The Biophysicist

Open Microscopy in Challenge-Based Learning

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ABSTRACT Microscopy is an essential technique in biology, chemistry, and physics. Therefore, training in microscopy is crucial in science education. However, there is a gap between theory and practice because microscopes are perceived as "black boxes" rather than instruments that use geometrical and wave optics to provide an image. Active learning methods such as challenge-based learning can bridge this gap. We present a challenge-based learning course using the open-source microscopy platform UC2 to encourage students to answer a relevant research question while exploring the anatomy of microscopes. The students follow a full research path, in which they start with the design of a microscope, followed by building, calibrating, and using it for sample analysis. We describe how we designed the course, which components we added as options for the students, and how we encouraged the students to think outside the box. The challenges we offer are open and versatile and tailored to the interests of the students. We describe what results the students obtained and how the course was received by the students. When the students successfully fulfill all the requirements of the course, we believe we give them the tools they will need in future microscopy projects, from choosing the correct microscopy setup to scientifically correct processing of the data.

KEY WORDS challenge-based learning; microscopy; imaging; open source

I. INTRODUCTION

In the fields of biology, chemistry, and physics, microscopy is an essential technique. Microscopes are among the most used tools by many researchers, and training in microscopy is a fundamental part of science education. This is not an easy task because of the technical complexities of imaging, the multidisciplinary nature of optical imaging, and the continuous developments in the field. Indeed, optical microscopy is in continuous evolution, and new methods are continuously developed, hundreds of years after the development of the first microscope (1).

To be a skilled microscopist, it is essential to connect theory and practice. Mastering geometrical and wave optics is crucial to understand what is inside the microscope instead of treating it like a "black box." However, theoretical optics may be perceived as very abstract by students and disconnected from practical applications. Operating a microscope in a real setting is, of course, also important, and it is often taught in internships and practical laboratory experiments. However, this typically happens years after the initial training in optics; therefore, concepts and notions may have been lost. This gap between theory and practice is a serious challenge in optical microscopy education.

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Nowadays, active learning methods, such as challenge-based learning (CBL), stimulate students to learn theory in a more hands-on way. Due to this teaching approach, the barrier between teacher and students is lowered, and students are engaged in the learning process. With hands-on tasks and by thinking about what they are doing, students develop skills that require higher-order thinking, such as analysis and evaluation (2). Thus, students are more creative and more encouraged to think critically, which could potentially promote personal growth (3). Optics is a suitable candidate for active learning because there is a large practical component in which the exploration of microscopy configurations is easily connected to scientific challenges that interest the students (4–6). Therefore, implementing CBL for microscopy is an interesting option. However, microscopes are usually expensive equipment, with sensitive components, making it hard for every student in a course to have access to a microscope. In addition, the microscopes traditionally used in a lab are closed boxes, resulting in low visibility of the optical components.

Recently, open microscopy has emerged, and microscopes are built from affordable materials, with open frameworks that can be shared with other labs (6–8). Examples of open microscopy initiatives are UC2 (7), OpenFlexure (8), FlyPi (9), μCube (10), miCube (11), and OpenSPIM (12). In these initiatives, protocols for building and image analysis can be shared by properly documenting the protocols and publishing them with open access, allowing for straightforward implementation and improved reproducibility of results. For microscopy, this usually entails sharing the bill of materials, guidelines for setup, component designs, and video tutorials. By explaining in the guides why each component is applied, new users learn about the technique, and they can apply it in other projects (6). In terms of costs, the initiatives usually consist of materials that are easily accessible for any researcher in any country. For instance, 3-dimensional (3D)–printed materials are often used for the body and the holders for the optical components. Furthermore, smartphone cameras are often very powerful and perfectly suitable for microscopy, and nowadays almost every student has one, eliminating the need to purchase expensive pieces of equipment. Combined, this allows for modular and cheap microscopes that can be used for teaching optics on a large scale.

Here, we describe a microscopy CBL course that makes use of open microscopy initiatives and applies them to real-life challenges within the Department of Biomedical Engineering at Eindhoven University of Technology (The Netherlands). In this course, a colearning environment is created, allowing a large number of students to build their own microscopes, with steps to solve real-world microscopy-related problems.

II. SCIENTIFIC AND PEDAGOGIC BACKGROUND

A. Approach

The course is designed for second-year bachelor students in the Medical Sciences and Technology program at Eindhoven University of Technology. The course is also open as an elective for other departments, such as mechanical engineering and physics, where microscopy also plays a prominent role, as well as for master's students in biomedical engineering. During the course, the students learn the concepts of microscopy with active learning. The course is shaped as CBL and contains concepts relevant to engineering education such as collaboration, an iterative approach, practicing science, and, most importantly, scientific relevance. The students are presented with challenges that they must tackle. These scientifically relevant challenges come from the faculty's research groups; the students use microscopy theory to solve challenge questions that are unanswered. These challenges are, thus, based on real-world examples, meaning the challenges are open ended and can be tackled in multiple ways. During the course, the research groups will be involved as challenge owners, which the students can approach to ask for advice or feedback regarding the samples. CBL is based on a collaborative colearning environment, where

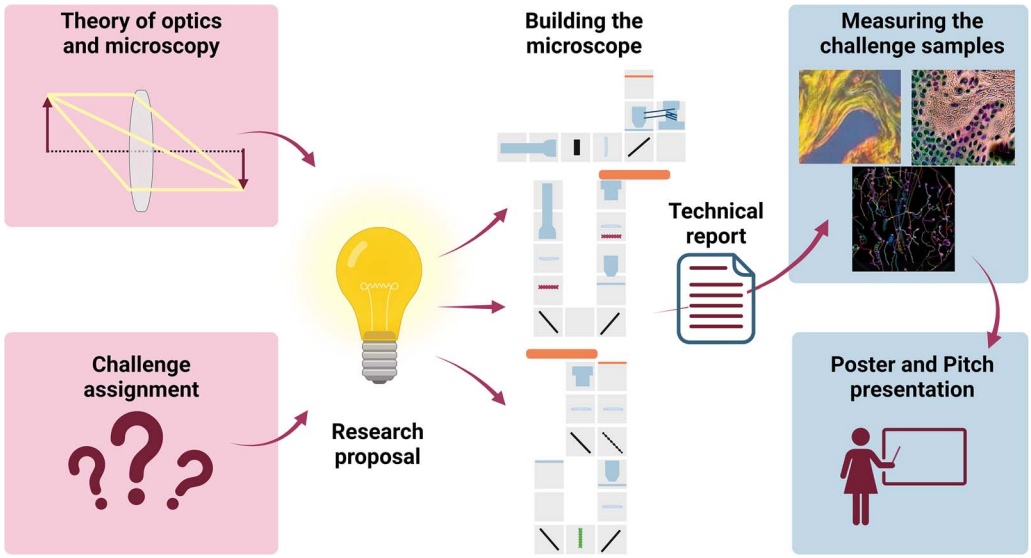

Fig 1. Workflow of the course. Students start with theory of optics and microscopy, and they will be presented a challenge. They apply the theory to come up with a research proposal to solve the question of the challenge. This is followed by converting ideas into a self-built microscope. This microscope is then tested, which is reported in the technical report and used for measuring the challenge samples and to answer the research questions. The results will be presented in a poster pitch presentation. Created with BioRender. Tholen, M. (2025) https://BioRender.com/c67c130.

not only the students are the learners but also the teachers and the challenge owners. This allows the students to learn more about collaborating and communicating within a project group and with the challenge owners. The teachers are information experts, knowledge collaborators, and coaches; this will be more elaborately discussed in later sections (13, 14).

The structure of the course is shown in Figure 1 and Supplemental Figure S1. The first step is the foundation and includes a few lectures about the basics of optics and microscopy. The purpose of lectures is to provide basic knowledge, with all students starting from the same page. The students will research more specific optics knowledge related to the challenge.

After the first lecture, the challenges are presented by the challenge owners (usually a PhD student, postdoc, or professor of the research group from which the question originates), and the students can indicate which challenge they prefer. Within the course, 7 different challenges are offered, which all come with different sub-challenges. Challenges can have more emphasis on the microscope design, the automation of the process, the data processing, or a specific biological application of imaging. By choosing, the students feel relatedness, which is one of the components of the self-determination theory by Ryan and Deci (15). To answer these research questions, the students need to work in small groups (4 to 5 students) that are assembled on the basis of preference for a topic (greatly relating to the autonomy part of the aforementioned self-determination theory). Together, they will perform a theory-supported trial-and-error iterative learning process, granting them a deeper understanding of the theory. All projects are adaptable, so students that want to put more effort in can make the project more challenging. Supervision during the practical part of the course is done by the responsible teachers, 1 or 2 researchers (PhDs or postdocs), and 3 student assistants for a group of ∼50 students. These supervisors are available for questions and feedback on the tinkering process, to keep them away from a rabbit hole, as well as for support on the coding part of the course.

B. Assessment

Within the course, students are assessed by 3 assignments: a research proposal presentation; a technical report; and a final poster pitch presentation. The first time the students are assessed is in

the second week of the course (Figs 1 and S1). As a group, they have formulated a research proposal, in which they discuss what the challenge is, which microscopy setup they envision building to answer it, and which data analysis methods they are going to use. This assessment is a group grade and accounts for 30% of the final grade. It is assessed by the responsible teachers, the teaching assistants, and the challenge owners with a rubric.

Halfway through the course, the students write a technical report based on the design. This is not intended to be a long report on all activities, but rather a technical description of the final prototype and its performance. Beforehand, they receive a list of possible calibrations and additional questions that need to be answered. They choose which calibrations should be performed for the system. For instance, for some microscopes, a stability test is required; however, other challenges need high resolution, so resolution calibration should be more extensive. Furthermore, they must validate the technical details of the system, such as magnification and pixel size. This report is a group product and is graded by the teachers. The report is assessed on the basis of an answer model and accounts for 30% of the final grade.

At the end of the course, the students will present results in a poster pitch presentation. The setup is mostly like a poster session at a conference, where the assessors, invited researchers, and students walk around. Each group member should be able to do the pitch (2-min elevator pitch) and answer questions. Assessment is again based on a rubric and contributes to 30% of the final grade. All challenge owners, teachers, and student assistants are involved in formulating these grades.

To grade the student's contribution to the group work, the students assess themselves and each other in a peer review. The average of the grades received from their peers is worth 10% of the final grade. If this grade is insufficient, they fail the course and will have to do an alternative assignment. To prevent this, there is a formative intermediate assessment in week 5, in which they give each other tips to improve contributions to the group. Usually, this is fairly evaluated and gives the teachers a good view of the dynamics within the group.

III. MATERIALS AND METHODS

A. Challenges

An overview of the challenges proposed by research groups within the department is given in Figure 2. During the experiments, the students received samples made by the challenge owners. To optimize and calibrate the design, the groups first received a calibration slide to check if the setup meets the set requirements. In most challenges, samples were prepared before the start of the course, which made the workload on the challenge owners light. Only for challenges 6 and 7 (Fig 2, 6. and 7.) did the moving samples need to be freshly made. For troubleshooting and optimization, they received a sample, with nonmotile particles. Note that making fresh samples might not be ideal for all labs.

Each challenge had difficulties. The first 3 challenges (Fig 2, 1.–3.) required some level of automation in the microscope, either in the movement through the sample and/or for data processing. In addition, students are required to write pieces of code, a skill that is still being developed. The polarized light microscopy of diseased bone (Fig 2, 4.) and volumetric imaging of 3D-printed biomaterials (Fig 2, 5.) challenges, on the other hand, do not necessarily require automation, but the students must be aware that they need a special mode of imaging for the samples. Bone tissue is birefringent, and they need to use this to their advantage to answer research questions. The 3D-printed samples are in a cuvette rather than a microscopy slide, meaning that they have to find a way to image a large 3D sample. As discussed, the challenges involving microparticles have challenges in terms of sample preparation. Finally, in all challenges, the data analysis is not straightforward. The students need to find proper plug-ins for existing image analysis software or find a way of analysis.

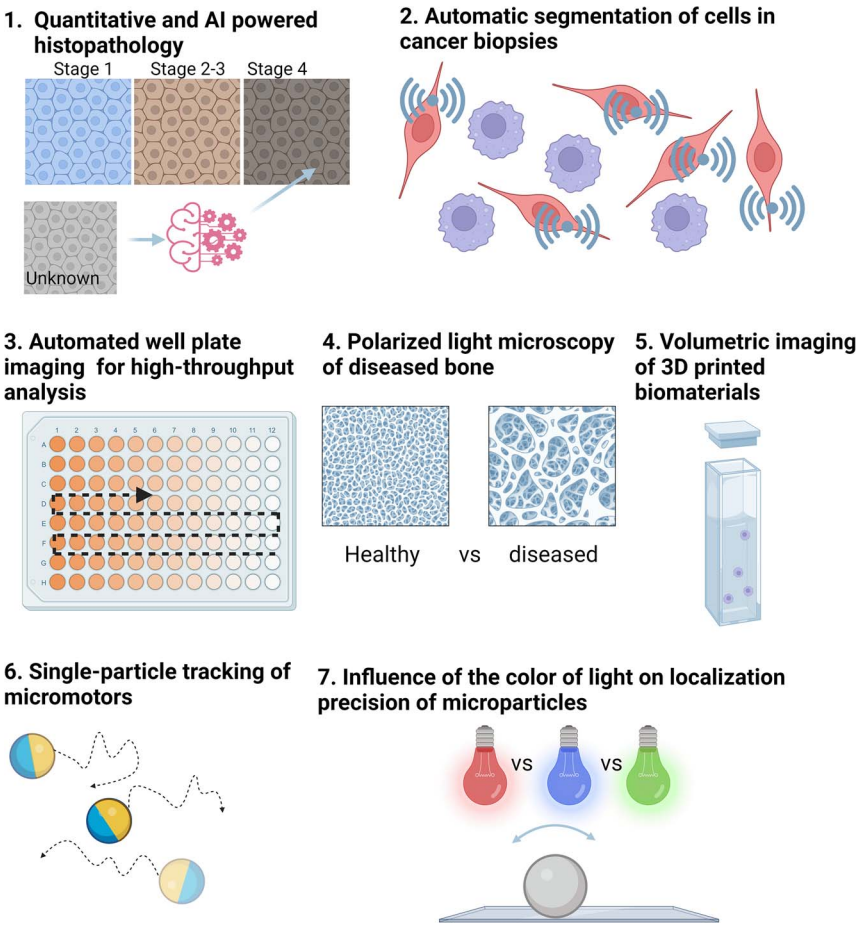

Fig 2. Schematic overview of the challenges in the course. (1) In quantitative and artificial intelligence (AI)–powered histopathology, the aim is to use AI tools to classify images of biopsies of cancer patients. (2) In the challenge for automatically finding cells, the aim is to find rare cells in a population of other cells, with an automated imaging and analysis pipeline. (3) The aim in the challenge of high-throughput microscopy is to image a 96-well plate in an efficient and fast way to create a time lapse. (4) The students explore the organization of bone tissue in different diseases in the organization of bone tissue challenge. (5) In volumetric imaging, the students aim to image a cuvette filled with a gel and beads that mimic cells sheet by sheet. (6) The movement of micromotors in complex media is analyzed in the tracking micromotors challenge. (7) The influence of the color of light on the localization precision on beads immobilized on a glass surface is analyzed in this challenge. Created with BioRender.com. Tholen, M. (2025) https://BioRender.com/c67c130.

B. Lectures and educational materials

To provide a theoretical background, a number of resources are provided. In the first week, the students had 2 × 2 h of lectures. The first lecture covered the theory of optics, including the definition of light, concepts such as reflection, refraction, and magnification, and lens theory. The lecture was followed by a quiz in Mentimeter (16) to support student learning and modify the lecture to fit the knowledge of the students. In the second lecture, they learned about the basics of microscopy (resolution, contrast, magnification, and sampling) and the anatomy of the microscope, a description of the basic components they will encounter in the building process (condensers, filters, sample holders, objectives, tube lenses, eyepieces, and detector). They received theory about these components and also a clear description of the practical components offered to understand all the option designs. The experimental process was further supported with 2 workshops: 1 for the UC2 (Jena, Germany) initiative and 1 for the use of ImageJ (Fiji) for image analysis. Students received a number of documents as additional material. Some of these documents were general, and others were specific for each challenge. The general documents consisted of additional exercises on optics, a guide to the components available during the course, and the rubrics for the assessments. Each group also received additional reading material more specified for the challenge, including background information such as scientific papers and links to useful tutorials. These documents were shared with the students via the learning management system Canvas (17).

A OneNote (Office 365) lab journal tracked the progress of the students, allowing communication between group members about progress made during the experimental phase and also allowing the lecturers to monitor progress (18).

The teaching assistants were supported by a guide that walked them through the theory of optics and explained how to approach the groups. The different role for the teacher and the potential unfamiliarity with the topic of the challenge, in combination with the open-endedness of the challenges, require good training and teamwork of the lecturers. We also have frequent building sessions with new teaching assistants to familiarize them with the building process.

C. Microscopes

The UC2 3D-printed open-source microscope toolbox was used as a basis for the microscopy development. The UC2 microscope toolbox consists of injection-molded cubes and baseplates to build the body of the microscope (7). Cubes click in modular fashion like Legos, which allows building different geometries of the device. Inside each cube, an optical component can be placed through 3D-printed inserts. These components are easy to use and suited for repetitive use by inexperienced users. These components provide all the materials needed to build 4 types of microscopes: bright-field, dark-field, phase contrast, and polarization microscopy. During the experimental phase of the course, the components were displayed on a table, as if it were a store, and the students were allowed to choose which components they wanted to use. An overview of the components can be found in Figure 3. The students had to think about the magnification required for the sample and, in turn, which objective and extra lenses they needed. Students were encouraged to first calculate metrics such as system magnification and then verify during building if the calculation was correct. The available objectives had a magnification ranging from 2.5× to 60× and were provided in both infinity corrected and finite versions. They could place these objectives in multiple holders: a static holder that can manually be moved in *Z* direction, a linear motorized holder, and a Delta Stage designed by OpenFlexure (Cambridge, UK) (8). The latter one was provided with manual or motorized movement, allowing the stage to move in *X*, *Y*, and *Z* directions, and a self-designed adapter to attach the stage to the UC2 components. The Delta Stage also functions as a sample holder. Other sample holders are a static sample holder or the gantry sample holder for 96-well plates. They could illuminate the sample with a simple flashlight or with a computer-controlled red, green, and blue light-emitting diode array. Light could be controlled or blocked by using neutral density filters, color filters, blockers, apertures, polarizers, and annular rings. Multiple lenses were provided for control of illumination and for focusing the light in an eyepiece or on the camera sensor. Mirrors were provided to prevent unstable tower microscopes, and 50/50, 30/70, and 70/30 mirrors were provided to split the beam. For visualization, the students were allowed to use their phones, or we provided (colored) Arducams (Amazon, Seattle, Washington, USA) and Allied Vision (Edmund Optics, Barrington, New Jersey, USA) cameras, recommended for automated systems. For the control of the light-emitting diode array and the motorized components (objective holder and Delta Stage), ESP32-based microcontrollers from UC2 were available. A basic Python Jupyter (3.8) notebook using the UC2-REST and VmbPy libraries was provided for tasks such as motor control and image acquisition. The students had to implement functions, troubleshoot, and combine functions to tailor it for the challenge. In addition, the students also had access to the 3D-printing facilities of the university to stimulate them to be creative and design new parts to go beyond what the teachers envisioned. They were also encouraged to look online for 3D-printable part designs outside the scope of the provided toolbox. Depending on the challenge they chose, they had to make the best choices to achieve the microscope most suited for the challenge. The students could choose to have a manual microscope using a simple light source and phone camera for a detector or build an electronically controlled setup.

The challenges given to the students involve a full microscopy workflow, including image analysis. The students will have to look independently for more specific tools related to the challenge (i.e., ImageJ plug-in or Python libraries) and analyze the data on laptops (19, 20).

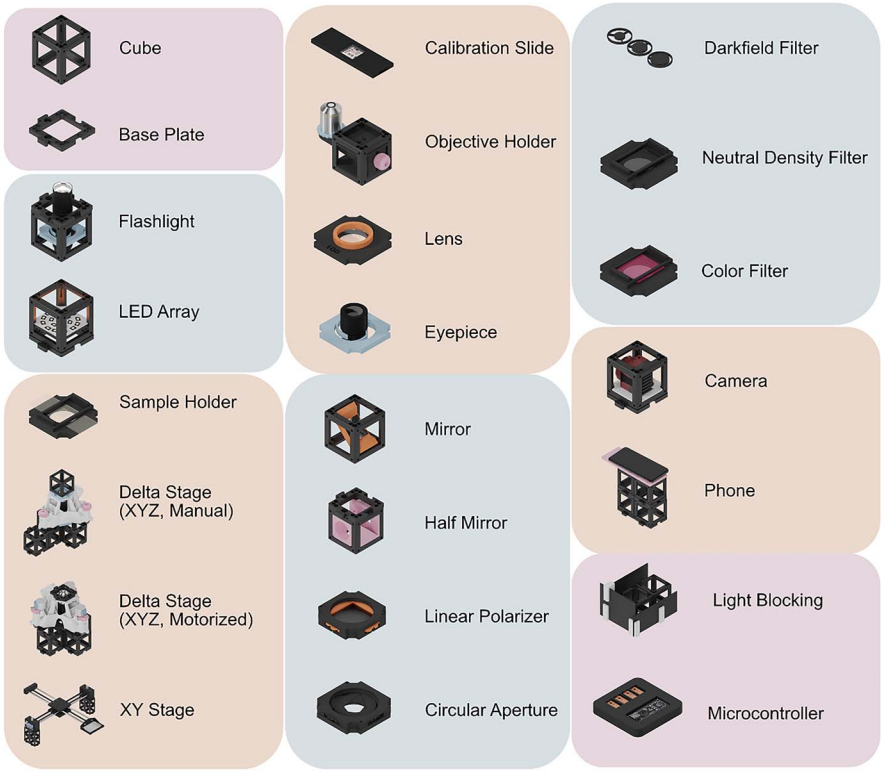

Fig 3. The components used in the course. All components have a holder or fit in a cube by themselves. Students can also propose and print the components. Renderings not to scale.

D. Methods

1. Overview of the schedule

This course guides students through 3 phases: design, building, and imaging and data processing. Because the course is a CBL, most work is done in group work. However, all students work on different parts of the design in parallel. The learning goals and assessments are aligned with the phases and the type of the course and use Bloom's taxonomy (Table 1). In the design phase (weeks 1–2), students begin with lectures introducing core principles and select design challenges. They attend a UC2 workshop to explore available components and finalize microscope designs, applying optical theory to create a research proposal. It is most important that the lecturers promote the use of optical theory for the design of the microscope. Furthermore, because the challenge is open, they need to keep the students within the boundaries of the course without limiting the creative process.

In the building phase (weeks 3–5), students build microscopes based on the feedback received, while beginning the imaging and data processing phase with an ImageJ workshop.

During weeks 6–8, students refine the imaging techniques, analyze data, and synthesize findings in a poster pitch that is presented publicly in the final week. Key challenges we observed included reliance on trial and error rather than theory and issues in task distribution within groups, affecting both understanding and project complexity. To address these, a technical report was introduced, requiring theoretical explanations, and an online lab journal was implemented to improve collaborative tracking and integration across group members.

Outside contact hours, students were encouraged to work on the project as well, by providing access to the material. The amount of guidance was flexible. Usually, we started with a quick catchup at the beginning of each session with each group to see where they needed help. On a page in the learning management system, we also had an overview of all teachers available and their skills, so the students could reach out to a specific lecturer or teaching assistant with specific questions. With this type of guidance, the students can explore aspects of the scientific process, from using the microscope to performing

Table 1. Overview of the learning goals of CBL Microscopy during each phase and the corresponding assessment method.

Phase	Learning outcomes	Assessment
Design	Design an optical microscope to answer a biomedical question	Research proposal
Design	Choose the most suitable optical microscopy technique for a sample of interest	Technical report
Building	Optimize the actual microscope by testing and analyzing the test results	Technical report
Sample imaging	Perform laboratory experimental work in the field of optics and microscopy (calibration, measurements)	Poster pitch
Design, building, sample imaging	Present the choices of the optical design and the results in a poster pitch	Poster pitch
Collaboration	Collaborate with other students when together, creating a group product	Peer review
Collaboration	Reflect on own work and the work of others in a group	Peer review

calibrations and data analysis and communicating it to a broad public.

2. Considerations for guidance

CBL is significantly different from a standard course. The teacher is not only a source of knowledge but also a coach and sparring partner. We divide the practical side of the CBL in 3 different phases: engage, investigate, and act (21). These can be further divided in smaller stages: from case to challenge, setting the foundation, identifying the best solution, implementation and evaluation, and sharing results and reflections. In all these stages, the teachers are responsible for keeping the big picture in mind and giving the students feedback and questioning the next steps to keep them on track for reaching this big-picture goal. The most important thing is to notice when they are making mistakes but not to interfere. Once they notice they made a mistake, the teacher's role is to evaluate with the group what went wrong and how they can move forward. In these instances, we use coaching for a learning approach (22), where we first ask open questions to find the obstacle. This might already give them enough answers to continue with the project, but if that is not the case, the teacher helps them find the next step to overcome this obstacle by asking questions, providing them feedback, or giving hints or clues, with an emphasis on the questions. This freedom of teaching also is reflected in the lack of schedule planning for the students. Note that all groups have a different pace for the course, and by giving strict topics for the sessions, the students know they should work on those. On the other hand, this level of freedom might make them feel overwhelmed. When that happens, the lecturers should step in and help with planning. For inexperienced teachers, we wrote a teaching (assistants') guide that explains the philosophy of this teaching approach.

IV. RESULTS AND DISCUSSION

A. Preparation phase

CBL Microscopy is an open course, but the basics evolve around microscopy. Therefore, it is recommended that the teachers of such a course be very familiar with, or even specialized in, the field. When designing the course, the limited time and the skill level of the student need to be taken into account. Therefore, sessions consisting of building new setups and trying out samples to assess the level of difficulty are essential during the preparation of the course. For example, UC2 has a lot of potential options, including fluorescence microscopy, but we decided that in the time frame of the course, we would stick to more basic setups such as bright-field and dark-field because we noticed that it took too much time or effort to build a fluorescent microscope. When designing the challenges, we should take the background of the students into account. When teaching physics students, a more quantitative approach on optics is possible; however, for biologists or biomedical engineers, it is important to find a good balance between the physics and the applied side of microscopy. Furthermore, the question asked should be open, and no answers should be known yet. Often, a variation on what has been

done so far can easily be used as a challenge. When we were designing the challenges, we approached several research groups to ask for ideas. We aimed to show that microscopy is applied in a broad range of research groups by implementing challenges from a clinical point of view, such as tissue engineering research groups but also from chemical biology groups. For each challenge, an open topic was chosen, after which subchallenges were formulated that focused on a specific microscopy or sample issue. The students chose a broad challenge, after which we assigned the subchallenges to them. In this way, each group needs to design a dedicated microscope for the challenge, but they can still ask for help from groups with similar challenges. We envisioned that each challenge was modular, meaning that they could choose the level of difficulty for each part of the project.

B. Microscope design and data processing

During the design phase, we saw a number of groups taking creative approaches (Fig 4). One of the groups wanted to have a dual-camera system, so they chose to use a half mirror for splitting the beams after the sample (Fig 4B). After reading extra literature, other groups took interest in parts that were not proposed as options and requested them to build a more original microscope. We evaluated these requests, and if well thought through, we purchased or 3D-printed extra components.

After the design phase, the timing of the building phase and that of the imaging and data processing phase are not strictly divided, because one challenge might need more time building the microscope and the other needs more focus on data processing. The building phase can be further divided into multiple tasks: building a simple microscope, expanding the microscope with more advanced components, and calibrating the microscope. The students will translate the drawings into practice, and they will realize that building might not be as easy as they initially thought. We noticed that students tend to skip some basic parts and directly move to advanced features such as motorization and automation. However, they typically run into issues because the basics are not in place (e.g., alignment) and the advanced features are significantly more challenging for inexperienced users. Automation also poses challenges, and this goes hand in hand with coding, which the students are still beginning to learn. For the groups that want to implement this, we have extra material that helps them once they are stuck, and we make sure that a student assistant is specialized in this part of the course. We see that students who follow the sequence of first building a simple setup and then adding in more advanced components are more successful in reaching a working setup in the end.

In addition, students need to think about which calibrations are needed before they trust the results the microscope produces. For these calibrations, we have USAF calibration slides (Thorlabs, Newton, New Jersey, USA) for the resolution, slides with rulers for measurement of pixel size and field of view (FOV; Fig 4A3, B3), field distortion test slides, and a slide with beads for testing mechanical stability and contrast. According to the calibration results, the students need to adapt designs to improve resolution, FOV, mechanical stability, or other desired parameters. These calibrations are assessed in the technical report and lab journal, in which they have to document the design process and the results of the calibration.

In the image and data processing phase, students can use different approaches (Fig 5). The simplest approach is to use a phone camera to make the images and simply process them in the basic version of ImageJ. However, most challenges ask for more than this. The students can decide if they want to use existing plug-ins for ImageJ, MATLAB (2023a), or Python (3.8) or if they want to write a short data acquisition and processing script themselves. They need to consider what they need to answer the questions (e.g., number of samples, number of the FOV, or size of the FOV), and they need to acquire them in a scientifically correct way. Many groups want to create a large FOV by scanning through the sample with the Delta Stage. To do this, no open-source movement

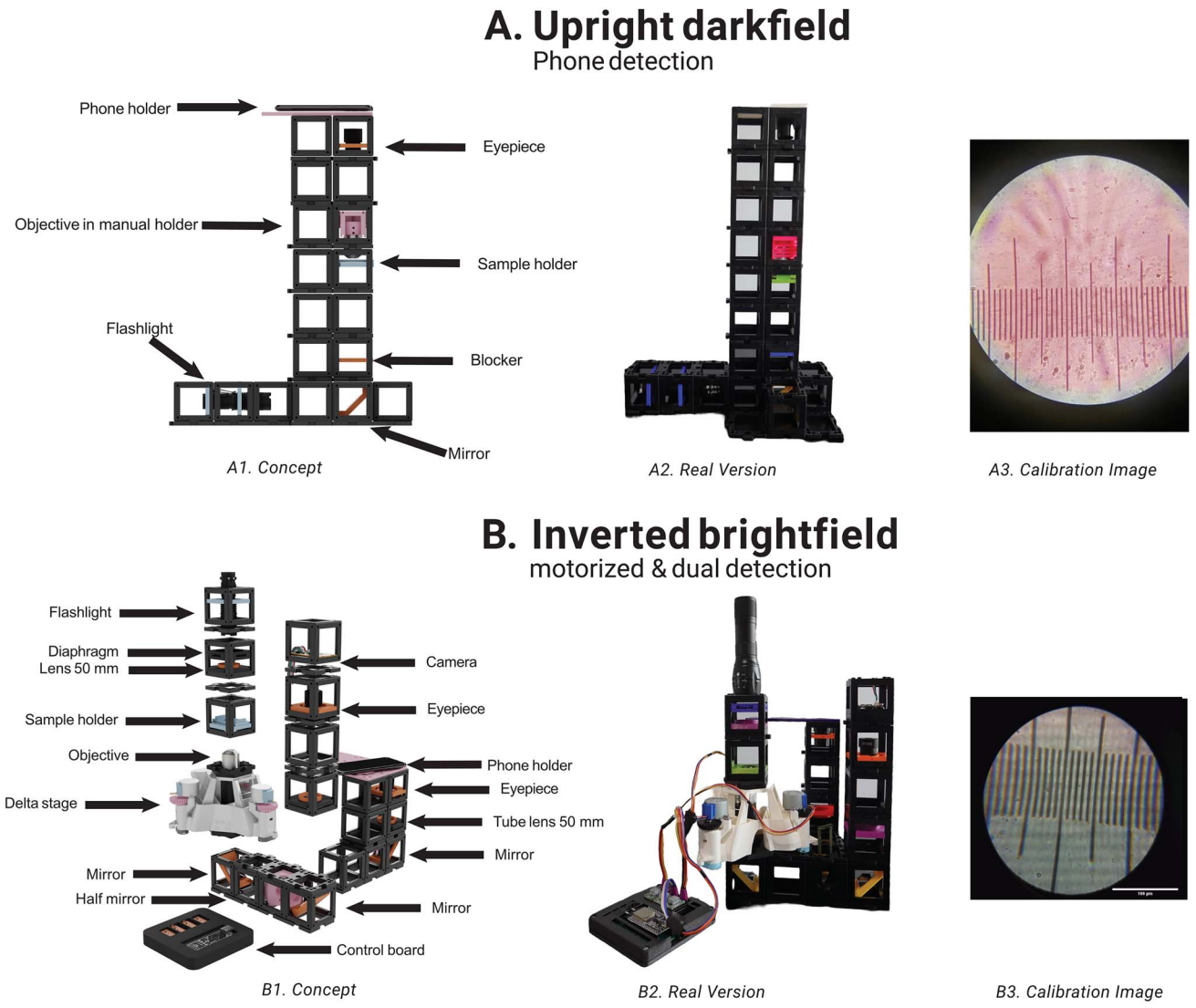

Fig 4. Examples of microscopes built by the students. (A1) Rendering of an upright dark-field microscope that uses a phone as the detector. (A2) Photo of the eventual microscope built by the students. (A3) An image of a microscopic ruler taken with this microscope for the technical report; the space between 2 long lines is 0.1 mm. (B1) Exploded rendering of an inverted bright-field microscope, which is motorized and uses a half mirror for dual detection by both an Arducam camera (STEP file used in the rendering from Allied Vision) and a phone. (B2) Photo of the eventual microscope built by the students. (B3) An image of a microscopic ruler taken with this microscope for the technical report; the space between 2 long lines is 0.1 mm. Pictures of the microscopes were taken with a Sony camera. Background removed with Adobe Express (https://new.express.adobe.com/tools/remove-background. Accessed October 2024). Renderings made with Blender (4.3 LTS; Blender Foundation, The Netherlands) and edited in Affinity Designer (Affinity Designer 2.6.0, Serif Ltd., UK).

pattern for the stage is available online for the used configuration, so the students start playing with a coordinate system to acquire the data. For challenges that involve machine learning, some groups decided to use standard tools such as QuPath (23), and other students trained their own models. Again, we noticed that students want to achieve the most difficult approach as fast as possible, resulting in forgetting essential data-processing steps such as adding scale bars.

Despite using only inexpensive microscope components, the images obtained from the students were impressive, with clever solutions for the problems. A number of groups managed to make the motorized stage work and obtained large images of the sample through the tiling of multiple images (Fig 5A). Others decided not to use a motorized Delta Stage and used the panorama function of a smartphone camera or manually moved the sample (Fig 5B) to obtain a

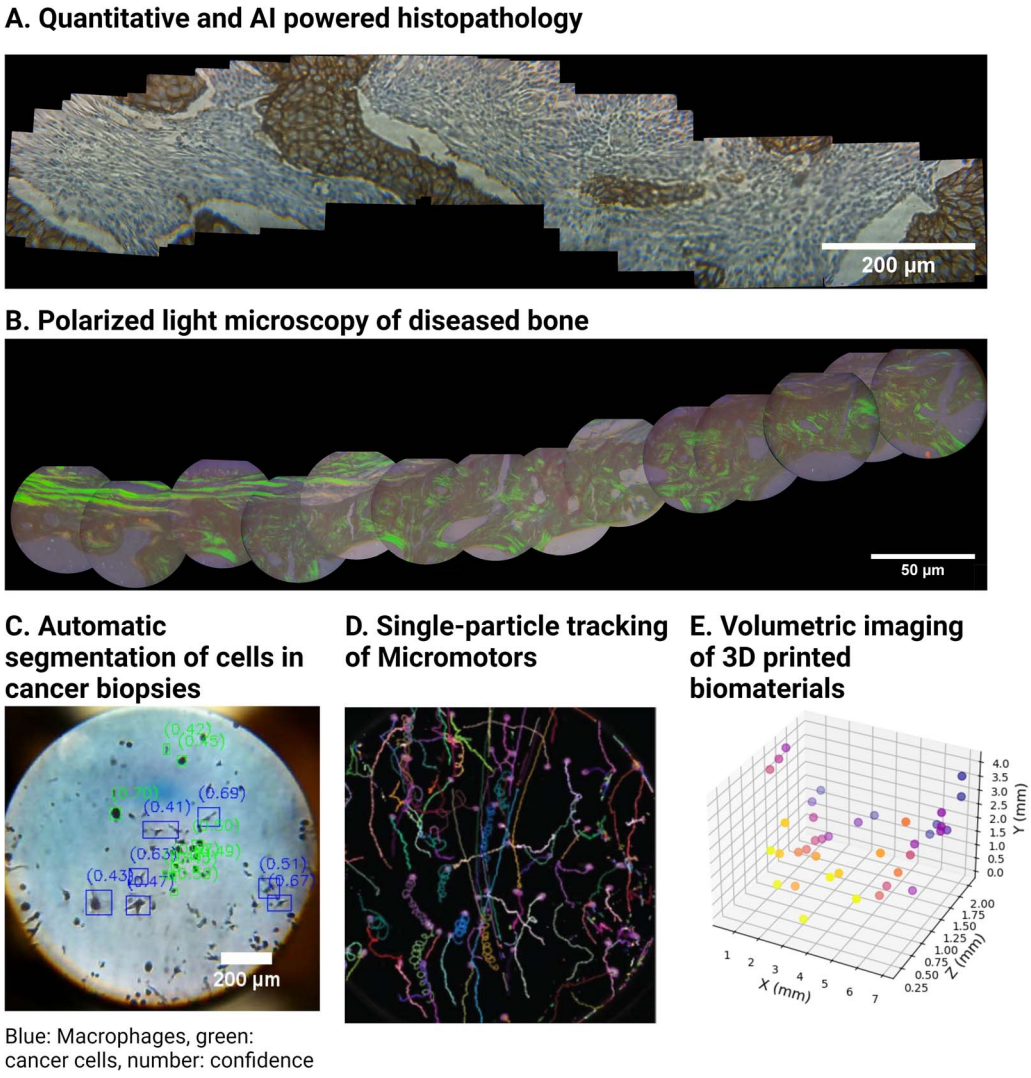

Fig 5. Examples of results obtained by students in the course. (A) The students in the quantitative and AI-powered histopathology challenge managed to do a scan of a large part of the tissue. (B) Also with scanning, the students in the polarized light microscopy of diseased bone challenge were able to visualize a big part of a rheumatoid arthritis sample. (C) With a machine learning algorithm, the students in the automatic segmentation of cells in cancer biopsies challenge were able to assign labels to the cells in the images. (D) By using TrackMate, the students in the single-particle tracking of micromotors challenge were able to track the movement of the micromotors in time. (E) With a light-sheet setup, the students in the volumetric imaging in 3D-printed biomaterials challenge could map the locations of microparticles in 3D. Created with BioRender. Tholen, M. (2025) https://BioRender.com/c67c130.

large FOV of the sample. After image acquisition, the students applied different software tools to analyze the data, such as machine learning algorithms (Fig 5C) and single-particle tracking plug-ins for ImageJ (Fig 5D). One of the groups decided to use a low-power laser to build a light-sheet microscope. The signal in this case is not based on fluorescence but on light scattering of the particles in the sample. These students used OpenCV (4.8.1.78) to segment slices and reconstruct the 3D location (Fig 5E).

When the students successfully fulfill all phases of the course, we believe we give them the tools needed for future microscopy projects, from choosing the correct microscopy setup to scientifically correct processing of the data.

C. Assessment and learning outcomes and student and educator experiences

Between November 2022 and November 2024, CBL Microscopy was run 3 times in the

department. The first 2 runs were pilot studies, and any interested student could enroll in the elective course. Both runs consisted of 10–15 students. For the third run, the course became mandatory. This run consisted of 50 students. Each time the course was run, a student evaluation was performed directly after the course.

Overall, students were very enthusiastic about the course. In the first year, the students ($N = 7$) rated the course with an 8.3 of 10. The difficulty was perceived as suitable for knowledge and skills. Furthermore, the educational setup was considered feasible and well structured. Students commented that the working environment was very good, learning by doing was good for understanding of the optical concepts, and the link with the biomedical challenges made it more interesting for them to follow. However, they indicated that they spent less time than required to obtain the European Credit Transfer and Accumulation System for this course, so we implemented an additional summative assessment in the following years. The year after, the course was rated with a 7.4 of 10 ($N = 5$). Difficulty increased, as well as the hours the students spent on the course. Furthermore, the organization and feasibility of the course were scored higher than before. When the course became mandatory, the students were still enthusiastic about the course and awarded it with a 9 of 10 ($N = 3$). Overall, this means that CBL Microscopy was well received by the students and that the way of teaching was positive for understanding of the optical concepts. This is in agreement with the results of the technical report, which demonstrated good understanding of concepts of lens optics, aberration, and resolution. We acknowledge that the statistics of students that filled in the survey was not high enough to draw any conclusions, but we also received positive feedback from informal talks with the students. In 2023 to 2024, a few students indicated that by dividing tasks, they felt like they were missing things that the other group members did. Therefore, we implemented the lab journal, as discussed before.

For further understanding of the impact of the CBL course on student learning and development, a more pedagogic approach should be applied, and students should be followed for a longer period.

V. CONCLUSION

Here, we presented a CBL educational concept centered around microscopy, where students shape projects according to their interests. Teaching the fundamentals of microscopy is essential for the development of future scientists who will contribute to the improvement of microscopes and use them to make biologically relevant discoveries. By making use of open-source microscopy, a large number of students are able to build their own microscopes, with an affordable budget for the educational institution. The students can make use of the community already established by users of UC2, and the implementation of this system is very efficient. This concept was successfully applied in the bachelor curriculum of biomedical engineering, but we envision that it can be extended to various faculties in life sciences. Students specifically appreciated the hands-on experience with the optics theory, and they felt very motivated to build an appropriate microscope. In contrast to other open-source microscopy projects, UC2 is a flexible system, which allows for tinkering and creativity, resulting in different microscopes for each group. These elements distinguish the course from standard optics courses, because the learning-by-doing approach encourages students to develop unique solutions and enhance critical thinking skills. By using a colearning environment and a coaching-for-learning approach, we believe that the course not only contributes to student learning but also contributes to learning for the whole community involved in the course, fostering a dynamic educational environment. The course is also an opportunity to exchange knowledge and skills between research groups and to initiate new collaborations. In a way, the course not only contributes to student learning, but it also contributes to the broader academic community, creating an effect that goes beyond the classroom.

SUPPLEMENTAL MATERIAL

All Supplemental Material is available at: https://doi.org/10.35459/tbp.2024.000287.S1.

AUTHOR CONTRIBUTIONS

MMET and LA designed and developed the course and taught the course. TCvH was a student assistant in the course that developed many custom components of the microscopes. MMET wrote the manuscript. TCvH aided in the figure development and wrote about the technical details of the microscopes in the manuscript. All authors reviewed and edited the manuscript.

DATA AVAILABILITY

The course content, including course material, can be shared upon request. An example of a challenge, with the code for moving the stage and STL models for UC2 components developed by the teaching team, is available via Github: https://github.com/n4nlab/CBL_Microscopy.

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