Open-Source Virtual Labs with Failure-Mode-Inspired Physics and Optics Experiments

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An essential goal for physics and optical science instructors is to encourage students to find excitement and beauty in physical and optical phenomena while helping them learn the theoretical concepts and conducting experiments that can test the validity of the concepts. Such motivation largely relies on realistic hands-on lab opportunities where students can interact with physics-based phenomena as well as their corresponding laws and principles. Virtual simulation and modeling tools[1,2] provide a great alternative to deliver interactive experiences when participating in physical lab environments is limited or unavailable (i.e., during distance learning due to the COVID-19 pandemic). The use of computer-based simulations can improve students' ability to make predictions and explain the phenomena practiced in the experiments.[3] The educational value of virtual labs has been extensively investigated and reported, showing that students who use simulated equipment outperformed their peers.[2-4]

What is a failure mode in virtual labs?

One of the unique and critical differences between lab experiences and textbook-based lectures is the presence of practical limits. Textbook-based lectures generally discuss idealized cases, as do many virtual labs or simulations. Therefore, students do not experience failure such as measuring incorrect results due to extraneous circumstances. Failure gives students an important opportunity to develop troubleshooting skills. No-failure approaches often do not provide a realistic sense of the measurement, which includes errors from factors such as fabrication or misalignment. Most virtual labs or simulations have a similar non-realistic aspect as they are often designed to only work within a specific range or correctly configured setup.

For instance, a Snell's law experiment explores the behavior of light when encountering an interface between two media with different refractive indexes. The refractive index is defined as a ratio of the speed of light in a given medium to the speed of light in a vacuum. As shown in Fig. 1(a), the setup of a Snell's law experiment illustrates the effect of light rays bending when exiting one medium (e.g., glass) with refractive of index n_1 and entering another (e.g., air) of n_2. Figure 1(a) represents an ideal case, whereas Fig. 1(b) represents a situation affected by a misaligned glass block on the rotating angle measuring disk plate.

At the bottom of Fig. 1 the measured refraction angle is wrong due to a misalignment error. If students cannot experience this *failure mode*, when the lab setup produces incorrect outputs or faces practical limits of measurement uncertainties (e.g., coarse ruler's resolution), then the educational value of a lab is severely diminished. Successfully completing a lab while starting from an initial failure can help students appreciate the presented concept and theory.

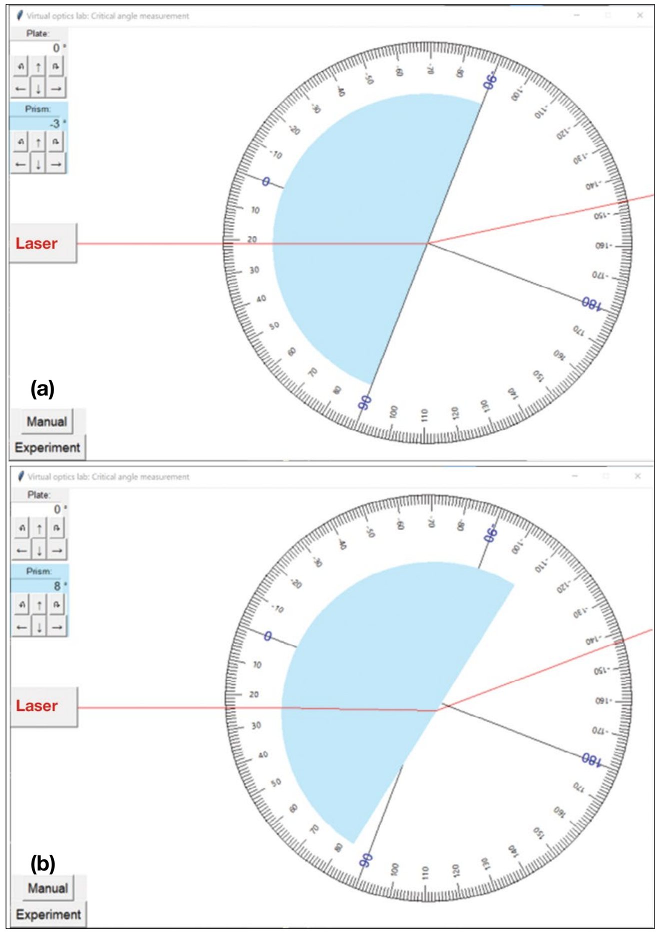

Fig. 1. Screen capture of a virtual lab illustrating the index of refraction of the glass block (blue) and Snell's law of refraction measurements. Examples show a nominal setup (top) and a failure-mode case (bottom). Movement of the rotating disk and the glass block are controlled from the top-left corner of the virtual lab panel.

An example of failure-mode labs are the Physics Education Technology (PhET) interactive simulations.[5,6] These are diverse and highly accessible virtual labs that have provided educational value to teachers and students since 2002. It is important to acknowledge the possible misuses of a PhET simulation to obtain results that do not follow theoretical predictions. This can be thought of as a built-in failure-mode lab, but they are not intended to be used as part of the educational learning process. The virtual labs inspired by failure-mode options are intentionally designed to be misused (e.g., misaligned optical components with respect to the measuring tick marks) to simulate real-world challenges faced during an in-person lab experience. The failure-mode labs therefore do not compete with the existing virtual labs; instead, they fill in

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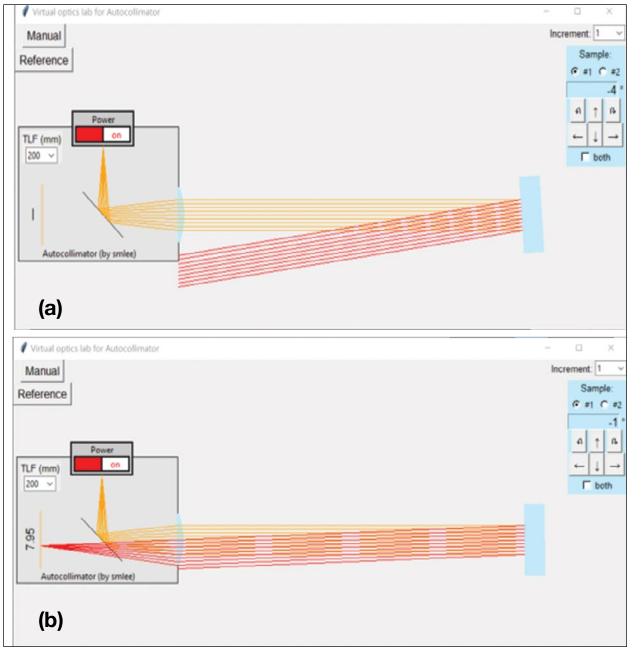

Fig. 2. Screen capture of a virtual lab focusing on optical surface alignment with an autocollimator. (a and b) The failure-mode-enabled case (a) shows large misalignment errors when compared to the nominal case (b). The disk (blue) is the unit under alignment and the incoming beam (orange) and reflected beam (red) are used for measurements of the surface.

a missing piece between a virtual and an in-person lab, which has not yet been explored.

The American Association of Physics Teachers (AAPT) has highlighted the importance of developing students' troubleshooting abilities through laboratory experiments. The AAPT "Recommendations for the Undergraduate Physics Laboratory Curriculum" report[7] states that "the hands-on experience of constructing an experimental set-up or apparatus and of troubleshooting it is a very important part of a laboratory experience. Students should emerge with demonstrable skills in executing technical projects from conception to completion." Failure-mode physics and optics virtual labs are specifically designed to build these troubleshooting skills and complement existing high-quality virtual lab resources such as PhET.[5,6]

Another example of a failure-mode option lab is the optical flat surface alignment virtual lab (Fig. 2). In this experiment a simple instrument called an autocollimator is used to align a flat optical element. An autocollimator uses a point source followed by a lens to collimate a beam (i.e., parallel rays) illustrated by the orange rays. The rays are then reflected by the sample under alignment (i.e., blue block in Fig. 2), shown as the red rays. The deflection angle of this reflected beam is measured by the autocollimator.

When the sample is misaligned [Fig. 2(a)], the light reflecting off the surface will not pass into the autocollimator. At this point, there is no signal to guide the rest of the experiment. As the student adjusts the orientation of the blue block, which is possible in the failure-mode-enabled virtual lab, the light eventually will be directed to the measurement system [Fig. 2(b)] and produce a signal to guide the remaining fine alignment process. This is the moment that sparks a sense of accomplishment and excitement for students and can build educational interest in the subject. This experience is a natural occurrence in an in-person lab session but is lost when engaging in a virtual alternative. The failure-mode-enabled virtual labs let students explore these natural learning steps and enjoy the discoveries of working on experiments.

Virtual labs are not intended to replace traditional lectures or teach the basic principles, theories, and concepts of optics. Instead, they add a sense of realism to a virtual lab experience by offering more opportunities to learn from failure.

These types of failure-mode simulation labs could prove beneficial within the context of today's public schools. When failure mode is enabled, it allows for students to engage in problem solving as well as use critical thinking skills. Giving students opportunities to experience failure gives them the ability to practice problem solving and facilitate discussion with their peers, thus, encouraging solution-based discussions. These discussions can help students learn how to communicate within the context of academia.

Further, experiencing failure can lead to increased resiliency. When students are confronted with challenges that can be overcome within the context of the classroom, their confidence can grow. They may feel more equipped to handle problems outside of the classroom, thus increasing their resiliency.

Free license open-source Python script

Many physics and optical science virtual labs, including more than 30 failure-mode-enabled publicly available options,[8,9] were developed using the freely available Python license and environment. Examples of the virtual labs include: an Autocollimator Lab to practice aligning flat mirrors, a Darkfield Microscope Lab to detect defects and scattering features on microscopy samples, a Spherometer Lab to measure the curvature of a mirror and lens surface, and a Prism Refraction Lab to determine the refractive index of a prism material.

All the lab scripts are open source, thus anyone can access and modify the virtual lab code using a standard editor (e.g., Microsoft Windows Notepad) without requiring purchase of a software package such as MATLAB.

Python's accessibility means there are infinite opportunities to deeply explore and develop more failure-mode versions of labs, so long as the student has experience with the scripting syntax and programming. For instance, an advanced option of the Snell's law virtual lab (Fig. 1) and its code (Fig. 3) can be modified to include a failure mode caused by manufacturing errors of tick marks and angle values on the protractor.

Teaching and evaluation guideline

Guidance of virtual labs can be conducted in various ways. The following is an example of steps for the Snell's law lab:

1. ***Study Snell's law theory*** with students in class or through reading material.
2. ***Encourage students*** to predict the angle of refraction for the given lab configuration, shown in Fig. 1 (top).

3. ***Deduce the relationship*** between the refractive index of the prism material and the exiting ray's angle of refraction based on the discussion with students in Step 2.
4. ***Ask students to write*** a procedure to determine the refractive of index using the given setup.
5. ***Let students run the virtual lab*** and use the procedure from Step 4 and record all the experimental data. While students are running the labs, ask them some failure-mode questions like "What happens if the prism is not located at the center but on the edge of the rotating plate?" or "How do you know if the rotating plate is located correctly?"
6. ***Engage students in an open discussion*** to determine the challenges that can be faced in acquiring accurate measurements (e.g., reading the angle when the prism, rotating disk, and incoming beam are not properly positioned). Ask students to describe them in a clear and concise method.
7. ***Troubleshoot*** the possible solutions to the challenges and describe them in class altogether.
8. ***Let students re-run the virtual lab***, record all the experimental data, and calculate the refractive index of the prism using Step 3.

The suggested evaluation criterion is an open-ended report with the following sections: experimental steps, experiment challenges, troubleshooting process, measured data, discussion of data, measurement errors, and a conclusion. The main goal of the failure modes is to let students test the scientific concepts and discover the practical challenges that occur in each lab.

```
def getPlateRotated():
    dA = p[0]+float(entries[0].get())
    dx = p[1]+p0x
    dy = p[2]+p0y

    # Rotating Disk
    hC.coords(plate, (dx-pR, dy-pR, dx+pR, dy+pR))

    # Rotating Disk Tick Markings
    for item in hC.find_withtag('plate'):
        hC.delete(item)

    for i in range(360):
        rA=math.radians(dA-i)
        cosA=-math.cos(rA); sinA=-math.sin(rA)
        if i%90:
            if i%10:
                hC.create_line(pR*cosA+dx, pR*sinA+dy,
                               (pR-15)*cosA+dx, (pR-15)*sinA+dy, tag='plate'
            else:
                hC.create_line(pR*cosA+dx, pR*sinA+dy,
                               (pR-25)*cosA+dx, (pR-25)*sinA+dy, tag='plate'
                if i>180: i-=360
                hC.create_text((pR-40)*cosA+dx, (pR-40)*sinA+dy,
                               text=f'{i:>3d}', fill='black', angle=i-dA,
tag='plate')
        else:
                hC.create_line(pR*cosA+dx, pR*sinA+dy, dx, dy, tag='plate')
                if i>180: i-=360
                hC.create_text((pR-40)*cosA+dx, (pR-40)*sinA+dy,
                               text=f'{i:>3d}', font=('',14), fill='blue',
angle=i-dA, tag='plate')

    getPrismRotated()
    hC.tag_raise(prism)
    hC.tag_raise(laser)
    for item in hC.find_withtag('warning'):
        hC.tag_raise(item)
```

Fig. 3. A segment of the open-source Python script used for the Snell's law virtual lab shown in Fig. 1. This segment of the script defines the rotating protractor disk measuring the angle of the ray.

The instructor may let each lab group present their experimental procedure and outcomes in front of their peers. Other groups can evaluate and provide feedback to the presenting team. Due to the failure-mode nature of the virtual lab, the presentations and challenges will be different between the lab groups.

An open discussion will allow for increased learning opportunities and a more in-depth understanding of the lab and the failures that occurred along the way. Teachers should facilitate the presentation and discussion session and evaluate each team's performance.

The teacher may grade the students based on the completeness (e.g., experimental steps, data table) of the written report (40%), structure/contents/time of the group presentation (30%), and the active participation (e.g., questions and answers) during the open discussion (30%). Of course, this should be adapted to the educational setting such as the level of class and student-to-teacher ratio.

Conclusion

The failure mode is a simulation feature used to configure an experimental setup incorrectly and introduce realistic errors to a system. The goal is not to fail students, but to help them truly succeed. If a virtual lab begins with a successful configuration, students will not learn how to build an experiment. In many simulations, students simply click buttons to confirm theoretical predictions that they have already learned through lectures. While these virtual labs have value, they miss a unique educational opportunity present in physical lab experiences by succeeding through failure.

Teachers want to motivate students to learn and apply this knowledge to their work as they progress through their education. The failure-mode-enabled physics and optical science virtual labs are meaningful and powerful solutions to complement the classroom-based teaching curricula when physical labs are not readily available. Students and instructors can freely access the Python scripts, using any available editor on their computer to dive into and experiment with the realistic versions of virtual labs. Through this experimentation students will learn important lessons and key concepts by failing and overcoming realistic system errors.

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8. The open-source Python virtual labs are available through the project website at the Wyant College of Optical Sciences, University of Arizona: http://www.loft.optics.arizona.edu/vlabs/.
9. More than 30 virtual labs are available and can be acquired by contacting the authors by email. More labs will be added and shared with the public through the outreach website.[8]

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