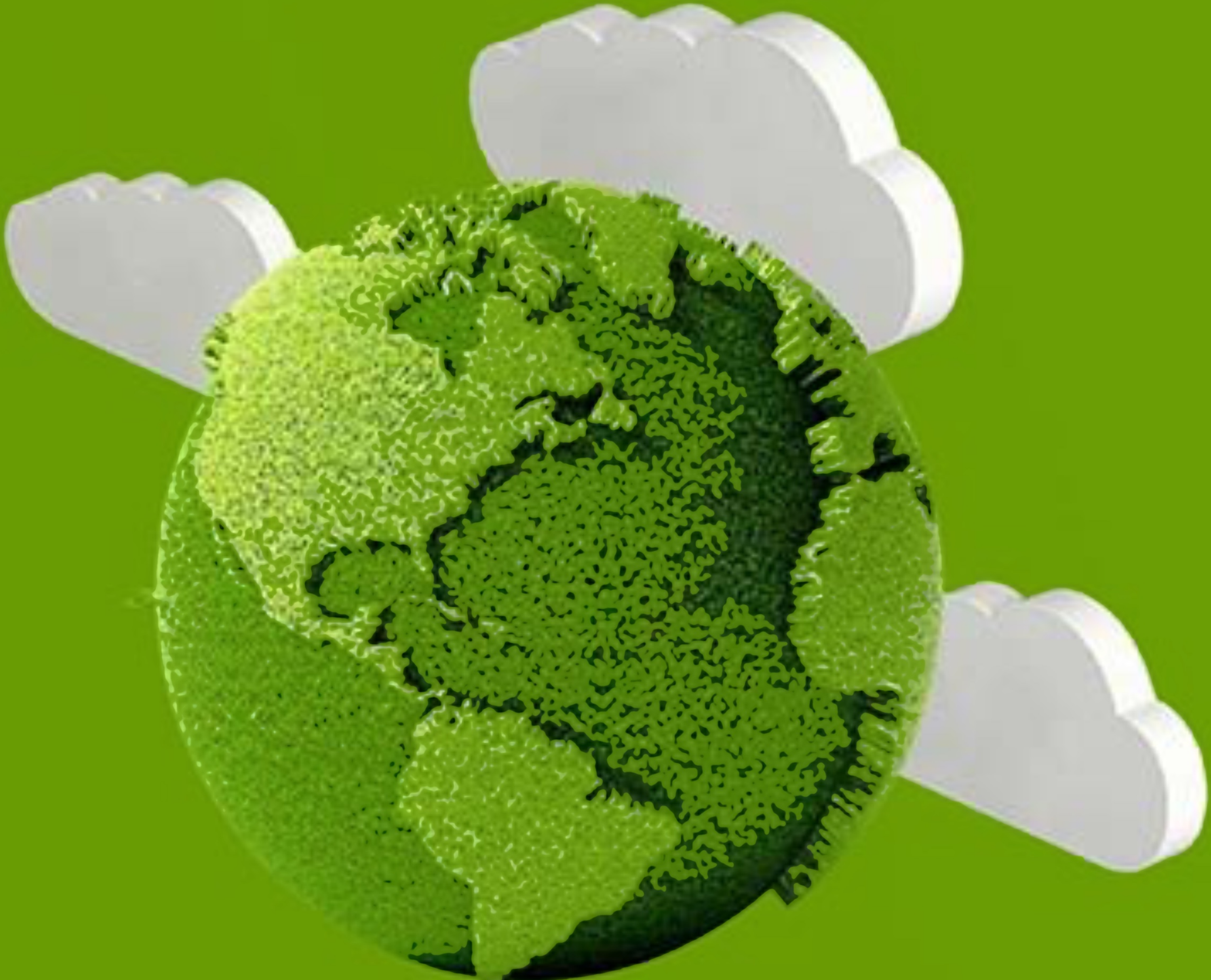

Sustainability Pedagogy In Computer Science Education (SPICE)

2022 Framework Report

A Note From the Authors

We are a group of students from Cornell University who are interested in computer science education reform and diversification. Coming to Cornell from a range of high schools with computer science programs ranging from one of the best in the country to essentially non-existent, one commonality we identified is a lack of computational sustainability incorporated into the curriculum.

With our report, as a final project for Dr. Steven Jackson's Information Science course *Computing On Earth: Extraction, Consumption, and the Material Ethics of Computing*, we aim to provide educational resources and a framework for computer science departments and educational bodies to better teach computer science topics through a sustainability lens.

This report, framework, sample exercises, and coding activities were prepared by Geoffrey Brann [gwb73@cornell.edu], Dylan Van Bramer [dcv26@cornell.edu], Kyle Ruhl [kr548@cornell.edu], and Sofiya Tsenter [st848@cornell.edu].

Acknowledgements

We would like to thank Dr. Steven Jackson, Cornell University, for inspiration of the computational sustainability topics covered in this report and for some sample activities inspired by his course.

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Introduction

Today's students are deeply concerned with the outlook of the environment around them regarding climate change. A 2021 survey from Students Organizing for Sustainability (SOS) reports that 92% of university students agree that sustainability is something which all universities and colleges should actively incorporate and promote; yet, 40% reported low or no coverage of sustainability concepts in their university course curriculum[1]. This already minimal coverage worsens in high school curricula, where a lack of institutional focus on sustainability beyond the elementary reduce-reuse-recycle mantra, along with a knowledge and resource gap for educators, leaves students unsatisfied.

As the higher education matriculation of students increases in computer science fields, introducing a sustainability lens for computer science classes allows for understanding the consequences of tools that are historically taught without much concern for their environmental ramifications. Our framework breaks computational sustainability into three chapters; Sourcing, Extraction, Waste & Repair; Data, 'The Cloud', and AI; and Applications of Sustainable Computer Science. The combination of these topics provides a somewhat holistic overview of two aspects of technological sustainability: sustainability regarding the technology itself and sustainability related to use of the technology.

In addition to splitting the framework into the three chapters listed above, each chapter is divided into sub-modules. This approach allows for customization of the content based on the subject, academic rigor of the course, or the size of the computing department. This format allows, for example, a course to survey sustainability for "the cloud" without necessarily discussing AI.

While our framework is appropriate and useful for all computer science departments, we designed the framework and activities to be most accessible to high school level classes and introductory programming courses at a university or delivered through an online course provider. Integrating sustainability into high schools has shown

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[1] 2021 Students, Sustainability, and Education Report https://sos.earth/wp-content/uploads/2021/02/SOS-International-Sustainability-in-Education-International-Survey-Report_FINAL.pdf

to be the most impactful place for implementation[2], as not everyone who makes an impact in computer science goes to college. Even for those who do go to college, implementation at the high school level allows for us to teach about sustainability before habits regarding programming are solidified. Additionally, implementing a widespread curriculum is more reasonable for pre-college education, given unifying bodies like the College Board and state education committees that could incorporate our work from this report.

Each chapter of this report contains four main sections to assist in sustainability integration. First, each chapter has an introduction explaining its importance, intended audience, and key terms and information needed to understand the content. Next, each chapter has the curriculum framework with learning objectives and suggested content for educators to instruct. In an appendix for each chapter, there is a compilation of activities we've developed and compiled for students to engage with. Lastly, each chapter has a list of resources educators can reference with additional content to assist them in their instruction.

Our recommended approach for implementation of this framework is through incorporating the skills and concepts outlined in each module into appropriate existing courses as opposed to the creation of a new standalone computational sustainability course. As previously noted, many teachers report lacking a depth of knowledge about sustainability concepts, and a modular inclusion method would allow for easier integration on course staff. This approach also allows for staff specialization in sustainability concepts where teachers can choose what to include in each class according to their personal or students' interests.

In a modular integration, sustainability topics can be incorporated through classroom instruction, discussions, readings, videos, projects, and sustainability themed programming exercises and datasets to meet the framework goals. This method has been shown to be effective in pilot programs at the university level[3], where students are still

[2] Pahnke, J., O'Donnell, C. & Bascopé, M. (2019). Using Science to Do Social Good: STEM Education for Sustainable Development. Position paper developed in preparation for the second "International Dialogue on STEM Education" (IDoS) in Berlin, December 5–6, 2019. See: www.haus-der-kleinen-forscher.de

[3] Jeffrey A. Stone, "A Sustainability Theme for Introductory Programming Courses", International Journal of Modern Education and Computer Science(IJMECS), Vol.11, No.2, pp. 1-8, 2019. DOI: 10.5815/ijmecs.2019.02.01

chiefly learning important programming concepts while also thinking about what they are doing through a sustainability lens.

Finally, as university students who have taken a variety of computer science courses over their education, the authors personally believe that this approach would reinforce sustainability concepts throughout students' education as opposed to only a singular survey presented by one instructor. Beyond providing a variety of viewpoints, a thorough integration could also dissuade the perception of computational sustainability being a 'boring requirement' class, instead highlighting its societal importance through repetition. In all, we believe that integrating sustainability into computer science education would allow for computer scientists of the future to be well rounded and environmentally conscious as we face the threat of climate change.

Chapter 1

Sourcing, Extraction, Waste & Repair

Purpose

Digital technology has become irrevocably ingrained into our lives. Our phones are an extension of our hands, our fingertips rest comfortably on laptops, television screens lie flush in walls, and gaming consoles adorn countless tables and shelves. However, by design, we know little about digital technology relative to other items present in everyday life. A desk, made of wood, comes from trees; an association can be made to the forests in which those trees once grew, and maybe even the deforestation that might have occurred, reshaping the lives of people and animals that once called that forest home. A water bottle, made of plastic, might make one think about the oil that plastic is formed from, and the contestation over the use of oil as a tool for energy. The impacts of a computer are less familiar; a metal frame and plastic keys are visible, but recognition might stop there. As digital technology becomes further established in society, as the dominant tool for work and outlet for pleasure, it only becomes more important to understand the environmental, social, and political impacts of these technologies: from their origins in mines in the DRC, to e-waste processing facilities in Thailand.

Gaining an understanding of the consequences of purchasing and using technology will allow students to make informed, sustainable decisions. The question "should I purchase a new laptop?" takes new forms after exposure to this module; this is no longer just a question of price and hardware specifications, but of the impact that purchasing a new laptop has on those who turn raw ore into a computer, the ability one has to repair or upgrade an older machine, and the consequences that throwing away an old computer might have.

The purpose of this module is to replace ignorance of the widespread consequences of the production, use, and waste of digital technology with the understanding that consequences do exist even if we do not see them, and how to mitigate those consequences.

Audience

The audience of this chapter is extremely general: any intro-level course that *relies* heavily on digital technology, whether a computer science course or a class in another discipline in which students use computers. Activities like Activity 1B in Appendix A are more suited toward a programming class, but understanding social, political, and economic factors should be done in a way best suited for each individual course.

Key Terms

Conflict Minerals: Also known as **3TG minerals**, conflict minerals include tantalum, tungsten, tin, and gold. They are known as conflict minerals because 3TG extracted from the Democratic Republic of the Congo and neighboring countries is known to fund armed conflict in that same area. Section 1502 of U.S. Dodd Frank Act requires that US companies perform due diligence to ensure that 3TG minerals in their supply chains do not fund armed conflict or human rights abuses.

Circular Economy: The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible[4]. Such an economy is at odds with current business practices of technological manufacturers.

[4] See https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits

E-waste: All electrical or electronic equipment (EEE) that has been discarded without the intent of reuse. E-waste includes in its definition items with circuitry or with a battery supply. E-waste is unique in its value, and in the harmful effects it can have on those who work with it[5].

Neocolonialism: The economic and political policies by which a great power indirectly maintains or extends its influence over other areas or people. Neocolonialism literally means "new colonialism," referring to colonial practices occurring in the present day, rather than in the colonial eras of the past. Neocolonialism can be exemplified by large corporations or countries exploiting poorer nations for minerals extracted from those smaller countries.

Planned Obsolescence: A policy of deliberately planning or designing a product with a limited useful life, so it will become obsolete or nonfunctional after a certain period. Planned obsolescence is a key business strategy, allowing companies to sell more new products faster, rather than building products sustainably that are useful for long periods of time.

Framework

Example learning activities/resources, discussion questions, and coding activities that complement this chapter's framework are provided in **Appendix A**

This module covers the journey of digital technologies from being mined from the ground to being purchased by consumers. This module will also examine local impacts of sourcing and extraction of components of digital technology. Topics will be particularly engaging for those interested in History, Mechanical Engineering, and Policy. This module is appropriate for introductory computing classes in which students use computers, tablets, smartphones, or other modern consumer electronics, as well as computational sustainability courses.

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5 See https://globalewaste.org/what-is-e-waste/

Objective: Students will obtain general knowledge surrounding the raw materials used to create the technology they use on a daily basis, and the consequences of the use of those materials on the environment and various communities worldwide.

By the end of this module, students should be able to:

1. **Understand Supply Chains of Important Minerals and Materials**
    1. Students should be able to identify crucial material components of computers, as well as the countries of origin of said materials
        1. Components might include batteries, circuits, and solder
        2. Material components include lithium, coltan, cobalt, or 3TG minerals
    2. Students should be able to describe the journey these materials take from the mine to their computer (Activity 1A in Appendix A)
        1. Geographic location of materials throughout the supply chain
        2. Who or what possesses the materials throughout the supply chain
2. **Examine Local Impact of Sourcing and Extraction**
    1. Students should understand the high-level political and socio-economic impacts of sourcing and extraction, such as
        1. Armed conflict in the Democratic Republic of the Congo
        2. Legislative responses to lithium mining in Chile
    2. Students should understand impacts of extraction on the environment, such as
        1. Mine by-products polluting air and water
        2. Terraforming disrupting local ecosystems
    3. Students should understand the impacts of sourcing and extraction on local populations, such as
        1. The Resource Curse
        2. The impact of neocolonialism on indigenous populations
    4. Students should recognize the impact that sourcing and extraction has on local individuals who participate in the processes of sourcing and extraction
        1. Individual stories[6]

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[6] Stories such as Suge's, which you can read about in this The Guardian article https://www.theguardian.com/environment/2012/nov/23/tin-mining-indonesia-bangka

3. **Describe Actions Taken to Address Impacts of Sourcing and Extraction**
    1. Students should be able to identify policies that have been enacted at local and international levels to address problems of sourcing and extraction
        1. IRMA, OECD
    2. Students should be able to recognize what action corporations, such as Apple, Fairphone, HP, Microsoft, MSI, ASUS, Dell, Lenovo, Google, LG, and more, have taken to mitigate or propagate effects of sourcing and extraction
        1. Fairphone and Apple are good examples of companies that detail their supply chains and sustainability standards
        2. Some corporations do not produce sustainability reports or actions taken to mitigate consequences of sourcing and extraction
    3. Students should be able to recognize the role that NGOs play in combating negative effects of sourcing and extraction
        1. IRMA and NGOs

A. E-Waste & Repair

This module covers topics related to the second half of a technological device's life, including its use and eventual discard. Topics include the circular economy, the right to repair, and e-waste. By gaining an understanding of what happens to technology once it reaches the end of its life cycle, students can use what they learn in this module to more closely model the circular economy with their choices.

Objective: Students will learn about the concept of the circular economy, understand the benefits of repair and analyze arguments surrounding the right-to-repair movement, and examine the dangers of e-waste to local and international communities.

By the end of this module, students should be able to:

1. **Define the Circular Economy**
    1. Students should be able to define the linear and circular economies
    2. Students should be able to compare and contrast linear and circular economies on a variety of factors, such as sustainability, economics, and more (See Activity 1D, Appendix A)

    3. Students should be able to identify industries that exist and benefit from a linear economy, and identify industries that can aid the transition to a circular economy
2. **Discuss Repair and the Right to Repair**
    1. Students should understand different components of the debate on the right to repair
        1. History of planned obsolescence and restrictions on independent repair, and why companies take these actions
        2. The benefits of the right to repair for consumers
        3. Pivotal right to repair case (John Deere software case)
    2. Students should be able to identify resources designed to support independent repair efforts
        1. iFixit and repair.org (See Activity 1C, Appendix A)
    3. Students should be able to identify legislation that has been designed to encourage repair and reduce e-waste[7]
3. **Describe E-Waste and its Impact**
    1. Students should be able to examine the process that e-waste undergoes from its discard to its reintroduction into the supply chain, or final resting place in a landfill
        1. Examine where e-waste is collected and processed
        2. Determine which materials are re-integrated into supply chains, and which are not
    2. Students should be able to examine the consequences of e-waste (See Activity 1B, Appendix A)
        1. Impacts of exposure to raw materials on the environment and individual health
        2. Neocolonial significance of which countries handle large amounts of e-waste, like Thailand[8]
    3. Students should be able to consider strategies for reducing e-waste, synthesizing the other aspects of this module

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[7] See https://www.clm.com/right-to-repair-legislation-advances-in-new-york-and-elsewhere/

[8] See this New York Times article https://www.nytimes.com/2019/12/08/world/asia/e-waste-thailand-southeast-asia.html

Chapter 2
The Real Costs of Data, The Cloud, & AI

Purpose

There is no doubt that as technology improves, data is becoming increasingly ingrained in our society and our choices. As more and more sources of data collection on humans' habits become available through emerging technology, the field of data science has exploded, driving more students to pursue the field of computing in their secondary and university studies. Increases in efficiency and decreases in costs have incentivized businesses and organizations to move their operations from in house data servers to "The Cloud", which stores data at large scale data servers across the globe and allows for easier and rapid access for users. Artificial intelligence (AI) has also become an incredibly popular tool for computer scientists to solve computational problems, serve as assistants on cellular phones, and to assist humans in physical tasks such as driving.

With progress comes an environmental cost. As the world attempts to switch to green energy sources to meet net-zero carbon climate goals, the electricity and water demand of large scale data centers has drastically increased, straining water resources in drought-stricken areas and increasing electricity demand of fossil fuel power.

As more and more students take up interest in the computing field, it is important for students to be well versed in their technical skills to excel in their future studies and career. It is equally important for students to understand the environmental and sustainability impacts that data processing brings with it. As the future computer scientists who may be designing the next self driving car program, the future data analyst creating and analyzing datasets, or any user of a cloud-based platform, having a diverse background in both technical skills and computational sustainability is essential for future generations of students

Audience

This chapter may appeal to many computer science courses looking to incorporate sustainability into their curriculum.

For introductory programming and/or data science courses at both the high school and collegiate level, the authors recommend inclusion of modules A and B. In upper level data science courses (where lower level courses have already covered modules A/B) we recommend incorporating module C when the class discusses/uses AI or machine learning in data analysis.

For cloud computing specific courses[9] the authors recommend a full implementation of module A, with a focus of incorporating sustainability concepts learned into the cloud computing process in sustainable design. A survey into module B is also recommended for cloud computing courses that discuss data center design.

For courses that incorporate artificial intelligence, the authors recommend a full survey of module C with implementation of module B to ensure that students successfully understand the environmental aspect.

For computational sustainability or environmental science classes looking to study the impacts of computing, the authors recommend focusing on module B while briefly discussing module A and C at an accessible level.

Key Terms

"The Cloud": Software and services that run on the Internet powered by off site data storage centers instead of locally, and are accessible to many users from anywhere (for example Google Drive, iCloud, Netflix)

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[9] One such example is Carnegie Mellon University's Cloud Computing Course, a syllabus is available at http://www.cs.cmu.edu/~msakr/15619-s17/15319_15619_s17_Syllabus.pdf

Cloud Provider: A third-party company selling a cloud-based platform, infrastructure, application, or storage services powered by physical large scale data centers (for example Amazon Web Services (AWS), Microsoft Azure)

Data Center: A physical location, often a group of buildings designed for storage purposes, that houses core IT and computing services and infrastructure to store and compute data

Clean Energy: Energy that, when used, does not pollute the atmosphere; creating little or no greenhouse gasses (for example solar, wind, hydroelectric power)

Artificial Intelligence (AI): Processes that leverage computers and machines to mimic the problem-solving and decision-making capabilities of the human mind (for example self driving cars, Siri)

Framework

Example learning activities/resources, discussion questions, and coding activities that complement this chapter's framework are provided in **Appendix B**

A. The Cloud

This module explores 'The Cloud' and the positive and negative impacts it has on sustainability. Exposing users of 'The Cloud' to how their programs are ran and powered will ideally inspire computer scientists to create and code with a greater care for the environment. Topics will be engaging to those interested in cloud computing, introductory computing, computational sustainability, and environmental-conscious users of technology.

Objective: Students will examine the rise of 'The Cloud' in general aspects of their personal online activity and consider the impacts of its oft-hidden global infrastructure.

By the end of the module, students should be able to:

1. **Describe 'The Cloud' and the rise of 'Cloud Computing'**
    1. Students should be able to identify examples where the cloud is integrated behind the scenes in everyday life with technology that people and businesses use and rely on (See Activity 2A, Appendix B)
    2. Students should be able to understand the connection between the cloud and physical data centers and infrastructure spread across the globe

2. **Analyze the benefits and motivations for individuals and businesses to utilize 'The Cloud'**
    1. Students should be able to understand the benefits and drawbacks of various stakeholders to migrating services to 'The Cloud.' (See Activity 2B, Appendix B)
    2. Students should be able to analyze the incentives, including economic benefits of cloud computing from the perspective of cloud providers (Amazon's AWS, Microsoft's Azure, etc.)

3. **Recognize the sustainability concerns and opportunities with 'The Cloud'**
    1. Students should be able to identify how upgrading cloud infrastructure can lead to increased e-waste and identify potential solutions
    2. Students should be able to identify consumptions of 'The Cloud' and its physical infrastructure, including energy, water, and land
    3. Students should understand how digital products and services using 'The Cloud' can contribute a carbon footprint
    4. Students should consider how more efficient cloud data processing can lead to more energy efficient processes and be able to implement efficient designs into assignments and projects[10]

[10] Note: Grading structures for assignments using rented cloud-based computing resources should incorporate both cost and efficiency of the deliverable into the grade.

B. Energy and Water in Computing

This module explores the energy and water consumption of data centers and methods by virtue of clean energy and innovative design that can help alleviate these effects on the communities where data centers are located in. This material will be particularly engaging for students interested in green energy, data science, cloud computing, environmental engineering, and environmentally-minded students of all fields.

Objective: Students will examine the role that computing and data storage centers have on water and energy resources in communities.

By the end of the module, students should be able to:

1. **Understand the foundations of data center operations**
    1. Students should be able to establish and explain the processes behind the key functions of data centers (See Activity 2D, Appendix B)
    2. Students should be able to understand how resources that enable data center functionality (particularly water) are accessed for use. Students should also be able to discern the legal and ethical concerns that frame said accessibility
    3. Students should be able to recognize which industries/companies/political entities are key stakeholders in terms of establishing and operating data centers and identify each stakeholder's interests and concerns
2. **Assess the environmental toll of data center operations and how that impacts local communities**
    1. Students should know how much water/other energy data centers typically use, and explain how this consumption may vary across industry, region, and any other distinguishing factors. Additionally, students should be able to explain how this information is found, tracked, and recorded (See Activity 2C, Appendix B)
    2. Students should be able to recognize and explicate the geopolitical effects of data center operations
    3. Students should be able to determine the impacts of data center operations on local communities as well as the implications of said impacts

3. **Evaluate future road maps for data center development / redevelopment**
    1. Students should be able to recall what legislation is currently in circulation regarding the regulation of data center development and operations. They should also be able to discern the stakes for each key stakeholder in said pieces of legislation, as well as the stakes for the average consumer
    2. Students should be able to explain how developing, and any other possible future technologies, may impact those stakes as well as proposed legislation
    3. Students should be able to identify which elements of technological design can be altered to reduce energy consumption (both small and large scale) as well as the role that the average consumer could play in shaping new technologies and technological processes

C. Artificial Intelligence

This module explores Artificial Intelligence systems and the sustainability concerns that come with its increasing integration into everyday human life. Topics will be impactful to students interested in robotics/engineering, machine learning, programming, and fields that foresee the integration of AI into their future work.

Objective: Students will examine sustainability concerns and opportunities within the field of Artificial Intelligence.

By the end of the module, students should be able to:

1. **Understand the development of Artificial Intelligence systems**
    1. Students should be able to describe the life cycle and anatomy of an AI system and the infrastructure required to develop it
    2. Students should be able to identify the different methods involved in the development of said technological systems, as well as the kinds of energy processes involved in execution and maintenance
2. **Analyze how the processes of Artificial Intelligence systems affect energy and climate**
    1. Students should be able to identify specific effects of AI systems on energy and climate and how these effects may vary by global region

2. Students should be able to explain how AI systems alter the supply and demand of various energy sources
3. Students should be able to recognize and discuss the ethical concerns regarding AI systems and their development

3. **Understand how energy and climate impacts could be managed**
    1. Students should be able to recognize how AI systems could be utilized to generate positive environmental impacts and mitigate environmental degradation
    2. Students should be able to explain how the processes of AI system could be altered to better manage energy consumption and climate effects
    3. Students should be able to advise how computer science education could adapt to perpetuate the aforementioned changes

Chapter 3

Applications of Sustainable Computer Science

Purpose

The previous two modules have explored the ethical and environmental costs that computing imposes on the Earth and its inhabitants. In this chapter, the perspective is shifted to look at the positive impacts that computing, and technology at large, can have upon the pursuit of sustainability. By applying computational methods to the social good, we hope to inspire students to consider both what their larger social goals are, and what the tools they plan on making a difference with are. Teaching computer science through the lens of other disciplines and "real-life" datasets has been shown to attract a more diverse body of students,[11] encouraging those who don't necessarily see themselves as "computer scientists" to take an introductory course.

Audience

As described in the purpose statement above, this section aims to address the positive impacts that computing can have on the pursuit of sustainability throughout the disciplines. The audience is composed of all students, perhaps best classified into two

[11] Jeffrey A. Stone, "A Sustainability Theme for Introductory Programming Courses", International Journal of Modern Education and Computer Science(IJMECS), Vol.11, No.2, pp. 1-8, 2019. DOI: 10.5815/ijmecs.2019.02.01

groups: students initially interested in computer science, for whom this module aims to encourage to apply the *skills* they enjoy to analyze and begin to solve social, economic, and environmental issues; and students whose passions lie in the field of sustainability, for whom we aim to push them to consider learning programming as a means of doing the work they wish to do for the world.

Key Terms

Computational Sustainability: The application of computational and algorithmic methods from computer science and related analytical disciplines to the pursuit of environmental, economic, and social needs for a sustainable future[12]

Machine Learning: A type of artificial intelligence that trains software applications to analyze data with increasing accuracy; relies on the computer "learning" from historical data and patterns with minimal direct input from humans

Climate Models: Computer programs that quantitatively simulate the Earth's behavior over time; have components representing weather patterns in the atmosphere, ocean dynamics, and land behavior; used in analysis of current conditions and prediction of future climatic activity

Web Scraping: The process of fetching information from websites; often done by accessing the HTML code that structures a website and its data, and exporting this into a more organized format; the automation of web scraping using scripts allows large amounts of data to be collected at once

Open Source Projects: Coding projects online that are completely available and free of charge for any user to download, study, modify, and distribute; allows for collaboration and transparency

[12] See Dr. Carla Gomes' website on the topic: https://www.computational-sustainability.org/

Remote Sensing: The process of obtaining data about an area without physically being at that location; typically done via satellites to gather environmental and surface data; information attained through remote sensing often undergoes heavy analysis via computational methods

Digital Agriculture: The use of technology including data storage and analysis to help farmers implement best practices to increase food production sustainably; often relies on interaction between sensors and devices in the field and data processing that happens remotely

Framework

Example learning activities/resources, discussion questions, and coding activities that complement this chapter's framework are provided in **Appendix C**

A. Applications to Ecological and Agricultural Data

This module explores the applications of computer science to the life sciences and agriculture. Diving into the collection and analysis of data, as well as the tangible impacts data-supported decision makes, students will see how these fields are being transformed. Topics may be particularly engaging for students interested in biology, environmental science, agriculture, and business.

Objective: Students will explore the applications of computational methods to the biological side of sustainability, focusing specifically on ecological analysis and agricultural methods.

By the end of the module, students should be able to:

1. **Describe the uses of computational methods within the field of ecology**
    1. Students should be able to define "computational sustainability"
        1. Understand the difference between traditional data analysis methods and the new ones that computer science allows for

2. Students should understand the extended functionality that computational methods introduce to ecological analysis
    1. Make predictions over longer timescales and larger geographical regions than previously possible
    2. Model relationships between species without ethical concerns of harming living things or damaging ecosystems
    3. Preview the potential effects of human development on an ecosystem prior to often irreversible damage
    4. Estimate the efficacy of human-built ecological solutions (like wildlife crossings over highways) before executing costly projects
3. Students should be able to identify various applications of computer science to the study of ecosystems
    1. Simulate predator-prey relationships with models developed by programmers to predict future population levels of endangered and invasive species
    2. Track populations over time given changing conditions (temperature, precipitation, ocean acidity, etc.)
    3. Determine ideal locations for conservation projects like wildlife sanctuaries/zones to facilitate breeding

2. **Describe the optimization of agriculture using technology and computing**
    1. Students should be able to identify various physical devices used in the implementation of digital agriculture
        1. Mechanical tools and "robots" to aid in livestock maintenance
        2. Sensors to monitor soil chemistry and moisture, and automatically make adjustments
        3. Drones and other small technologies used to survey entire farms
    2. Students should be able to identify forms of digital agriculture used in decision making and business (not directly in crop or livestock production)
        1. Improved communication between farmers and buyers
        2. Collection of data on resource use (water, fertilizer, hours working)
        3. Modeling and simulation of crops to predict yield and monitor potential environmental impacts (See Activity 3A, Appendix C)

3. Students should be able to discuss the feasibility of introducing digital agriculture on a large scale
    1. High costs for devices and data analysis
    2. Requirement of internet infrastructure in rural communities where farms are located
    3. Specialized training to properly use these technologies

B. Earth Modeling Systems

This module outlines the application of computing to the physical sciences sphere of environmental science. It focuses on both the creation and compilation of Earth models and datasets, as well as the impacts these developments have on policy and decision-making. Topics may be particularly engaging for students interested in physics, chemistry, atmospheric science, geology, and the phenomenon of a changing climate change, at large.

Objective: Students will learn about the development and application of Earth modeling systems, including climate and ocean simulations powered by remote sensing.

By the end of the module, students should be able to:

1. **Understand the broad range of what "Earth model" can define**
    1. Students should be able to identify the varying levels of precision that models implement
        1. The most basic climate models view the Earth as a whole, depicting only energy transfer in and out of the atmosphere
        2. More complex climate models simulate the physics of the atmosphere and Earth, allowing for more precise findings
    2. Students should be able to compare standalone models to integrated "coupled" models
        1. Standalone models represent a single component of the Earth system: typically either atmosphere, ocean, or land
        2. Coupled models integrate the above sectors, allowing scientists to evaluate relationships and determine patterns between them

        3. Climate models typically represent only the atmosphere, while Earth system models, more generally, are likely to refer to a coupled model
        4. As the technology advances, more complex simulations are being added to coupled models, like those that represent specific biological elements, crops, and human activities

2. **Compare models/simulations and data representations**
    1. Students should understand the differences between simulations and compilations of existing data
        1. Simulations can be run on very large timescales and are used in making predictions
        2. Compilations of data, often based on remote sensing, can describe only past and current phenomena
    2. Students should be able to discuss how these two forms of analysis complement each other
        1. Climate models and simulations are reliant on previously collected data, and can only run accurately because of this information

3. **Identify the applications of Earth modeling and data analysis**
    1. Students should understand how utilizing these different forms of data analysis allows scientists to comprehend patterns in the climate and other Earth systems (See Activity 3B, Appendix C)
        1. By understanding past cycles, they are better able to judge the severity of climate change today
    2. Students should be able to explain how simulating future events can impact global decision making
        1. Through simulations, scientists can determine likely sea level rise and temperature projections
        2. These projections can determine necessary restrictions on emissions established by policy
    3. Students should understand the use of live data collection on local decision making

1. Through remote sensing, meteorologists are able to determine extremely precise short-term predictions of weather events
2. The prediction of potential flooding, storms, natural disasters, and other inclement weather before it happens allows for evacuation and resource management that protects humans and the natural environments around them

C. Sustainability Science and Citizen Engagement

This module describes the "human" aspect of sustainability: from recycling to information distribution to actions individuals can make through computing to benefit social and environmental sustainability. This portion offers truly interdisciplinary content, and will be of interest to students focused on business, environmental science, sociology and decision making, communication, and those with a passion for computer science looking to have real world experience.

Objective: Students will learn about how computing can be asset to sustainability science and increase meaningful citizen engagement within the field of sustainability.

By the end of the module, students should be able to:

1. **Explore Computing Within Corporate and Consumer Sustainability**
    1. Students should be able to describe how data analysis via computing is essential to the pursuit of sustainability in industry
        1. By collecting data on emissions, energy use, water use, and other metrics of environmental sustainability, companies have a grasp on their environmental toll
        2. With this data, restrictions and policies implemented by governing bodies can be enforced
    2. Students should understand how computing can be used to improve the efficiency and efficacy of sustainability industries
        1. Data analysis and predictive modeling using programming can help the management of food waste and recycling

        2. Computer programs within the field of material science can be used to design products with minimal resource use
2. **Understand the Uses of Programming In Information Distribution**
    1. Students should be able to discuss how coding-enabled data visualization is useful for science communication
        1. The use of data visualization technology - either directly through programming or through web programs (that are, too, powered by code) in making complex information easier to understand and analyze
    2. Students should understand the concept of automated monitoring of information published online
        1. The use of web scraping to analyze patterns in the information published by companies and governing bodies
        2. Using these patterns and changes in environmental information to understand the motives of different agencies
    3. Students should be able to discuss the implementation of algorithms for determining misinformation
        1. Versions of these used on social media apps and as browser extensions to notify a user when misinformation is likely
        2. The potential negative consequences of misinformation and "pseudoscience" regarding environmental issues
3. **Understand the Potential of Open Source Projects**
    1. Students should be able to identify the benefits of open source projects
        1. Allows for collaboration globally to tackle larger problems
        2. Are not reliant upon funding from research institutions or companies, allowing individuals to focus on sustainability issues meaningful to them
        3. Allows for local mobilization to collect data or begin to find solutions for environmental and social sustainability issues within a given community[13]

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[13] See Appendix C's "Resources for Further Engagement" for a few examples of open source projects and otherwise collaborative projects created for social and environmental good

Appendices

Coding exercises, along with sample answers and datasets, are listed in the following appendices and available on our Github page https://github.com/KyleRuhl/SPICE-Exercises

Appendix A

Exercises and Learning Resources for Instructors

Chapter 1: Sourcing, Extraction, Waste & Repair

Sample Instructional Activities

Activity 1A: Supply Chain Mapping Activity

Individually or in groups, students will determine the geographical supply chain of a piece of technology they own. For 3-5 important minerals and materials in their electronic device, they will research where the manufacturer of that electronic device sources that material from, and to the best of their ability determine where that material travels to be processed, smelted, and manufactured, before arriving at the final retail location or warehouse.

This activity is engaging and personal: each student will discover the journey of materials they personally own, and along with the rest of this module understand the personal impact of buying a piece of technology. They might not be able to put together a full supply chain, but failing to do so is not a failure on their part: it is a lesson that the companies themselves either do not know the contents of their supply chain, or are unwilling to share.

Activity 1B: Coding an E-waste Calculator[14]

Students should code an e-waste calculator program that calculates a user's total material usage (plastic, aluminum, copper, total materials) and carbon footprint based on the number of common e-waste items they have used/discarded in their lifetime. Use the provided dataset Ewaste_Product_Breakdown.csv, available on the SPICE Github, as a key for the material costs and carbon footprint of one of 18

[14] Accessible at https://github.com/KyleRuhl/SPICE-Exercises/tree/main/Ewaste_Calculator_Python

common products. Programming language and tasks may be changed to fit course goals, including adding a GUI. A sample code is posted in python.

Activity 1C: Repair!

Students, in teams, are given a broken piece of technology and access to the iFixit.com website, along with tools and parts they might need. In a group, students repair the technology to the best of their ability.

This activity is rewarding when completed, but also shows the utility of a resource like iFixit, provides a perspective of those who work in repair, and gives students the confidence to repair their own devices or trust a repair shop to fix them instead of immediately resorting to buying a new piece of technology.

Activity 1D: Circular Economy vs. Linear Economy

Students will, for a specific item (a piece of technology or not), trace its life cycle on a circular economy and on a linear economy. Once they have determined the paths for each case, the two will be compared to determine differences.

This activity will give students understanding of the impact of their decisions when purchasing, repairing, or disposing of items they own. The goal of this activity is not specifically related to technology, but to further an understanding of the differences between the circular and linear economies.

Instructor Learning Resources

Sourcing & Extraction - *Suggested Readings*

1. https://www.plymouth.ac.uk/news/scientists-use-a-blender-to-reveal-whats-in-our-smartphones A smartphone is blended to reveal its mineral components.
2. https://www.apple.com/environment/ Individual apple product sustainability reports are short (10 pages) and contain helpful graphics.

3. https://www.engineering.com/story/what-raw-materials-are-used-to-make-hardware-in-computing-devices Breaks down to a very low level the physical components of computers.
4. https://www.cobaltinstitute.org/ Information specifically on cobalt.
5. https://www.nytimes.com/2021/11/20/world/china-congo-cobalt.html Cobalt mining in the Congo.
6. https://supplychains.resourcematters.org/explore Map of cobalt supply chains.
7. https://www.theguardian.com/environment/2012/nov/23/tin-mining-indonesia-bangka Tin mining in Indonesia.
8. https://www.nytimes.com/2021/12/30/world/asia/tesla-batteries-nickel-new-caledonia.html Nickel in New Caledonia.
9. https://www.theguardian.com/commentisfree/2021/jun/14/electric-cost-lithium-mining-decarbonasation-salt-flats-chile Lithium mining in Chile.

Waste & Repair - *Suggested Readings*

1. https://www.nytimes.com/2019/12/08/world/asia/e-waste-thailand-southeast-asia.html E-waste in Thailand.
2. https://weee4future.eitrawmaterials.eu/learn-teach/ Resource to learn about e-waste for instructors.

Appendix B

Exercises and Learning Resources for Instructors

Chapter 2: The Real Costs of Data, The Cloud, & AI

Sample Instructional Activities

Activity 2A: The Cloud & Everyday Life: Brainstorm Competition

Break students into groups and ask students to list aspects of or things in their lives that rely on the cloud. Review lists as a class to ensure that the concept of the cloud is understood.

Activity 2B: The Cloud & Education: Classroom Discussion/Reflection

Ask students to reflect on how their education (homework, quizzes, grading, etc) over time has moved from pen and paper to cloud-based learning platforms such as Google Classroom, Canvas, Blackboard, etc. What are the benefits of a cloud-based learning system for students? For teachers? Which method do you prefer?

Activity 2C: Data Analysis in R on Energy & Power Plants in the US

From the Github folder[15], download the dataset PowerPlants.csv[16]. The provided blank RMD markdown file can be used as an assignment for data visualization using tables, barplots, and stacked bar plots looking into energy from power plants in the lower 48 states. An answer key is included with sample code and sample answers to the non-coding reflection/understanding questions. Alternatively, the assignment could be used as a demonstration in class where different states are examined in part 1. The PowerPlants.csv dataset may also be used for other analysis, or the instructor may develop additional questions to the provided RMD

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[15] https://github.com/KyleRuhl/SPICE-Exercises/tree/main/Energy_Data_inR

[16] Data from Md Abu Bakar Siddik et al 2021, https://doi.org/10.7294/14504913

file, including the potential for mapping spatial data or further analysis with other incorporated datasets.

Activity 2D: Data Center Operations and Sustainability Efforts

Ask students to reflect on how different companies (ex. Google, Amazon, Meta) manage their data science operations. Suggested reading prior to this activity could be the environmental reports of the companies selected for this activity. What is each company doing to ensure that their data centers are powered sustainably? Are they doing enough? Have students brainstorm what they believe could help companies work towards sustainable operations: what factors do companies need to consider and what are possible routes to implementing sustainability into their business models?

Add other stakeholders into consideration: the consumer, the government, representatives of communities directly impacted by the operations of data centers. Split the students into four groups (one group representing each key player) and discern their key interests. What responsibilities, if any, does each group have towards the common good? Then, have the four groups work together to discuss possible paths forward that may accommodate, or address, the interests of all parties.

Helpful Links:
https://datacenters.fb.com/
https://www.google.com/about/datacenters/
https://aws.amazon.com/compliance/data-center/data-centers/

Instructor Learning Resources

The Cloud

1. https://earth.org/environmental-impact-of-cloud-computing/ A good overview of cloud computing from earth.org, discusses the positive and negative environmental impacts, free of bias from cloud computing companies.
2. https://www.dataversity.net/how-the-cloud-has-evolved-over-the-past-10-years/ A good overview of the history of cloud computing.
3. The Cloud Isn't Inherently More Sustainable environmental impacts/carbon footprint of computing and how organizations can improve their sustainability for their products (physical) and services (cloud-based). Also includes suggestions on how cloud computing can become more eco-friendly.
4. https://www.cmswire.com/information-management/towards-a-sustainable-transition-to-the-green-cloud/ The green cloud and the connection to power-intense, often fossil-fuel powered data centers

Data Centers, Energy & Water in Computing

1. https://www.datacenterdynamics.com/en/analysis/data-center-water-usage-remains-hidden/ An overview of current methods (or lack thereof) for identifying and tracking water and energy consumption of data centers.
2. https://www.youtube.com/watch?v=Amow8BJm5Go, https://www.youtube.com/watch?v=UFK4hqeRhIc An overview of basic definitions of data science operations, and insight into how Google operates and maintains their data center. Also discusses how Google is changing the way they operate their data centers to power them sustainably.
3. https://www.youtube.com/watch?v=q6WlzHLxNKI An overview of the operations of Amazon Web Services.
4. https://www.youtube.com/watch?v=4krpOapkEp0, https://greenmountain.no/global-thought-leaders/ An example of how data centers can be created to incorporate sustainability in their design, construction, and operations.
5. https://time.com/6085525/big-tech-data-centers/ An overview of how data centers are impacting local communities.

6. https://www.supermicro.com/wekeepitgreen/Data_Centers_and_the_Environment_Dec2018_Final.pdf A report that analyzes what business are doing in order to measure and address the environmental impacts of their data centers.
7. https://iopscience.iop.org/article/10.1088/1748-9326/abfba1/pdf This study calculates carbon and water footprints of data centers within the United States. Researchers explore synergies between the water and energy utilization of data centers to design a path towards decease the environmental impact of increasing data usage.
8. https://www.forbes.com/sites/forbestechcouncil/2021/05/03/renewable-energy-alone-cant-address-data-centers-adverse-environmental-impact/?sh=416706405ddc An overview of what businesses need to do to address the adverse environmental impact of data centers.

AI

1. https://anatomyof.ai/ Overview of the anatomy of an AI system.
2. https://www.climate-kic.org/opinion/ai-and-climate-change-the-promise-the-perils-and-pillars-for-action/ An overview of the potential of AI systems to address environmental degradation, as well as the risks that the energy consumption of AI system poses.
3. https://www.brookings.edu/research/how-artificial-intelligence-will-affect-the-future-of-energy-and-climate/ An overview of how AI may be affecting the supply and demand of energy, and the implications of AI in climate change.
4. https://www.weforum.org/agenda/2022/05/artificial-intelligence-sustainable-development-goals/ An overview of the role that AI systems can play in helping meet the 17 Sustainable Development Goals

Appendix C

Exercises and Learning Resources for Instructors

Chapter 3: Applications of Sustainable Computer Science

Sample Instructional Activities

Activity 3A: Computer Science and Agriculture: Using Python to Model the Corn Growing Season[17]

Advancements in technology have greatly helped the agriculture industry evolve since their roots 12,000 years ago, and today such technology is allowing farmers to improve their sustainability through increased productivity, leading to less food insecurity and less land use change for agriculture. In this coding exercise, students will use provided weather data to calculate growing degree days (GDD) for a two month period at the beginning of the 2021 corn growing season. Growing degree days assist farmers in knowing how corn (and other crops) growth is progressing and assists in calculating the risk of pests, allowing them to make adjustments during the growing season to improve and maximize crop yields and better manage pesticide use. A sample solution, along with additional information about downloading data for alternative years or locations is available on the SPICE Github. This coding task involves 2D lists, if/else statements, math, and for loops.

[17] Access at https://github.com/KyleRuhl/SPICE-Exercises/tree/main/Corn_Degree_Days_Python

Activity 3B: Plotting Temperature Trends with Time Series in Python & Recognizing Climate Trends[18]

Task: Create and plot a time series of average yearly maximum and minimum temperatures at a given location. The sample response uses weather data from the weather station at an airport in Phoenix, Arizona from 1933-2021. This project incorporates matplotlib, pandas, datetime string conversions, and temperature trends. To download a CSV datafile, students should go to https://crt-climate-explorer.nemac.org/ and enter a city of their choice. Then, click on 'Historical Weather Data'. They should then select a station. Next, press 'Downloads' > 'Download temperature data' and retrieve their CSV file. The instructor may want to preselect a dataset(s) as some stations have significant gaps in data collection. SPICE has provided a few preselected datasets on the Github along with a sample code answer. After plotting, have students analyze the plot- are temperatures increasing or decreasing at your location over time? Consider climate change trends vs weather variability. What do you think your plot is telling you? What other factors could account for the yearly changes in temperature at your location?

Suggested Modifications to Existing CS Curriculum/Activities:

- CS Topic: Types and String Manipulation
  - Students break down and reconstruct strings relevant to sustainability
    - Could be information from a database relating to any of the topics mentioned throughout chapter 3
- CS Topic: Trees and Graphs
  - Students construct phylogenetic trees
    - One field of each “organism” object as its current population or risk of extinction using real ecological data
- CS Topic: GUIs (Graphical User Interfaces)
  - Students develop user-friendly, interactive maps representing relevant sustainability data
    - Use agricultural, climate, or biodiversity data

[18] Access at https://github.com/KyleRuhl/SPICE-Exercises/tree/main/Climatology_Python

Instructor Learning Resources

Resources for Further Engagement

1. Environmental Data and Governance Initiative (EDGI)- An organization relevant to information mentioned in Chapter 3, Module 3, Learning Objective II
2. Public Lab - An organization relevant to Chapter 3 as a whole: with projects centered around life sciences sustainability, earth systems, and human-behavior related sustainability science. This lab is compiled based on individual volunteer action in the spirit of open source
3. Compilation of Environmentally Focused Open Source Projects- These are relevant to Chapter 3, Module 3, Learning Objective III

Additional Sources Used for the Development of this Chapter:

https://sdw-blog.eun.org/2020/03/02/coding-to-save-the-planet/
https://umaine.edu/cs/research/features/computational-ecology/
https://engineering.oregonstate.edu/combining-passions-impact-environment
https://www.khoury.northeastern.edu/programs/bs-combined-major-for-computer-science-and-environmental-science/
https://www.ischool.berkeley.edu/news/2019/why-we-need-data-science-fight-climate-justice
https://opensource.com/article/19/4/environment-projects
https://cacm.acm.org/magazines/2019/9/238970-computational-sustainability/fulltext
https://www.computational-sustainability.org/
https://climate.mit.edu/explainers/climate-models
https://www.geeksforgeeks.org/what-is-web-scraping-and-how-to-use-it/
https://opensource.guide/starting-a-project/#:~:text=What%20does%20%E2%80%9Copen%20source%E2%80%9D%20mean,through%20an%20open%20source%20license.
https://www.mecs-press.org/ijmecs/ijmecs-v11-n2/IJMECS-V11-N2-1.pdf
https://www.usaid.gov/sites/default/files/documents/15396/Digital_Tools_for_Agriculture.pdf
https://cuaes.cals.cornell.edu/digital-agriculture/
https://www.carbonbrief.org/qa-how-do-climate-models-work/