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The Possible Uses of Foldscopes as a Form of Frugal Science in the Biology Classroom As Well As in Out-of-School Science Activities

Jannie Pretorius*[a], Josef de Beer[b], & Cherine Jackson[c]

* Corresponding author
Email: pretoriusjph@ufs.ac.za

a. Department of Mathematics, Natural Sciences and Technology Education, Faculty of Education, University of the Free State, Bloemfontein, South Africa

b. Science Learning Centre for Africa University of the Western Cape Bellville, Cape Town, South Africa

c. School of Mathematics, Science and Technology Education, Research Focus Area Self-Directed Learning, North-West University, Potchefstroom, South Africa

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ABSTRACT
This article explores the possibilities of a cheap one-dollar microscope, the Foldscope, for enhancing out-of-school science education. Developed by Manu Prakash and Jim Cybulski from Stanford University, these origami-type paper microscopes make it possible to provide all students with their own microscopes, due to the low cost. This provides students the opportunity to engage in science outside of the classroom, as amateur sleuths engaged in environmental inquiries, e.g., determining the levels of pollution of local water resources. In this article the authors share two sets of research data: an activity where school students engaged in authentic problem-based learning using the Foldscopes, as well as student teachers' experiences of engaging with Foldscope microscopes. The outcomes of the first research project indicate that affective outcomes and cognitive gains were achieved. Responses in the second research project included five categories: preparation and presentation; potential of the Foldscope; use of slideshow; energy/complements; and limitations. The conclusion reached was that Foldscopes hold possibilities for enhancing STS (science-technology-society) approaches inside and outside the classroom. One recommendation is that such frugal-science approaches are emphasized more in both pre-and in-service teacher education.

KEYWORDS
Foldscope microscope; scientific sleuths; environmental investigations; frugal science; science-technology-society approaches.

INTRODUCTION

The science-technology-society (STS) movement was called a mega-trend in science education in the early 2000's (Mansour, 2009). STS as an interdisciplinary approach to science education advocates for a topical curriculum that addresses a broad range of environmental, industrial, technological, social, and political problems (Wraga & Hlebowitsch, 1991). One may ask, however, how successful the STS movement is in "teaching and learning science in the context of human experience" (NSTA, 1993). For many students, science is an activity that is performed in the classroom or laboratory; for many students, out-of-school science mean tedious homework assignments.

The STS agenda could be better served if we provide students with opportunities to engage with authentic science outside the classroom. For example, students could investigate the levels of pollution of a nearby river or lake, or determine what type of microbes infect plants in their gardens. Such activities would provide students an experience of how *real* science impacts our daily lives. This is often hampered by the fact that students do not have scientific equipment or apparatus at home. How many students have microscopes at home? To address this problem, Manu Prakash from Stanford University developed a cheap origami-type microscope that could facilitate such microscopy investigations.

Before describing the Foldscope microscope, it is essential to focus on what literature refers to as 'frugal science.' Rao (2019, p. 1) describes frugal innovations as 'doing-more-with-less' and shows that such approaches have become popular due to a no-frills nature and lower costs. Sarkar and Mateus (2022, p. 1) describe frugal approaches as "the way to produce efficacious and affordable products using fewer resources to reach underserved customers." There is the added advantage that these simple designs or approaches often leave a minimal carbon footprint, thus addressing issues of sustainability and tackling the global climate change problem facing humankind (Rao, 2019).

The development of the Foldscope – A brief history and theoretical analysis

The Foldscope (see Figures 1 and 2) was invented by Manu Prakash and Jim Cybulski at Stanford University (https://www.foldscope.com; Cybulski et al., 2014).

Their inspiration for the Foldscope came from field visits around the world where they continually encountered bulky, broken microscopes or a lack of microscopes entirely. Inspired by the idea of cheap field diagnostics, the project blossomed into the invention of the Foldscope, a foldable microscope made mostly of paper, with a cost of less than 1 U.S. dollar. The developers were mindful of the concern expressed by Rao (2019, p. 1), namely that such frugal-science interventions need the "sound application of design methodologies that are deeply rooted in science". This ultra-affordable, paper-based microscope can be assembled by the students themselves. It was designed to be inexpensive, durable, and give optical quality equal to conventional research microscopes. It provides the opportunity for *in situ* examination of specimens in the field (Cybulski et al., 2014).

Figures 1 and 2

The unfolded microscope and its packaging (left), and an assembled Foldscope microscope (right).

Cybulski et al. (2014) argue that *in situ* examination of specimens in the field provides important opportunities for ecological studies, biological research, and medical screening. Further, they point out, low-cost DIY microscopes provide means for hands-on science education in schools and universities. Finally, they say, this platform could empower a worldwide community of amateur microscopists to capture and share images of a broad range of specimens.

Ganesan et al. (2022) show that Foldscope microscopes have been used in various disciplines, such as the health sciences sector, clinical diagnosis, forensic sciences, agriculture, developmental biology, and education. We will briefly reflect on the literature related to the affordances of the Foldscope in each of these sectors. A gap in the literature is its use in an educational setting, and very little has been published in the use of the Foldscope in the science classroom.

Banerjee (2018) reported on the affordances of the Foldscope in studying the bacterial count in food samples. Several authors have worked on the use of the Foldscope in medical sciences. Hasandka et al. (2012) showed how the Foldscope has been used in the diagnosis of urinary infections. Ephraim et al. (2015) evaluated the Foldscope and the reversed-lens CellScope, using single-ply paper towels as filter paper, for the diagnosis of a *Schistosoma haematobium* infection in Ghana, Africa. They reported that the mobile phone-mounted Foldscope and reversed-lens CellScope had sensitivities of 55.9% and 67.6%, and specificities of 93.3% and 100.0%, respectively, compared with conventional light microscopy for diagnosing *S. haematobium* infection. Their results indicated that, with conventional light microscopy, urine filtration using single-ply paper towels as filter paper showed a sensitivity of 67.6% and specificity of 80.0% compared with centrifugation for the diagnosis of *S. haematobium* infection. They argued that, with future improvements to diagnostic sensitivity, newer generation handheld and mobile phone microscopes may be valuable tools for global health applications.

Moya-Salazar et al. (2016), on the other hand, monitored and evaluated the implementation of Foldscope technology in the screening of cervical cancer in conventional exfoliative cytology. An exploratory, quasi-experimental double-blind research was conducted in the Prakash Lab, the Department of Bioengineering at Stanford University during May 2016. They selected 10 slides of cervical cytology, four negatives for intraepithelial lesion or malignancy (NLIM) and six with cervical uterine abnormalities. The cytological characteristics of the smears were evaluated with both Foldscope and optical microscopy, using 10x and 40x magnification lenses. Microphotography, an image station tool and image projection were used. The researchers reported that, based on the comparison of images between the optical microscope and Foldscope, the same cytological features were found in the cells of both NLIM and preneoplastic or neoplastic lesions ($p < 0.001$). However, they also reported that the Foldscope showed a lack of clarity around the focal point as well as constraints in focus, which necessitated the use of the image station and image projection. They concluded that Foldscope is an extraordinary tool for the diagnosis of cervical cancer.

Maithil (2008) showed how the Foldscope could be useful in the forensic sciences and in solving crimes. Kumar et al. (2019) focused on the agricultural use of the Foldscope, e.g., in the identification of phyllosphere microbes in rice. Yesudhason et al. (2020) focused on the use of the Foldscope in developmental biology, namely the developmental stages of zebrafish.

Jackson et al. (2020) highlight the affordances of the Foldscope in educational contexts-with gains for both teachers and students. In the latter authors' research, teachers indicated that their engagement in classroom action research projects linked to the Foldscope, assisted them to develop critical reflective skills. The teachers also emphasized the affective affordances of the Foldscope, in so far that students found the activities exciting, and that it stimulated student interest in science. The Foldscope could provide a learning space characterized by cognitive dissonance (Jackson et al., 2020) to both teachers and students alike. Students, who are accustomed to often receiving ready-made answers, have to engage in rather complex activities, in which there are not immediate answers. Teachers again are challenged to engage in classroom action research, that they might find challenging.

A report about two research projects

We would like to shed light on two research projects that we engaged in.

First, we should point out that the subject biology is known as life sciences in South Africa. The first study focused on grade 10 life science students' experiences of engaging with Foldscopes, while the second study determined the possibilities of the Foldscope in the field of higher education, namely for the training of life sciences student teachers in South Africa. Abd-El-Khalick et al. (1998) mention that a relationship exists between teachers' views on certain concepts and how they teach. It is therefore essential in both pre-service and in-service teacher education to focus on STS approaches, and how instruments such as the Foldscope could serve such an agenda.

Grade 10 students

This study among grade 10 students was guided by two research questions:

1. What are the affordances of utilizing Foldscopes in promoting affective outcomes in the life science classroom?
2. What are the grade 10 students' experiences of engaging with Foldscopes, during a water-quality practical?

We identified a current issue flagged in the Life Science curriculum, namely water quality in South Africa. The Foldscope activity included two parts. In activity 1 (see Figures 3 and 4) the students were required to collect a water sample from a nearby water source.

While collecting the sample they had to practice their observation skills, i.e., look at the color of the water and identify organisms found in or around the water. Students also had to engage in practical tasks such as measuring the pH and the temperature of the water. Activity 2 (see Table 1) was performed during class time. They were required to assemble the Foldscope microscopes and make prepared microscope slides of their water samples to view with their Foldscope microscopes. Students were asked to complete a water quality project and write reflections with regard to their overall experience of using the Foldscope.

We also conducted focus group interviews with the grade 10 students after the investigation to establish how they experienced using the Foldscopes. The following themes emerged from the data:

Affective outcomes were achieved

Some of the students' comments were:

> "At first I thought that it would be impossible to be able to see clearly through the Foldscope because it seemed to be 'too simple'. I was presently surprised as I put my water sample on the slide and inserted it into the Foldscope. My cellphone camera picked up a clear image of small organisms. I figured out that it was helpful holding the Foldscope at an angle against a bright background, such as the classroom whiteboard".
>
> "I found the practical extremely fascinating and exciting. I was amazed at the organisms that exist and how hardly anyone knows about them. The Foldscope was lots of fun to assemble but I struggled a little with the instructions".

Although the task was perceived as being challenging by the learners, they reported cognitive gains

One student remarked: "This practical experiment was a fun learning adventure which taught me many new things. It gave me problem-solving skills when working to build my microscope. The Foldscope was a valuable tool as it brings microscopes to everyone at a very cheap price, which will end up exposing more people to Life Science, and increase knowledge and learning within schools. The overall practical gave me some insight into how people cause pollution; using the Foldscope allowed me to really get involved in the investigation and to get us into the hang of biological thinking and experimentation".

Figures 3 and 4

Grade 10 students using the Foldscope microscopes to study water quality.

The use of Foldscopes during simulated teaching

The second project was guided by the following research questions:

1. What are the affordances of utilizing Foldscopes in promoting teaching and learning in the life science classroom?
2. What are student teachers' experiences of the Methodology of Life Sciences when engaging with Foldscopes during a water quality practical?

To develop the skills of the Methodology of Life Sciences student teachers at the University of the Free State in Bloemfontein, South Africa we have introduced a simulated teaching environment in the laboratory. Simulated teaching differs from the better-known microteaching in one important aspect. In microteaching, individual teaching skills (like introduction skill, questioning skill, reinforcement skills, and explanation skill) are scaled down or broken down into a micro level and then practiced one at a time (Ahmad, 2011, p. 68–9).

In simulated teaching, though, all the teaching skills are considered and practiced together rather than individually (Ahmad, 2011, p. 172). His definition of simulated teaching is applicable within the context of our study: "A teaching practice by teacher-trainees in a simulated or artificial environment wherein a small group of 5–10 student teachers are taught a minor concept by a pupil-teacher for 5–10 minutes using various skills of teaching to get perfection in these skills and in teaching as a whole."

We handed Foldscopes to five of the final-year student teachers in the above-mentioned module and asked them to prepare a simulated lesson during which they would use Foldscopes to present any of the topics in the school science curriculum. The group decided that the lesson would be planned and presented by Carina (see Figure 5).

Table 1

The activity sheet that was given to the Grade 10 students.

GRADE 10 INVESTIGATION
WATER QUALITY USING THE FOLDSCOPE

Core Skills:	Communicating; organisational skills; fine-motor skills; conceptual thinking; analytical thinking and practical skills – Equipment use, microscopy, tabulation, and graphing.
Aims:	Investigating phenomena in life sciences. Appreciating and understanding the history, importance, and applications of Life Sciences in society. Show awareness and sensitivity towards the environment.

Task Overview

In this investigation you will complete the following:

Exercise 1 – at the water site

- Collect water from a water source near you.
- Test the water for pH and the temperature of the water.

Exercise 2 – in the laboratory (class)

- Test the water for pH, temperature and dissolved oxygen.
- View the water sample using the Foldscope microscope. Identify the microorganisms that occur in the water sample.
- Do desktop research on which microorganisms are indicators of eutrophication/ pollution.
- Make a poster, in which you reflect on your investigation.

Background information for investigation: Ways in which the quality of water can be tested

1. ***Testing for ammonia in water (NH_3)***
   NH_3 is the principal form of toxic ammonia. It has been reported to be toxic to freshwater organisms at concentrations ranging from 0.53 to 22.8 mg/L. Toxic levels are both pH and temperature dependent. Plants are more tolerant of ammonia than animals, and invertebrates are more tolerant than fish.
2. ***pH of water***
   pH is one of the most common water quality tests performed. A change in the pH of water can alter the behaviour of chemicals in the water, which is detrimental to aquatic fauna and flora. Use the universal pH paper to get an exact pH measurement.
3. ***Microscopic aquatic organisms and the Foldscope***
   Organisms belonging to the Monera and the Protista kingdoms could also be an indicator of water quality. Use the field guide card from the Foldscope microscope to identify the variety of unicellular organisms in the water sample collected. Consult articles on the Internet, and write a report on the quality of the water, based on the organisms that occur in the water source.

Task: Making a poster, in which you reflect on the data obtained during the investigation

Be creative when designing your poster. However, the following aspects must be included:

1. Procedures followed to determine water quality
2. Data obtained (also include photographs or drawings of the organisms that you saw in your water sample)
3. Analysis of the data
4. Conclusion
5. Recommendations
6. References used

Figure 5

Student presenter Carina presenting to a group of peers. (Photo printed with the permission of the identifiable student teachers.)

The lesson presented was on the characteristics of cells. To give the learners maximum time to use the Foldscope, the theoretical part of the lesson was quite short. The goal of the lesson was to encourage learner participation and engagement with the topic of the session: how can a Foldscope be used to study the differences between plant and animal cells?

Carina prepared the lesson with meticulous precision. She had the light source of the Foldscope and Foldscope slide set *A-Set06* available (see Figure 6), and she had taken photos of plant tissue and (her own) blood with her cellular phone's camera (see Figures 7 and 8). She included them in a *PowerPoint* presentation, which turned out to be very handy when she wanted to demonstrate what her group members should be looking for.

Figure 6

Foldscope slide set and light source – Adding great value to the Foldscope experience.

Figure 7

Kelp tissue as seen under the Foldscope.

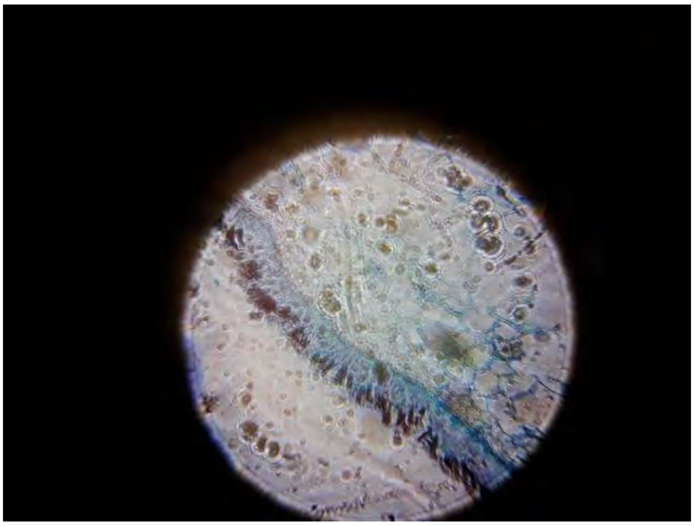

Figure 8

Blood as seen under the Foldscope.

After an enjoyable lesson, which she presented with passion and enthusiasm (see Figures 9 and 10), group members provided qualitative feedback. In Table I we have divided the responses into five categories: preparation and presentation; the potential of the Foldscope; use of the slideshow; energy/complements; and limitations (see Table 2). Under each of these categories, we have added the relevant responses of the students.

Figure 9

Carina presenting passionately.

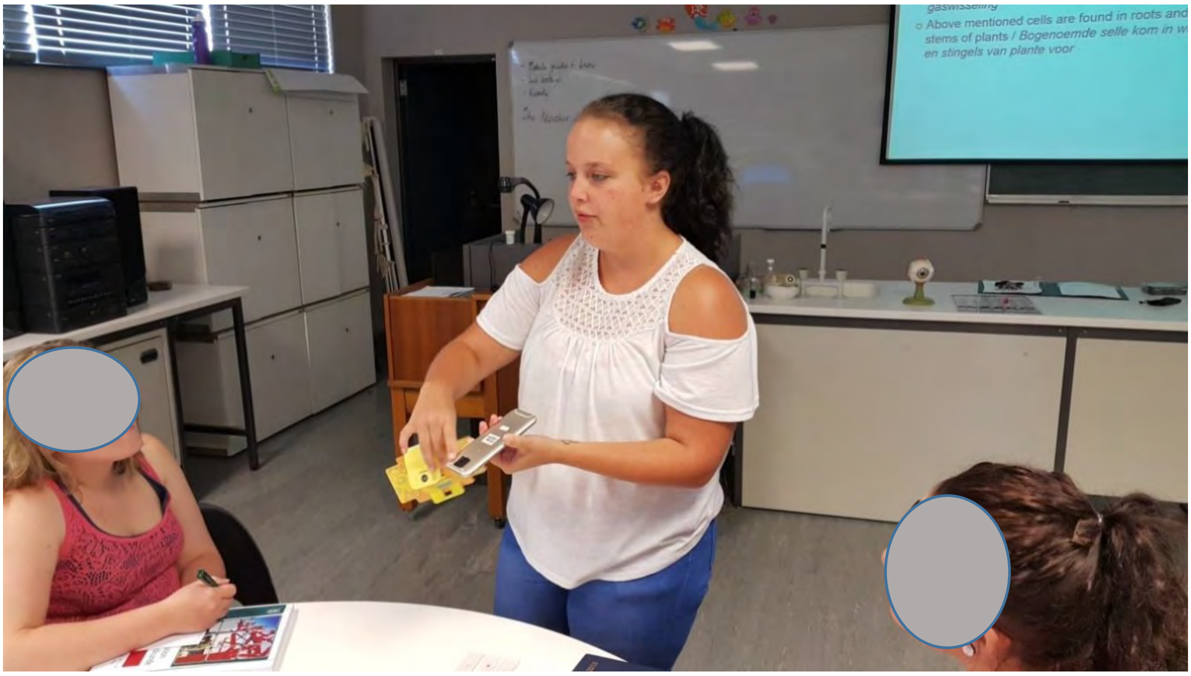

Figure 10

Taking pictures of an image with a cellphone.

Table 2

Peer feedback on the Foldscope lesson presented by Carina.

Preparation and presentation (6 comments)	Potential of Foldscope (5 comments)	Use of slideshow (6 comments)	Energy/Complements (5 comments)	Limitations(3 comments)
Well prepared and confident.	I love the portable microscope idea and it has wonderful potential in classrooms.	The slides were well prepared.	Very interesting and enlightening.	List plant organelles – could have used pictures.
Very well prepared and presented.	Foldscope very interesting – elicits curiosity of learners.	Back up photos an excellent idea (3X).	I liked the practical part best.	Perhaps more visual PowerPoint.
It helps a lot when you know exactly what you're talking about.	Connects Foldscope and plant tissue well.	Very good bilingual [Afrikaans and English] PowerPoint.	Excited, enthusiasm!	Information at the start of the lesson: perhaps show it later again on a diagram.
A lot of preparation went into this lesson.	Explained very well how to use the Foldscope.	Good use of photos of slides.	Well done!	
Group participation was enhanced, and every learner is reached.	You've put a lot of effort into Foldscope and slides.	-	Creative to use blood in slide.	
Good preparation – knew exactly how and where the Foldscope functions.				

We also had a focus group discussion about the group members' experiences in using the Foldscope, the possible uses of the Foldscopes in 'real' classrooms or laboratories, the possible challenges in the context of these venues, and the extent to which the Foldscopes have enhanced their understanding of the topic. Jomari, one of the group members, summarized our discussion:

With almost every topic explained in the life sciences class, it is possible to use the Foldscope. Learners can take a topic, go home, and use the Foldscope to analyze any part of the content they see as relevant. Examples may include different plants, water-testing or even insects. We would make sure that the Foldscope is used at least once during the presentation for every main topic – whether with direct instruction and guidelines from the teacher or when it is up to the children to decide for themselves what they see as relevant.

It is very affordable since it costs only about 1 dollar. It may not always be possible for schools to give one to every learner, but two learners might share a Foldscope. We also think that if learners work together, it makes them more comfortable as they are not as scared of making mistakes; they help one another and share experiences. In addition – most learners have cellphones so it can be practical to make use of the Foldscopes when it comes to urban schools; however, one should still consider rural schools when it comes to technology.

As fourth-year student teachers, this was the first time we learned about a 'pocket-sized' microscope, and it was quite easy to assemble it, especially with the use of YouTube videos. Presenting and creating lessons with the Foldscope is a new, creative, and exciting part of Life Sciences. It enables the teacher to facilitate lessons where learners are 100% involved in content analysis, problem-solving and discovery. We do not know who would enjoy the Foldscopes the most, the teachers or the students. We should also note that it is very effective to teach final-year education students the uses of the Foldscope, as we will then go into schools with the necessary knowledge to implement Foldscopes. Teachers already in the field should be invited to attend training workshops on the Foldscope.

Learners often lose their sense of discipline with discovery- or problem-based activities, thus it will be extremely important to make sure that the class rules and guidelines are clear before the Foldscopes are used. Learners may get confused with putting the Foldscope together, so we talked about first showing the learners the YouTube video and then following (reading out loud) the instructions to assemble the Foldscopes step-by-step. It would also be important to teach learners to take care of their Foldscopes and, although they may not tear easily, it is still necessary for them to handle the Foldscopes with care, and not just to stuff them into their backpacks.

Learners from all areas can implement the Foldscopes wherever they are to investigate their surroundings. This will surely contribute a lot to enabling learners to become scientists. The Foldscope will most certainly be a valuable instrument in any Natural Science, Life Science or Mathematics class. The possibilities of the Foldscope are endless. The Foldscope can also be implemented in primary school, from grade 6/7 so that learners become equipped. Foldscopes should be equipped with the specialized light sources since it enhances their possible applications.

CONCLUSION

Foldscopes hold possibilities of enhancing STS approaches inside and outside the classroom. In the literature review section, we have shown how the Foldscope has been used in a variety of contexts in health sciences, clinical diagnosis, forensic sciences, agriculture, and developmental biology to address problems through research. We concur with Mansour (2009) that teachers' beliefs about STS approaches are of cardinal importance in promoting this agenda. It is therefore important to sensitize both in-service and pre-service teachers to STS approaches and, in the context of this paper, on the affordances of Foldscope microscopes in Life Science teaching and learning. Foldscopes can support the realization of affective outcomes in the Life Science classroom. The literature review identified a gap, in as far as Foldscope research in the science classroom is scant. It is recommended that such frugal-science approaches are emphasized more in both pre-and in-service teacher education. This is especially important in the context of the climate change crisis facing the planet, due to the low carbon footprint of such low-cost science equipment.

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TEXTBOX 1: RESOURCES WHEN USING FOLDSCOPES TO DO WATER QUALITY TESTS

On assembling the Foldscope:

Tutorial video: https://www.foldscope.com/foldscope-instructions/

Foldscope home page: https://www.foldscope.com/

Manu Prakash talking about the Foldscope (video):

https://www.ted.com/talks/manu_prakash_a_50_cent_microscope_that_folds_like_origami

On microbial indicators of water quality:

Ismail, A.H. & Adnan, A.M. (2016). Zooplankton composition and abundance as indicators of eutrophication in two small man-made lakes. *Tropical Life Sciences Research* 27(1), 31–38.

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