1.5 Degrees of Separation: Computer Science Education in the Age of the Anthropocene

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ABSTRACT

Climate change is the defining challenge now facing our planet. Limiting global warming to 1.5 degrees, as advocated by the Intergovernmental Panel on Climate Change, requires rapid, far-reaching, and unprecedented changes in how governments, industries, and societies function by 2030. Computer Science plays an important role in these efforts, both in providing tools for greater understanding of climate science and in reducing the environmental costs of computing. It is vital for Computer Science students to understand how their chosen field can both exacerbate and mitigate the problem of climate change.

We have reviewed the existing literature, interviewed leading experts, and held conversations at the ITiCSE 2019 conference, to identify how universities, departments, and CS educators can most effectively address climate change within Computer Science education. We find that the level of engagement with the issue is still low, and we discuss obstacles at the level of institutional, program and departmental support as well as faculty and student attitudes. We also report on successful efforts to date, and we identify responses, strategies, seed ideas, and resources to assist educators as they prepare their students for a world shaped by climate change.

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ITiCSE-WGR '19, July 15–17, 2019, Aberdeen, Scotland Uk

ACM ISBN 978-1-4503-7567-2/19/07...$15.00
https://doi.org/10.1145/3344429.3372500

CCS CONCEPTS

• **General and reference → Surveys and overviews**; • **Social and professional topics → Sustainability**; **Computer science education**; **Adult education**; *Model curricula.*

KEYWORDS

Anthropocene, ICT4S, S/CC sustainability, climate change, global warming, global heating, climate crisis, climate emergency, climate breakdown, model curricula, IPCC, CS education

ACM Reference Format:
Ian Pollock, Bedour Alshaigy, Andrew Bradley, Birgit R. Krogstie, Viraj Kumar, Linda Ott, Anne-Kathrin Peters, Charles Riedesel, and Charles Wallace. 2019. 1.5 Degrees of Separation: Computer Science Education in the Age of the Anthropocene. In *2019 ITiCSE Working Group Reports (ITiCSE-WGR '19), July 15–17, 2019, Aberdeen, Scotland Uk*. ACM, New York, NY, USA, 25 pages. https://doi.org/10.1145/3344429.3372500

1 INTRODUCTION

From rising sea levels to greater extremes in temperature to more frequent, more intense hurricanes, droughts, and floods, the social, economic, and environmental consequences of climate change are increasingly grave as the resource-stressed planet nears 9 billion human inhabitants by mid-century [100]. Anthropogenic climate change [34] has been on the international agenda since 1988, when the United Nations General Assembly endorsed the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) establishment of an Intergovernmental Panel on Climate Change (IPCC) [124]. In 2018, the IPCC concluded that limiting global warning to 1.5 degrees would require rapid, far-reaching, and unprecedented changes in how governments, industries and societies function [68]. The climate crisis requires effort from professionals across the spectrum; it cannot be localized to a single field or specialty. Moreover, this effort must happen immediately; a recent UN report establishes 2030 as the deadline beyond which climate change becomes irreversible.

The 2018 IPCC report [68] has highlighted the urgent need for action in response to climate change. Unlike previous IPCC reports, it recognizes climate change as a threat to sustainable development [80] and asserts clearly that climate change is a certainty even in the event of serious mitigation efforts. The inevitability of climate change means that we need to think about sustainable climate adaptation [43] as we prepare our students for the world in which they must live and work.

In the field of Computer Science (CS), we have a responsibility to help mitigate this crisis. Computing technology is a large contributor to the enormous growth in energy consumption in recent times [40], and "[t]he majority of software systems are created unsustainably, and often decrease sustainability" [14]. At the same time, the power of computing to model and analyze climate systems and to optimize resource usage is a promising force for good.

While institutions of higher education are increasingly addressing climate change at the institutional level, for instance by declaring Climate Emergencies [31], it is not always clear how instructors can respond to this call in their courses. Persistence of climate change doubters [81] and *anupholesteraphobia* (the fear of not being able to teach unfamiliar material [91]) are some of the obvious barriers to including climate change in CS education. According to Mann et al. [92], other barriers may include limited knowledge about sustainability on the part of the faculty, the feeling that computing may not play a significant role in social or environmental sustainability, and the lack of easily accessible resources for the integration of sustainability into the computing curriculum.

This report explores the current status of climate change education in CS education. How can climate change education be implemented, and what research is being conducted to understand and advance climate change education in computing? We conduct a literature review, we interview "experts" (people who have developed and researched sustainability education in computing), and we study reactions and experiences of a sampling of the CS education research community. We find that little work has been done within our discipline of CS education research, so this work provides grounds for an important area of investigation.

1.1 Objective of the Report

Looking ahead at a ten year time frame, we set out to pursue the following strategies for creating a set of recommendations:

(1) Identify the current state of research into addressing climate change in CS education.
   (a) Specifically examine what universities have done and what obstacles to the inclusion of climate change in CS education exist at the level of:
      (i) Institutional support and responses
      (ii) Program and departmental support and responses
      (iii) Faculty attitudes and responses, and reactions of students
(2) Provide current responses and ideas for implementing strategies to address climate change in CS education
(3) Provide ideas for teaching and assessment of including climate change in CS education
(4) Develop a repository that allows for the dissemination of resources for institutions and faculty interested in addressing climate change in CS education.

1.2 Structure of the Report

This report was written to share results from three distinct activities: a systematic review of the literature, interviews with faculty who are leading efforts in sustainability education, and a focused conversation with CS instructors attending ITiCSE 2019 who represented the readership of this report as faculty with an interest in responding to climate change in their discipline. For clarity of reading, we have opted to give each of the strategies a section in this paper in which the methods were discussed in detail and the results were elaborated. Thus there is a section each on the literature review, interviews with experts, and the World Cafe [49] involving a focused conversation with educators. Following this is a section that looks to integrating the results into a discussion and a conclusion with recommendations. Finally, there is an appendix of materials to help in the implementation of climate change in CS education. In addition, we are working on making these and additional materials available through an online repository separate from this paper.

1.3 Related Work and Terminology

The scientific community and the general public have increasingly acknowledged the effects of human activity on the environment [143]. As more becomes known about anthropogenic environmental change, and as public acknowledgment shifts, terms emerge or shift meaning to accommodate current understanding. As this process is still in play, there is a potentially confusing mixture of terms in both public and academic spheres. Here we survey both the work and the terminology relevant to our focus.

The focus of this working group is *anthropogenic climate change*, which refers to the ongoing temperature changes in the troposphere (the lowest region of the atmosphere, extending 6-10km above the earth's surface) as effected through human activity. An abbreviated form, *Climate Change (CC)*, is commonly used in both scientific and public discourse, and we will use this form in this report.

Climate change is one of nine processes that are being monitored in the planetary boundary framework [127], which identifies levels of anthropogenic perturbation below which the risk of destabilization of the earth system is likely to remain low - "a safe operating space". Climate change is one of four processes, along with biosphere integrity, biogeochemical flows, and land system change, that exceed the proposed planetary boundary.

Anthropocene refers to the Paul Crutzen's [34] suggestion that human activities have grown to become such a significant geological force, for instance through land use changes, deforestation and fossil fuel burning, that it is justified to assign the term "Anthropocene" to the current geological epoch. This epoch may be defined to have started about two centuries ago, coinciding with James Watt's design of the steam engine in 1784 [35].

Global warming refers to the marked rise in average temperatures across the troposphere over the past century, as established through a combination of direct measurements and historical reconstructions. A seminal 1998 *Nature* article reported that "Northern

Hemisphere mean annual temperatures for three of the past eight years are warmer than any other year since (at least) AD1400" [89], and a following report introduced the famous "hockey stick" graph indicating an unprecedented climb in Northern Hemisphere temperatures starting in the 20th century [90]. A 2013 Intergovernmental Panel on Climate Change (IPCC) report asserts that "[it] is extremely likely that human influence has been the dominant cause of this rise" [129].

According to a recent study in the United States, "global warming" has a stronger emotional effect than "climate change", indicating a deeper sense of threat and need for action [82]. Although global warming does accurately describe a real phenomenon in a global, long-term context, it does not capture the multiple ways in which climate change affects the troposphere: for instance, changes in rainfall patterns, and greater frequency of extreme weather phenomena. According to NASA, "[c]hanges to precipitation patterns and sea level are likely to have much greater human impact than the higher temperatures alone" [30].

Sustainability refers to an intentional approach to resource consumption that balances the human and environmental needs of today with those of tomorrow. The term was first used in an environmental context in a 1972 MIT report, covering a number of negative anthropogenic changes, but asserting "It is possible to alter these growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future. The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has an equal opportunity to realize his individual human potential" [96]. Similarly, the 1987 Bruntland Report characterizes sustainability as a challenge to be met by human will and ingenuity: "Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" [142].

Sustainability can be understood through three dimensions: social sustainability, economic sustainability, and environmental sustainability [14, 66]. A central idea is that human society is only sustainable if it can be sustained in these three dimensions. One approach is to balance the three concerns, which many have rejected as "weak sustainability". To achieve "strong sustainability", we need to acknowledge that society exists in biophysical limits that constrain the flows of natural resources. The economy and society need to be understood as "nested" in the environment. A society can only be considered sustainable if it lives within these environmental limits.

Although sustainability is often used in the context of climate change and environmental issues, it is also frequently used quite broadly in the context of numerous types of systems. Thus context becomes important when reviewing work on sustainability. From an educational perspective, the broad quality of the term is both a strength and a weakness. It can be useful to think of a sustainability mindset as a broad awareness of the effects of technology [22], but it can also lead to a lack of specificity in terms of expected learning outcomes. For instance, our literature review discovered climate change as a topic within sustainability-focused course projects, but in these contexts, climate change is one of many project options, so there is no guarantee that students will emerge from the projects with a heightened understanding of climate change in particular.

Green computing typically refers to technologies and practices that reduce the environmental cost of computing itself, primarily in terms of energy consumption. Our digital infrastructure consumes a significant portion of the world's electricity generation. According to a 2016 Lawrence Berkeley National Lab report, data centers in the United States consumed an estimated 70 billion kWh in 2014, representing about 1.8% of total U.S. electricity consumption [125]. The report also indicates that it is difficult to forecast future energy consumption, as massive expansions of Internet connectivity (e.g. 5G mobile technology, Internet of Things, cryptocurrencies like BitCoin) are mitigated by technological developments (e.g. shifting to hyperscale data centers, eliminating "zombie" servers [83], users moving to smaller, lower-energy devices) [71].

An early example of a green computing initiative is the EnergyStar initiative, a voluntary labeling program launched in 1992 by the United States Environmental Protection Agency and designed to promote the awareness of energy efficiency in electricity-consuming technologies, including computing technologies.[1] Green ICT initiatives by Japan, Denmark, and the United Kingdom have supported research and development on resource efficient ICTs and implemented government procurement strategies that value energy efficiency [78]. Research in energy-efficient computing includes power-aware processor and storage system design, but also brings advanced optimization techniques to bear on the problem [10, 15, 20, 26, 38].

Sustainable computing and *Computational sustainability* refer to technological approaches to mitigating the environmental costs of human activity and creating a long-term balance between human needs and environmental resources. These terms tend to encompass both mitigating computing-related costs and employing computing technology for sustainability objectives. For instance, the IEEE Special Technical Committee on Sustainable Computing[2] lists its primary goals as "promot[ing] the design and implementation of sustainable computing" and "facilitat[ing] computing for sustainability", and includes as relevant topics "energy efficient design and operation of IT equipment" and "sustainability across the lifecycle of IT equipment and processes", and also "use of computing to systematically improve the sustainability of non-IT processes". Sustainable computing can therefore be understood in two ways: sustainability in computing referring to efforts that reduce environmental impacts, and sustainability by or through computing, i.e. using computing to reduce the environmental impacts in other sectors of society [66]. Another way to understand this distinction is to study ICT as part of the problem vs. as part of the solution.

Hilty and Aebischer [66] give an overview of *Information and Communications Technology for Sustainability (ICT4S)*, an emerging research field in the intersection between sustainability and computing. They envision ICT4S as an "umbrella" or "bridge" between sustainability and efforts in various computing subdisciplines. Similarly, Gomes *et al.* give a survey of research directions in computational sustainability in a recent issue of *Communications of the ACM* [55]. The focus here is on leveraging new computational capabilities in machine learning, optimization, remote sensing, and decision

[1] http://www.energystar.gov
[2] http://stc-sustainable-computing.ieee.net

making [4, 29, 70, 117], and engaging the public in sustainability through gamification and citizen science [45, 132].

The Karlskrona Manifesto [14] addresses sustainability in the context of software development, stating "As designers of software technology, we are responsible for the long-term consequences of our designs". The report emphasizes the need for greater awareness of sustainability in the software industry: "the majority of software systems are created unsustainably and often decrease sustainability instead of increasing it." Signers of the manifesto see sustainability as an essential property of systems we develop, stating "sustainability does not apply simply to the system we are designing, but most importantly to the environmental, economic, individual, technical and social contexts of that system, and the relationships between them." They speak of both the beneficial and confounding aspects of software technology on sustainability, in terms of first-order effects ("the immediate opportunities and effects created by the physical existence of software technology and the processes involved in its design and production"), second order effects ("the opportunities and effects arising from the application and usage of software"), and third-order effects ("the effects and opportunities that are caused by wide-scale use of software systems over time"):.

The literature review in this report gives a thorough coverage of work related to climate change within CS education (Section 3). In addition, it is worth considering other efforts like *Writing Across the Curriculum* [32] and *Ethics Across the Curriculum* [41] to integrate cross-cutting topics into the computing curriculum. Writing Across the Curriculum (WAC) and Educational Advisory Council (EAC) both acknowledge the importance of positioning such topics within "disciplinary" courses, rather than consigning them solely to standalone courses taught outside students' home departments. These initiatives are motivated by acknowledgment of the need for students to develop professional competencies (i.e., to communicate and to make thoughtful ethical decisions), often through the impetus of accreditation. WAC has a long history in North American higher education; a 2010 survey indicates growth in programs across the United States and Canada, but challenges in keeping programs alive over time [134]. Also related is the recent work on incorporating accessibility into CS education, as exemplified by the Access Computing Alliance[3]. Educators involved in this initiative underscore the importance of embedding the topic into multiple courses rather than a single standalone course, but also acknowledge the challenges in educating instructors about accessibility.

2 METHODOLOGY

While climate change is a global problem, education about climate change is still defined by local action. Research has shown that this topic resonates with diverse audiences when it is situated in their cultural values and beliefs, and when it empowers specific action [123]. Thus it was deemed important to understand the current state of climate change in CS education, and to approach CS education practitioners and experts in the field to obtain their views on how the inclusion of climate change in CS education should be achieved. Three approaches are employed in this report: a review of the literature relating to the inclusion of climate change in CS education, interviews with experts, and focus groups with CS education practitioners.

To investigate the current state of research on environmental sustainability and climate change (S/CC) in CS education, we conducted a literature review. Our primary source for the literature review was the ACM Digital Library, which includes the proceedings of top CS education conferences. A secondary source was the IEEE Xplore digital library.

The use of interviews with experts and focus groups with CS education practitioners was a deliberate choice by the authors of choosing inductive over deductive strategies. This is in part predicated by the rapid social change [47] and diversity of academic and cultural context in CS education and the need to quickly address the impending climate emergency.

Experts in the field of climate change in CS education were identified by searching the literature for authors who had published in computer science, climate change and education, and were contacted to participate in the study. The experts were asked about their views on and experiences with climate change education for CS students. Semi-structured interviews were conducted, allowing the interviewees the freedom to express their opinions in their own terms [79], and thus enabling us to gather information that the interviewees consider to be important.

Focus groups were carried out in the form of a "World Cafe" hosted during the ITiCSE 2019 conference in Aberdeen as a means to engage the attendees of the larger conference with the research subject, and to explore the views of the peer community of CS education practitioners. The World Cafe is a structured approach to a conversation that engages groups in constructive dialogue around topical questions by drawing upon the collective knowledge and life experiences of the participants [23]. A selection of open ended questions were used to gather thoughts on topics including: what the world may be like when our near future students graduate, what they may need to be learning; strategies for addressing this; and ideas and resources for implementation in CS education.

Interviewing, whether in the form of remote and in-person interviews, email communications, or in-focus groups as exemplified above constitute research methods using language. Such methods are, according to Hamilton and Bowers [58], an attempt to expand on any given experience seeking complexity and depth of thought in contrast to quantitative researchers' attempts to reduce a phenomenon to measurable quantities.

Qualitative research has been described as bricolage, quilt making, or montage—a pieced-together set of representations that are fitted to the specifics of a complex situation, as a set of interpretive activities, privileging no single methodological practice over another, exploring how social experience is created and given meaning [36]. In this study, we mix several methods to assess the current state of climate change in the CS education literature by counting articles and keywords (quantitative), and exploring questions about how climate change is addressed in contemporary CS education by researching the literature and performing interviews (qualitative).

As we explored and analysed the interviewees, we also discovered a general interest in addressing climate change combined with a general inability to think about how to do it, and a lack of knowledge of where to find suitable data for use in teaching. Therefore, in addition to the methods used above, a search was performed

[3]https://www.washington.edu/accesscomputing/

to collate links to datasets and other readily available material, providing easy access to assist the readers in getting started with including climate change in the CS curriculum. These are included in the resources in Appendix C and linked in an accompanying repository.

3 LITERATURE REVIEW

3.1 Literature Review Method

To investigate the current state of research on environmental sustainability and climate change (S/CC) in CS education, we conducted a literature review. We limited the scope of our search to publications in the ACM and IEEE databases. These can be taken to provide good coverage of published research in the computing area. The ACM Digital Library in particular is a key source of research literature on computing education, covering top conferences within CS education including ICER, SIGCSE, ITiCSE, Koli Calling and ACE.

Our search in the ACM Digital library consisted of:

- Items from the full text collection
- Any year
- CCS (ACM Computing Classification System) = Computer Science Education
- Search string: sustainable OR sustainability OR green OR 'climate change' OR 'global warming'.

The search results comprised 1445 items. The search terms 'sustainable', 'sustainability' and 'green' led to many results that were irrelevant to us, but at the same time these terms were necessary to capture relevant items. For instance, some authors have a last name 'Green', and curriculum changes are often described as sustainable. By manually examining titles and abstracts of the 1445 items and eliminating obviously irrelevant ones, we identified 31 papers from the search results that appeared to be relevant.

A similar search of the entire ACM Digital library, *i.e.*, removing the CCS=CSE constraint, resulted in more than 70,000 items. These were not checked for relevance, as the purpose of this search was to get a rough picture of the amount of research in the area of S/CC within computing in general.

After completing our analysis of the items found from the ACM Digital Library, we also did a search of the IEEE Xplore Digital Library using:

- search string: (education AND ('computer science' OR 'software engineering') AND (sustainable OR sustainability OR green OR 'climate change' OR 'global warming'))
- Filter: conferences, journals, early access papers

This search resulted in 972 items. A scan of the search results indicated that, similar to what we found in the ACM Digital Library search, many items were not relevant given our purpose. We will discuss the most relevant items found in this search in our detailed results section below.

To get a picture of the kind of research published in the CS education community in this area, we hoped to examine the papers and start a bottom-up process to identify appropriate ways of categorizing the research. The purpose of such a categorization is to provide a tool for structuring the research, identifying the extent to which different kinds of research are being conducted, and the types of studies that are being published. Given the limited set of papers found through our search, we focused on only a limited number of dimensions that capture characteristics and differences in the published studies.

One immediately apparent characteristic of the importance of a research contribution in the area of integrating S/CC in CS education is how much S/CC is the actual focus of the research. Is sustainability or climate change the main issue? Is it considered part of the main issue (*e.g.,* being an important element/application of ethics, societal good etc.)? Or is it more incidental, *e.g.*, one possible source for project material? Whereas research with a clear S/CC focus is likely to have a more significant contribution to research in this area, there may be studies that prove valuable even if the link to S/CC is weaker or more indirect. For instance, a study might address ways to support student projects that may or may not have S/CC-related objectives, depending on the characteristics of each specific project (*e.g.* [17]).

Other dimensions that might prove relevant to categorize the literature with the purpose of helping researchers and practitioners find useful information include

- Does the research address challenges of education, research, S/CC?
- Does the research propose solutions to these challenges? (*e.g.*, technologies, processes, policies), and can the presented solutions be considered as exemplary for others?

Apart from the above categorization, we will briefly point to some more general categories of classifying research publications that might help the CS education researcher or practitioner identify relevant research in the S/CC area. It may be useful to classify publications according to their scope. This includes the scope of the educational approach/intervention in question, the institutional level, the curricular scope (*e.g.*, study program, course, module, assignment), and the school level (*e.g.*, graduate/undergraduate, K12). Also it is useful to include the type of technology and/or educational methodology applied in the study and the main topic area (*e.g.*, learning activities, syllabus, policy). Finally, the research may be categorized in accordance with the general type of study (empirical, theoretical, literature review, meta-review), which could be further detailed into more specific research methods and also include the maturity of the research (*e.g.* for empirical research: idea, plan, implemented, evaluated, empirically-based theory building).

The categories we have in mind to provide researchers and practitioners with a useful overview of S/CC-related CS education literature would not be a substitute for classification *e.g.,* in databases like the ACM Digital Library, but might serve as an important tool to facilitate convenient access to useful resources. Continued development of a classification framework for our purposes should include looking more thoroughly into existing frameworks to avoid re-inventing general and well-proven approaches.

3.2 Literature Review Results

As noted above, we identified 31 items from our literature search in the ACM Digital Library that appeared to be relevant to this study based on title and abstract. Further examination of the full publications revealed that 12 of these items were not relevant. Thus, we ultimately identified only 19 relevant publications through our

ACM Digital Library search that discussed issues related to S/CC in CS education. Eight items in the relevant 19 were abstracts for talks, posters, or panels. Following is a quick survey of the publications identified as relevant.

Several of these papers make a case for including S/CC into CS courses. A few papers focused on incorporating these topics into an ethics or professionalism course. We identified four such publications.

- Hamilton [57] (Abstract only) reports briefly on sustainability-related modules within a course on professionalism in computing, covering topics such as green mobile cloud computing systems; integration of green clouds and the internet of things; energy saving solutions and trade-offs; and sensors and monitoring software tools for evaluating energy use.
- Dodig-Crnkovic [37] argues for the need to teach professional ethics and sustainable development to graduate computing students in order to reach future researchers capable of dealing with the complex problems facing society. Courses at two Swedish universities are discussed. In one of the courses environmental impact is one of several topics listed. The second course discussed includes 'sustainable development' in the course title.
- A paper by Jones [72] focuses more broadly on an interdisciplinary approach to teaching ethics based on smartphones. Included among the numerous impacts on society of the design of smartphones and the associated infrastructure is the environmental impact of the manufacturing, use and disposal of smartphones.
- The 2008 Revision of the 2001 ACM Computer Science Curriculum [24] included environmental sustainability as a recommended topic under Social and Profession Issues. An associated Learning Objective "Identify ways to support environmental computing (*e.g.,* green operations, recyclable products, reduced green house emissions)" was included. More recent curriculum recommendations were not identified through our targeted search, but are discussed below.

Several publications incorporate S/CC more broadly into computing curricula:

- Cai [21] outlines a range of possible intervention strategies for integrating sustainability into a computing curriculum: as a standalone course, as an incremental approach that integrates modules into existing courses, and in a transformative approach that redesigns existing courses around a sustainability theme. He describes a particular course of his design on energy-aware IT approaches. Survey results conclude that students in the course understood green computing concepts and techniques and maintained high confidence and enthusiasm in green computing, but the author does acknowledge the limited effect of a single course.
- Erkan *et al.* [44] describe a multidisciplinary collaboration which involves students from several disciplines working collaboratively on climate change issues. In particular, they present several exercises CS students have done using satellite images.
- Penzenstadler and Bauer [106] make a strong case for "sustainability" as a vital but underrepresented topic within software engineering. They note the lack of substantial work on this topic within Software Engineering education, and point out that "[s]ustainability is not yet a first class citizen in the family of quality attributes, currently taught to future software engineers, as, *e.g.*,, the ISO criteria". They describe a series of seminars for SE students at bachelor and masters levels, focusing on requirements engineering with sustainability as a quality attribute. The seminars are centered around case studies in "ICT for environmental sustainability" (ICT4ES) systems. The paper is an experience report rather than a research study, so it remains to be seen how effective the seminars are. The authors do not define any learning objectives in the paper.
- A panel [120] (Abstract only) at Computing Sciences in Colleges in 2012 discussed topics such as sustainability aimed at fostering an environmental awareness in students.
- Fox [50] (Abstract only) presents a CS 1 course centered on topics related to S/CC such as increasing energy efficiency and how the Internet enables sustainable practices such as telecommuting.
- Beck and Joyce [13] (Abstract only) introduce the Sustainability Improves Student Learning (SISL) project aimed at encouraging CS teachers to introduce sustainability throughout the CS curriculum. SIGCSE is indicated as one of eleven professional societies involved in SISL.
- Stone [130, 131] (Abstracts only) discusses using sustainability projects in introductory CS courses. One of their goals was to encourage students to act on their new knowledge of sustainability in their own lives.

One paper discussed incorporating S/CC and computing into other subject areas.

- The paper by Martin and Kuhn [93] discusses integrating a computing project into a social science course on sustainable development. The focus of the paper is the integration and impact of the computing project in the course. The projects developed by the students all focused on sustainability issues. Examples include a personal waste scale and an ecological footprint quiz machine.

Several papers used S/CC topics as material for course projects and activities.

- Lo, Qian and Yang [85] (Abstract only) present a portable Wireless Sensor Network in a box (WinBox) system that facilitates student development of such networks. They briefly describe an application of this system: monitoring of power usage, hence the connection to 'green technology'. The focus of the work, however, is primarily on the 'learning by doing' afforded by WinBox, and learning objectives explicitly concerning climate change are not articulated.
- Inclezan [67] (Abstract only) suggests using environmental problems in a CS classroom to engage students in the challenges we are facing today.
- Gaither *et al.* [52] briefly mentions using water sustainability as the basis of projects in a program designed to engage

Native Hawaiian and Pacific Island students to pursue STEM fields as they develop competency in big data.

A few papers mentioned S/CC as possible topics in a broader context.

- In 1999 Schneider [121] published the earliest paper we found that mentions S/CC. As part of the justification for a course in computational science for STEM students, he mentions global warming as one of the problems being investigated by scientists using computational science.
- Goldweber *et al.* [54] mention green computing and computing for sustainability as examples of topics that could make students aware of the possibility of computing as a force for positive change.
- Torngren *et al.* [135] identify the need for cyberphysical systems engineers to be aware of life-cycle concerns including environmental effects, recycling and disposal.
- Finally, a paper by He *et al.* [61] used energy-aware practices to improve battery performance in the development of a cloud-of-things (CoT) framework to support student CoT projects.

Due to the small number of papers that we found in our literature survey, we performed a much simpler classification than we originally envisioned. The table below summarizes our classification. Publications were classified based on three categorizations: Type of Publication, Curriculum Focus and Primary Focus of the research. Publications were classified as either an Abstract (typically one page or less) or a Paper. Curriculum Focus is meant to capture the type of students and course in which S/CC is covered. The categories we identified were courses for non-CS majors, introductory CS courses, CS ethics courses, and other CS courses. Finally, we indicated whether the focus of the publication was primarily on S/CC versus S/CC being one of several topics mentioned. Table 1 captures our classifications.

There are several observations we can make on the status of S/CC in CS education from Table 1. With only 19 entries we clearly see how limited the discussion on S/CC in CS education has been. Although the first paper published in the CS education literature that discusses S/CC was published 20 years ago, there was only one additional paper the following decade. Even in the current decade, the largest number of publications in a given year was three. In slightly over half of the papers S/CC was not the primary focus. Indeed, in some cases S/CC was merely mentioned as one possible topic that might be considered in the given course context. Perhaps the most significant indicator of how limited the research has been in this area is the fact that only two of the items listed in Table 1 were full papers with a primary focus on S/CC.

Interestingly, our limited search in the IEEE Xplore Digital Library produced more relevant full papers, though the total is still quite low. Here are the most relevant papers as indicated by the IEEE Xplore search:

- Turkin and Vykhodets [138] describe a SE sustainability course for masters students.
- Porras *et al.* [112] describe a sustainability focused ICT program for graduate students and present the findings of their analysis of the first three years of the course.

Table 1: Classification of Literature Review Items

Publication	Curriculum Focus	S/CC Primary Focus?
Full papers		
Cai [21]	CS	Yes
Dodig-Crnkovic [37]	CS Ethics	No
Erkan [44]	Non-CS	No
Gaither [52]	Non-CS	No
Goldweber [54]	CS	No
He [61]	CS	No
Jones [72]	CS Ethics	No
Martin [93]	Non-CS	No
Penzenstadler [106]	CS	Yes
Schneider [121]	Non-CS	No
Torngren [135]	CS	No
Abstracts		
Beck [13]	CS	Yes
Fox [50]	CS First Year	Yes
Hamilton [58]	CS Ethics	Yes
Inclezan [67]	CS	Yes
Lo [85]	CS	No
Schaeffer [120]	CS	Yes
Stone [130]	CS First Year	Yes
Stone [131]	CS First Year	Yes

- Torre *et al.* [136] present the results of a target survey of 33 academics on sustainability in SE curricula. Their findings indicate that sustainability is not well represented in SE curricula.
- Zalewski and Sybramanian [147] present a model for integrating sustainable development into computing education.
- Penzenstadler *et al.* [107] describe a summer school course on Software Engineering for Sustainability that they have offered. Their materials and a report of their experiences were made available in an effort to further collaborations and development of similar courses.
- Ashmed and Shuaib [5] discuss a software requirements engineering course in which Green IT characteristics are treated as quality factors.

The inclusion of a version of the ACM Curriculum Guidelines [24] in our literature search prompted an examination of the more recent curriculum guidelines. The CS 2013 model curricula for Computer Science [2] (and the 2018 update), developed by the ACM/IEEE-CS Joint Task Force, recommend inclusion of sustainability: 1 hour at "Core-Tier 1" and 1 hour at "Core-Tier 2" within the "Social Issues and Professional Practice" knowledge area (pp. 200-201). It is noted that "[t]opics in this emerging area can be naturally integrated into other familiar areas and units, such as human-computer interaction and software evolution."- though as we have seen in our literature review, it may not be as simple as the authors suggest.

Accreditation organizations for computing programs in higher education do not mention sustainability as a central topic. The British Computer Society's accreditation guidelines [3] (see p. 16, section 2.6.1) include as a learning objective an "awareness of external factors which may affect the work of the computer professional". A long list of examples of such factors is given, including "environmental and sustainability aspects". The Criteria for computing programs developed by the Accreditation Board for Engineering and Technology (ABET) [1] in the United States are even less focused on climate change, including as a topic "local and global impacts of computing solutions on individuals, organizations, and society" without specifically mentioning environment, sustainability, or climate change.

3.3 Literature Review Discussion

The literature review provided two key insights. The first insight is that published research on environmental sustainability and climate change (S/CC) is very limited within the CS education community. This corroborates findings from related work, adding to the argument that the community should increase its activity in this area. The second insight applies to the complexity of identifying relevant work on S/CC in CS education, both in terms of identifying the relevant research communities and in terms of recognizing the specific contributions as relevant.

The limited findings from our search in the CS literature can be taken to reflect a lack of research on S/CC within the CS education community specifically. This was evident in our initial, exploratory search for literature as well as when we tried out different sets of search terms. At the same time, it is clear that relevant research can be found for the CS educator seeking ideas for including sustainability and climate change in CS education. In what follows, we briefly address the 'landscape' of relevant research fields.

First, by not limiting the search on S/CC in CS to education, it becomes obvious that sustainability, climate change and related topics are indeed addressed in the general body of computer science research. This research is diverse, covering "green IT" as well as "IT for green". To illustrate the diversity: the research includes contributions on the use of deep learning to detect climate deniers on Twitter [27], how virtualization impacts the energy consumption of cloud computing [7], how one may increase player engagement in a global warming sensitization video game [16], and how to achieve sustainable smart cities by participatory design challenging and extending the human-centered perspective [64]. This highly varied body of research obviously contributes as a source of knowledge of S/CC challenges and solutions for CS researchers, educators and students, and may be utilized in CS education to illustrate and deepen understanding in this area.

Secondly, looking into related areas of computing, it is clear that fields such as human-computer interaction (*e.g.,* [88]) and software engineering (*e.g.,* [108])) have a relatively higher level of research activity related to the incorporation of S/CC in education. There is an overlap among many of these areas, and a researcher within CS education may be a participant on several adjacent arenas, both as a user and contributor of research.

Thirdly, looking into literature on S/CC in higher education more widely, *e.g.,* in the International Journal of Sustainability in Higher Education, there is a wide array of research on challenges and solutions to how higher education institutions can include S/CC on different levels: across and within institutions, in study programs, courses and smaller pedagogical units. For instance, Hay *et al.* [59] look into how students perceive and trust sustainability information; Hill and Wang [65] present a case study showing how a university can successfully integrate sustainability learning outcomes into their curriculum; Wiek *et al.* [144] discusses key competencies in sustainability that students should acquire. Also, more general journals on sustainability include research about higher education, *e.g.,* in special issues. One example is the Journal of Cleaner Production, with contributions like Alexio *et al.* [6] on roles, barriers and challenges for sustainability in higher education institutions, and Palacin-Silva *et al.* [101] on how to infuse sustainability into software engineering education through capstone projects.

Next, there are other research fields linked to pedagogy and education that may be particularly useful to CS educators who want to include S/CC in teaching and learning or to CS education researchers. One such field is environmental psychology (*e.g.,* [128]) offering insight on how to achieve behavioural change, whether in students or *e.g.,* in stakeholders CS practitioners can relate to, for instance clients of software development projects. Another relevant research field is ecological modelling, which provides contributions that can help educators and students conceptualize and gain an understanding of complex issues of sustainability and climate change, as shown in *e.g.,* [145]. Finally, the learning technologies /technology-enhanced learning field has much to offer in terms of how to utilize technology to support learning about S/CC. For instance, Parvathy *et al.* [105] addresses the use of augmented reality simulation to visualize global warming, Linn [84] compares different forms of scaffolding of learning from dynamic visualizations of climate change, and Tsang *et al.* [137] present a teaching kit consisting of components to enable students to build different green technology systems for purposes of learning green technology.

Furthermore, there is of course a body of research addressing solutions and challenges of sustainability more widely and/or within particular application areas. This research can serve as a source of informative and inspiring cases, and in some instances, relevant data sets for use in CS education. Thus, in the wider landscape beyond our search results but within the CS education community, there are many sources of literature potentially useful to the CS education researcher and practitioner interested in incorporating S/CC into education. Some of these research contributions may be directly applicable within CS education, i.e. when finding examples of green IT in the CS literature and having students read and discuss them. In other cases, the relevant research is likely to need the work of CS education researchers to synthesize, translate and apply the research to CS education, thus building and strengthening the body of research on S/CC in CS education.

4 INTERVIEWS WITH EXPERTS

4.1 Interview Methodology

The aim of the interviews with the experts or forerunners was to learn about their views and experiences with implementing sustainability education in computing. The goal was to understand the current state of sustainability education in computing and beyond, resources and ideas for implementation, as well as how sustainability education can be improved. For the recruitment process, individual email invitations were sent to approximately 16 expert leaders in this field and also more broadly to the mailing lists of SIGCSE and ICT4S. The working group identified experts as educators who had published in computer science, climate change and education in ACM publications. This definition was chosen because it reflects the goal of the project. Twelve expressions of interest were received. The relatively low response rate is likely due to the timing of the invitations (after the academic term was over) as well as the general challenge of recruiting for studies via email.

The interviews were semi-structured to create a discussion space in which participants are given the freedom to express their opinions in their own terms [79]. Our interview script contained six lead questions and follow-up questions that we chose to ask depending on the interviewee's answer to the lead question. Appendix A shows the final interview script. Four pilot interviews were carried out and based on the results of these interviews, the interview script was developed in a discussion with the whole group. Using the final script, five members of the group, alone or in pairs, conducted six interviews that each lasted approximately 60 minutes. Two of the interviews were conducted with the contribution of the whole group listening, though only one working group member took the lead in asking the questions. We consulted experts from all over the world, and so we conducted interviews via Skype and recorded the interview. One interview was conducted in person. All of the interviews were conducted in English.

For this report, we chose to focus on analysing the six interviews conducted with the final script. We limited the analysis to these interviews partly due to time constraints, while we also found that those six interviews gave us a rich picture of expert views. The six interviews were transcribed using Otter[4] as a transcription software, and the resulting transcripts were checked against the sound file. The transcripts were analyzed using thematic analysis in order to identify and examine patterns within the conversations that addressed the research issues [18]. The analysis was inductive, we identified themes, sub-themes and codes, restructured as we were analysing and re-visiting the transcripts. We developed and agreed on a preliminary structure of themes and sub-themes that was then finalised in a last round of analysing and coding the interviews. To write the report, we revisited and summarised the excerpts that were marked with certain themes. Three group members were involved in the analysis of the interviews. We analysed certain interviews together, to ensure the validity of results.

4.2 Interview Results

Table 2 provides an overview of the experts' experiences teaching and researching sustainability and IT.

Three main themes have been identified that will be presented in detail in the following:

(1) Experts' journeys developing sustainability and computing education and
(2) Experts' views on the implementation of computing and sustainability education,
(3) Experts views of the current status and hopes for the future.

[4]https://otter.ai/

Several sub-themes and codes were identified for each of the three theme. Appendix B shows the code structure, thereby providing an overview of the results.

4.2.1 Experts' journeys developing sustainability and computing education. The experts talk about their experiences developing sustainability education over the years, the barriers and challenges they have encountered, ways of approaching challenges, as well as the support that they have gained.

The support that the experts have received has changed over time. While some of the experts encountered resistance, were questioned, or had little possibilities to be heard a few years ago, the experts said that sustainability is now acknowledged as important by students, faculty, and universities. The increasing awareness of sustainability by the public and by media has contributed to a change in attitude:

> I think there's been a shift in how climate change and the Anthropocene is talked about in the media. I think there's a very palpable change. All the way from the way that protest groups are working, you know, you look at this year's protests, the extinction rebellion protest in London, and Greta Thunberg, getting the students out on strike, and so on. That's all new. And that's radically different from how climate protest groups organized in the past. And it's working.

Experts say that they nowadays are being approached by faculty but also other people working on educational development, e.g. university leaders, to develop education for sustainability.

Sustainability education has been developed in collaboration across universities, as a university-wide initiative, as well as within CS institutions. The experts also talked about nation-wide policies or policies across several universities that mandate sustainability education in universities.

All of the experts talked about university structures that support the development of sustainability education. The universities' image was seen as supportive by the experts, e.g. the universities were recognised as a "sustainability focusing university", as one of the best universities concerning "impact on sustainability", or a university that acknowledges "climate emergency". Furthermore, the experts mentioned the following university support structures: directives to integrate sustainability into education, staff development opportunities such as pedagogical development courses as well as incentives to take those, education structures such as university-wide learning outcomes. The following quote shows how sustainability is integrated in university-wide learning outcomes, but how it also still can be forgotten, as well as the role of the experts:

> [The university developed a] university wide learning outcomes document, a two pager that says undergraduates should emerge from their degree with the following attributes. It didn't mention sustainability. They put out a draft for consultation and then I was prompted by a couple of our students to write back to the committee that they forgot sustainability. [...] A few years ago, if I'd done this, I would almost certainly got the brush off. This year, the response I got was "Oh, yeah, that's a huge mistake missing that out, help

Table 2: Overview of interviewees.

	Place	Field, Position	Experience
1	N. America	Prof. CS, research university, Director of the School of Environment	*Teaching:* IT and sustainability, climate change modelling, systems thinking *Research:* Computational climate models in collaboration with climate scientists, Systems Thinking
2	Europe	Computer Science (HCI), Assistant Professor	*Teaching:* Introductory IT4S course for Media and Technology Students, Continuation IT4S course, Supervision of projects, thesis *Research:* HCI & sustainability, sustainability, education
3	Australia	Computer Science, Professor	*Teaching: Sustainability Education* *Research:* Computing for sustainability
4	Europe	CS Associate Professor (Computer Architecture)	*Teaching:* Computer Architecture, projects including sustainability *Research:* Computing and Sustainability, Education
5	Asia	Ecological Informatics, Professor	*Teaching:* Environmental Informatics, Geospatial Analytics, Data Analytics *Research:* Ecological Physics, Social Engineering and Sustainable Development
6	Europe	Professor, School of Business and Management	*Teaching:* Software and Application Innovation, Green IT and Sustainable Computing, Running a software project, Personal literature study *Research:* Software for sustainability, Innovation, Technologies and approaches for Communications, Parallel and distributed computing, Networks (social, technical, business), Education development

> us rewrite it!" So from the top down, we're starting to see at an institutional level of the university wanting to write this into learning outcomes.

Another strategy to integrate sustainability into all education programs is a sustainable practitioner program. Students of all study programs learn to become sustainable practitioners as a part of their education. The expert involved in the development of the program said that "he worked with every school to "think about what it means to be a sustainable practitioner". The aim has been reformulated, students should learn to "make a better world".

Such initiatives and incentives are seen as supportive. Academics could also oppose the idea of being told what to teach. One of the universities responded that academics would not have to include sustainability if they could demonstrate that their subject had no real world implications. The progress within computing education overall has been described as slow. One of the experts referred to a computing curriculum in which sustainability has been included in many courses that is being implemented by 17 universities. Otherwise, computing and engineering institutions are doing badly compared to other institutions. People from the Information Technology and Electro Technology institution, along with the engineering people, are hardest to convince about university directives to teach about sustainability. They argue that "sustainability has nothing to do with us". Several experts say that academics in computing resist to teach about sustainability, maybe thinking that sustainability does not lie in their core interest. The experts also reported on climate deniers among students and teachers and that there also is an inappropriate belief in technical solutions and quick fixes.

> I think that the, the Susan crumb diet calls that the green myth, there's technical fix just around the corner. And therefore we can carry on living like there's no tomorrow. And computing is seriously complicit.

The expert pointed to the book "Digital Technology and Sustainability: Engaging the Paradox" [60] in which those narrow focuses, e.g. on energy efficiency or "techno utopia solutions", are criticised . One of the experts described that his "ecology background" causes the engineering colleagues to question his computing competence. This expert however succeeded in establishing an Ecological Informatics programme that integrates Ecological Science with Computing and Social Science.

One explanation for why the progress at CS institutions is rather slow is that there are no or few structures in place that support CS teachers to integrate sustainability, compared to what has been established at many universities. There seem to be few incentives, teachers that are keen to integrate sustainability (many of the younger teachers) and who want to invest time in developing sustainability education are told to focus on research instead. Experts also pointed out that there is little financial support to develop and research sustainability education at the institution. Some of the projects that the experts engaged in were not funded or the funding ran out.

Several of the experts were conducting research on sustainability and IT and were part of a research environment that helped them develop their teaching. One of the experts said that she is working in an inter-disciplinary division, which might make teaching sustainability easier because the people are used to inter-disciplinary questions.

The experts talked about different courses that they had developed or that were in place in which sustainability had its place. In general, the experts have been working on integrating sustainability into existing courses, e.g. into a course on computing and society. Sustainability has also become a part of projects. One of the experts talked about courses dedicated to teach about sustainability and IT that she had developed with her colleagues. Section 4.2.2 provides details on the experts' views for how to implement sustainability education in computing.

A challenge when developing sustainability education is faculty competence, which is also indicated by the faculty's reactions that sustainability is not their concern. CS faculty is often used to dealing with numbers or statistics, so a response could be to provide them with numbers or statistics on climate change, sustainability and computing. However, there are also faculty who are keen on teaching about sustainability, that miss an understanding of how sustainability and computing can go together. One of the experts said that sustainability education for CS students, while being mandated by the head of the university, was outsourced to the School of Architecture and Built Environment. At that time, the expert was a part of starting a research group within the field of IT and sustainability and developed education on sustainability for students enrolled in a media and technology program. Once the decision had been made to outsource education, it has then been difficult to get responsibility back. The experts argued that sustainability education should not be left to others and that everyone needs to engage if we are to succeed with the sustainability goals. One of the experts made an argument against developing separate centres that teach about sustainability, but rather to have a dialogue with each institution about what sustainability can mean. Currently, there may only be sole individuals with sustainability interests and competence and there is a risk that what has been established at one institution through these individuals disappears when those individuals leave the department. An important question that emerges from this research therefore is how to built competence among faculty and what competencies are needed.

Student reactions is another theme that was brought up by the experts. While students in general are found to be positive and demanding to learn about sustainability and IT, the experts also reported about problematic attitudes, that the students are not interested to learn about or question sustainability. The expert offering courses focusing on sustainability and IT said that the students mostly embraced the content. However, few students applied to the non-compulsory courses.

> One difficulty we have relates to students – the best students typically don't opt for a [sustainability] program such as ours, and there are few opportunities for students to take electives in this area. It is usually academically weaker students who opt for our program.

The problem of few students choosing sustainability classes has been described as a matter of disciplinary identity [109, 110]. However, this may be changing as the awareness of sustainability increases.

The experts talked about challenges to find spaces in the curriculum to teach about sustainability. Making space for sustainability education is a matter of priority:

> We decide on an arbitrary amount of time and we need to decide on an arbitrary selection of stuff. So the argument that you cannot possibly lose this particular thing in order to put sustainability in is nonsense to me. [...] Actually, it's about rethinking how we're teaching. [...] We are on this great educational journey to develop systems for social, ecological improvement and regeneration.

Addressing sustainability is urgent, humanity is facing a crisis according to the experts. One of the interviewees stated that he realised how complex sustainability is. Learning about climate modelling and computational models of the climate system is also challenging as it requires advanced competencies from different disciplines:

> Climate science itself has a very steep learning curve, essentially, you need an undergrad degree in, if not physics, at least something close, you need all the applied math numerics, you've got to learn computational fluid dynamics.

If teaching about climate models is too difficult, a solution could be to focus on the broader impact of technology on sustainability. Suggestions for the implementation of sustainability in computing education are elaborated on in the following Section.

4.2.2 Experts's views on the Implementation of Computing and Sustainability Education. In terms of strategies to implement sustainability in computing education, several of the experts argued that we need to reimagine the education as a whole instead of incorporating sustainability into education or fixing it.

> [I think, we need] to take a step back and reconsider the whole educational program, like the whole university. [...] Like why should we integrate stuff? Like piece meal? What would it change, really, but on the other hand, making it like turning it upside down and starting with sustainability? There's a long way before we come there, because it's going to question so many things, in not only the university structure, but also in society at large, like economical systems, what are the goals that we're striving for? Why are we even teaching people these things? Why should you have a higher education? And what are you going to work with when you come out in society?

There are however ways to teach about sustainability also in the existing education system. We identified five strategies to integrate sustainability into CS education from the interviews. One approach of incorporating sustainability into existing courses is through re-contextualising existing content or assignments, making assignments relevant for sustainability. For example, a course on data analysis or data mining could include an example of how data analysis can be used to make a city more sustainable. Sustainability could be addressed in the advanced-level courses and less so in the lower-level course. In that case, one strategy would be to push down the content into the early-level curriculum. Disciplinary structures could be another source of inspiration, e.g. the division of hardware and software. Sustainability education could be developed thinking about how sustainability can be understood in these different sub-fields. Another approach to developing sustainability education is to ask the students about their ideas and interests. Students today are worried, making their voice heard in protests, so educators should open up for discussions of how to develop education. Almost all experts emphasised that sustainability shouldn't be singled out into a separate course on sustainability. However, one of the experts argued that it is actually valuable to have a course dedicated to sustainability and IT.

> We can see that the students really, really engage with the subjects. We've had students come to us afterwards, like almost one half asked us "Should I change my career?" after taking the course. It's because we don't shy away from difficult subjects, we're reading things from the IPCC reports, we are reading the planetary boundaries, we're discussing population growth, we go into peak resources in general and peak oil in particular, we go into energy, and the kind of energy that we use. So, I mean, we go head on with many difficult questions. And I think that is important to kind of have a grounded understanding of the problems.

As argued in Section 5.2.1, when developing strategies to make students learn, we should also develop strategies to educate faculty.

The experts argued that the students should gain an understanding of sustainability as a complex and inter-disciplinary topic in order to be able to contribute to the sustainable development of our society. Examples mentioned by the experts were the difference between weak and strong sustainability models as discussed by [14, 66], the relationship between sustainability and climate change, as well as incremental versus transformative change.

> If we wish to transform ourselves in society, [. . . students need to learn about] social ecological restoration over economic justification, transformative system change over small steps to keep business as usual, and so on. [Having classified all of our capstone projects, we have seen that] most projects, even with me as Head of School, most projects do not even come anywhere close to a weak sustainability position, they're still very much in an unsustainable position.

The students also need to learn about the connection between sustainability and technology and they need to be prepared to battle climate change and deal with an uncertain future.

> [The students] are facing a future in which we're going to be continually battling the impacts of climate change, you know, extreme weather events, [. . .] I think it's fairly easy to predict over the next couple of decades, several major cities become uninhabitable around the world. We're potentially talking government instability, and so on. And meanwhile, we're we're busy trying to try to navigate this transition of fossil fuels as fast as possible. So we need a set of students who are much more resilient, much more dynamic, much more entrepreneurial, because they'll have to not only invent the technologies that get us out of this, but they'll have to invent the organizational structures that get us out of this.

The experts also gave more concrete advice on what should be learnt that could be used to develop competencies that consist of attitudes, skills, and knowledge [51]. Students should have a general disposition: They should be critical, reflective, taking responsibility, thinking holistically, and not just comply with top-level orders. Students need to learn how to find out about their foot- and handprint (actions towards sustainability), they need to learn asking questions such as "Why?", "What do we really need this product for?", "What problem are we actually solving?", and we need students to see opportunities to use those skills. The students should develop a sustainable behaviour and hopefully apply that also in their careers. What happens when the students are told "stop mucking around, we are here to get this job done!", in their career? One of the experts saw this as a more difficult question than actually supporting the students to develop the skills.

The students should learn to analyse the impact of a system, e.g. understanding the first and second order or indirect impact [66]. As a part of understanding the impact of a system, a student should learn systems thinking as is e.g. described by Easterbrook [14] in his article "From Computational Thinking to Systems Thinking". The students should learn to consider the totality of the systems. Lifecycle analysis would be another way to understand the impact of a system.

The students should engage in debates and thereby learn to address problems from many different angles. Computing education has had a focus on problems, but addressing dilemmas would be more suitable for sustainability education [14].

Students should engage with values [75] and should learn about values that are more suitable to achieve sustainability. However, as educators we are not in a position to tell the students what to do. Students need to be dynamic, not only developing technologies but also new organisation forms for societal transitions. For that, we should support the students to gain new kinds of entrepreneurial skills:

> We're training them [the students] for careers [...] either in one of the large Silicon Valley style companies, who as far as I'm concerned, [are] more and more part of the problem than the solution at the moment. Or we're training them to build their own startup companies, to make that first billion dollars, sell the company, you know. I'm thinking now we've got to flip that, because the most likely thing that entrepreneurial students in the future will be doing is starting either nonprofit organizations or organizations that build in so shortly, they might build a technology, and it'll be profitable, but they'll be much more like the B corporation tax style model the triple bottom line style model, a company that balance profitability with their social environmental impact. But we don't train them in any of that.

The experts more generally pointed out ethics to be important to learn for the students. To prepare the students to become sustainable practitioners, education needs to handle failure in more constructive ways. Being open about mistakes was seen as a step towards more sustainable solutions.

The experts pointed to several resources, literature and other resources such as conferences, that we list in Appendix C. They also pointed to resources that would be useful to advance sustainability education such as repositories of assignments or MOOCs.

4.2.3 Experts views of the current status and hopes for the future. "Dire", "immature", "awefully bad" were words used to describe the current situation of sustainability education in computing.

> [The current situation is] dire. We are still at the position where it's mostly one or perhaps two people per

> institution doing it as their hobby. There's very few people who do sustainability, sustainable education and computing for sustainable education.

There is a lack of reflection on the problems that are being solved, a lack of the question "why" in computing. We are lacking knowledge on sustainability and IT and too little knowledge is being generated both in computing and computing education. The solutions being developed are not scalable. Decisions and negotiations take a long time, while technology is developing quickly. Sustainability can feel like an "add-on", for a smaller group of students.

On the other hand, the experts expressed hope. Experts said that they feel "it's bubbling", e.g. companies are getting more aware of sustainability issues, many universities are developing guidelines and new programs, students are demanding sustainability education. Asking the experts for their hopes and vision for the future, several experts expressed that they are hoping for radical changes, for a cultural shift.

> My ultimate hope is some kind of revolution, that we don't have to integrate sustainability, but sustainability becomes the core tenant of all education, that all education is about how do we make a better society [. . .] that is more just and safe.

Changes need to happen fast as is expressed in the following:

> If we had enough time, you know, if you take a 50 or hundred year period, we can easily make the switch from fossil fuels to 100% renewables. The problem is we don't have enough time. So my hopes for the future is that we speed up all of these changes we're trying to make so this cultural shift happens faster. [We need to] start changing the way that we're educating students faster so that even within the next few years, we're starting to produce students that understand the problem and have the skill set needed to tackle it.

Education and research on education were seen as important by the experts to achieve sustainability. To build up competencies, repositories were seen as valuable.

5 WORLD CAFE

5.1 World Cafe Methodology

To understand the lack of literature in CS Education on climate change, we wanted to understand the values that framed this discussion. The World Cafe differs from brainstorming, delphi, or focus groups in that it fosters dialog across small groups and generates actionable knowledge in conversations that matter [69].

In order to explore the views of the peer community, the World Cafe was hosted during lunch at the ITICSE'19 conference. Fouché and Light [48] explored this approach to gather research for social work and as a way to use cross-pollination of ideas through evolving rounds of information exchange. In the words of Brown and Isaacs [69], the creator of this structured event, "... people often move rapidly from ordinary conversations ... toward conversations that matter, fostering dialogue in which the goal is not only thinking together, but also creating actionable knowledge", while Pamphilon, Chevalier and Chevalier [103] emphasize the benefit of involving participants in authentic discussion.

The World Cafe is a series of iterative conversations based on seven design principles [49]:

(1) Setting the Context by paying attention to the context, purpose and parameters.
(2) Creating a Hospitable Space that feels safe and inviting to facilitate creative thinking, speaking, and listening.
(3) Exploring compelling and authentic questions that matter.
(4) Encouraging Everyone to contribute their ideas and perspectives.
(5) Connecting diverse perspectives to increase the possibility for surprising new insights.
(6) Engage in shared Listening for themes, patterns and insights.
(7) Sharing the collective discoveries.

A self-selecting group of approximately 25 CS education practitioners attending the ITiCSE 2019 conference in Aberdeen sat down to join the World Cafe at one of five tables, joined by one or two of the authors of this paper. Whilst a few knew the topic of the discussion in advance, the majority of participants joined purely on the basis of there being a place to sit during lunch - and thus were unaware of the subject material that would follow.

At each table, two questions were discussed. The first was "Imagine the world of 2030. . . What are the challenges our CS graduates will face?" — the year 2030 was selected due to the IPCC's 2018 recommendation that drastic reductions in our CO2 emissions are implemented by this date. This set the scene for the second question, which was used to focus the conversation towards how we might tackle the inclusion of climate change in the CS curriculum. The second question was different at each table, to ensure a broad coverage of thoughts and ideas about how to include climate change in the curriculum, how to include it at module level, where to find information to assist, what resources or support are required, and ideas for assignments.

The questions used at each table were:

- 1. Imagine the world of 2030
  - What are the challenges our CS students will face?
- 2a. How do you think sustainability / climate change should be included in CS curriculum as a priority?
- 2b. How might you include sustainability / CC in any courses / modules etc.
- 2c. How would you learn about ways to address climate change in CS education, where might you look?
- 2d. What resources / support do you need to address climate change in CS ?
- 2e. Faced with the charge of addressing climate change in your course/module, what assignments might you develop for students?

The questions were written on a large paper that was lying on the table. Coloured marker pens were provided for the participants to take notes. The members of the working group that were sitting at the table were also taking notes on what the participants said. They also engaged in the discussion, largely in a role to keep the conversation moving forwards, or to elaborate on topics that were brought up.

The World Cafe notes and interview data were analysed in a thematic analysis [18]. The analysis of the second questions was inductive, with the following themes emerging from the discussions; barriers to overcome, strategies to implement change, ideas for implementation, and resources that could assist CS educators.

5.2 World Cafe Results

5.2.1 Imagine the world of 2030. When imagining the world in 2030, some of the tables did not immediately raise the issue of climate change - instead choosing to focus on other issues such as sociological and economic concerns, technological advancements leading to great change in our lives, risks of digital warfare, a shift in the way formal education is taught, and autonomous vehicles and robots being present. One table did not raise climate issues until prompted by the facilitator.

It became clear that whilst climate issues are generally perceived as important, they may not be at the forefront of people's minds when thinking about the world of tomorrow - and a handful of people were still sceptical about the issue. The climate-related issues that were raised included wild weather, sudden winds, tornadoes, climate migration, food scarcity, water shortages, flooding and resource scarcity.

5.2.2 Requirements of future CS graduates. A recurring theme was that there would be a requirement for graduates of the future to be working across disciplines, rather than simply rooted in Computer Science. An interesting vision was that of the "digital polymath" — a CS graduate who would be able to connect people, ideas and theories across multiple disciplines like "Leonardo Da Vinci of the future".

It was also felt important that computer scientists should be responsible for helping to change people's perspectives on climate change, by providing evidence to support the science, and that students need to have a good understanding of the impact of what they do/design/make upon the world.

Other areas people felt were important included autonomous vehicle development, technology in medical sciences, surgical robotics, nanotechnology and security.

5.2.3 Barriers to overcome. A frequently cited barrier to adoption is the need to convince people (instructors and students) that climate change is real, and human caused; part of the challenge here is fighting the misinformation that has spread through social media.

Even if convinced about the reality of climate change, instructors and students must also be convinced that it belongs as a topic in the CS curriculum; a balance must be drawn between it and other priorities.

The scale of climate science as a topic in addition to computer science was cited by several as a barrier to adoption within Computer Science.

Access must be provided to instructional materials, including climate data, and instructors must be empowered to teach the material.

Computer Science culture is also cited as a barrier. Experts such as those within the Computer Science faculty are not necessarily setting a good example, given their consumption behavior. There can also be a tendency to think of technology as the solution, when it could in fact be part of the problem.

5.2.4 Strategies. It was stated by one of the participants that teachers should not be preachers – this dynamic can create a negative attitude among students. That may have been in many of the respondents' mind as many of the suggested strategies were focused on letting the students discover the problem on their own. One of the most frequently suggested strategies was the use of real data in assignments as a way to make students aware of the seriousness of the situation. A few suggested ideas for convincing skeptical students including labeling the data after students had used the data to ensure that their analysis of the results were not biased by preconceptions. It was suggested that providing repositories of such data, along with suggestions for how to use the data, would facilitate integrating such use into the classroom. The use of simulations and models could also be used to educate students. One novel idea was the use of VR to show students what the future would look like given various scenarios. Other suggestions included bringing external speakers and stakeholders into the classroom to discuss problems that the students would then work on.

A general theme that emerged was that whilst it may be easiest to introduce a module on climate science, given the scale of the problem the most appropriate way to deal with this may be to introduce elements in different modules throughout the curriculum.

Not all suggestions were positive. Some participants suggested that this material belongs in other areas of education, not in CS. Others suggested that students will think this material does not belong in CS. Participants also indicated that the system cannot be changed from within, that courses are already too full, that there aren't teachers to deliver this material and that departments aren't motivated to change the curriculum. Finally, not surprisingly perhaps, some stated that they hadn't given this question much thought.

5.2.5 Ideas for implementation. Several interesting suggestions were made for ways in which the strategies above could be implemented. Some of these focused on content that should be included in the course, but perhaps the most interesting and useful elements that came from this discussion were the seeds of ideas that could be developed for use in class exercises and/or assignments.

These ideas were centred around themes like; analysing environmental data (e.g. from NOAA) to increase awareness and convince the sceptics; developing more efficient hardware and software; building tools to help convey the climate impact of computing to a wider audience; simulating simplified climate models; developing the use of VR and AR to simulate the future effects; performing calculations such that students understand the climate impact of their own, and others' designs; and image processing to quantify the change in the world over time (e.g. deforestation).

A commonly recurring theme (possibly due to its popularity at the time of writing) was that of analysing the climate impact of "Bitcoin" mining, and perhaps an interesting idea is that of comparing the energy consumption of an operation (e.g. a data scraping algorithm) to that of a typical home.

5.2.6 Resources. Ideas for resources generally centered around places that good quality, reliable datasets could be found, and suggestions were made including NOAA, satellite imagery from NASA, Google Maps and open city datasets. Participants were keen that an open repository was made available to support CS educators. As a result of this, the authors of this paper used the suggestions from participants to search for resources online, and compiled a list of links to relevant open datasets and teaching materials relevant to the inclusion of climate change in the CS curriculum (Appendix C).

6 SUMMARY DISCUSSION

The results of all three investigations demonstrate that the integration of climate change into Computer Science education is at an immature stage. Significant effort is needed to prepare computing professionals of the future for their roles in mitigating the complex and unpredictable costs of anthropogenic climate change.

While issues related to S/CC are widely addressed in the general body of computer science research literature, there is comparatively little research in how to incorporate S/CC into the computing curriculum, nor in how to define or assess related learning goals. A number of papers acknowledge the importance of the topic, but more as a "call to action" than a proposed way forward. Very few papers describe specific interventions that incorporate climate change and environmental sustainability. When S/CC is addressed in a course or project, it is often within a broad context like "humanitarian computing", which though laudable is too general in nature to address even basic learning goals concerning climate change. We have identified a clear need to appropriately categorize such research. In the absence of a categorization such as the one we have proposed (Table 1), it is challenging to access relevant publications.

Interviews with experts at the intersection of computing and S/CC underscore the isolation in which several of these experts are working. However, these experts are advancing sustainability education through research and education development and are establishing platforms and strategies to connect and exchange ideas. There is a large group of researchers discussing sustainability at CHI, the largest conference in the field of Human Computer Interaction, and sustainability education is discussed at the conference called "ICT4S". Those conferences could serve as resources for less experienced faculty interested in engaging with and learning about the challenge of S/CC in computing education.

The interviewees report that universities are developing strategies to address sustainability and sustainability education, while progress within computing institutions is viewed as slow. This is also reflected by the reactions of the computing education community in the World Cafe. Being prompted to think broadly about future challenges in computing at our World Cafe sessions, the Cafe tables raised issues including sociological and economic concerns, technological advancements leading to great change in our lives, risks of digital warfare, a shift in the way formal education is taught, and the presence of autonomous vehicles and robots. S/CC was not necessarily raised as the first issue, and at one of the Cafe tables climate issues were not discussed at all until prompted by the facilitator.

The experts we interviewed stressed that sustainability and computing is a complex, rather new research area and they pointed to different strategies to develop education on this topic. Several experts pointed out that the education system as a whole needs to be re-thought, but they also pointed to resources that can be used with less effort. Our experts cited literature indicating that in order to fully understand the contributions of IT to the solutions and also problems in S/CC, direct, indirect, and systemic effects [102] need to be taken into account. Technology needs to be developed purposefully, which requires a holistic understanding of technology in the larger ecologic, economic, and social system. Systems thinking is a valuable tool to achieve such a broader perspective on system development, which however is not part of the computer science curriculum yet [39]. Appendix C contains a collated list of suggestions, seed ideas and resources that we have collected from the expert interviews and the participants from the World Cafe, with the aim of giving inspiration to CS educators at all levels within the university structure who would like to address the issue, but may not know where to start.

Our experts reported that while a younger generation of computing educators is willing to address S/CC in their courses, they are often lacking the competence to do so. Many of our World Cafe participants said that they were aware of the issue, that it was urgent, but that they did not know what to do. They indicated that they would benefit from incentives, resources, peer support, and additional training in order to incorporate the issue into their curricula. As sustainability and climate change is a complex matter, faculty need to get opportunities to develop competencies in those areas. Just as we would not expect teachers lacking programming competence to teach programming, we cannot expect teachers without competence in sustainability education to teach about sustainability. Likewise, we cannot just expect students to deal with sustainability assignments without supporting students in developing the necessary competencies.

However, some of the participants of the World Cafe thought that climate change does not belong in the CS curriculum and that it should be taught in other disciplines. Some of these educators elaborated that they did not feel prepared to address this issue; others did not see the role that CS plays in climate change, and some held positions we would call climate change deniers. This might suggest that some CS educators need better resources and example curriculum. The group that does not see the connection between CS and climate change would benefit from resources that draw out the relationships of CS to climate change and that CS has a vital role to play in monitoring, mitigating, and dealing with the effects of climate change.

We have in this work identified a disconnect between the urgent need for action identified by the IPCC [68], and CS education and its current development prospects. CS faculty has little experience with teaching about sustainability, sustainability and climate change get little or no attention in the CS curriculum. Research on sustainability is sparse within CS education research and overall, the community of CS educators has not embraced sustainability as an important topic yet.

7 CONCLUSION

We conclude by summarizing our key contributions and by suggesting further work.

7.1 Contributions

In our study, we established two major research objectives:

> **Objective 1:** to make a compelling case that incorporating the study of sustainability in general, and issues of climate change in particular, into computing education, is both appropriate and urgently needed.

and

> **Objective 2:** to discover and share the work already being done in this regard by experts in this field, and thereby promote and facilitate a more widespread acceptance and implementation of best practices.

Our expert interviewees agree that a compelling case seems to be easier to make now because (1) there is greater general awareness and attention to S/CC issues, (2) some institutions are acknowledging the climate crisis and are developing institutional strategies, and (3) there is a trend away from training students for specific careers, and toward providing entrepreneurial abilities to work on a range of dynamic problems grounded in real-world needs. We have, however, identified a substantial lack of attention within the CS educational research community to these issues, underscoring the urgency of further consideration by the computing education community.

We observed that the relevant existing research contains studies with various degrees of focus on S/CC and that so far the connections to computing have been mostly indirect. Input from World Cafe participants supports the tendentious reliance on an indirect connection in which computing serves as an enabler for stakeholders in other areas to conduct activity benefiting sustainability and the climate. The experts are assertive, arguing that sustainability can and should become a central issue within computing, and could in fact be a guiding principle for education at large.

Learning about enabling technologies is only one response to tackling climate change. Another approach is a climate entrepreneurial mindset that includes not only the development of technologies but also of new kinds of organizations suitable to address climate change effectively on a large scale. Our work in regard to our second objective to discover and share related educational materials has revealed a nascent subfield of computing education with much left to develop. We have identified a range of implementation strategies from experts and published work. Some experts believe that integrating sustainability into the present educational framework is impossible and that a complete reimagining of the purpose of education is necessary. Others are attempting a range of incremental approaches: new degree programs focused on leadership for change; certificate programs/minors in sustainability; infusing sustainability throughout multiple courses within the existing curriculum.

Our literature search reveals an interest in incorporating S/CC into computing education, but primarily at an aspirational level, without many tangible results to date. We made the first steps towards classifying the literature in a way that might help capture and illuminate the diversity (and lack) of research in the area as well as help practitioners and researchers navigate the existing research.

Experts agree on the importance of systems thinking, a holistic and critical understanding of computing, as exemplified by Easterbrook's article "From Computational Thinking to Systems Thinking" [14]. Specifically, students should develop an understanding of the *totality* of a system and the place of ICT within it, including the first and second orders or indirect impact [66] of ICT, and the *lifecycle* of ICT within the larger lifecycle of the system.

7.2 Further Work

In the context of increasing public awareness of issues related to S/CC, we see the emergence of national and institutional policies mandating sustainability education and the articulation of sustainability-related graduate attributes, backed with institutional structures to support its development. However, several experts believe that computing departments are comparatively slow in increasing their educational focus on S/CC issues. We discovered how little had been done in response to climate change in our community in contrast to the initiatives by many universities and other disciplines who have done more work in this area. We see a gap between research literature, a small body of expert practitioners and researchers, and a popular and university mandate on one side, and the disconnect of faculty who feel they do not have the knowledge and support they need to act on the other side.

We have identified two significant challenges, along with possible steps towards solutions.

7.2.1 Challenge 1: The lack of research in teaching issues of S/CC within the computing curriculum and the challenge for CS educators to find relevant research.

- Build on research identified in Section 3.2, for instance, by evaluating best practices proposed by experts across a variety of educational contexts.
- Possible solution: Establish competencies and attitudes that both computing instructors and students must have to engage in S/CC work.
- Extend the classification scheme presented in Table 1.

7.2.2 Challenge 2: The belief that sustainability has nothing to do with computing or concerns that an educational emphasis on S/CC would be inappropriately construed as supporting "techno-utopia solutions", or opinions that there are more pressing issues (e.g. autonomous vehicles, digital warfare) that computing education should focus on. To change such beliefs into a recognition that the need to address climate change is urgent and of existential importance, that computing graduates can play an important role in developing effective solutions (and resist harmful practices), and to begin addressing the critical lack of computing graduates with the relevant attributes through educational initiatives requires a sustained effort in building faculty competence.

- Identify the requisite baseline domain knowledge that faculty need to teach/discuss specific topics related to S/CC, and translate these into appropriate training resources. Clearly, the need for these resources is not restricted only to computing departments. Hence, such efforts are best handled at the national or institutional/multi-institutional level.

- Establish a repository as a resource for computing educators who wish to get involved. We have identified several strategies for implementing the inclusion of climate change into the CS curriculum (Appendix C.1). We have also proposed seedlings of ideas for assignments or class exercises (Appendix C.2.2) and have set up a repository to facilitate sharing and access on GitHub at http://climatechangecurriculum.org/.
- Train faculty coming from typical computing backgrounds in a basic understanding of physical models of climate change and systems thinking.
- Students should engage with values [75] and should learn about values that are more suitable to achieve sustainability. Students need to be dynamic, not only developing technologies but also new organization forms for societal transitions. For that, we should support students in gaining new kinds of entrepreneurial skills.

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A APPENDIX - INTERVIEW SCRIPT

We are a group of researchers aiming to investigate how sustainability can be incorporated in computing education. We are conducting several interviews and collaboratively review the literature, gather, assemble and compile resources, *such as sample syllabi, case studies, and coursework* that address sustainability and climate change in the context of computer science education. We will work together to think through how best to equip our students with the tools needed to adapt to a world shaped by climate change. The results will be published in the companion to the proceedings of ITiCSE.

(1) We have chosen to talk to you because we perceive you as an expert (forerunner) when it comes to implementing sustainability in computing education. What do you think about our perception, can you please tell us about your experiences with implementing sustainability in computing?

(2) Please tell us about your environment, who and what have been an important support in your work? (*culture, work, institutional mandate, people, institutional learning outcomes (ILO),...*)

(3) Have you experienced obstacles, e.g. people that question your activities, goals, or visions and how have you worked with these obstacles or people?
   - (a) How do you respond to people that there is no or little place or not enough time for sustainability education in computing, e.g. that computing is only about algorithms and their implementation?
   - (b) Some people are not incorporating sustainability in education. Do you have experiences with those people and know how they are thinking, or perhaps the reasons behind their difficulties?

(4) What is your view/ideas on how sustainability can be incorporated in computing?
   - (a) What do you think is important for students to learn? (*knowledge, skills and attitudes of students*)
   - (b) Do you think it is important to distinguish between sustainability and climate change?
   - (c) What ideas do you have for certain topics or courses? (*instead of relegating/dedicating an entire course*)
   - (d) The introductory programming course, also called CS1, is a course that is taught at many institutions all over the world and that is most researched in the computing education research community. Do you have recommendations for how to incorporate sustainability in that course?
   - (e) Are there any particular methods or resources that are particularly useful? Can you share resources, material, examples, course syllabi? (*possible use of / collaboration with organizations/expert and what is published / unpublished Are there unpublished/ uncirculated resources that you are using that you would like in particular?* ***Note to the interviewers: make sure you can access the material to describe it in the paper***)

(5) How would you describe the current status of sustainability education, in computing education in particular? (nationally, globally)

(6) What are your hopes and wishes for future education in computing?
   - (a) What will computing education look like in 10 years from now?

(7) *Wrap Up:* One last question - Thank you for all your time - What other thoughts do you have about sustainability and climate change in higher education?
   - (a) What would you like to add?
   - (b) Is there anything you like to qualify in your answers?

B APPENDIX - INTERVIEW CODES

1. Changes over time
   1. Changes in the public, media
   2. Changes in students
   3. Changes in faculty
2. Cooperation across universities
3. University-wide initiative (some of them being top-down initiatives)
   1. University general sustainability strategies / image to the public
   2. Support Structures:
      1. Directives and initiatives to integrate sustainability into education

    2. Staff development: Pedagogical courses (& maybe an incentive to take those courses)
    3. Teaching structures, e.g. University-wide learning outcomes, University-wide sustainability certificate programme
    4. Organisations, e.g. rectors, centers, commissions etc.
4. CS Institutional-wide initiative:
  1. Slow progress: Many don't teach sustainability, resistance, outside the course
  2. Support structures:
    1. Interdisciplinary division,
    2. research environment,
    3. supporting centers
    4. Teaching structures, e.g. course(s), concepts, learning outcomes, etc.
    5. Financial support
  3. Faculty Competence (includes attitudes):
    1. Perceptions of IT & Sustainability: sustainability is seen as not technical enough ("CS or Engineering has nothing to do with sustainability")
    2. Climate deniers
    3. Limits and opportunities of Academic Freedom
  4. Student Reactions: Few students,
  5. Other Challenges and Responses:
    1. Curriculum, e.g. challenge finding space
    2. Who?, e.g. Outsourcing sustainability education!?
    3. Classroom equipment
5. The importance of a dedicated expert
6. Lessons learned
  1. complexity correct. This was mirrored by Jaris experience. There were several misconceptions that have been challenged since getting involved in CS and sustainability and as a result his perception about the topic has "evolved" in his own terms.
  2. Crisis, urgency.
  3. Perhaps don't teach CS students about climate modelling
  4. Focus on one computing discipline to implement sustainability instead of incorporating it in every subject, otherwise you will lose focus on the greater goal and experience difficulties in implementation.
  5. Case against using singular entities, centers
  6. Special disciplinary coursework
  7. Resource dependencies for initiatives
  8. Living campus (theme B?)

Experts' views on the implementation of computing and sustainability education:

1. Strategies: Ways to think about and advance the implementation of sustainability and computing education.
  1. Reimagining the education as a whole
  2. Incorporating / Fixing / Grafting:
    1. Incorporate sustainability into existing courses, e.g. through more relevant assignments (re-contextualisation)
    2. Develop new courses on Sustainability and ICT
    3. Pushing down content into the early curriculum
    4. Based on disciplinary content / structures / the department at university- In France for example the focus is on networking and making the process more efficient (as that was the department's area of specialty). In Jaris institute it was about the indirect effects of software (given that he is working in the software engineering domain).
    5. Teach sustainable thinking (computational thinking was fashionable years ago, why not sustainable thinking). Change the student mentality so they can be more involved.
  3. Train the professors!
  4. Change students attitudes about sustainability
2. What the students should learn
  1. About sustainability:
    1. difference between weak and strong sustainability models
    2. incremental versus transformational change
    3. Relationship between sustainability and climate change
  2. The connection between sustainability and tech
  3. Prepare them to battle climate change
  4. Prepare them for an uncertain future
  5. Values
  6. Concrete competencies (knowledge, skills, and attitudes):
    1. General: Being critical, reflective, taking responsibility, following values, holistic thinking, understanding impact
    2. Systems thinking
    3. Life-cycle assessment
    4. Addressing dilemmas / Looking at problems from many angles
    5. Reflect on the totality of the system (e.g. when learning programming)
    6. Entrepreneurial skills for an uncertain future, battling climate change
    7. Ethics
3. How to teach
  1. Non-normative ("can't tell them which attitudes to have" - Elina) / dealing with value-ladeness
  2. Have Debates
  3. Constructive work with failure (instead of hiding them)
  4. Chain saw metaphor, parable?
  5. Footprint and Handprint metaphors
4. Resources
  1. Literature
    1. Systems thinking: Easterbrook, Donella Meadows Leverage points, Systems Thinking Playbook (Linda Booth Sweeney)
    2. Economy for the common good (Christian Felber book)
    3. Common cause handbook, values (Reference Knowles)
    4. Karlskrona Manifesto (Becker et al.) about sustainable design
    5. ACM code of ethics
    6. Machine learning, AI, data science and climate change (Yoshua Bengio)
    7. Technology and climate change paper (Brett Victor)
    8. Hazas, M. & Nathan, L.P. (eds.). (2018). Digital Technology and Sustainability: Engaging the Paradox. Routledge

2. Others, such as conferences
   1. ICT4S, education workshop & its blog
   2. Open MOOC (Jari said he'd be interested I'm creating something like that)
   3. Living Campus initiative
   4. CHI - largest single group of people in cs sustainability
   5. ACM Limits
   6. Sustainable Lens (http://sustainablelens.org/) 392 videos, ~100 in cs sustainability

Experts views of the current status and hopes for the future

1. Status
   1. "Bubbling", e.g. companies getting more aware
   2. Immature
   3. Awfully bad
   4. No reflection on the problems being solved (lack of why)
   5. Research going on
   6. Non-scalable solutions
2. Vision
   1. a revolution, fast cultural change
   2. All education is about making society better
   3. Education and research of technology blogg
   4. constructive science
   5. Repositories will exist

C APPENDIX - RESOURCES

C.1 Resources Derived from Experts' Interviews

C.1.1 Literature.

- Software Engineering for Sustainability: Find The Leverage Points! Penzenstadler, Birgit and Duboc, Leticia and Venters, Colin C and Betz, Stefanie and Seyff, Norbert and Wnuk, Krzsztof and Chitchyan, Ruzanna and Easterbrook, Steve M and Becker, Christoph [108].
- Leverage Points. Meadows, Donella [95].
- The Systems Thinking Playbook: Exercises to Stretch and Build Learning and Systems Thinking Capabilities. Sweeney, Linda Booth and Meadows, Dennis [133].
- The Climate Change Playbook: 22 Systems Thinking Games for More Effective Communication About Climate Change. Meadows, Dennis and Sweeney, Linda Booth and Mehers, Gillian Martin [94].
- Change Everything: Creating an Economy for The Common Good. Felber, Christian [46].
- The Common Cause Handbook - A Guide to Values and Frames for Campaigners, Community Organisers, Civil Servants, Fundraisers, Educators, Social Entrepreneurs, Activists, Funders, Politicians, and Everyone in between. PIRC [111].
- Sustainability Design and Software: The Karlskrona Manifesto. Becker, Christoph and Chitchyan, Ruzanna and Duboc, Leticia and Easterbrook, Steve and Penzenstadler, Birgit and Seyff, Norbert and Venters, Colin C [14].
- Tackling Climate Change with Machine Learning. Rolnick, David and Donti, Priya L and Kaack, Lynn H and Kochanski, Kelly and Lacoste, Alexandre and Sankaran, Kris and Ross, Andrew Slavin and Milojevic-Dupont, Nikola and Jaques, Natasha and Waldman-Brown, Anna and Luccioni, Alexandra and Maharaj, Tegan and Sherwin, Evan D. and Mukkavilli, S. Karthik and Kording, , Konrad P. and Gomes, Carla and Ng, Andrew Y., and Hassabis, Demis and Platt, John C. and Creutzig, Felix and Chayes, Jennifer and Bengio, Yoshua [118].
- What Can A Technologist Do About Climate Change? Victor, Bret [140].
- Digital Technology and Sustainability: Engaging the Paradox. Hazas, Mike and Nathan, Lisa [60].
- ACM code of ethics[5].
- UN Sustainable Development Goals[6].

C.1.2 Other Resources such as Conferences, Initiatives, and Blogs.

- ICT4S Organization and Conference[7].
- CHI[8].
- Otago Polytechnic Living Campus Initiative[9].
- ACM SIGCAS Conference on Computing and Sustainable Societies[10].
- ACM Limits[11].
- Sustainable Lens Blog, features 392+ videos, 100 on CS sustainability[12].
- Computing for Sustainability Blog[13].

C.2 Resources Derived From World Cafe Session

C.2.1 Strategies for implementation.

- "Teachers should not be preachers" - To convince doubters, present the data, and allow students to draw their own conclusions.
- Encourage interdisciplinary work between CS and other fields that are more "climate conscious".
- Develop assignments to convince the doubters with data, or challenge cognitive bias by anonymising data.
- Bring in external stakeholders & guest speakers - e.g. NGOs, climate scientists etc.
- Embed climate change across modules throughout the curriculum, not just a single optional module.
- Provide a repository of suitable datasets to staff across the department.
- Employ a "Climate Champion" to help other staff implement climate change in their individual modules.
- Lead by example - e.g. display the CO_2 emissions of the University in real-time.
- Implement training courses for staff in "how to implement climate change in the curriculum".

[5] https://www.acm.org/code-of-ethics
[6] https://sustainabledevelopment.un.org/
[7] http://ict4s.org/
[8] https://chi2019.acm.org/for-attendees/sustainability/
[9] https://tinyurl.com/yf37vsej
[10] https://acmcompass.org/
[11] http://computingwithinlimits.org
[12] http://sustainablelens.org/
[13] https://computingforsustainability.com

C.2.2 Seed Ideas for Teaching / assignments.

- Measure the power usage of running an algorithm, and calculate the CO_2 emissions caused by this.
- Calculate the climate cost of cryptocurrency mining, versus the value of a Bitcoin.
- Model the effect of sea level rise upon coastal areas.
- Model the effect of drought upon food production in at risk areas.
- Analyse the rising "price of a bar of soap" with "household income" then reveal that the underlying data is actually global temperature rise with atmospheric CO_2.
- Develop virtual reality simulations to visualise the predictions of what the environment might be like in the future.
- Analyse datasets from open resources to model trends in; CO_2 emissions, global temperature, sea level rise, forest coverage etc.
- Use NOAA data etc to look for trends in atmospheric CO_2, global temperature, sea levels.
- Open ended problems; e.g. "how can computing help to mitigate the risks of global warming?".
- Develop "Mission Impossible" group challenges to save a valuable resource that is running out, or reduce CO_2 emissions.
- Develop data visualisations to convey climate cost of common activities to the public e.g. display the climate cost of flights vs tree planting required to offset CO_2 emissions.
- Design computer architecture for low power consumption, and calculate reduction in CO_2 emissions.
- Identify how many miles an electric car must drive before the lifetime CO_2 emissions are lower than that of a petrol or diesel vehicle.
- Analyse the energy consumption and CO_2 emissions of an Apple data centre, and compare to those of a typical home.
- Develop group assignments with architecture students to model the environment of the future, and design buildings equipped for this.
- Design IoT devices and strategies with an objective to save energy (e.g. in the smart home) and calculate the global reduction in CO_2 emissions as a result.
- Develop image processing techniques to analyse satellite imagery to analyze deforestation over time.
- Develop software / apps to control device charging / operation based upon energy price from smart meter / internet data.
- Develop hurricane tracker using Stanford's assignment[14].

C.2.3 Online Resources and Datasets.

- NOAA Climate.gov - Contains resources specifically designed for teaching[15].
- Kaggle - Provides access to open datasets. Currently 41 datasets avaiable with keywords "Climate Change"[16].
- Github Open Datasets - Currently 18 open datasets listed relating to climate and weather[17].
- Hurricane Irma Tracker - Nifty Assignment by Stanford University to track Hurricane Irma[18].
- NASA EarthData - Provides satellite imagery and visualisations of realtime and historic data on fires, weather, temperatures etc[19].
- Global Forest Watch - Provides data of deforestation and forest fires[20].
- NOAA Climate Data - Online repository for climate data[21].
- NASA Climate Education Resources - Resources for educators teaching climate change[22].
- IPCC Data Distribution Centre - Data designed for climate change researchers and educators[23].
- WWF Wildlife and Climate Change Educator Resources[24].
- National Science Teaching Association - A collection of links to relevant ideas and datasets[25].
- EarthStat - Geographical datasets that "help solve the grand challenge of feeding a growing global population while reducing agriculture's impact on the environment"[26].

C.3 Introductory Sustainability Course Materials

C.3.1 Sustainability and sustainable development.

- Chat with Johan Rockström, Professor in Environmental Science at Stockholm University, and the Executive Director of Stockholm Resilience Centre[27].
- "What Is Sustainability?." - The Post Carbon Reader, Heinberg, Richard, and Daniel Lerch [63].
- St Matthew Island reindeer comic about overpopulation: by Stuart McMillen Webcomix[28].

C.3.2 Planetary boundaries and climate change.

- Planetary Boundaries: Guiding Human Development On A Changing Planet. Steffen, Will and Richardson, Katherine and Rockström, Johan and Cornell, Sarah E and Fetzer, Ingo and Bennett, Elena M and Biggs, Reinette and Carpenter, Stephen R and De Vries, Wim and De Wit, Cynthia A and Folke, Carl and Gerten, Dieter and Heinke, Jens and Mace, Georgina M and Persson, Linn M. and Ramanathan, Veerabhadran and Reyers, Belinda and Sorlin, Sverker [127].
- Living Planet: Report 2016: Risk and Resilience in a New Era. World wide fund for nature [146].

C.3.3 Global resource challenges and implications for ICT and media.

[14] http://nifty.stanford.edu/2018/ventura-hurricane-tracker/irma-assignment.html
[15] www.climate.gov/teaching
[16] www.kaggle.com/datasets
[17] www.github.com/awesomedata/awesome-public-datasets
[18] See footnote 17.
[19] https://earthdata.nasa.gov/earth-observation-data/visualize-data
[20] https://www.globalforestwatch.org/howto/tags/odp/
[21] https://www.ncdc.noaa.gov/cdo-web/datasets
[22] www.climate.nasa.gov/resources/education/
[23] www.ipcc-data.org
[24] https://www.worldwildlife.org/pages/wildlife-and-climate-change-educator-resources
[25] www.nsta.org/climate
[26] http://www.earthstat.org/
[27] https://sverigesradio.se/sida/avsnitt/595082?programid=2071
[28] http://www.stuartmcmillen.com/comic/st-matthew-island/

- There's No Tomorrow (limits to growth & the future) - A quick journey through oil formation, peak oil, energy, economic growth, and resource depletion[29].
- Why your world is about to get a whole lot smaller. Random House Canada, Chapter 1, "Redefining recovery", Rubin, Jeff [119].
- The Party's Over: Oil, War and the Fate of Industrial Societies". Parts of chapter 1 ("Energy, nature and society") and chapter 2 ("Party time: The historic interval of cheap, abundant energy". Heinberg, Richard [62].

C.3.4 *Natural resources and economic development.*

- In search of Lost Time: The Rise and Fall of Limits to Growth in International Sustainability Policy.p. 385-395, Gómez-Baggethun, Erik, and Jose Manuel Naredo [56].
- Planet Money makes a t-shirt - On the paradoxes of the global supply chains in the clothing business. Garcia, Cardiff and Vanek Smith, Stacey [139].

C.3.5 *First order effects of ICT and Obsolescence.*

- The universal mining machine. Bardi, Ugo [11][30].
- Man's need or man's greed: The human rights ramifications of green ICTs. Cramer, Benjamin [33].
- Addressing the obsolescence of end-user devices: Approaches from the field of sustainable HCI. Remy, Christian, and Elaine M. Huang [116].
- Pargman D, Wallsten B. Resource scarcity and socially just internet access over time and space. Pargman, Daniel, and Björn Wallsten [104].
- Macroscopically sustainable networking: on internet quines. Raghavan, Barath, and Shaddi Hasan [113].

C.3.6 *Important and more important: On values for transition.*

- Re-imagining persuasion: designing for self-transcendence. p.2713-2718. Knowles, Bran [75].
- Patterns of persuasion for sustainability. p. 1035-1044. Knowles, Bran, Lynne Blair, Stuart Walker, Paul Coulton, Lisa Thomas, and Louise Mullagh [76].
- Common Cause network[31].
- The Transition Network - Transition is a movement of communities coming together to reimagine and rebuild our world[32].

C.3.7 *Who is pedaling when you are watching kittens on YouTube?*

- Human Power Station - Bang Goes The Theory TV Show (58 minutes)[33].
- You and Your Slaves, Nikiforuk, Andrew[98].
- The energy of slaves: Oil and the new servitude (Chapter 2 Slaves to Energy), Nikiforuk, Andrew[99].
- Destructive momentum: can an enlightened environmental movement overcome it. Life on the brink: environmentalists confront overpopulation, 123-129, Catton Jr, W.R[25].

[29]https://www.youtube.com/watch?v=VOMWzjrRiBg
[30]http://theoildrum.com/node/3451
[31]https://valuesandframes.org/
[32]www.transitionnetwork.org
[33]https://youtu.bevPxuuB_ZBuk

C.3.8 *A design perspective on sustainable practices and energy use.*

- Coffee maker patterns and the design of energy feedback artefacts, Broms, Loove, Cecilia Katzeff, Magnus BÃěng, ÃĚsa Nyblom, Sara Ilstedt Hjelm, and Karin Ehrnberge[19].
- Eco-feedback on the go: Motivating energy awareness, Spagnolli, Anna and Corradi, Nicola and Gamberini, Luciano and Hoggan, Eve and Jacucci, Giulio and Katzeff, Cecilia and Broms, Loove and Jonsson, Li[126].
- "Mama, It's Peacetime!": Planning, Shifting and Designing Activities in the Smart Grid Scenario, Katzeff, Cecilia and Wessman, Stina and Colombo, Sara[74].

C.3.9 *Designing for collective action.*

- FeedFinder: a location-mapping mobile application for breastfeeding women, Balaam, Madeline and Comber, Rob and Jenkins, Ed and Sutton, Selina and Garbett, Andrew[8].
- HCI, solidarity movements and the solidarity economy, Vlachokyriakos, Vasillis and Crivellaro, Clara and Wright, Pete and Karamagioli, Evika and Staiou, Eleni-Revekka and Gouscos, Dimitris and Thorpe, Rowan and Krüger, Antonio and Schöning, Johannes and Jones, Matt and Lawson, Shaun and Olivier, Patrick[141].

C.3.10 *Smart resource management with digitalization in public and private.* organizations (industry guest lecture)

- Debating the Sharing Economy, Schor, Juliet[122].
- Fair Share: Reclaiming power in the sharing economy, Balaram, Brhmie [9].

C.3.11 *Sustainability at Ericsson - Using technology in smart ways to become more sustainable.*

- Exploring the effect of ICT solutions on GHG emissions in 2030, Malmodin, Jens and Bergmark, Pernilla[86].
- The energy and carbon footprint of the ICT and E&M sector in Sweden 1990-2015 and beyond, Malmodin, Jens and Lundén, Dag[87].

C.3.12 *Social sustainability and ICT.*

- A safe and just space for humanity: can we live within the doughnut, Raworth, Kate[115].
- 'Socializing'sustainability: a critical review on current development status of social life cycle impact assessment method, Chhipi-Shrestha, Gyan Kumar and Hewage, Kasun and Sadiq, Rehan [28].

C.3.13 *The split-brain experiment (activist guest lecture).*

- Deviant and guilt-ridden: Computing within psychological limits, Knowles, Bran and Eriksson, Elina[77].
- Crossroads tempered radicalism and the politics of ambivalence and change, Meyerson, Debra E and Scully, Maureen A[97].

C.3.14 *Various literature from seminar instructions.*

- Loss and climate change: The cost of parallel narratives, Randall, Rosemary[114].
- Warm words: How we are telling the climate story and can we tell it better, Ereaut, Gill and Segnit, Nat[42].

- On fairness & sustainability: Motivating change in the networked society, Joshi, Somya and Pargman, Teresa Cerratto [73].
- The Monster Footprint of Digital Technologies, De Decker, Kris [34]
- Towards an holistic view of the energy and environmental impacts of domestic media and IT, Bates, Oliver and Hazas, Mike and Friday, Adrian and Morley, Janine and Clear, Adrian K[12].
- SMARTer2030. ICT Solutions for 21st Century Challenges [53] [35]

[34]https://tinyurl.com/y6fufmt4
[35]http://smarter2030.gesi.org/downloads/Full_report.pdf