Electronic Supplementary Material (ESI) for Lab on a Chip.
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Supplementary Material

An economical in-class sticker microfluidic activity develops student expertise in microscale physics and device manufacturing

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Video Legend & Captions

Supplemental Video 1: Hand actuated T-mixer. Here an individual simultaneously injected blue and yellow colored water showing the limited mixing that occurs in the center channel.

Supplemental Video 2: Hand actuated F-mixer. The video shows an individual experimenting with different pressures in the syringes and later achieves mixing.

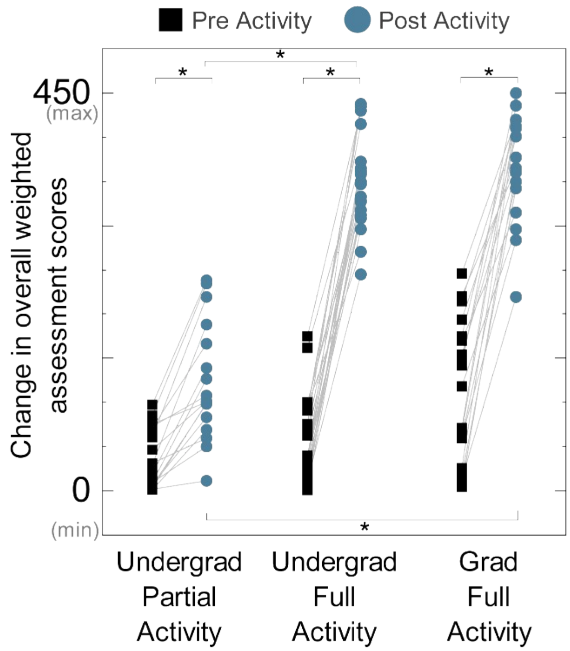
Supplemental Video 3: Bubble Generator. Here an individual experiments with different hand actuated pressures, showing both good and suboptimal operation of the device

Supplemental Video 4: Valve. Here blue fluid is seen flowing through the channel when the valve is open, and moving at a reduced speed when the valve is closed.

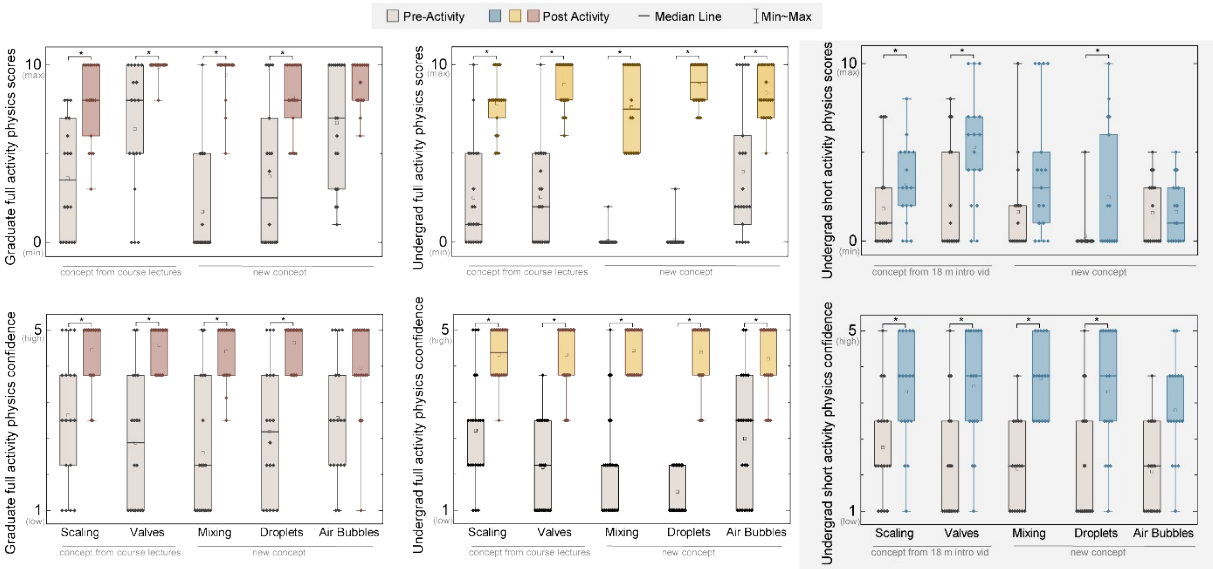
Additional Included Files:

Class Handout – This handout includes instructions that guides students through the construction and testing of their microfluidics

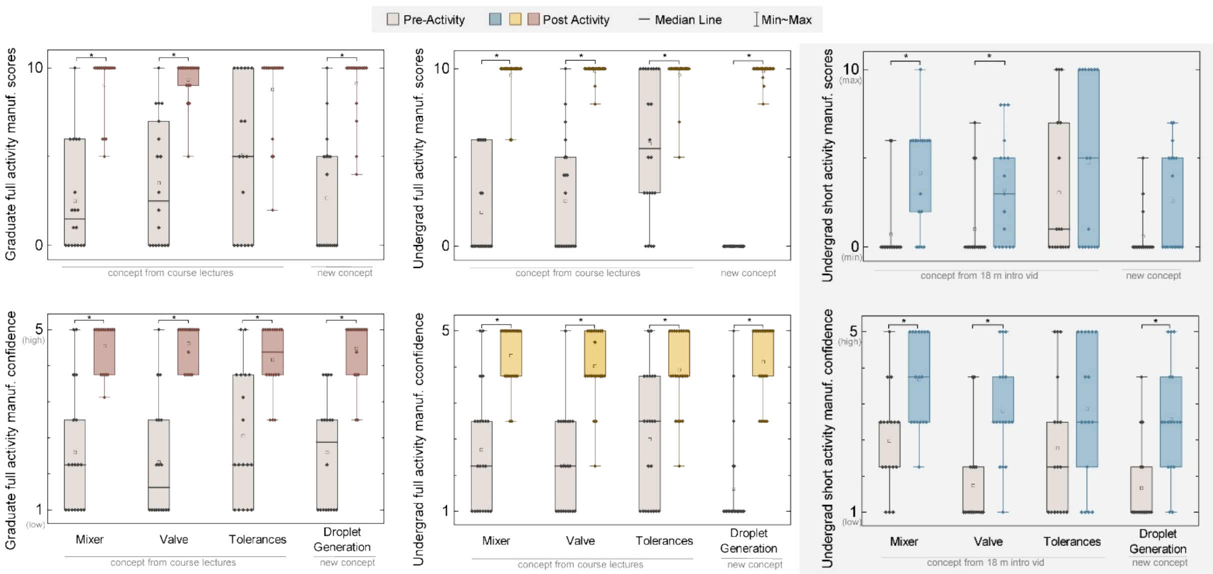
Templates for Devices – Illustrator file and pdf file of the individual layers of the devices used for this activity



Supplementary Figure 1: All participants showed a significant improvement in both understanding and confidence in microfluidic concepts as measured by pre- and post- short answer written assessments. Participants were stratified as undergraduates who had completed the partial activity, undergraduates who completed the full activity, and graduate students who had enrolled in the full activity. Undergraduate students had volunteered that they had little to no prior experience with microdevices/microfluidics. The Graduate Full Activity loosely correlates with student experience in microfluidic/microdevices as some graduate level participants had already engaged in microfluidic research as undergraduates. Mann-Whitney non-parametric test used, * indicates significance <0.001.



Supplementary Figure 2 – Participant proficiency and confidence in microscale physics both increased after completing the activity. The pre-assessment was designed to evaluate participant understanding and confidence in microfluidic physical concepts that were discussed in preceding lectures as well as those that would be encountered by those using microfluidics for research, such as the detrimental effects of air bubbles. After completing the activity, a) proficiency as measured by evaluations to written responses for each subject area and b) self-rated student confidence in each subject area increased.



Supplementary Figure 3 - Participants experienced significant increases in both proficiency and confidence device assembly as measured by pre- and post-assessments. The pre-assessment was designed to establish participant's baseline understanding and confidence in microfluidic manufacturing and design, and included multiple questions asking participants to draw cross-sections and top views of devices. As these questions have more definitive answers and evaluate a necessary yet more specialized skill related to microfluidics research, the initial scores were lower. After completing the activity, participants showed similar levels of a) proficiency and b) confidence the physical based questions.

Disposable Materials	Company	Catalogue Number	Cost per kit	Comments	Total Cost	Quantity /device
Double Sided Tape	3M	36042	$ 0.004	Sold in bulk	$ 1,941.00	
PDMS sheets	Rogers	HT6240-0.01"	$ 0.054	Sold in bulk, only used for valve	$ 1,009.50	
Slygard 184	Ellsworth Adhesives	184 SIL ELAST KIT 0.5KG	$ 3.360	Cheaper when bought in bulk	$ 168.25	1
Acrylic Sheet	Acme plastics	ACRYLIC-EXTRUDED-CLEAR-SHEET__0625_24x48	$ 0.172	Low cost substitution for glass slides	$ 16.41	
5 mL Syringe with Leur lock	VWR	BD309646	$ 0.640	Could be reused after flushing with water	$ 40.00	2
Pink Needle tip	Ellsworth Adhesives	EA20TE-1/2	$ 2.500	Could be reused after flushing with water	$ 25.50	2
TUBING PTFE 0.012X0.030" 100'	VWR	MISC-INSTRUMNT	$ 0.001	Could be reused after flushing with water	$ 27.06	2
Tygon Tubing 0.02X0.060" 100'	Cole-parmer	EW-06419-01	$ 0.002	Could be reused after flushing with water	$ 77.30	2
Food Dye	McCormick		$ 0.203		$ 4.69	2
Plastic Tweezers	Amazon	THCP1304	$ 0.990	Reusable	$ 9.99	1
Plastic Scraper	Amazon	Grevosea-bhr	$ 0.690	Reusable	$ 6.99	1
Mineral Oil	UltraSource	501333	$ 0.06		$ 23.12	1
Tape Dispenser	Scotch	6122	$ 2.50	Reusable	$ 14.99	1
Total cost/kit			11.1755207		$ 3,383.63	

Supplementary Table 1 – The per student to participate in this activity cost can be kept very low when materials are judiciously re-used. If the total cost of acquiring the 3M tape is too high, some retailers offer less expensive form factors, such as a 1 ” x 60 yds (2.54 mm x 54.864 m) for ~$100USD, that could easily be adapted.

Participant responses to open-ended question “What did you learn in this activity?”
I learned how the F-mixer works to increase mixing efficiency. I also learned about where I should be injecting liquid into the microfluidic to achieve the desired result. I learned a lot with the droplet generator and the valve. Lastly, microfluidics are super cool
The main thing I learned was that the laminar flow that microfluidics exhibit and how it is much harder to mix it at the microscale
How microfluidics actually work in person. Also, learned the difficulties of alignment on such a small scale
I learned how layering is used to create on overall unit, and saw how laminar flows are utilized to do specific functions like mixing and generating drops. It was cool to see a valve done at the microscale like this.
I learned how the different microfluidics physically work. I also saw some of the easy to make, small errors that can prevent a device from working. I also learned microfluidics are surprisingly easy to make
I learned how to build microfluidics, and different ways to manipulate liquids of the microscale.
I learned how to build a microfluidic and was better able to visualize the physical properties that make them work.
Laminar flow is very cool. Challenges in mixing in micro vs macro scale has unique challenges
In this activity I learned how to make simple microfluidics that are effective for mixing, making droplets, and making valves
I learned how to make, draw, and use microfluidics! I also learned how to form droplets.
I learned everything above and how easy it can be to make microfluidics.
A lot. Specifically, I got more comfortable drawing multi-layered cross-sections.
I learned about the operation of microfluidic devices such as valves, droplet generators, and mixers, which I had little exposure to before
During this activity I learnt that the simple arrangement of layers can lead to different microfluidic devices being created, which can range from creating droplets to making valves.
I learned from the lab mainly why droplets form in the oil water situation. I also learned the basics of microfluidics and the process of creating one. Specifically, how different channels and valves affect fluid flow
"soft" microfluidic fundamentals. Previous experience was with electronic devices or paper-based
That hands-on experience is the best way to learn, and that creating a microfluidic requires a lot of precision and care.
We learnt about how although the concepts behind microfluidics are simple, the implementation can be tricky. However, it was a really fun activity, where I personally got few ideas to implement in my own research. We also learnt about how flow mixes and how to generate droplets and control the flow
I learned how to build microfluidic devices (a variety of them) and how to take their 3D structure and visualize the different layers that make up the assembly
I learned to apply engineering logic to the mechanics of microfluidics. Additionally, I was better able to understand the implications of flow and devices @ the microscale. Most importantly, I learned how to interpret and draw cross-sections more readily.
This activity was very fun and really interesting. Making simple microfluidics were really not as hard as I expected. I learned a lot about how the different layers should align and how difficult it can be to get them aligned properly. Additionally, I learned how to make different types of microfluidics and why each of them works.
A lot, I learned how to create microfluidics--something that yes, I listened to you lecture about, but didn't really stick in my head until now. I'm a very hands-on and visual learner, so this has been great!
1) How to draw cross-sections and top down views of microfluidic devices. 2) How T-mixer, F-mixer, droplet generator, and valves work. 3) Flow at the microscale are all laminar 4) Dust and bubbles

disrupt microfluidic function (flow) and are hard to get rid of due to high adhesion
I learned how fluids interact on a microscale after only working with fluids in macroscale. In BME and AE, I often only think of Reynold's number on a large scale, not on a compact scale.
I did not realize microfluids always more laminar nor did I previously realize how bad an air bubble can be
I learned a lot about the motion of fluid through the different layers and fluids used in the experiment. Its easier to understand the fluid through visual demonstration
This activity allowed me to appreciate diffusion and better understand laminar flow with different liquids. I would love doing this again
How the device for microfluidics looks like and how to control them to form a working system
Interactions between different fluids within a microfluidic. Hands on: how to create microfluidic devices and how to test them. Visualizing cross sections for the created microfluidics
Learnt how to operate microfluidic devices and the principles based on which they operate. Also learnt how the fluid properties and structure of the device generates droplets. Got to know the various forces driving fluid flow in microfluidic devices
The hands-on activity was fun and I learnt how to align the different layers to assemble devices. Handling the tubing, and connecting it to ports. My favorite part was the droplet generator.
All the answer to the things in this packet! (More importantly, gave me something tangible to focus/study on) -- very helpful!
1) Engineering is nothing fancy and can be messy but exciting (especially when playing around). 2) Design in macroscale would device microscale, but need to know the (physical/chemical) rules first!
I learned about the influence of laminar flow in microfluidics as a result of inertia and viscosity @ small dimensions and how pressures of mediums with different physical properties like oil and water or combined with device design in values to manipulate and control microfluidic flow
1) Learnt how to make new microfluidic chips. 2) Learn how to draw specifications for my microfluidic chips.
A LOT! CLeared up a lot of microfluidic fundamentals
I learned how to create a few different types of microfluidics. I learned the purpose and function of a valve. I learned how to troubleshoot some assembly errors. I learned about droplets
I learned about how the F-mixer folds fluid. I thought it created turbulence
Can use simple methods to create devices; Another mixer type besides herringbone structures; How to set up the flows (where to add samples vs sheath fluids)
I learned how the F-mixer operates in real life and saw how easy it is to actually fabricate
I learned a lot. More than I come into the class with.
** How an f-mixer actually works to mix fluids; * How to think about and draw the layers of a microfluidic device; * How to troubleshoot during the process of actually making the device (some parts can be finnicky and requires patience, skill build up); *How valves at work look like*
I learned about new ways to control fluid flow in mixing, especially with the construction of the Quake valve and F-mixers
I learned various methods for mixing in microfluidics, how to generate bubbles, and manipulate fluid flow in a channel.
I learned visually about how microfluidic structures operate, and how to use them.

Supplementary Table 2 - Participant responses at the conclusion of the activity inquiring about self-identified learning

Participant responses to open ended question “What three things did you learn that you found most important?
1) Leant about how fluids with different viscosities interact and flow with each other at the microscale. 2) Learnt about the various forces which regulate the fluid flow inside a microfluidic system and cross-sections. 3) Learnt how exactly fluids get mixed in a F-mixer and what happens when the fluid flows through a mixer.
1) The role of viscosity in the pressure required to push the fluid. 2) How slow diffusion is across a single interface. 3) Role of the F mixer, how we can create multiple diffusion interfaces to make it faster.
1) Observing diffusion on the microscale. 2) Mixing efficiency. 3) Drawing the individual layers of the structures
1) The importance/significance of layering in microfluidic design. 2) Fluid flow at the microscale. 3) How microfluidic devices can be harmed at the micro-scale (air, dust, etc.)
1) Streams of F-mixer. 2) How tight tolerances are. 3) Visualizing droplets generating
1) Visualizing the F, flow 2) visualizing the two nonmixing flows
1) I learned that it’s a really tiny volume of fluid moving through. 2) The effectiveness of some of the devices is largely dependent on the flow rate of the 2 liquids compare, and 3) generically how the f mixer, valve, and droplet generator work
1) The droplet generator-how it is important for the oil t come from the sides. 2) The importance of having a PDMS layer in between the two tape layers in the valve microfluidic. 3) How the 2 tape layers work in the F mixer
1) The folding/better mixing associated w/ the F mixer, 2) the effect of varying pressures/flow rates when using the droplet generator, 3) and the importance of precise alignment in microfluidics.
1) Laminar flow, always laminar flow 2) Soft layers and pressure is useful (valve). 3) Fabrication can be easy if designed properly
1) One thing I learnt was that the shape/structure of the templates also affects efficiency of mixing/flow. 2) The placement/insertion of liquids is important when using a droplet generator. 3) The alignment of PDMS and layers is important
1) Microfluid can be seen w/ the naked eye. 2) Diffusion is how microfluids mix. 3) That microfluids do not require a cleanroom
1) The basic structure of microfluidic device. 2) How to generate droplets. 3) Valve!
1) F-mixing (turbulent vs laminar) 2) Manufacturing process (tape, PDMS) 3) Inlets and outlets
1) How to make a microfluidic by layering tape 2) How to make bubbles 3) The difference between fluid flow of microfluidics vs. larger fluidics (laminar vs. turbulent)
1) The most important thing I learnt was to analyze the top view and the cross-sections of the microfluidic devices. 2) Fluid flow through the valves and mixing of the fluids. 3) Bubble formation
1) The alignment of layers 2) Connecting the tubes 3) Making sure the flow rates are correct and steady
1) More in depth mixing 2) Valve functions 3) How simple fabrication can be
1) Building (layer by layer and how they stack/connect, tolerances) 2) Streamlines (how they are guided/split) 3) Connections (making sure you flow into the correct tubes)
1) Cross sections (how to draw!) 2) How fluid flows @ the microscale 3) How important fluid properties are @ the microscale
1) All flow is laminar at this scale. 2) The valve goes both ways (top or bottom). 3) Surface tension and adhesion forces are strong forces at the microscale
1) How F-mixers layer the streams and double the amount of "F" 2) How geometry of a microfluidic can result in different outcomes 3) How pressure can allow and dis-allow fluid to move through and create a valve
1) It’s important to be precise. 2) It's okay to have imperfections, as long as you plan for it. 3) How pressure impacts flow for valves.

1) The type of fluid effects the outcome of the generator. 2) How the order of layers work and why it is important to follow. 3) How F mixer duplicates the streams and makes its mixture.
1) Flow at the microscale is always laminar. 2) Bubbles and dust block microfluidic channels. 3) Cross-sections
1) Liquids can be easily manipulated just with the shape of the microchip. 2) Increasing bends and turns increases mixing efficiency. 3) Air bubbles and dust particles can introduce error into the system.
1) That all flow @ a microscale is laminar. 2) Learned much better intuition for the way these microfluidics worked physically. 3) How to properly draw cross-sections in a way that made sense
[Redacted to maintain anonymity] I don't have much experience with the concepts taught in class so just to physically create a microfluidic system out of the materials we talk about in class was helpful. I found out how functional microfluidics systems were using small amounts of fluid or their ability to move large amounts of fluid
1) Steady pressure to devices 2) Bubbles bad (but also good) 3) Steady hands are key
1) I learned that the problem/task takes time, practice and patience. 2) You need to leave room for error (tolerances). 3) In class activities are very fun and sticks to memory more.
1) Scale of flow learning that microscale flow is laminar so mixing has to occur through other factors; 2) cross-section / layer diagrams helped understand how each structure worked; 3) Valves! didn't know how they worked before so that was very cool
1) That bubbles are made using two immiscible fluids; 2) Microfluidics can be broken down into layers; 3) The importance of tolerances in designing microfluidics
1) How micromixers work; 2) drawing cross-sections of each structure; 3) I like microfluidics
1) How does the Quake valve work? 2) How you can use tape and PDMS to make microfluidic devices (do not always need soft lithography) 3) The height of the liquid determines the flow through gravity
*1) How to actually make and 2) run the tape microfluidics for complicated structures 3) Flow rate control *?*
1) These devices are easy to put together & incorporate into ongoing projects; 2) Traditional fabrication techniques are not the end all-be-all; 3) Microfluidics do not always need to be frustrating
1) The flow rate control of the quake valve and how that is related to (+/-) pressure applied in the air channel; 2) Understanding which samples form the bubbles and which guide the bubble along in the droplet generator; 3) Understanding tolerances in constructing devices
1) How the layers of MF devices are assembled; 2) How the devices actually work; 3) How to troubleshoot MF production

Supplementary Table 3 - Participant responses 1 week after completing the activity inquiring about self-identified learning

Q: What were the best features of the course such as lectures, activities, assignments, and projects? (13 of 31 responses mentioned in class activity)
The experience with doing the real life microfluidic system to understand the different fluid behaviors and mixture designs
The hands-on microfluidics demonstration is a highlight of my academic career. Although I have extensive experience with microfluidics, I learned a new fabrication technique and gained a better understanding of the physical phenomena that govern fluid flow at that scale. Team paper presentations were done excellently in this course. Often these type of presentations are very one way but, in this course they led to fruitful discussion thanks to moderation by David. Additionally, the environment in the room allowed students to make all types of critiques freely which can not be said about other courses. I appreciated the lecture given earlier in the week to guide into the paper presentations.

The best feature of the course was the hands on activity. It really added so much to tying in all of the materials from the lecture together. The format of the lecture notes was also really great. It made the lectures really engaging.
The best feature of this course was the lab. The microsystems lab was really cool to do.
The best feature of the course was the beginning lab practice working with novel mixers and understanding the basics fab methods. This helped me understand more as we also got feedback and did a eval of our understanding of the material before and after. The discussions after projects and assignments were effective as well.
The best features of this course were the guest lectures and in-class activities. I learned the most when I got to do the hands-on microfluidic construction and the guest lectures were always very informative.
I really enjoyed the hands-on activity at the beginning of the semester!
I liked the DIY lab
The hands-on activity followed by group presentations. The hands-on activity provided an intuitive idea of how Microfluidics work, and make the group members know each other.
The class had a good balance of tests, quizzes, and hands on experiments.
In class activities were good, projects were tailored well to understanding new material and applying it.
Hands on activity, guest lectures were very useful
The professor was really engaging and fun during lectures. In class activities were extremely exciting to carry out, and allowed for experiential learning. Enjoyed coming up with the final project proposal.
Q: How could this course be improved? (7 out of 31 responses mention in-class activity)
I would say more practical or hands on activity. Speaking for myself I learn best when workings hands on, I may not be inclined to go out of my way to go to the labs mentioned in course. So an in class activity would give me the nudge to go out and try for myself. Thus improving my understanding
I would have liked more activities like the lab-->study guide-->first quiz. That was the only part of the course where I really felt like I learned a good bit about what was going on. o *[Instructor Note: The first part of the course involved the activity]*
more interactive activities
More activity pls
Not sure. Maybe more in person labs would be cool because we did one and it was a lot of fun and really made me see how microsystems worked.
More hands-on projects
Another lab if possible
Q: What was the greatest strength of the instructor? (1 out of 31 responses mention in-class activity)
Dr. Myers is very enthusiastic about his teaching subject, and he sparks my interest in microfluidics. The class has a good balance of lectures and presentations/projects. His lectures are always fun and engaging, and it is such a pleasure to be taking this class as a depth

elective. (I loved the hands-on build a microfluidics activity)
Q: How can instruction be improved? (1 out of 31 responses mention in-class activity)
More in-class activities!

Supplementary Table 4: Georgia Tech collects Course Instructor Opinion Surveys (CIOS) in every class. Responses are anonymous, and include 16 multiple choice questions about the student effort, quality of the course, and quality of the teaching. There are also 5 optional short answer questions for students to provide written effort about effort, best course features, suggestions for improvements, instructor strengths, and instructor improvements. Students automatically receive announcements and reminder emails asking them to complete the survey, and instructors may also send emails to the class encouraging participation. Here, the instructor sent supplemental emails every 2 days to the class.
In the Spring of 2022, the survey was open from April 18 to May 8, 2022, and was sent to 12 students, of which 100% responded. In the Spring of 2023, the survey was open from April 17 to May 7, 2023, and was sent to 33 students of which 85% responded. These dates are approximately 10-14 weeks after the conclusion of the activity). In both offerings, the instructor also provided a list of possible reflection points to students to comment on including: lecture format, invited guest speakers, projects, presentations of scientific papers, and the in-class activity.