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Beauty of Life in Dynamical Systems: Philosophical Musings and Resources for Students

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Synopsis

Information plays a key role in life and in complex biological systems, and dynamical systems underlie and can be used to represent many complex systems. Indeed, dynamical systems and information processing capabilities may be the hallmarks of life-like systems. In this paper we combine dynamical systems with a computational framework to generate art. The framework can be used to generate aesthetically appealing forms of life-like systems. Our work suggests that we may need an "aesthetic sense" to recognize life that we have not seen before. We also provide teaching resources for students in schools and undergraduate institutions.

1. Philosophical Musings

Information plays a critical role in life and in complex systems. Complex biological systems coordinate heterogeneous components in a decentralized fashion. How do these distributed and decentralized systems with billions of cells and components function? One key to answering this question is to investigate how these complex systems efficiently collect and process information.

In a previous paper, the first author hypothesized that information processing capabilities distinguish living from so-called non-living matter [1]. Information processing is a key ingredient for life. Chemical reaction systems called reaction-diffusion systems have been studied for their complex properties for a long time. One example is the Belousov-Zhabotinsky (B-Z) reaction which is a chemical oscillator and displays complex properties reminiscent of life, see Figure 1.

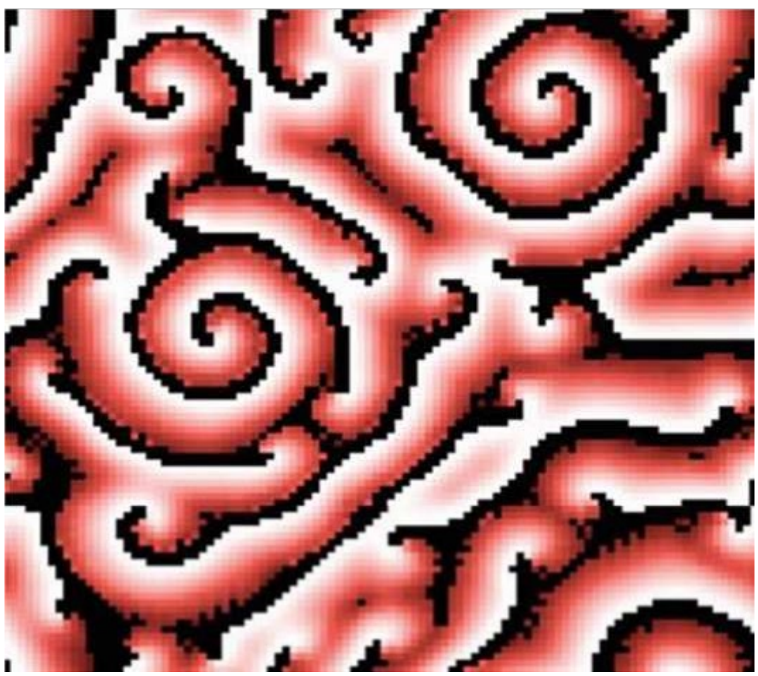

Figure 1: Screenshot from the NetLOGO simulation tool for the Belousov-Zhabotinsky (B-Z) reaction showing wave-like patterns that persist. We will say more about this image in Section 2.

We hypothesize that carbon-based life forms make up only one group amongst a continuum of life-like systems in our universe. Investigations into the role of computational substrates that allow information processing are important and could yield insights into novel non-carbon based computational substrates that may have "life-like" properties, as well as how living things may have actually originated from non-living things on Earth.

Life may exist as a continuum with inanimate things on one end and animate things on the other, and we may have to revise our notion of life and how common it is in the universe. Looking at life-like phenomena through the lens of information theory can yield a broader view of life.

The science fiction writer Arthur C. Clarke once described a potential alternate form of life that arises on an ultra-cold planet [**?**]. He envisioned electrical currents and waves forming in a superconducting fluid of liquid Helium 3. The entire planet is barely above absolute zero, yet harbours an intelligence that uses these electrical currents to perform computation. Very little material transport occurs and most information processing happens using waves of electrical currents that propagate to form a planetary scale global "brain". This form of intelligent alien life stretches the boundary of what we currently call life. It may not be recognized as intelligent life, if we did encounter it, using the guidelines of carbon-based lifeforms we have observed on Earth.

In this paper, we assume that dynamical systems and information processing capabilities are the hallmarks of life-like systems. With this assumption in the background, we combine dynamical systems with a computational framework to generate art. The framework can be used to generate aesthetically appealing forms of life-like systems. Our work suggests that we may need an "aesthetic sense" to recognize life that we have not seen before.

This aesthetic view also allows us to appreciate the beauty of life-like systems, life-forms around us, and their intimate connections with dynamical systems. This perspective can give us a sense of how every part of the universe computes and show us that the entire universe is alive and has intelligence. We hope this will give humanity a new sense of purpose, help us to appreciate our place in the universe, and also give a renewed thrust to conservation efforts to save our planet.

This paper presents teaching resources for students in schools and undergraduate institutions. It explains the role of information processing in life and suggests how computational simulations may yield insights into questions related to life-like systems. We hope our teaching resources will be especially useful in developing nations that are rapidly modernizing their education systems.

2. Teaching Resources: Belousov-Zhabotinsky (B-Z) Reaction

We assume that the students have a basic background and interest in science.

Our conception of life is shaped by what we see around us on Earth. What life forms might we expect to see on alien planets? Would they be carbon-based like us or can they be more exotic? In answering these questions, we must come up with an objective definition of life.

Chemical reaction systems called "reaction-diffusion systems" have been studied for their complex properties for a long time. One example is the Belousov-Zhabotinsky (B-Z) reaction, which is a chemical oscillator that displays complex properties and wave-like patterns reminiscent of life. We saw a screenshot of a simulation of this reaction in Figure 1. Another copy is in Figure 2 on the next page. The parameters chosen for the simulation are also shown in the second figure.

The full model is available on the NetLOGO online platform [5], see [6]. The program can be run completely online as well, at

http://www.netlogoweb.org/launch#http://ccl.northwestern.edu/netlogo/models/models/Sample%20Models/Chemistry%20&%20Physics/Chemical%20Reactions/B-Z%20Reaction.nlogo

Students can click on the *setup* button, play around with the sliders and set the parameters. They can then click on the *go* button. This will start the simulation. Simulation time is called *ticks* and is shown in the window.

2.1. Software Resources for Activities: Installation and Prerequisites

Some computational resources which can be used to create activities for students are available from the following repository:

https://github.com/neelsoumya/deep_dali.

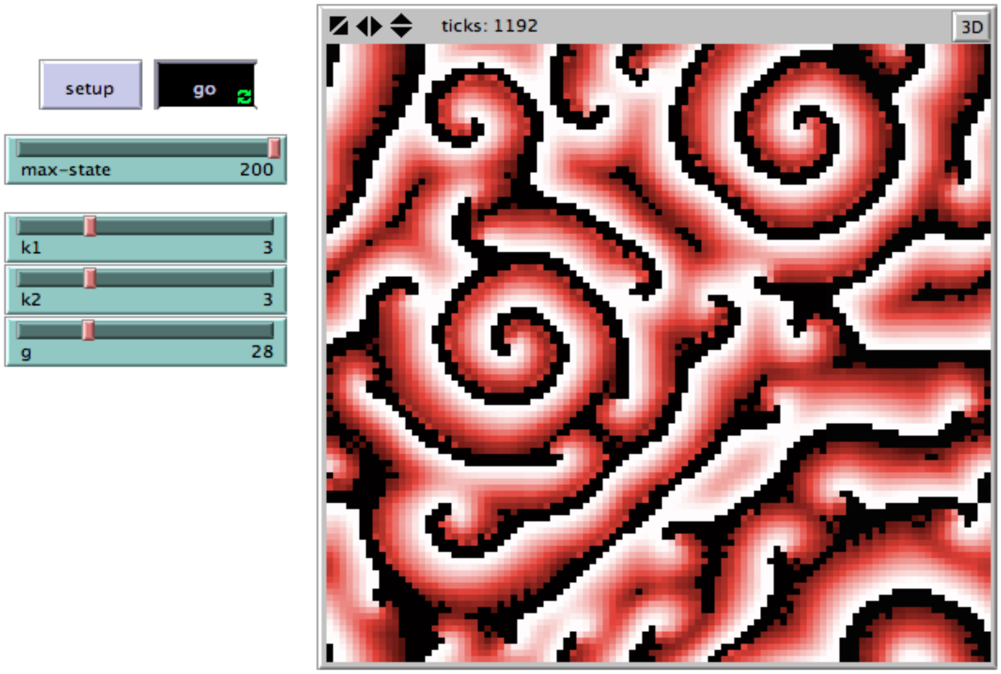

Figure 2: Screenshot from the NetLOGO simulation tool for the Belousov-Zhabotinsky (B-Z) reaction showing wave-like patterns that persist. Some further details may be found in [4]; also see [1].

This requires the Python programming language which can be installed from `https://www.python.org/downloads/`. The dependencies can then be installed by typing the following at the command line:

```
pip install -r requirements.txt
```

The NetLOGO language can then be installed from `https://ccl.northwestern.edu/netlogo/download.shtml`.

Alternatively a version of NetLOGO that can be run from the web browser is available at `http://netlogoweb.org/`. Students can generate the image in Figures 1-2 by going to this website which runs NetLOGO in the browser, and select

```
Sample Models/Chemistry & Physics/Chemical Reactions/B-Z Reaction
```

from the pulldown menu.

They can click on the *setup* button and then the *go* button. This will start the simulation of the B-Z model. The simulation will yield myriad beautiful patterns. Once the students observe a pattern they like, they can pause the simulation by clicking on the *go* button. They can then take a screenshot of the pattern and save it on their computer (say as `simulation.jpg`).

2.2. Introducing an AI-based "dream" step

The image of this reaction-diffusion system can then be modified using a deep-learning algorithm such as Google DeepDream, which can be viewed at https://deepdreamgenerator.com; see https://github.com/google/deepdream for a repository of an IPython Notebook with sample code.

The deep learning algorithm modifies the image and creates a new image with dream-like qualities. A sample of such a modified image is depicted in Figure 3.

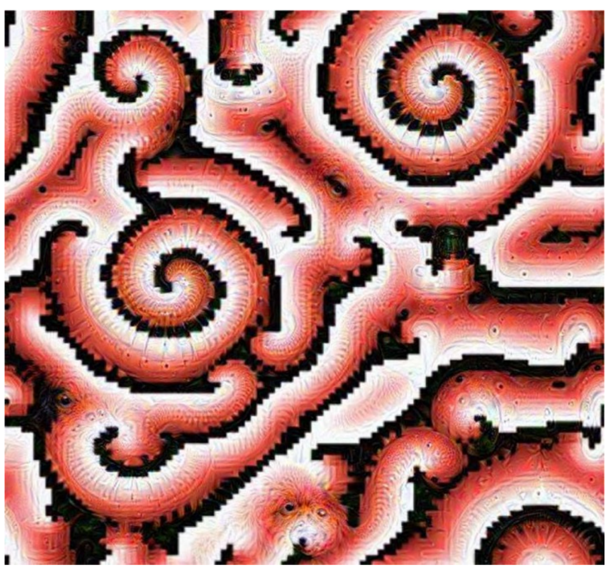

Figure 3: The image of a reaction-diffusion system as seen in Figures 1-2, modified using a deep-learning algorithm.

The deep learning "dreaming" program that can be used to obtain this image is available at https://github.com/neelsoumya/deep_dali/blob/main/deep_dream.py. Students can download the full code repository at https://github.com/neelsoumya/deep_dali.

The deep learning program can be executed by running the following at the command line:

`python3 deep_dream.py simulation.jpg result_dream`.

The new modified picture will be saved as `result_dream.jpg`. The image has a dream-like quality and emphasizes the beauty in life and in dynamical systems. It points to the computational origins of beauty in life itself. Our framework forms new representations of potential life-like systems.

Artificial Intelligence (AI) coupled to dynamical systems can be used to form new representations of life-like systems that may exist somewhere in our universe. More examples of computational art for dynamical systems can be found at https://github.com/neelsoumya/deep_dali.

2.3. Followup activities

We now outline some followup activities. Not all parameters in the B-Z reaction system will lead to patterns. We show an example below in Figure 4.

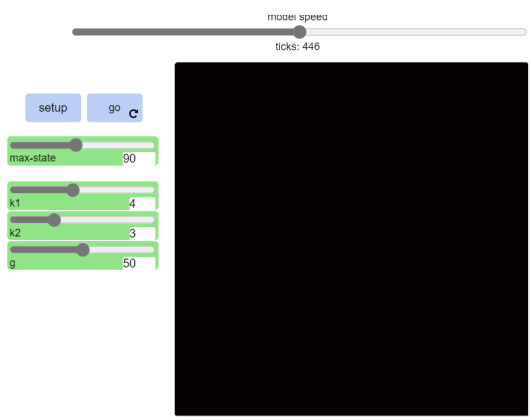

Figure 4: Screenshot from the NetLOGO simulation tool for the Belousov-Zhabotinsky (B-Z) reaction showing no patterns after the simulator is run for 446 time steps. See [4] for more details.

After 446 time steps, one can observe no patterns at all. This suggests that life-like systems are fragile. We note that since the simulation is stochastic, you will not get the same result every time, even if it is run with the same parameters.

Some parameters can also lead to persistent but very simple patterns (see Figure 5 below). We encourage students to play around with the parameters by moving the sliders.

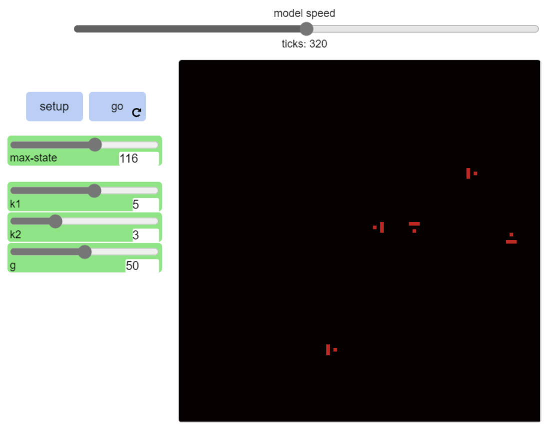

Figure 5: Screenshot from the NetLOGO simulation tool for the Belousov-Zhabotinsky (B-Z) reaction showing a pattern that is very simple but still persists over time. See [4] for more details.

3. Teaching Resources: Activities on Dynamical Systems

In this section we introduce another activity; this one involves modeling a forest fire. A forest fire model is a very simple way to visualize and think about complex dynamics and can help us reflect on the creation and destruction of life. A simulation tool for this activity can be found on the website `https://sandspiel.club/`.

3.1. Using the website to create simulations

Once the webpage is opened, students will see the screen shown in Figure 6 on the next page. If you do not see the blank canvas, then click on the "Reset" button. The next step is to add seeds. This can be done by clicking on the button labelled "Seed" and then clicking on the grey simulation area; see Figure 7. The next step is to add some water, which can be done by clicking on the button labelled "Water" and then clicking on the grey simulation area in the center of the screen. Alternate between adding seeds and water and the plants will begin growing. A snapshot of this simulation is shown in Figure 8.

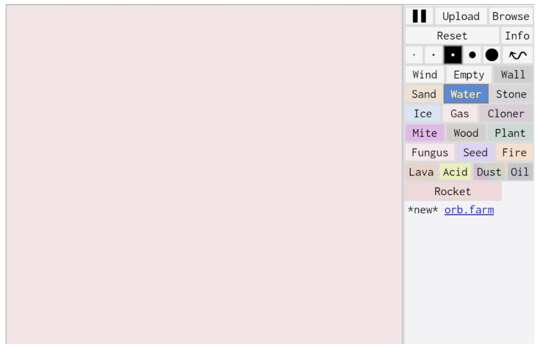

Figure 6: Screenshot of the first step of a forest fire model simulated on https://sandspiel.club/. This is the opening page and initial step.

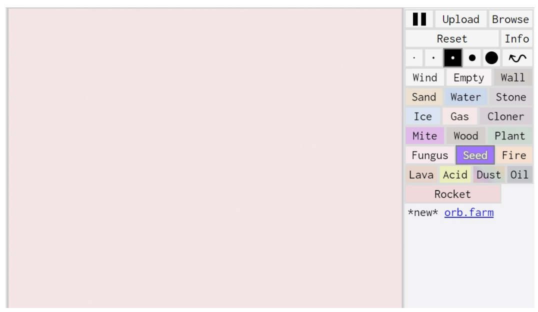

Figure 7: Screenshot of the second step of a forest fire model simulated on https://sandspiel.club/. The student has to click on the button labelled Seed and then click on the grey simulation area in the center of the screen.

Figure 8: Screenshot of the third step of a forest fire model simulated on https://sandspiel.club/. This shows the plants growing progressively as seed and water are added.

Once the plants have grown for some time, the student can add some fire by clicking on the button labelled "Fire" and then clicking on a plant in the grey simulation area. This would set fire to the plants and the fire would rapidly spread. A screenshot of a sample simulation is shown in Figure 9 below.

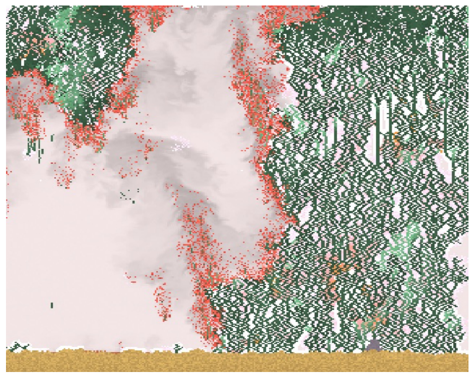

Figure 9: Screenshot of a forest fire model simulated on https://sandspiel.club/.

3.2. Additional activities for students

Students can now think of other ways to grow plants. Ask students what they think would happen if they added some fungus and mite by clicking on the buttons labelled "Fungus" and "Mite". Ask what they think would happen if they added some oil by playing around with the "Oil" button. Pair students up and ask them to run these simulations on two different computers, with each student following the same steps as their partner. Ask students if they can replicate the simulation on their partners' computers. If they are unable to do so, ask why they think the simulations are different on these two computers even though they have followed the same steps.

At this point students can modify the pictures they obtained using the deep learning "dreaming" program mentioned in Section 2.2; recall that this program is available at https://github.com/neelsoumya/deep_dali/blob/main/deep_dream.py. Students can download the full code repository from https://github.com/neelsoumya/deep_dali and then install python on a laptop as described earlier. The dependencies can be installed by typing the following command at the command line:

```
pip install -r requirements.txt
```

The deep learning program can be executed by running the command:

```
python3 deep_dream.py life_creation_destruction.jpg result
```

where `life_creation_destruction.jpg` is the name of the picture. The program will produce a modified picture named `result.jpg`. The picture obtained when we apply this procedure to the image in Figure 9 is shown below in Figure 10.

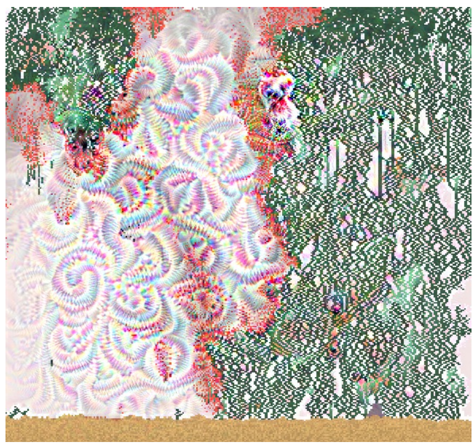

Figure 10: Screenshot of a forest fire model simulated on https://sandspiel.club/ modified with a deep learning dreaming program.

To compare the life-like systems in their simulations with what is really alive around them, or simply to play around more with the deep learning dreaming program, students can take a picture on their phone (for example, see Figure 11a on the next page) and then modify it using the deep learning computer program as before. This picture can then be modified using the deep learning algorithm (shown in Figure 11b).

4. Additional Activities on Life and Life-Like Systems

Here we outline additional activities that can be suitable for school students who do not have sufficient background in science or mathematics.

4.1. Reflection activities: On alternate life forms

Students can start by listening to the 1968 short story "Crusade" by Arthur C. Clarke which discusses an alternate life form; an audio rendition is available at: https://www.youtube.com/watch?v=Li0TnrRTmM8.

Figure 11: On the left (a): An example picture taken by the fourth author using a smartphone of a sunset in Kolkata, India. On the right (b): The same picture modified using a deep learning dreaming program.

They can then listen to a short video presentation *Life As We Do Not Know It* by the first author on how this alternative view can tell us what kinds of life forms can exist in the universe at https://youtu.be/jDIt6OLVyWY?t=76.

For school students who may not have enough scientific background, a very simple lay summary of the video above is given in Appendix A. This can be read and then discussed by students in small groups. They can then draw pictures of what kinds of life they think we can expect to find elsewhere in the universe.

4.2. A more comprehensive set of learning activities: On life and life-like systems

The following activities incorporate some of the activities introduced earlier in this paper, and would be appropriate for high school students or for those studying for an undergraduate degree.

1. Warm-up questions:
   (a) How might one define life?
   (b) How might we recognize life that is completely “alien” to us?
   (c) Does life need to be carbon-based?
   (d) How do movies bias our conception of alien life-forms? Do they have to be little green men?
   (e) How would you recognize life if it does not fit the definition of life we have seen on Earth?

2. Demonstration of software. Download the NetLOGO software and experiment with the Belousov-Zhabotinsky (B-Z) model.[1] For what parameters do you observe the emergence of “interesting” patterns?
   (a) Is this life-like?
   (b) Would you call this life if you saw it on another planet?
   (c) Peer-discussion and feedback: Share your answers with a peer and discuss.

3. Listen-read-watch:

   Listen to the audio version of the short story “Crusade” by Arthur C. Clarke describing a potential alternate form of life that arises from electrical currents and waves in a superconducting fluid.[2]

   Read the paper “The Chemical Basis of Morphogenesis” [3] by Alan Turing on a computational theory of the value of information in life.

   Watch the video of waves propagating in a cell visualized using a powerful microscope available at `http://movie.rupress.org/video/10.1083/jcb.201706052/video-5`.

[1]See Section 2 for the appropriate links.
[2]See Section 4.1 for the relevant link.

4. Discussion: What did you learn from listening-reading-watching the resources in the list above? What does Clarke's story tell you about life? What does Turing's paper tell you about life? Do you see similarities between the waves in the video you watched to the ones in the B-Z model?

5. Register on SAGANet at https://www.saganet.org to join a community of people interested in questions around origins of life and astrobiology. Contribute to a discussion forum on SAGANet.

6. Optional writing task and group presentation: Have a discussion about what life is and how you might recognize it if you were to find it in another part of the universe. Write up your ideas in two pages and make a five-minute presentation to your class on this. A basic rubric for this task is offered in Appendix B.

5. Discussion and More Philosophical Musings

In this paper, we have presented some teaching resources for school and university students. We hope our work will help popularize a computational view of life and educate students on how arts and mathematics can be unified. It will hopefully also instill an aesthetic sense of life in future scientists.

We anticipate that our teaching resources may be especially useful in developing nations that are investing in science education. We hope our resources can be used to teach students in low and medium income countries. The only requirements are a laptop, desktop computer, or smartphone with an internet connection.

Our approach emphasizes the beauty of mathematics and dynamical systems, especially regarding questions about the defining features of life. Our conception of life is shaped by what we see around us on Earth. What life forms might we expect to see on alien planets? Would they be carbon-based like us or can they be more exotic? Answering questions like these means we must come up with an objective definition of life. As mentioned earlier, the first author hypothesized in [1] that an objective definition of life should capture the notion that a "living being" is capable of information processing and computing. We may need to look at life through such a new lens to recognize life-like systems on other worlds.

The computational framework in this paper combines dynamical systems with deep learning to generate novel and aesthetically appealing forms of life-like systems. These potentially life-like systems can conceivably be present elsewhere in our universe. They can even broaden the search horizons beyond current searches for carbon-based lifeforms within the habitable zones of sun-like stellar systems.

Our work also suggests that we may need an “aesthetic sense” to recognize life we have never seen before. Such aesthetic versions of life-like systems can be generated using the computational framework presented here. This aesthetic view also allows us to appreciate the beauty of life, life-forms around us, and their intimate connections with dynamical systems. Such a perspective can give us a sense of how every part of the universe computes and show us that the entire universe is alive and has intelligence. We hope this will give humanity a new sense of purpose, help us appreciate our place in the Universe, and also give a renewed thrust to conservation efforts to save our planet.

Our work is also an example of how computational art can be created using empathetic Artificial Intelligence (eAI) and dynamical systems. Such forms of art can be used to educate the general public about the benefits of AI and bridge the gap between lay audiences, artists, and computer scientists. People from these groups can come together to co-create computational life-like systems using AI. This can also allow us to value and appreciate life on Earth and how precious it is.

Dynamical systems are general and powerful mathematical representations of our Universe. They can represent diverse complex systems ranging from intra-cellular regulatory networks to global scale models of how scientists collaborate with each other. As the first author posited in [2], dynamical systems underlie much of our Universe and we believe that they form the basis of computation, life, intelligence, and consciousness in our Universe.

This work originally started with a science fiction story (Arthur C. Clarke’s “Crusade”). We want to end with some questions: what if someday we journey to the stars and we do find life? what if we fail to recognize it? what kind of metrics and objective criteria should we have for life or life as we do not know it? Only by educating the next generation of students flexibly can we keep an open mind about life elsewhere in the Universe.

Only this way can we hope to creatively reimagine what kinds of life can exist. An aesthetic sense of life will help in this re-imagination of life or life-like forms that can exist elsewhere in the Universe. It will also allow us to better appreciate life here on Earth.

References

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[2] Soumya Banerjee, Emergent Rules of Computation in the Universe Lead to Life and Consciousness: A Computational Framework for Consciousness. Interdisciplinary Description of Complex Systems, 19(1):31-41, 2021

[3] Alan Turing. The Chemical Basis of Morphogenesis. Philosophical Transactions of the Royal Society of London B. 237(641):37-72, 1952.

[4] Soumya Banerjee Joyeeta Ghose, "A Teaching Resource for a Computational Framework of the Value of Information in Origin of Life," 2018. Available at `https://osf.io/ud6v2/`, last accessed on July 9, 2023.

[5] Uri Wilensky, NetLOGO, programmable modeling environment, Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1999. Available at `http://ccl.northwestern.edu/netlogo/`, last accessed on July 9, 2023.

[6] Uri Wilensky, "NetLOGO B-Z Reaction model," sample model for NetLOGO [5], 2003. Available at `http://ccl.northwestern.edu/netlogo/models/B-ZReaction`, last accessed on July 9, 2023.

A. Recap of Video Presentation: *Life As We Do Not Know It* (2020)

What kind of life forms can we expect to find on distant planets? We always talk about life as we know it. But what about life as we do *not* know it? Hence the presentation outlined here is titled "*Life as we do not know it*".

Life on Earth is carbon-based. It thrives on air, water, minerals and carbon in temperate conditions. This form of life consumes energy for its sustenance. Is it possible to have life forms in extreme cold conditions, say -270 degrees Celsius, without any air or water? We propose that life-like activity is possible in such conditions.

This life-form, however, may be very different. In extremely cold conditions in some distant planet without air, water, sunshine, carbon and such other earthly materials, life-like activity consuming very little or no energy at all may be possible. Helium can exhibit life-like properties in extremely cold conditions in liquid form.

For us to call a system a life-form, the system should essentially have:

1. Memory
2. Basic "intelligence" to process information
3. The ability to "sense" external stimulus and act.

These features can be presented in the form of a mathematical model.

At any rate, life on other planets is still a mystery.

B. A Partial Rubric for the Writing / Presentation Activity

Here we present a partial rubric for how performance can be evaluated by the instructor or by peers. These evaluations are suitable for high school students or undergraduates.

1. Delivery of presentation
   (a) Was the presentation on topic?
   (b) Were the main ideas clearly communicated?
2. Organization and format of write-up
   (a) Does the write-up have a good introduction?
   (b) Is it properly formatted?

   (c) Are there any grammatical errors?
   (d) Does the write-up have a conclusion?
3. Originality of content
   (a) Was the content original?
   (b) Did the students make an effort to develop new ideas?
4. Analysis of literature review
   (a) Did the group assimilate the findings of the background reading into the write-up and presentation?