Application Document - Overview

The Center for Computing in Science Education (CCSE) aims to become an international hub for the research-based integration of computational methods in science educations. The center will:

- Develop material, approaches and study programs for CSE teaching and learning,
- initiate, support and disseminate research into effective learning and assessment methods, and
- implement practices in educations across disciplines in collaboration with key partners.

Computing has changed the practice of science: The growth in computer power over the past decades has radically changed the practice of physics and other sciences - and is expected to affect all aspects of society [1]. Problem solving using computers – *computing* – is now an integrated and central part of research, development, business and industry. To prepare students for a lifelong career, computing must therefore be an integrated part of science educations. Surprisingly, most education programs have not been updated to integrate computing.

Integration of computing will change science education: In physics nature is described using mathematics, and examples and exercises rely on solving mathematical problems. Therefore, physics and mathematics are taught in a coordinated and sequential manner. However, with only traditional mathematics at our disposal, only a few carefully selected, simplified physics problems for which we know the mathematical solutions can be solved. Unfortunately, these limitations have shaped the contents and form of the education and teaching practices, and have contributed to the view that physics has little or no relevance in the real world. Now, the growth in computing power has provided us with robust mathematical methods that allow us to solve practically any physics problem. Thus we are no longer limited by traditional mathematics. Students can learn robust, powerful and adaptable solution methods - computing methods - in which they write computer programs to solve problems using workflows similar to that of research or industry. Contents and approaches can be chosen for pedagogical or motivational reasons instead of mathematical limitations. Examples can be based on real data, and realistic and research-inspired problems can be introduced from day one. This calls for a redesign of the contents and form of the education to integrate the use of computing - opening new pedagogical challenges and opportunities.

Computing in Science Education at UiO: We have initiated a project to integrate Computing in Science Education (CSE) in a systematic and unified manner across different subjects. The goal is for students to learn computational tools as part of their introduction to mathematics and then reapply and adapt the approaches in physics and other sciences. The CSE project has had significant success based on enthusiastic individuals, strong student engagement and leadership support. We have coordinated courses in mathematics, numerical methods, and programming in the first semester to form a basis in skills and methods. Full integration of computing has been achieved in some physics courses, with changes in curriculum, learning materials, teaching approaches and assessment methods. However, most courses in mathematics and physics have only partial or no integration of computing, and in other programs, such as in life sciences, computations are absent.

Establishing a world-leading center: Our ambition is to transform the CSE project into a world-leading *Center for Computing in Science Education (CCSE)*. The center will unleash the potential of CSE by implementing it fully in physics and by extending the approach to other disciplines and institutions - opening for interactive, creative, and collaborative learning approaches and providing students with essential skills. Since the research evidence for CSE methods is sparse, we need to build a CSE educational research activity to provide a research basis. Effective dissemination requires professional educational material. Integration in other disciplines with students with weak backgrounds in mathematics demands novel approaches through cross-disciplinary collaborations.

Center profile: This requires a coordinated and substantial development and research effort that can only be achieved through a center for excellence. The center will (i) develop research-based educational material and approaches in physics and other disciplines, (ii) build a CSE educational research activity, (iii) nurture a culture for cross-disciplinary teaching and learning in partnership with students, and (iv) adapt and extend CSE to schools, colleges and universities, nationally and internationally. The center will use CSE to transform practices and immerse undergraduate students in complex problems that motivate, foster creativity and prepare them for a lifelong career.

Basis for success: We are in a unique position to fulfil this ambition based on our documented excellence in research and education, student involvement, and stakeholder partnerships. Starting from 2017 the bachelor programs at the Faculty will be redesigned, providing an ideal time-frame to study the effect of changes in approaches, curriculum and program design.

Documented educational quality in existing provision

Input factors

Excellence in existing CSE initiative: The center builds on the Computing in Science Education (CSE) initiative at the Faculty[2], a flagship project with strong leadership support and financing (700kkr/yr) which aims to integrate computing in undergraduate curriculums. The Dean of Education heads the CSE management group that allocates resources for development and student activities, organizes yearly conferences, evaluates and reports. CSE is prominent in the strategy of both the Faculty and the host Departments [3], it is a key brand for the education of the Faculty, and it is often presented as an example of the outstanding educational quality of the Faculty and the University of Oslo [4]. The quality is demonstrated by external funding attracted to the project (4 mill. kr)[5]; partnership in an EU-funded iCSE center [6]; appointment by the Ministry of Education to develop a national guide for CSE[7]; invited talks at international conferences[8-12], universities [13, 14], and at numerous national conferences, meetings, and workgroups[15-23]. The CSE activity has published five top-selling international textbooks with integrated computational approaches[24-28], was awarded best article of 2015 in the pedagogical journal UniPed[29], and has won the prize for excellent learning environment at UiO in 2000, 2011, 2012, and 2015; the national (Nokut) prize for educational excellence in 2012, and the Thon national educator prize in 2015 and 2016.

Excellence in research: The ability to develop an excellent research-near education and a new research-based curriculum depends on excellent research. Our faculty are internationally leading researchers[30]. Key faculty were group and center leaders for three Centers of Excellence in Research[31]. It was indeed the research collaboration in these cross-disciplinary, computationally oriented centers that initiated the educational collaborations across departments that forms the basis of CCSE. The educational research activity of CCSE builds on the Physics Education Research group in collaboration with Professors Stensaker and Strømsø, Faculty of Education, and the Physics Education Research group at Michigan State University[32-35].

Educational leadership and study program design: CCSE will play a key role in the design, implementation and evaluation of the Faculty's new bachelor programs starting in 2017. The transition will provide a unique opportunity to develop programs and to evaluate the impact of program design, curricular changes, and teaching approaches. Resource allocation is monitored by education leaders who are part of the leadership groups at the Department and Faculty level.

Process factors

Research-based and research-near education: The development of a new curriculum is research-based in its motivation and in its realization: All faculty members involved in teaching have scientific activities that use computational methods, thus allowing a close coupling between research activities and curricular development. The integration of computing gives the students the skills needed to work on research-near and realistic problems early on, exposing students to realistic work methods and introducing a sense of wonder and exploration to undergraduate education. With these skills, students have contributed to research already from the second semester through organized undergraduate research activities. For example, using computational competence gained in the first semesters, a first-year student made a discovery that was published in the prestigious journal Proceedings of the National Academy of Sciences [36, 37], and an exam project that combined physics and computations was published in American Journal of Physics [38].

Research-based methods and student learning: The students are exposed to a wide range of learning methods from traditional lectures to innovative project-based research-near group projects and cross-disciplinary problem-based learning [39]. Many courses apply research-informed approaches to enhance learning and motivation. For example, "Fysmek1110: Mechanics" was one of the first courses in Norway to use peer instruction with clickers [40, 41], receiving exceptional student feedback [42]. The course "Fys3150: Computational Physics" has implemented project-based teaching with exceptional student feedback, such as "*I am a bit in love with this course. It is the best course I have ever taken!*" [43]. Good practice is studied [44-47] and disseminated to improve practice locally [15, 48, 49] and nationally [16, 17, 19, 20] through courses and seminars for the faculty, and in compulsory biannual seminars for teaching assistants to build their teaching competence.

Assessment and monitoring of learning: Assessment methods are aligned with the learning objectives and include: traditional, digital and oral exams, presentations, and peer and teacher reports. Science and math curricula are sequenced and require careful assessment of skill development to ensure progress. For peer and teacher assessment we employ a student-developed web-based delivery and reporting system, *Devilry*[50], which the students are more satisfied with than commercial alternatives. This gives us direct access to the assessment system, opening for studies of teacher-student interactions and their effect on learning.

Learning environment: The students have a strong community and organize their own spaces and resources including a supercomputer [51] as well as a new 400m^2 learning center, designed for social activities and active learning approaches [52]. They organize student mentors to build social networks from the very first week and the Faculty finances a two-day seminar to build class identity.

Student engagement: Students play an active role in curriculum development, strategy processes, and quality systems. They develop CSE learning material and extend the use of CSE through summer internships. Students have developed and taught preparatory courses in programming and developed course blogs[53]. The 2014 NOKUT evaluation of the Bachelor program in physics[54] stated (p. 16): *".. the institute hired strong students to develop CSE further… The committee considers such a stimulating development of the field, where the students are included, as an exciting process. The measure is a good example on how the basic education can be research-near and give a closer dialogue between teachers and students… The students that the committee met with were enthusiastic about the measures associated with the introduction of CSE".*

Student feedback: Student feedback is systematically used to improve teaching and learning with student organizations using focus groups, questionnaires, interviews and dialogue meetings as part of the quality system. In the StudentBarometer [55] our students report on "their possibility to affect the content and approaches of the program" and "how criticism and views from the students are followed through" with scores that are 0.8 and 0.7 above the national average (scale 0-5).

Outcome factors

Student achievement: The Physics BSc at UiO is the largest physics program in Norway. The program has the highest scores in the StudentBarometer with an overall score of 4.5/5 (second best:

4.2), student retention is 93% (83%) after 1 (5) semesters, and ECTS/year were 58 for students starting 2013 (national average: 40). Recruitment of women has increased from 25% in 2011to 38% in 2015 compared to 23% in physics nationally [55]. Special focus has been placed on understanding and improving first year retention through the research-near experience provided by CSE. The justification for the 2012 Nokut prize gives further evidence of the high standards achieved: *"Of learning outcomes described, the committee would highlight increased standards both in advanced subjects and in exams on the bachelor level. Students proceeding with a master degree are able to more quickly commence research since they are more operational in computational methods."* Student achievement is documented by student research publications[37, 38, 56, 57] and awards: former CSE students [58] won the 2015 UiO innovation award for a series of teaching apps [59, 60].

Relevance of education: The integration of computing into the science curricula answers to signals from research and industry that these skills are critical for a lifelong career. Almost all students continue with a master degree in physics. Educational relevance therefore includes results from the physics master program. Students are exceptionally satisfied. At studiekvalitet.no [61], a database compiled by the science and technology organizations, physics at UiO is the top rated program with 100% of its students in relevant jobs. This is also reflected in the Candidate Survey [62] p. 32, where 93% of the alumni reports that they are "very satisfied" or "satisfied" with the outcome of the education, 59% have relevant jobs before graduation, and 87% have relevant work half a year after graduation. In the StudieBarometer [55] the physics program scores 4.4/5 on "Working life relevance", 0.2 above the second best. The competence of our students is in high demand. For example, 60% of the graduates with a master in computational physics (2003-2015) were recruited to PhD studies in fields such as life science, geoscience, chemistry and physics.

The Center Plan

Vision: The vision of the center is to develop a research-based foundation for the integration of computing into basic education and to become an international hub for this activity. The center will lead research-based development of new learning materials, methods and practices, study their effects and how they transform student learning and teaching culture, involve students deeply in the development of new practices and methods, and disseminate and adapt the practices and results across disciplines in collaboration with key partners.

Innovation

The CSE initiative has been a success with innovations in select courses. CCSE will build on and extend this success to provide a new, research-based curriculum with professional learning materials and methods for the *entire* basic physics curriculum. CSE will be adapted to new institutions and disciplines, such as to university colleges to other sciences, which requires the innovation of new material and approaches beyond the scope of the current CSE initiative.

Importance for higher education: There is a general consensus that computing should be included in physics and science educations[63-66], but most degree programs only include isolated computational courses, instead of integrating computing in the basic curriculum[65]. This is because integration requires coordinated changes in mathematics, computer science, and physics - a difficult task - and because there is a lack of high-quality research-based material and approaches. There is also an international effort to make undergraduate education research-near and cross-disciplinary. The CSE approach will provide students with the skills needed to engage in research-near and industry-near problems using realistic workflows and scientific approaches early on. This opens for collaborative learning, unleashes creativity and allows students to connect disciplines with each other and with reality - important factors for motivation and retention[67].

Novelties and transformations of current practices: To unleash the advantages of CSE, the center will develop new textbooks, new problems, new teaching methods and new assessment methods that integrate computational methods – not only in physics, but also in supporting courses in mathematics and computer science. We will develop a research-based understanding for how computational methods and reasoning affects student learning of basic physical and mathematical principles compared to traditional practices, which teaching practices are effective and in what way, and how computing can make undergraduate education more research-relevant. We will develop and study case and project-based approaches that engage students in digital collaboration and creative problem-solving using real-world data - providing skills needed for a lifelong career. This transformation is challenging since traditional approaches have been finely honed over many years and poses a rare opportunity for a paradigmatic shift. However, since we have built a culture of trust and collaboration across departments, we can develop material and approaches and study their effect on student learning in mathematics, computer science, and physics simultaneously. This puts us in a unique position to build a sustainable curriculum that can be improved systematically.

Innovation beyond physics: Physics is a good starting point for a CSE reform because mathematics and computing are integrated in the practice of the discipline. However, computing is changing all sciences and all aspects of society[1]. The integration of computing, algorithmic thinking, and data will therefore gradually affect educations across disciplines, and experiences from CSE in physics will provide a foundation for adaptation in other sciences and disciplines.

Student involvement in development and innovation: Students will participate at all levels in development, evaluation, research and innovation in the center. Indeed, students are sometimes more competent than faculty to develop computational learning material and exercises. Students will serve as teaching assistants supported by pedagogical seminars and peer-support groups. Senior students may participate in educational research projects to observe learning processes and interview students, thus enhancing their meta-understanding of their own learning processes. The center will fund student-driven innovation projects to develop learning tools and data-collection platforms, and organize research projects for bachelor-students.

Relation to international developments in higher education: Physics Education Research is an active international research field that has developed well-established best practices for physics educations[41, 68]. New contents and approaches must therefore be research-based to gain wide acceptance. Thus there is a need for a robust educational research activity on CSE to develop pedagogical arguments for how such a renewal will improve student learning, motivation, and retention. Teaching in the center will be based on best practices including student-active[69] and project-based methods[68]. We will systematically study learning outcomes using our open-source student delivery and feedback system, *devilry.org*, which will provide important insights into student learning. We will build on existing initiatives, such as Matter & Interactions[70] and Open Source Physics[71], but our approach is far more ambitious as it combines changes in mathematics, computer science, and physics, and extensions to other fields.

Key steps to be taken for the vision to be realized: from the present state to the ten-year goal

Present state: Existing interdepartmental culture for CSE with some excellent teaching practices and strong student engagement. Math and programming integrated in first semester. Full CSE integration in 2 of 6 basic physic courses and partial integration in other courses. Two textbooks have been published internationally. The research basis for methods and approaches is sparse.

Five-year goal: The center has initiated a research-based approach to curriculum change and teaching and learning methods in partnership with students. Full integration of CSE in 4 of 6 basic physics courses, with two new textbooks, 2 of 4 math courses, and 1 astronomy course. A pilot extension of CSE into biology; a pilot adaptation by an external partner; a pilot school interaction program; and pilot studies of learning outcomes and teaching methods in 3 courses.

Ten-year goal: The center is an internationally leading hub for research-based approaches to CSE, with a strong educational research activity; an international repository for methods and materials; and strong student partnership. Full integration of CSE into 6 of 6 basic and 2 advanced physics courses, 4 of 4 math courses, and 2 astronomy courses. Extensions of CSE to 3 other disciplines at UiO. Adaptation of CSE at 2 external partners. A well-running school interaction program.

We aim to achieve this through the following coupled work-packages (WP) and actions (A):

WP0: Administration and **WP5: Dissemination** are described in the text.

WP1: Research-based development of teaching material: *A1.1*: Develop a repository of teaching material and evaluation methods; *A1.2*: Develop textbooks and interactive and modularized material with integration of computational methods and programming examples; *A1.3*: Study usage and effects using big data approaches, interviews, and observation; *A1.4*: Provide writer support including writing groups and use of students to improve texts; Develop CSE publishing tools; Build partnership with Springer on CSE book series.

WP2: Research-based development of methods and approaches: *A2.1*: Student-active learning: Develop, apply and evaluate traditional and new learning methods in CSE courses; *A2.2*: Develop and test research- and industry-near CSE cases in collaboration with stakeholders; *A2.3*: Develop and study methods for assessing student work and collecting data for CSE courses; *A2.4*: Develop and test methods that use innovative digital and physical learning environments; *A2.5*: Develop, test and evaluate study programs and courses; *A2.6*: Appoint a senior researcher to form a basis for the research activity and a conduit for transformative ideas.

WP3: Develop a culture for teaching and learning: *A3.1*: Develop school-university transition program and investigate effects on recruitment, retention, and results; *A3.2*: Improve student culture through student spaces, mentor programs and startup seminars; *A3.3*: Develop teacher culture through annual teacher retreat, teaching in teams, workshops and seminars with focus on teaching, and learning and curriculum development; *A3.4*: Develop quality systems and student evaluation methods to enhance constructive alignment and ensure quality development through systematic feedback and improvement; *A3.5*: Promote teaching skills renewal through pedagogical courses, educational sabbaticals, and career goals for teaching proficiency and excellence.

WP4: Student-driven activities: *A4.1*: Establish student partnership board; *A4.2*: Support educational research projects where students collaborate with pedagogical researchers; *A4.3*: Support student development of material, exercises and case studies; *A4.4*: Support that student teaching assistants develop, share and document expertise through mentoring, courses, and workshops; *A4.5*: Support student-developed instruction initiatives such as short courses, seminar series and science competitions; *A4.6*: Support student innovation projects; *A4.7*: Support research activities for bachelor students; *A4.8*: Support student internships in research and industry.

Additionality: Outcome and impact of the center that could not be achieved without support

The CSE initiative has produced exceptional results based on enthusiastic individuals paired with supportive students, leadership and a strong culture for collaboration. This is not a sustainable model for the high ambitions we have for the CSE activity. Further progress, dissemination and impact now depend on developing a research basis for the activity. This was argued by the Nokut evaluation in 2014: "*The Faculty should strengthen the CSE initiative by evaluating the consequences of the project*", and the Ministry-appointed work-group in 2010: "*The ministry should establish a national CSE Centre. This will be a resource for computing oriented education and will* *collect teaching material, examples and tasks. The CSE Centre will also initiate and coordinate research which will study different aspects of computing oriented education in order to document the results and help establish good teaching practice*". Well-founded research-based arguments and high quality, tested learning materials are needed to spread the practice across disciplines, nationally and internationally. However, there are no resources for a CSE educational research activity at UiO without a center. The ambition to turn CSE into an internationally leading research-based activity and to expand to other fields can therefore only be achieved by the coordinated effort of a center that combines internal and external resources and groups spanning educational development, research and practice as well as student partnership.

Evaluation and impact framework

The center will develop measures of progress based on milestones and deliverables in the activity plan and ten-year goals and development (i) in quality indicators at the individual, course/program and institutional level; (ii) in recruitment, retention and graduation rates; and (iii) in students scores on standardized and customized tests. Methods to assess student achievement and learning outcomes for CSE learning objectives will be developed, tested and applied, serving as benchmarks for dissemination practices. Scoring for CSE integration will be included in student evaluations.

Contributions to institutional development: The center will finance development and research of teaching and learning practices across the institution, and contribute to pedagogical education of students and teachers. The center will establish CSE quality committees with representation from students, teachers, leadership and external stakeholders to ensure that CSE elements are introduced in a coordinated way throughout the education. The CSE educational research activity will serve as a seed for the development of educational research at the Faculty.

Value for money: The educational research activity requires long-term financing, and will be reassessed after four years. The effect of short term financing to development, research, and student-driven activities will be evaluated based on contributions to milestones, deliverables and quality indicators and funding may be redistributed among the WPs to optimize value for money.

Post-funding and exit strategies: The educational research activity will be continued by the physics department and will have reached a standing that allows for funding through external projects. CSE will be integrated in study program design, curricula, and teaching practices beyond the center period. Tradition for teaching excellence will be embedded in lasting practices such as pedagogical courses, seminars, academic hiring, and a part of the student and teacher culture.

Dissemination, dialogue and communication through partnerships (WP5)

Learning material: New curricula require new learning material. The center will establish an interactive web-based repository for teaching methods, lectures, exercises and exams with experiences and feedback from practitioners and students. An international textbook series will be published through a partnership with Springer. Research results on CSE approaches will be published internationally, presented at conferences by students and faculty, presented to university and government officials by Faculty leadership, and popularized for general media and blogs by students, faculty, and Faculty leaders. Experiences, results and methods will be presented at a yearly national workshop that will include systematic training of university teachers.

Internal dissemination: The center will host regular research seminars, seminars on educational practices, and CSE workshops to educate leadership, teaching faculty and students. The center will support teacher and student development projects to adapt approaches to new fields and establish scholarships for excellent students to work on CSE development or research projects of choice.

Extension to new programs at UiO will be organized through partnerships illustrated by the approach in biology: (i) Develop plans with leadership and senior faculty. (ii) Competent PhD students develop new materials and approaches in collaboration with seniors. (iii) Pilot courses are tested with biology students and adjusted, (iv) and integrated into regular courses by faculty. (v) Regularly investigate and adjust approaches, (vi) and evaluate and review with leadership.

Extension to other institutions: Transition mechanisms will be developed through a pilot at the University College of Southeast Norway and then extended to other institutions. **International extensions** will be done with key international collaborators such as Michigan State University, and through our international platform for educational and research partnerships, INTPART[72].

School partnerships: The introduction of CSE may lead to new challenges for students as they transition from schools to university. We will therefore initiate studies of the transition process in partnerships with selected schools. For example, school classes with teachers can visit the university to work on a realistic, research-near project that integrates mathematics, computing, and physics taught by university teachers and student instructors, thus allowing us to address students and school teachers, in collaboration with the ProTed SFU at UiO.

Organization and Partners

Center organization (WP0): The center is hosted by the Department of Physics, UiO. The center will be lead by its director, a coordinator and a WP leadership group. The board, with stakeholder representatives, will have oversight of budget and strategy. An advisory board with international authorities on computing and science education will meet biennially to advise and evaluate the center's performance. The center will host a new CSE educational research group with faculty, post-docs, PhD-students, collaborators from the Faculty of Education and adjunct professor Caballero from MSU. Active partners include the Univ. College of Southeastern Norway, Michigan State University, Valler High School and a consortium of research and industry stakeholders.

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