity fields, particle tracking algorithms are used in microbial ecology applications to track single bacterial cells in the study of dynamic microbial processes.[7]

- **Group activity 4: Droplet-based microfluidics.**

The goal of the experiment was to produce water-in-oil droplets using a microfluidic device in the form of a flow-focusing droplet generator (Fig. 5). Silicon oil (378364, *Sigma-Aldrich*) was used as a continuous phase with de-ionized water as a dispersed phase. First, the influence of the channel wettability was studied by comparing the performance of uncoated and coated channels. The coating with hydrophilic polyacrylic acid (PAA) was performed following the procedure presented in Ref. 39. Finally, the flow rates of

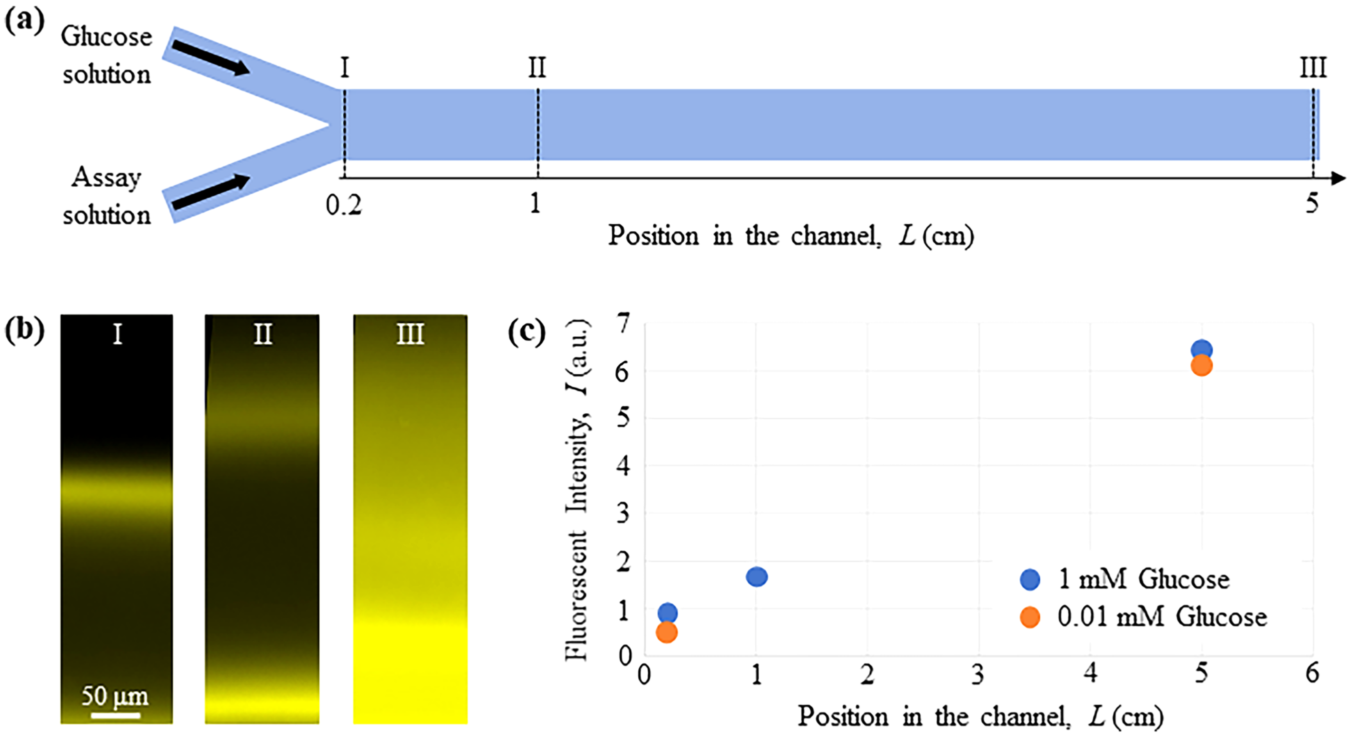

FIG. 2. Glucose detection in a microfluidic chip (group activity 1). (a) Sketch of the Y-shaped channel. (b) Fluorescence images of the microfluidic channel taken at different distances from the junction [0.2 cm in Sec. I, 1 cm in Sec. II, and 5 cm in Sec. III, as shown in panel (a)]. The channel walls are located at the top and bottom of the images. The increasing fluorescence intensity with distance is due to the increasing amount of glucose in the initial solution (1 mM) that was oxidized by the assay solution as the two solutions mixed. (c) Average fluorescence intensity measured in regions of the channel (dimensions $600 \times 600\,\mu m^2$) at different distances, L, from the junction, for initial glucose concentrations of 1 mM (blue) and 0.01 mM (orange). Intensity differences were not detected between the two glucose concentrations because at both concentrations the fluorescent signal produced by reaction had already reached saturation at 0.01 mM of glucose.

the dispersed and continuous phases were varied, and the impact of these parameters on the droplet generation frequency and droplet size were quantified. The size of the droplets was measured from images acquired using phase-contrast microscopy[40] with ImageJ (NIH) used for image analysis. This experiment allowed students to better understand the challenges and the possibilities of droplet-based microfluidic approaches. For example, during lectures, the students were able to watch experiments in which the isolation of single cells was accomplished in a droplet-based microfluidic device, and projects in which droplets were being used as individual micro-reactors for the synthesis of nanomaterials (e.g., for the synthesis of perovskite or quantum dot nanoparticles).

III. EVALUATION OF THE COURSE

A. Evaluation of students' learning

One of the advantages of this course format is the possibility to infer students' learning at several stages of the course and to immediately fill conceptual gaps to strive for a homogeneous level of understanding in the class.

The active learning activity involving the design of an individualized microfluidic experiment enabled instructors to understand how successfully students were able to immediately apply the theoretical topics covered in lectures to their experimental project. During this activity, the lecturer was available to discuss the topics with students, answer their questions, and infer the level and quality of learning of each student. At the end of the course, the students discussed their individual projects, giving instructors the opportunity to make a cumulative assessment of the quality of learning.

Similarly, the group learning activity allowed instructors to understand what students had learned by[41]

- *Monitoring group activity*: teaching assistants, during the supervision of the practical activity, could continuously infer the level of learning and intervene if misunderstanding arose. The ability of the students to argue their choices regarding the experimental procedure and to explain the experimental observations using the notions presented in the course was monitored. This allowed instructors to determine whether the overarching learning objectives of the course had been achieved.
- *Reviewing the quality of presentations with regard to the learning objectives*: both the presentations and the following discussions provided a measure of the level of understanding of individuals and the level of critical revision of the concepts presented during

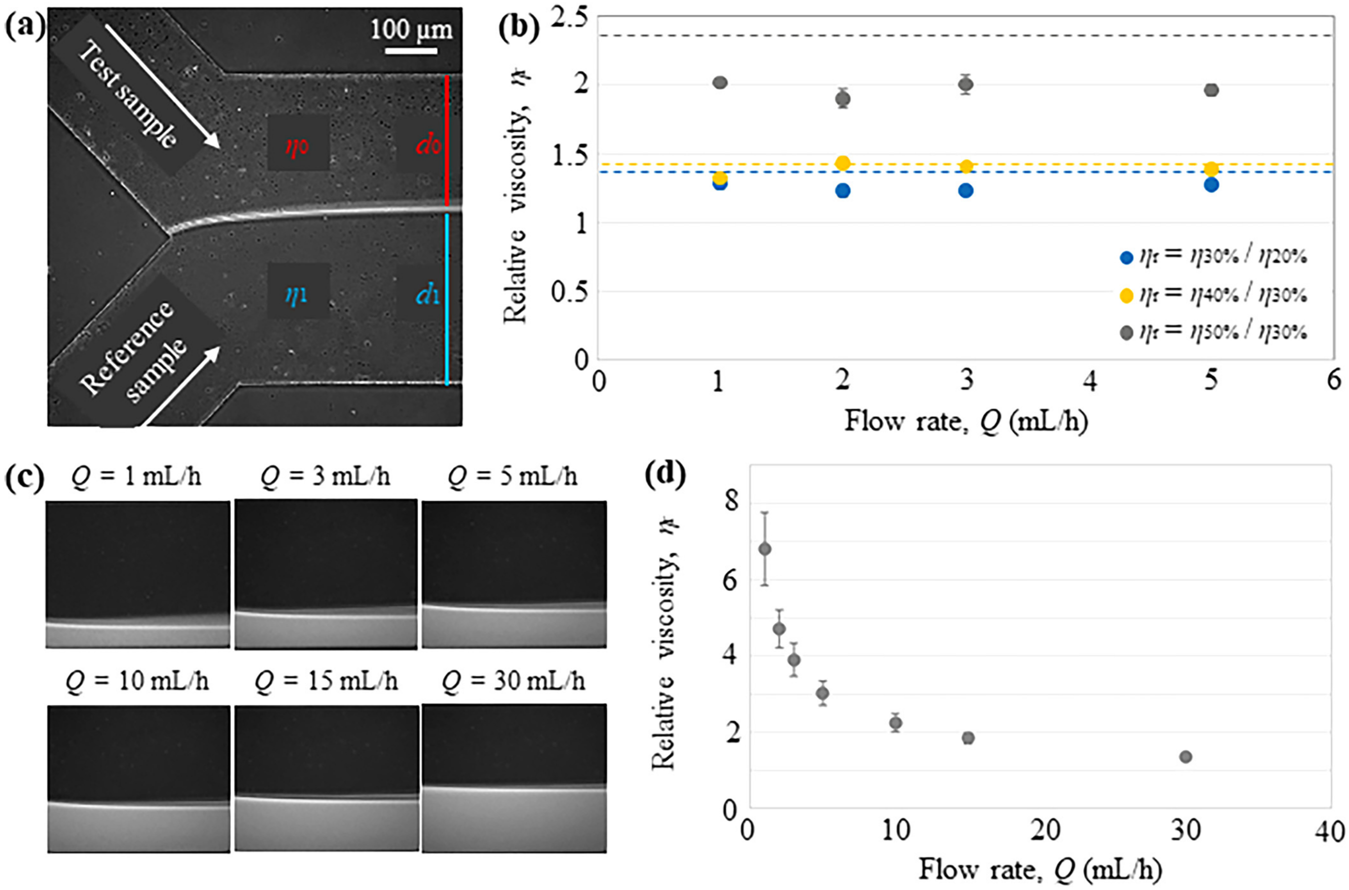

FIG. 3. Viscosimeter on a microfluidic chip (group activity 2). (a) Phase-contrast image of the Y-shaped channel. The arms are 300 μm wide, while the main channel is 600 μm wide. (b) Relative viscosity, η_r, defined as the ratio between the viscosity of the two fluids and measured as the ratio of the lateral width d_0 and d_1 that they occupy,[37,38] plotted against the flow rate for glycerol solutions at different concentrations (20%–50%, given as subscripts in the legend). Dotted lines indicate the expected values of the relative viscosity based on values found in the literature for water–glycerol mixtures. (c) Fluorescence images of the parallel flow of the 0.5% xanthan gum solution (upper part of the images) and the glycerol–water mixture (glycerol 60% by weight; lower part of the images) at different flow rates. Fluorescein powder was added to the mixture of water and glycerol to a final concentration of 0.1 mM. Scale bar is 100 μm. (d) Relative viscosity, η_r, of the 0.5% xanthan gum solution and the glycerol–water mixture (60%) as a function of the flow rate. Due to the non-Newtonian behavior of the xanthan gum solution, shear thinning behavior is observed.[37]

the lectures. Since the discussion was open to teaching assistants, it gave them the opportunity to directly provide feedback on students' contributions by relating them to the learning objectives.

B. Evaluation of the teaching

At the end of the course, an anonymous survey for the evaluation of teaching was given to students. Questions were selected from ETHZ's survey tool (using the ETH *Select Survey* portal). In particular, evaluation of the active learning activities was focused on the following questions, graded on a five-point scale:

A. The in-class exercises contributed to my understanding of the material.
B. The practical work contributed considerably to the understanding of the subject.
C. The practical exercises supported the learning of the scientific working method.
D. How satisfied were you with the practical activities?

Before delivering the survey, students were informed that the "in-class exercises" referred to the design of the individualized microfluidic experiments and the "practical work" to the group experimental activity.

IV. RESULTS

The active learning activities, namely, the design of the individualized microfluidic experiment and the group experimental activity, were found to be effective in promoting the learning of microfluidic technologies and increased the overall student satisfaction.

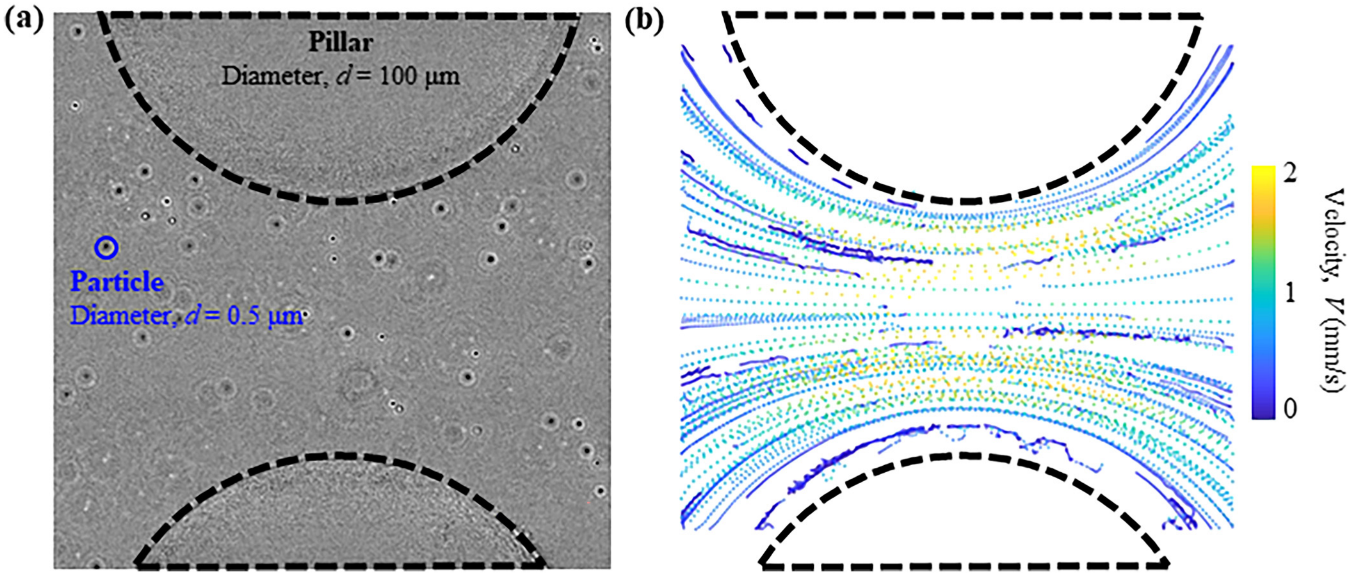

FIG. 4. Flow characterization in a model porous medium (group activity 3). (a) Phase-contrast image of the polystyrene particle suspension (particle diameter, $d = 0.5\,\mu$m; volume fraction 10^{-5}) within a pore space between two pillars. Flow (1 ml/h) is from right to left. (b) Particle trajectories obtained for the suspension shown in (a). Trajectories are color-coded according to instantaneous velocity values.

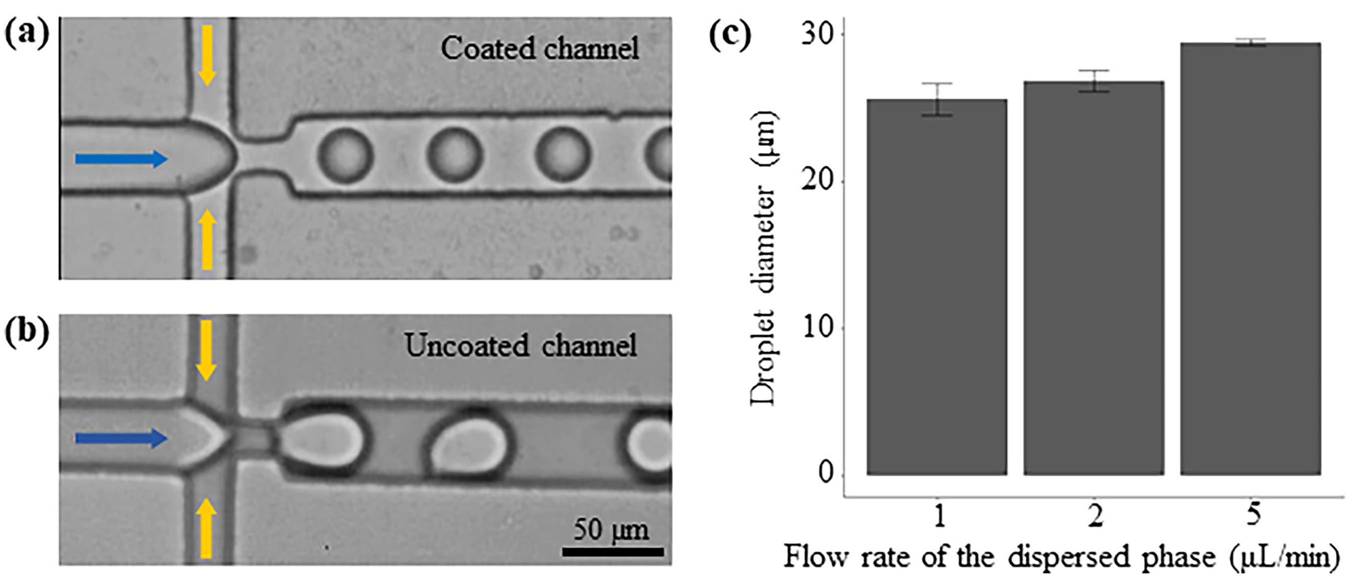

FIG. 5. Droplet-based microfluidics (group activity 4). (a) Phase-contrast image of oil droplet formation in a flow-focusing droplet generator at flow rates of $5\,\mu$l/s for the continuous phase (water, light blue arrow) and $1\,\mu$l/s for the dispersed phase (silicon oil, yellow arrow) in a channel coated with hydrophilic polyacrylic acid (PAA).[39] (b) Water droplet formation at flow rates of $3\,\mu$l/s for the continuous phase (silicon oil) and $1\,\mu$l/s for the dispersed phase (water) in an uncoated channel. (c) Oil droplet diameter as a function of the flow rate of the dispersed phase (silicon oil), formed in the coated channel of panel (a). The flow rate of the continuous phase (water) was fixed at $5\,\mu$l/s. Error bars show the standard deviation of 1000 droplets.

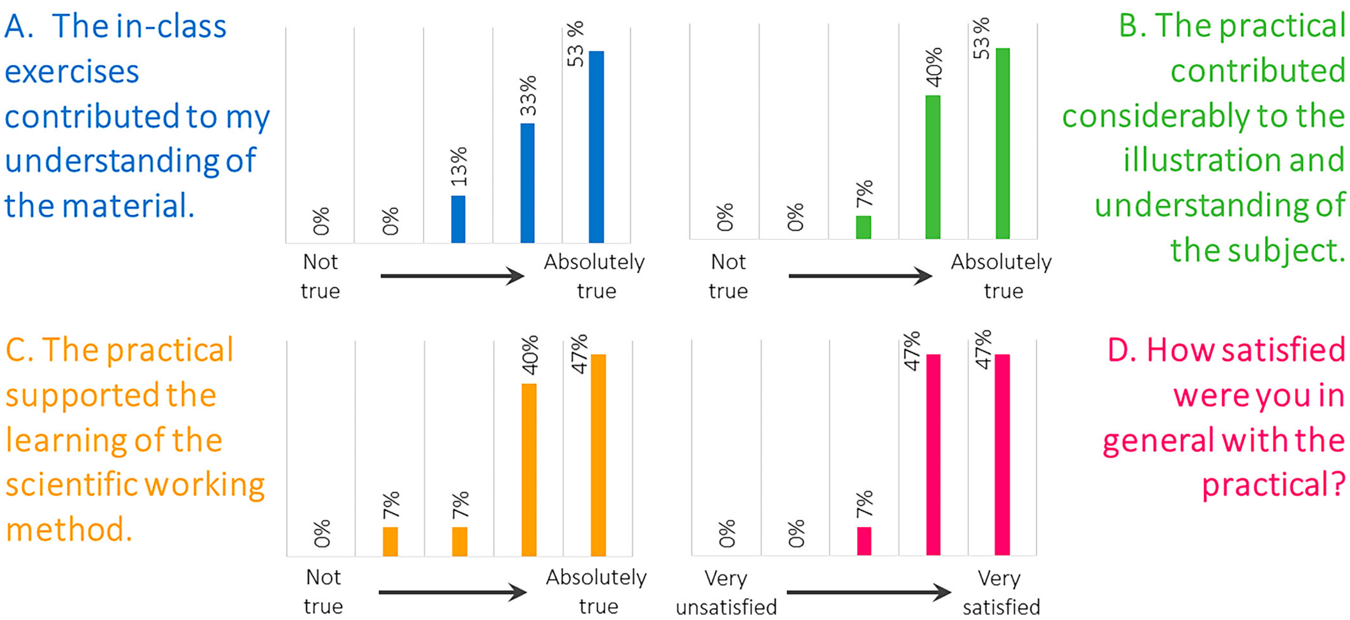

FIG. 6. Results of the written survey for the evaluation of teaching for the 2018 edition of the course. Based on ETH survey guidelines, "Not true" or "Very unsatisfied" correspond to a value of 1 and "Absolutely true" or "Very satisfied" correspond to a value of 5. The best possible mean value is 5; values of 3–3.5 are satisfactory, and values of 3.6–5 are very good.

During the design of the individualized microfluidic experiment, all the students were able to meaningfully answer and discuss the working questions (the supplementary material) based on what they had learned in the preceding lectures. In this way, students successfully designed a microfluidic experiment related to their research through this active learning exercise. In the present paper, we do not report the results of this active learning activity because the projects resulted in innovative applications of microfluidics to the specific research of the students. Discussions with lecturers showed that all the students made the effort to link theory with practical applications. The discussions established with peers demonstrated their enthusiasm and interest in this synergistic action. In addition, this activity was found to be highly effective in detecting gaps in understanding on topics, which enabled the lecturers to address them within the individual discussions. Typical gaps in understanding concerned the theoretical principles underlying the working of the presented experiments, especially when they were not intuitive based on macroscale everyday experience. For example, the delayed mixing of two miscible fluids flowing side-by-side was the subject of several questions and required repetition of the implications of the laminar regime.

During the group experimental activity, all groups were able to complete the experiments and analyze the data in the allotted time slots. The experimental results were in line with the expectations of the organizers, showing that the experimental procedures were implemented correctly and the data analysis was effective. During the experimental activity, students were involved, enthusiastic, and willing to cooperate. During the presentation, all groups were able to highlight the main take-home messages of their experiment and to report advantages and disadvantages of the technology that had emerged during the practical work. They actively took part in the collective discussion following the presentations. Through continued contact with students since the course, we are aware of several students who have incorporated microfluidic tools into their research, proving that after the course they were able to independently set up a microfluidic platform and perform experiments.

The written survey to evaluate teaching revealed that more than 80% of the students found that the design of the individualized experiment (described as "in-class exercises" in the survey) contributed to their understanding of the material [Fig. 6(a)]. In addition, more than 80% of the students thought that the group experimental activity (described as "practical" in the survey) was beneficial to their understanding of the subject and supported the learning of the scientific method [Figs. 6(b) and 6(c)]. More than 90% of the students declared themselves to be satisfied with the course [Fig. 6(d)]. The main suggestion about the group experimental activity concerned the time dedicated to data analysis (*block 3*), which according to 30% of the students should be increased in order to further promote group discussion. However, the majority of the students confirmed their appreciation of the application-oriented approach to teach microfluidics and expressed their desire to use this technology in future projects.

V. CONCLUSIONS

Both the evaluation of the student learning and the written survey to evaluate teaching revealed that the active learning activities promoted learning in line with the learning objectives of the course and increased student satisfaction. By promoting scientific discussions among students and with lecturers, these two activities favored active learning and critical thinking and enabled lecturers to assess students' learning.[42] Critically, this approach also provided an authentic experience of research using microfluidics, which helped students to understand the extent to which this technology could be beneficial for their scientific projects. Due to its success, the course was repeated with the same format in 2019, and student satisfaction was in line with that reported for the 2018 edition.

The design of the individualized experiment contributed to the learning process and the critical understanding of the notions presented in the course by fostering discussions on each lecture and creating a link to the current research of each student. During the group experimental activity, the learning objectives were successfully met: students were able to perform a microfluidic experiment and to understand the microfluidic elements involved. While the quality of the presentations of the different groups was homogeneous and high, the level of critical interpretation of the results of the individual students was more heterogeneous. In our opinion, this heterogeneity strongly depended on the educational level of the students (Master vs Ph.D. students), their background, and research experience. In view of this, we think that the choice of working in groups was crucial to the overall learning success of the students since it helped individuals to increase their learning through a group discussion that gave them the opportunity and motivation to remedy their individual gaps within a cooperative environment. In addition, during this activity, students had the chance to interact with peers from other scientific disciplines, make connections between concepts from different fields, and to learn how to establish a common conceptual ground, which is essential when approaching an interdisciplinary technology like microfluidics.

The course format presented is very flexible and can be adapted according to the teaching context and the department where it is hosted. The course we implemented had a particular focus on microbial ecology, which was concretized in the lectures dedicated to the presentation of research applications (Day 4 of Table I). The other lectures treated microfluidics in general and included examples of applications to chemistry, material sciences, and biomedical engineering. The focus of the course can be shifted to other disciplines by simply changing the type of research applications that are presented. In addition, we designed a course aimed at Master and Ph.D. students for an audience that had already gained some maturity and experience in research and who would have the opportunity to rapidly transfer the knowledge gained to research applications. However, it could be easily adapted to the undergraduate level by tailoring the information content of the lectures based on the students' knowledge and background.

To summarize, the application-oriented approach is particularly well suited to teach microfluidics to students at the Master or Ph.D. level since giving them authentic tasks increases their level of understanding and trains their cooperation and interdisciplinary communication skills.

SUPPLEMENTARY MATERIAL

In the supplementary material, we report the questions given to students at the end of the lectures (Table I) to guide them in the task of developing their individualized experiment in microfluidics.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon request.

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